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The Application of Life-Cycle Assessment to Solid Waste Management: Applications, Challenges and Modeling Techniques

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The Application of Life-Cycle Assessment to Solid Waste Management: Applications, Challenges and Modeling Techniques

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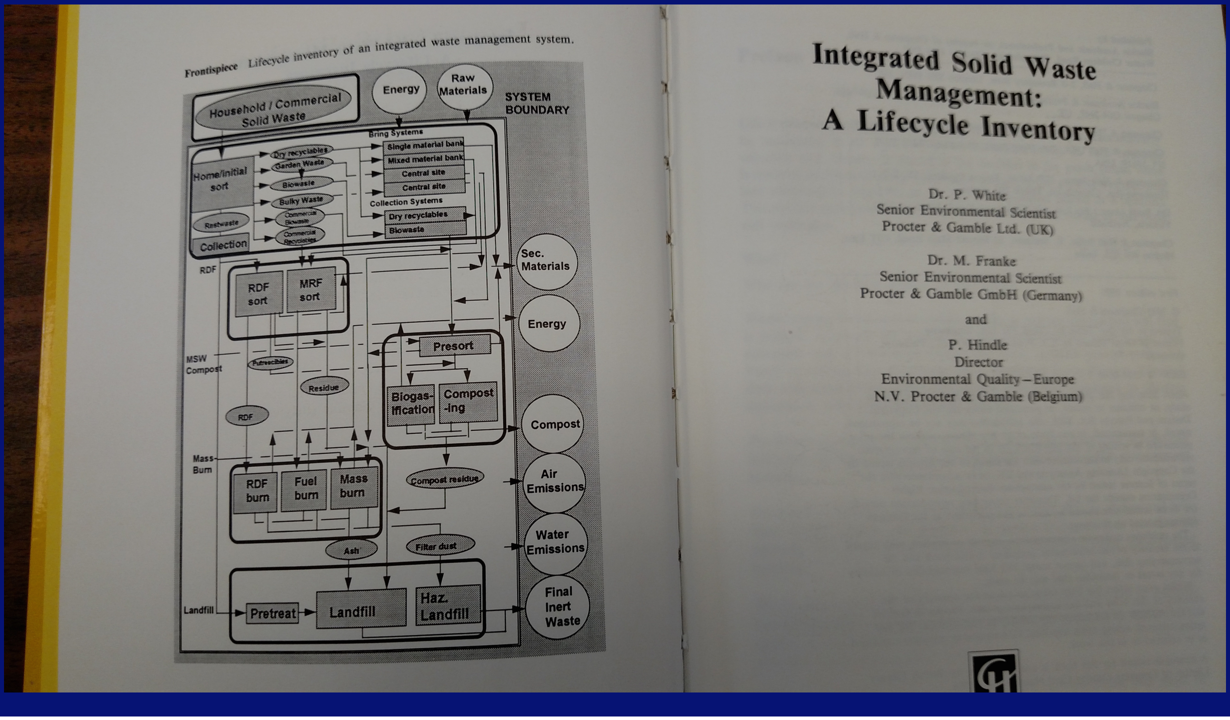
NC STATE UNIVERSITY

Introduction and Objectives

- Perspective on accomplishments to date
  - Observations on tools
  - Range of applications to illustrate methods
  - Methodologies
    - Uncertainties
    - Tradeoffs
  - Challenges
- Somewhat focused on U.S and very focused on waste
  - hope will stimulate dialog
- Municipal solid waste (MSW)
  - Residential, multifamily, commercial
  - Not industrial, biosolids

Introduction and Objectives

- The application of life-cycle assessment to solid waste management has been discussed for about 25 years
  - Integrated Solid Waste Management: A Life-Cycle Inventory (McDougall, White, Franke and Hindle, 1994)



Frontispiece Lifecycle inventory of an integrated waste management system.

Integrated Solid Waste Management: A Lifecycle Inventory

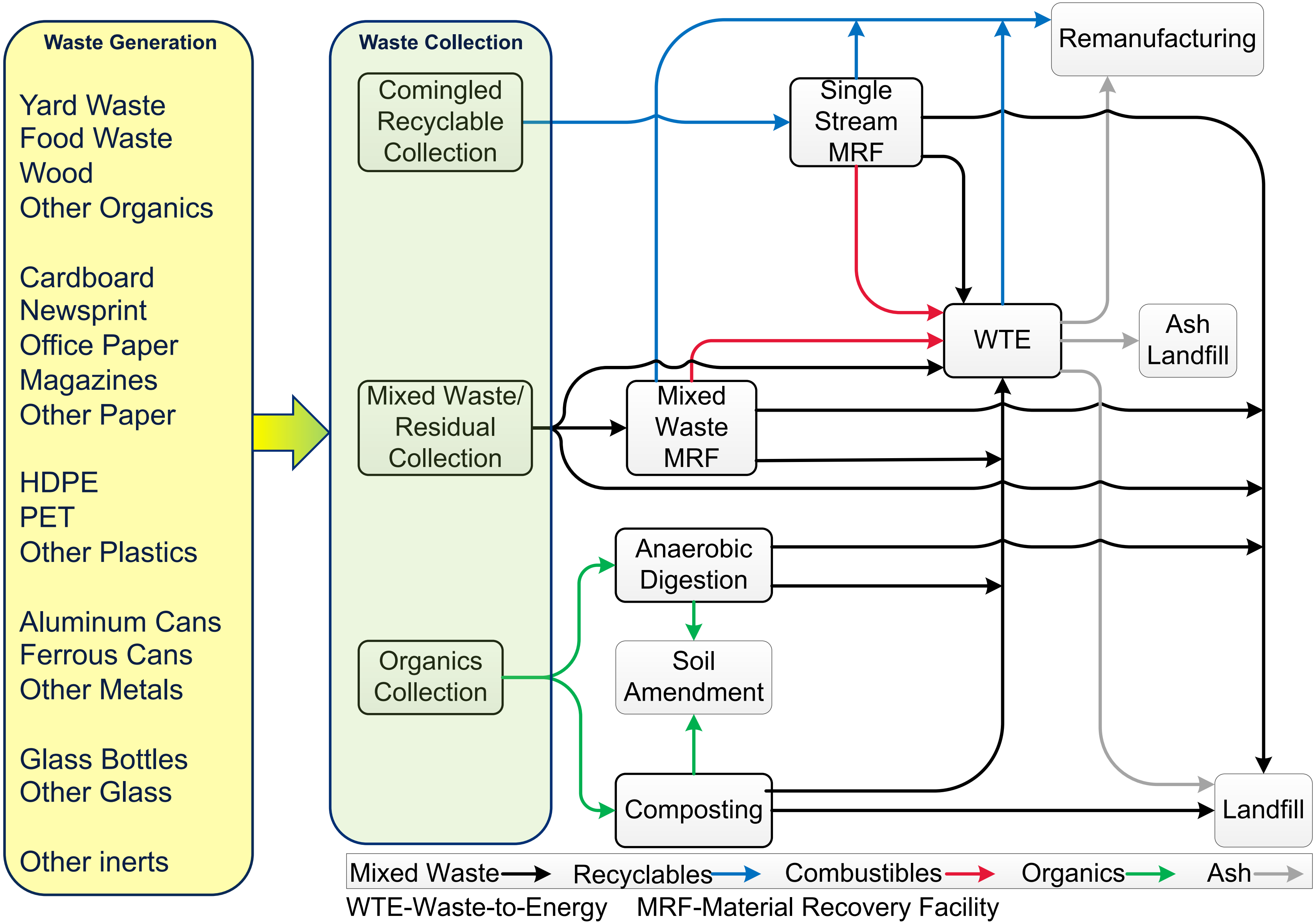
Dr. P. White
Senior Environmental Scientist
Procter & Gamble Ltd. (UK)

Dr. M. Franke
Senior Environmental Scientist
Procter & Gamble GmbH (Germany)

and

P. Hindle
Director
Environmental Quality – Europe
N.V. Procter & Gamble (Belgium)

The Solid Waste System is Complex



Waste Generation

Yard Waste
Food Waste
Wood
Other Organics

Cardboard
Newsprint
Office Paper
Magazines
Other Paper

HDPE
PET
Other Plastics

Aluminum Cans
Ferrous Cans
Other Metals

Glass Bottles
Other Glass

Other inerts

Waste Collection

Comingled Recyclable Collection

Mixed Waste/ Residual Collection

Organics Collection

Single Stream MRF

Remanufacturing

WTE

Ash Landfill

Mixed Waste MRF

Anaerobic Digestion

Soil Amendment

Composting

Landfill

Mixed Waste → Recyclables → Combustibles → Organics → Ash →

WTE-Waste-to-Energy MRF-Material Recovery Facility

Levis, J. W.; Barlaz, M. A; Decarolis, J. F.; Ranjithan, S. R. A Systematic Exploration of Efficient Strategies to Manage Solid Waste in U.S. Municipalities: Perspectives from the Solid Waste Optimization Life-Cycle Framework (SWOLF). *Environ. Sci. Technol.* **2014**.

The Solid Waste System

- The beneficial use of products is included
  - Energy from anaerobic digestion, landfill, combustion
  - Land application of compost
  - Offsets from recyclable materials

The Solid Waste System and Study Objectives

- Defining the study objective is essential and the system definition may vary
  - We understand the solid waste system very well
  - We can help with product LCAs with rigorous evaluations of the waste management component
  - We need to do a better job of integrating our expertise with others working on product and process LCAs

Product Manufacturing

Product Use and Durability

End of Life Management

Functional Units

- 1000 kg (1 Mg) of MSW at the curb
  - Neglects what happens in the house, backyard composting
  - Focus on what the local solid waste authority can influence which is useful for decision support at the local level
  - May be different for a policy analysis at the national level
- 1000 kg disposed in a landfill at time zero
- 1000 kg in a landfill regardless of time (the landfill is then the functional unit)
- The best way to deliver 500 mL of beer
- Waste elimination or “source reduction”

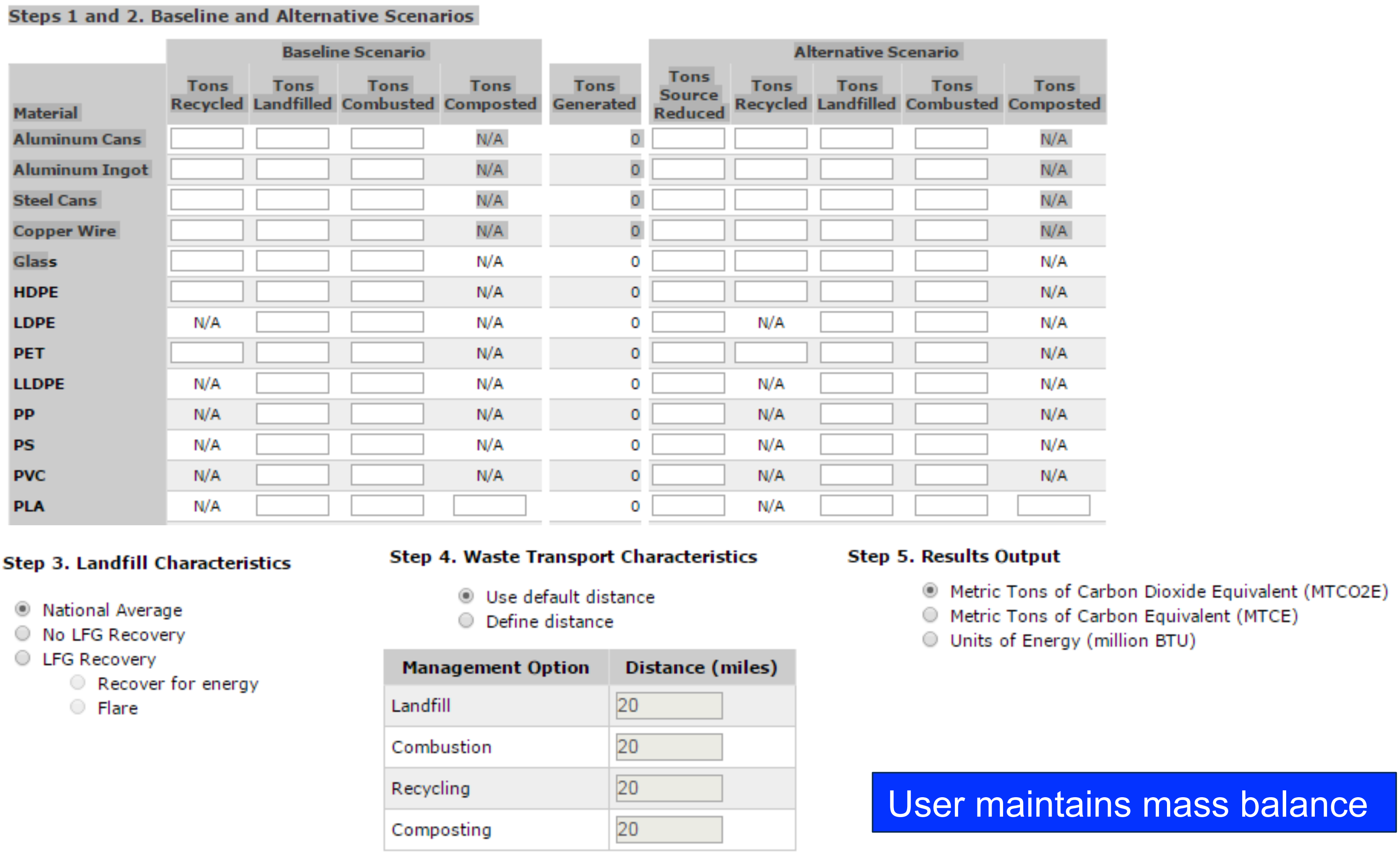
Observations: Simplicity vs Complexity

- What is the intended use? Who is the intended user?
  - Education
  - An LCA course
  - Policy research and local decision making
    - Engineering practice - still a screening tool
- Technology optimization/improvement assessment
- Challenging tradeoffs between simplicity and complexity (model flexibility) that must be considered in model design
  - Municipal solid waste vs ~30 waste components
  - Choices for the equipment configuration at a sorting plant vs. one option
  - Choices in impact factors and weighting schemes
  - Flexible energy grids

Advanced Models

- Solid waste management life-cycle optimization framework (SWOLF)
  - Allows user to explore alternate strategies in consideration of constraints
  - Multi-stage optimization model
    - Waste composition and energy grid are dynamic – allowed to change in 5 year intervals
  - Maximally flexible
  - Use in optimization or accounting mode
- EASETECH
  - Comprehensive model of the solid waste system; incorporates additional waste types and processes
  - Accounting mode only, superior interface
  - Uncertainty assessment

WARM Inputs (U.S. EPA) (GHG Only)



Steps 1 and 2. Baseline and Alternative Scenarios

	Baseline Scenario					Alternative Scenario				
Material	Tons Recycled	Tons Landfilled	Tons Combusted	Tons Composted	Tons Generated	Tons Source Reduced	Tons Recycled	Tons Landfilled	Tons Combusted	Tons Composted
Aluminum Cans				N/A	0					N/A
Aluminum Ingot				N/A	0					N/A
Steel Cans				N/A	0					N/A
Copper Wire				N/A	0					N/A
Glass				N/A	0					N/A
HDPE				N/A	0					N/A
LDPE	N/A			N/A	0		N/A			N/A
PET				N/A	0					N/A
LLDPE	N/A			N/A	0		N/A			N/A
PP	N/A			N/A	0		N/A			N/A
PS	N/A			N/A	0		N/A			N/A
PVC	N/A			N/A	0		N/A			N/A
PLA	N/A				0		N/A			

Step 3. Landfill Characteristics

- ● National Average
- ○ No LFG Recovery
- ○ LFG Recovery
  - ○ Recover for energy
  - ○ Flare

Step 4. Waste Transport Characteristics

- ● Use default distance
- ○ Define distance

Management Option	Distance (miles)
Landfill	20
Combustion	20
Recycling	20
Composting	20

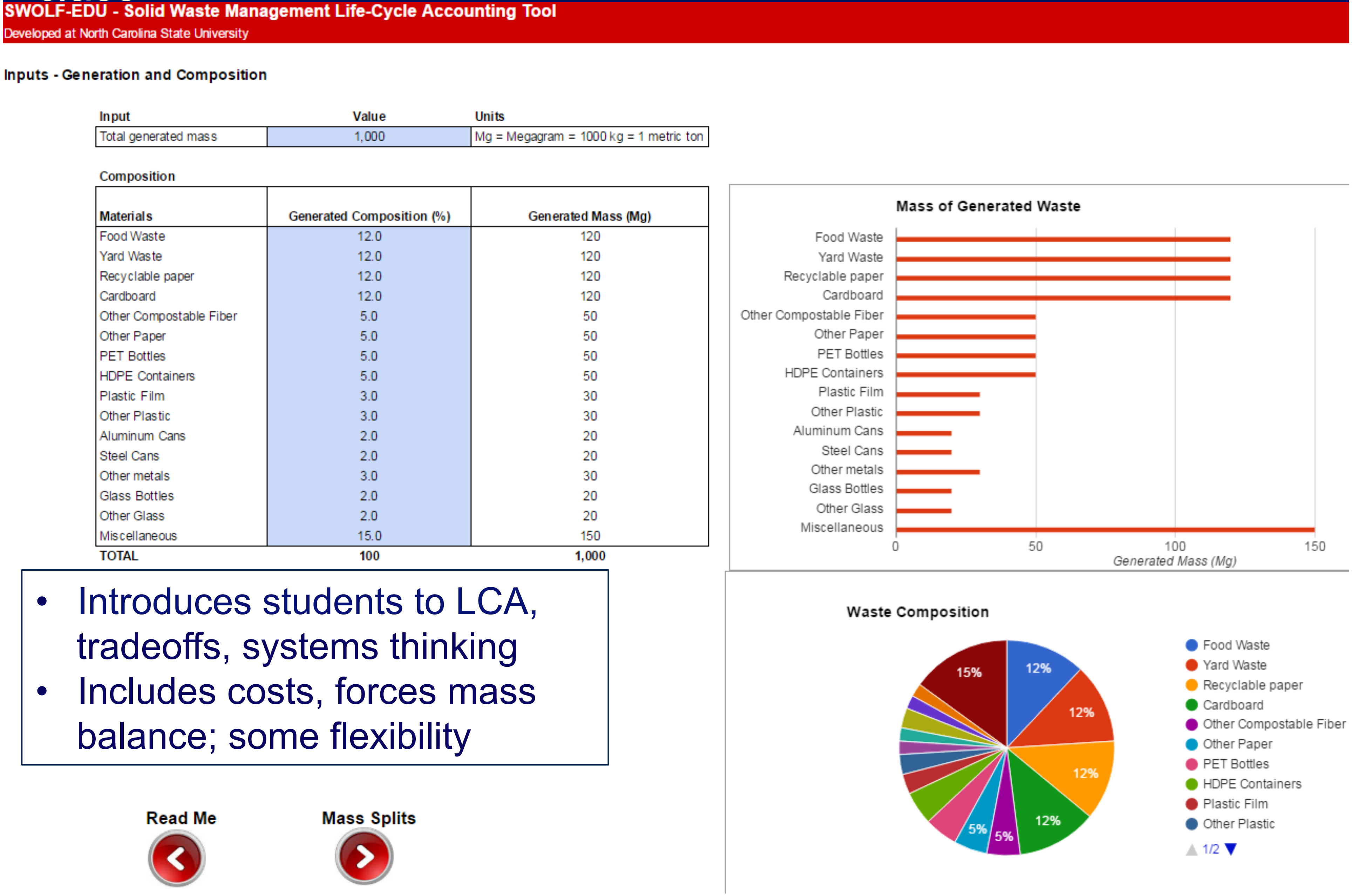
Step 5. Results Output

- ● Metric Tons of Carbon Dioxide Equivalent (MTCO2E)
- ○ Metric Tons of Carbon Equivalent (MTCE)
- ○ Units of Energy (million BTU)

User maintains mass balance

https://www3.epa.gov/warm/Warm_Form.html

SWOLF- EDU: used in undergraduate environmental science class



SWOLF-EDU - Solid Waste Management Life-Cycle Accounting Tool

Developed at North Carolina State University

Inputs - Generation and Composition

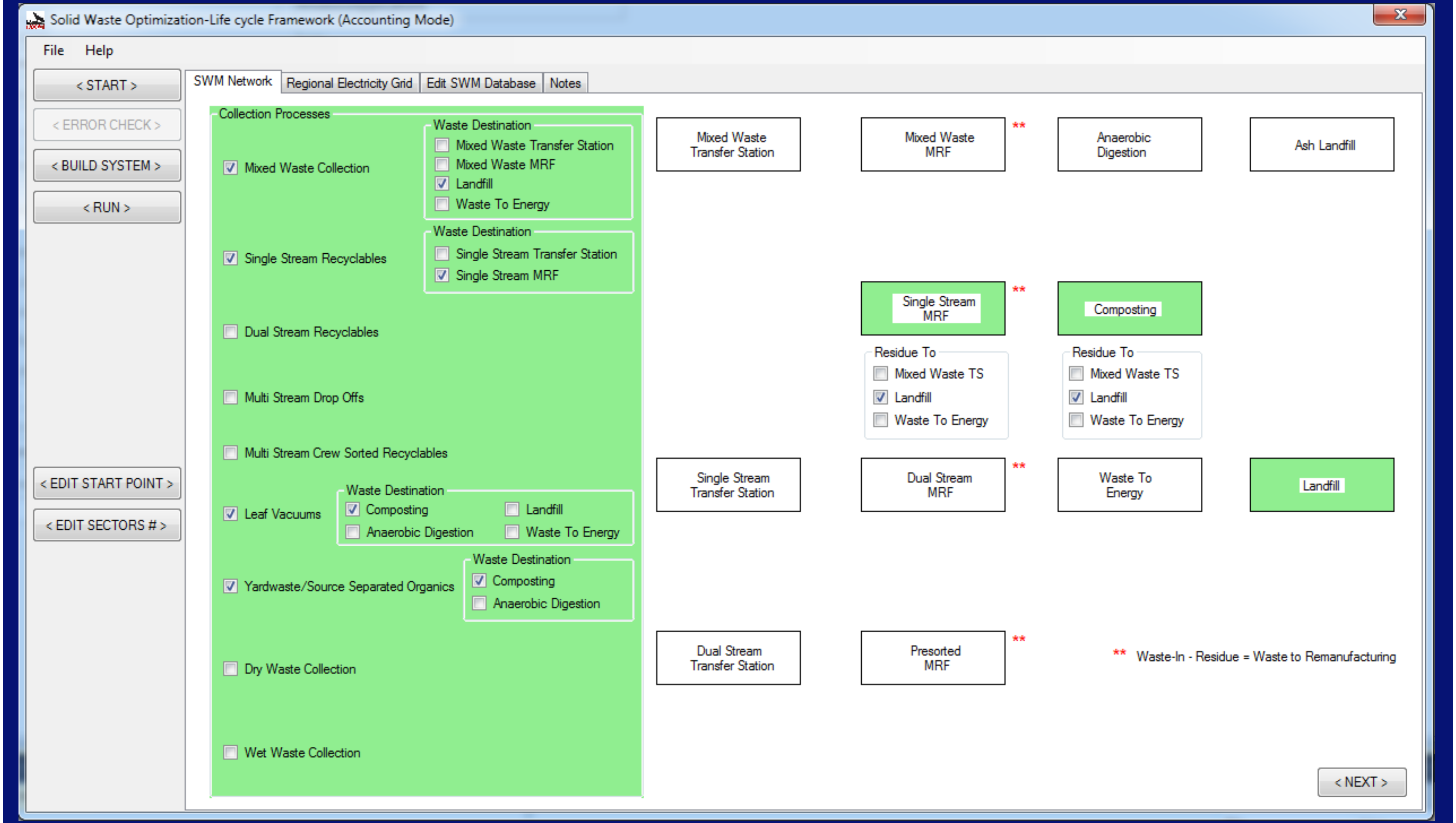
Input	Value	Units
Total generated mass	1,000	Mg = Megagram = 1000 kg = 1 metric ton

Composition

Materials	Generated Composition (%)	Generated Mass (Mg)
Food Waste	12.0	120
Yard Waste	12.0	120
Recyclable paper	12.0	120
Cardboard	12.0	120
Other Compostable Fiber	5.0	50
Other Paper	5.0	50
PET Bottles	5.0	50
HDPE Containers	5.0	50
Plastic Film	3.0	30
Other Plastic	3.0	30
Aluminum Cans	2.0	20
Steel Cans	2.0	20
Other metals	3.0	30
Glass Bottles	2.0	20
Other Glass	2.0	20
Miscellaneous	15.0	150
TOTAL	**100**	**1,000**

- Introduces students to LCA, tradeoffs, systems thinking
- Includes costs, forces mass balance; some flexibility

SWOLF



Collection Processes

☑ Mixed Waste Collection
Waste Destination
☐ Mixed Waste Transfer Station
☐ Mixed Waste MRF
☑ Landfill
☐ Waste To Energy

☑ Single Stream Recyclables
Waste Destination
☐ Single Stream Transfer Station
☑ Single Stream MRF

☐ Dual Stream Recyclables

☐ Multi Stream Drop Offs

☐ Multi Stream Crew Sorted Recyclables

☑ Leaf Vacuums
Waste Destination
☑ Composting
☐ Anaerobic Digestion
☐ Landfill
☐ Waste To Energy

☑ Yardwaste/Source Separated Organics
Waste Destination
☑ Composting
☐ Anaerobic Digestion

☐ Dry Waste Collection

☐ Wet Waste Collection

Single Stream MRF – Residue To
☐ Mixed Waste TS
☑ Landfill
☐ Waste To Energy

Composting – Residue To
☐ Mixed Waste TS
☑ Landfill
☐ Waste To Energy

** Waste-In - Residue = Waste to Remanufacturing

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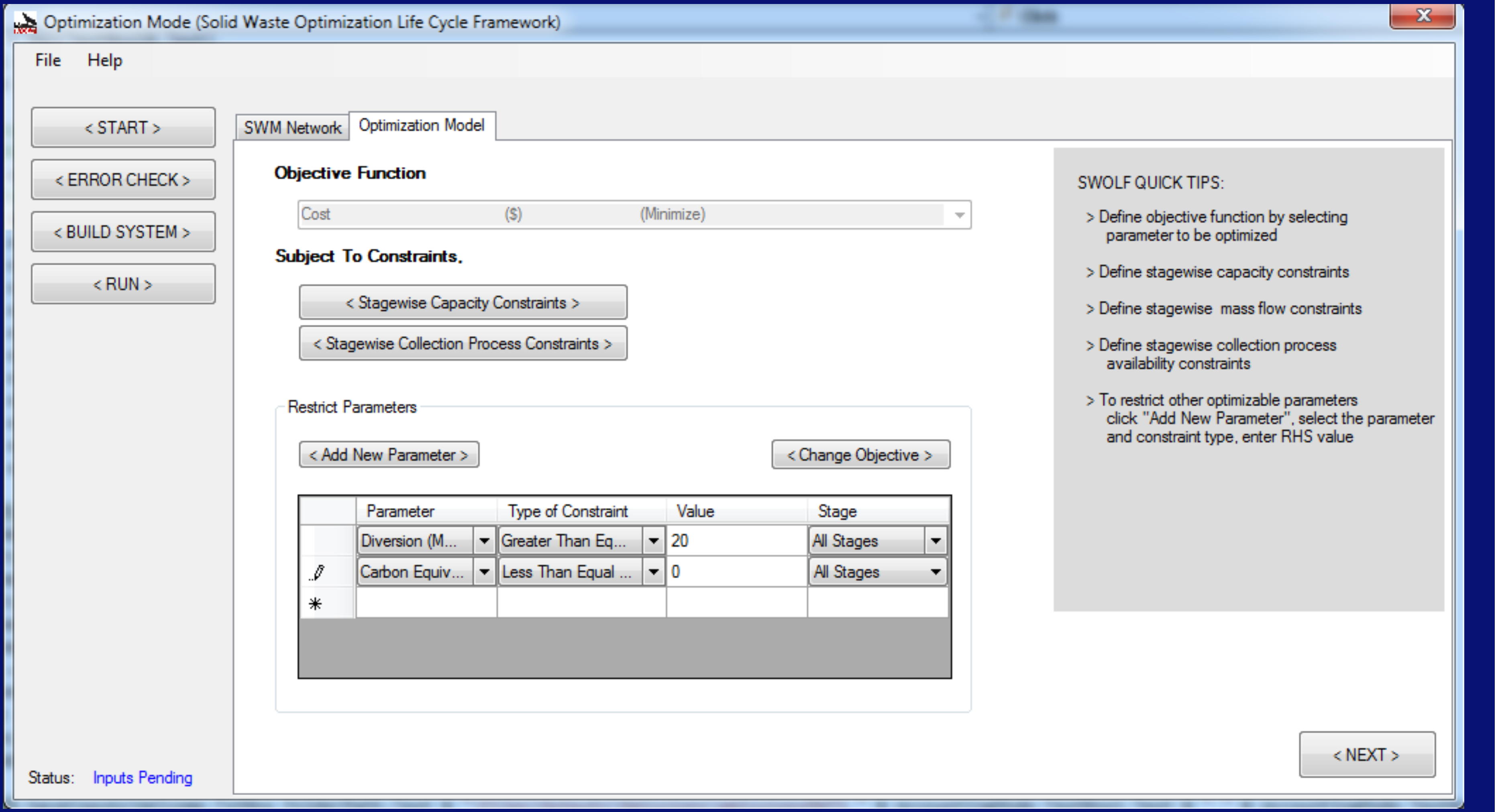
SWOLF



Objective Function

Cost ($) (Minimize)

Subject To Constraints.

Restrict Parameters

Parameter	Type of Constraint	Value	Stage
Diversion (M...	Greater Than Eq...	20	All Stages
Carbon Equiv...	Less Than Equal ...	0	All Stages

Status: Inputs Pending

SWOLF QUICK TIPS:

> Define objective function by selecting parameter to be optimized

> Define stagewise capacity constraints

> Define stagewise mass flow constraints

> Define stagewise collection process availability constraints

> To restrict other optimizable parameters click "Add New Parameter", select the parameter and constraint type, enter RHS value

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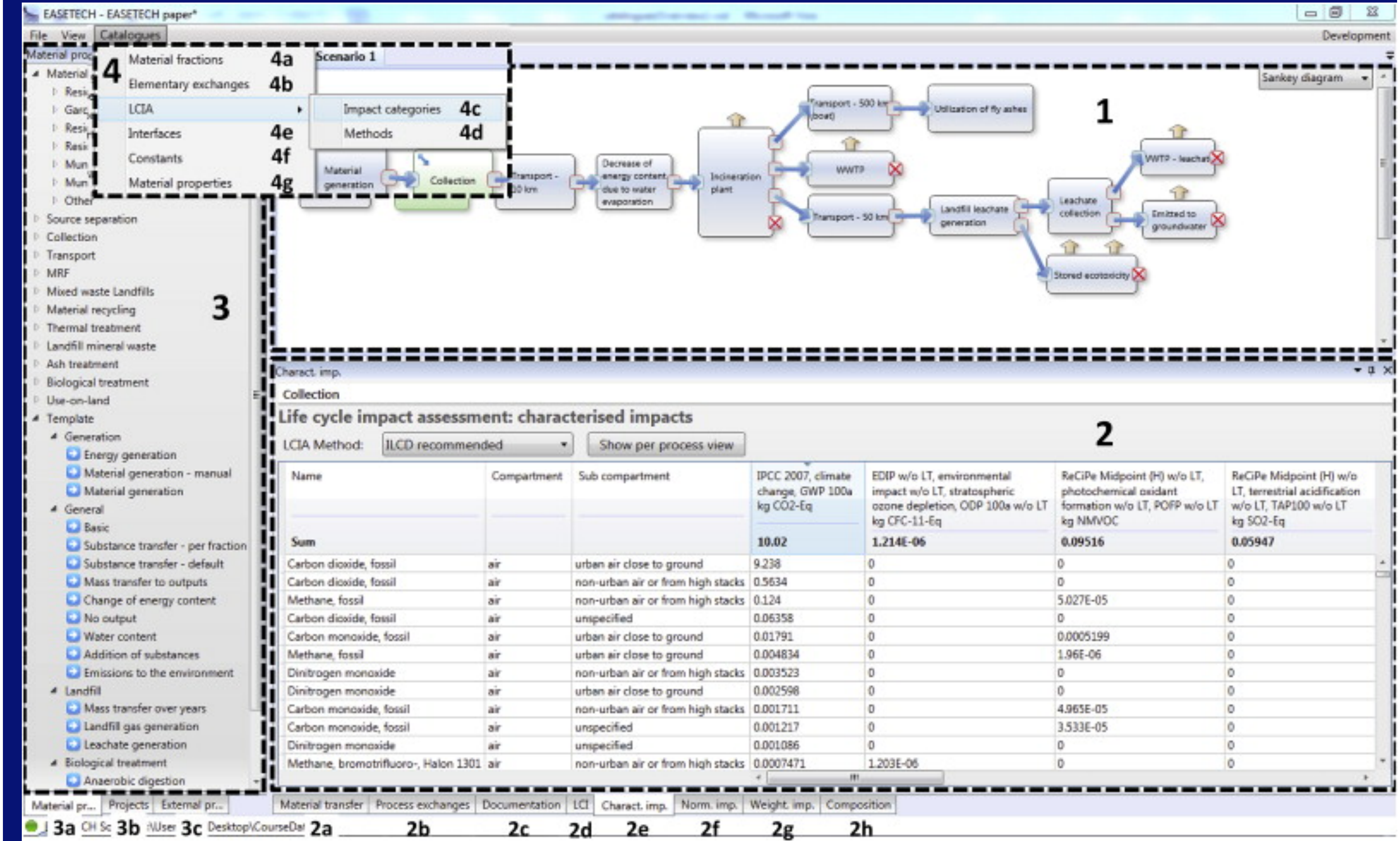
EASETECH

http://www.easetech.dk/



Life cycle impact assessment: characterised impacts

LCIA Method: ILCD recommended

Name	Compartment	Sub compartment	IPCC 2007, climate change, GWP 100a kg CO2-Eq	EDIP w/o LT, environmental impact w/o LT, stratospheric ozone depletion, ODP 100a w/o LT kg CFC-11-Eq	ReCiPe Midpoint (H) w/o LT, photochemical oxidant formation w/o LT, POFP w/o LT kg NMVOC	ReCiPe Midpoint (H) w/o LT, terrestrial acidification w/o LT, TAP100 w/o LT kg SO2-Eq
Sum			**10.02**	**1.214E-06**	**0.09516**	**0.05947**
Carbon dioxide, fossil	air	urban air close to ground	9.238	0	0	0
Carbon dioxide, fossil	air	non-urban air or from high stacks	0.5634	0	0	0
Methane, fossil	air	non-urban air or from high stacks	0.124	0	5.027E-05	0
Carbon dioxide, fossil	air	unspecified	0.06358	0	0	0
Carbon monoxide, fossil	air	urban air close to ground	0.01791	0	0.0005199	0
Methane, fossil	air	urban air close to ground	0.004834	0	1.96E-06	0
Dinitrogen monoxide	air	non-urban air or from high stacks	0.003523	0	0	0
Dinitrogen monoxide	air	urban air close to ground	0.002598	0	0	0
Carbon monoxide, fossil	air	non-urban air or from high stacks	0.001711	0	4.965E-05	0
Carbon monoxide, fossil	air	unspecified	0.001217	0	3.533E-05	0
Dinitrogen monoxide	air	unspecified	0.001086	0	0	0
Methane, bromotrifluoro-, Halon 1301	air	non-urban air or from high stacks	0.0007471	1.203E-06	0	0

Clavreul, J.; Baumeister, H.; Christensen, T. H.; Damgaard, A. An environmental assessment system for environmental technologies. *Environ. Model. Softw.* **2014**, *60*, 18–30.

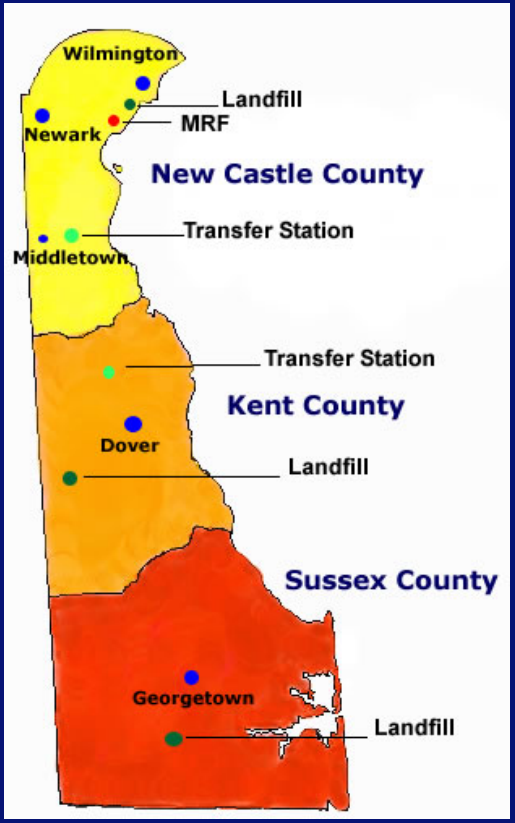
Application: Modeling Solid Waste Management in Delaware: A Statewide Analysis

- Use optimization modeling to evaluate multiple alternatives for solid waste management for State of Delaware
  - Consider cost, emissions, energy consumption
  - Consider scenarios that may differ from current practice
- Work conducted using the Municipal Solid Waste Decision Support tool (MSW-DST) (first generation tool)

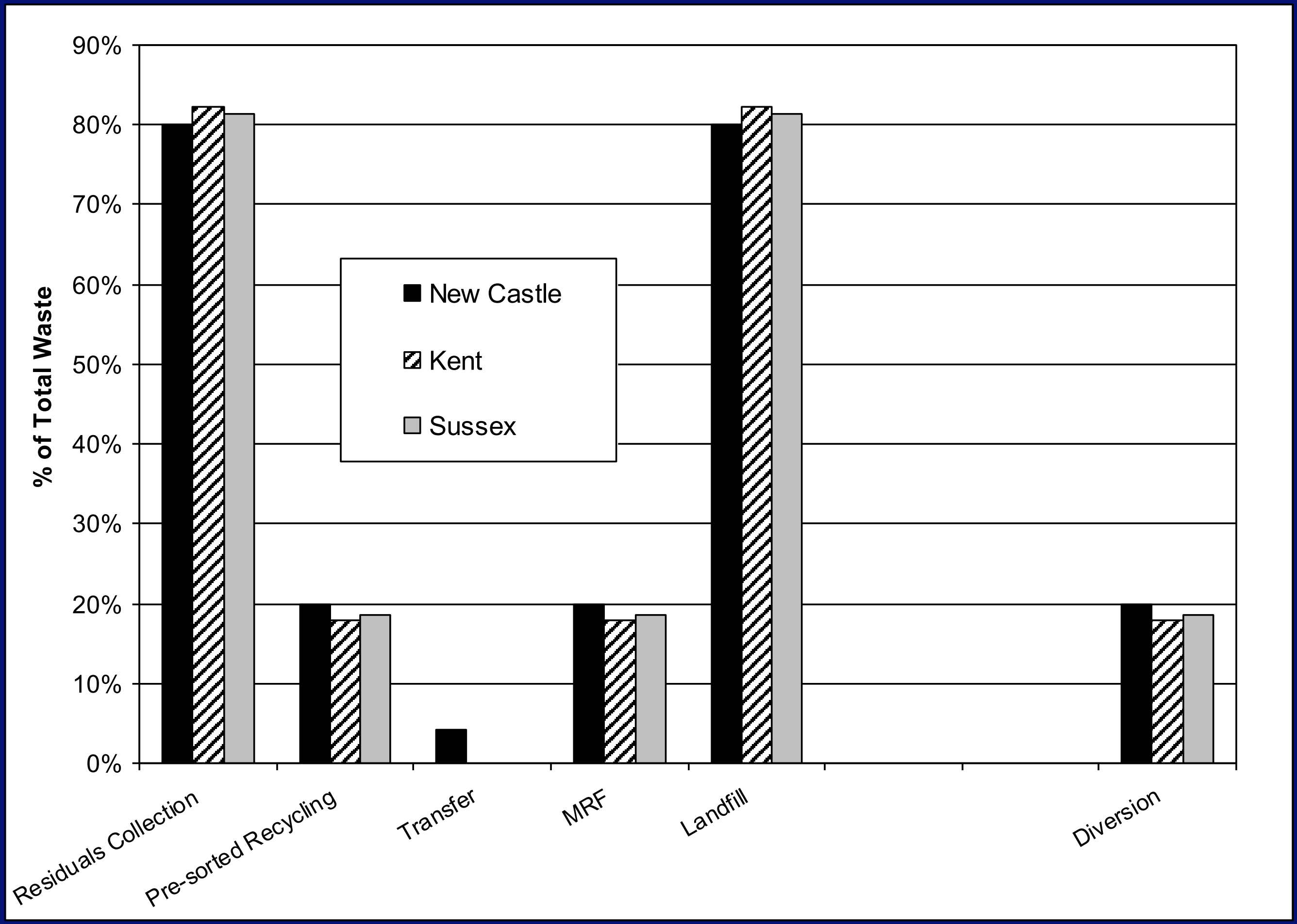
Kaplan, P. O.; Ranjithan, S. R.; Barlaz, M. a. Use of life-cycle analysis to support solid waste management planning for Delaware. *Environ. Sci. Technol.* **2009**, *43* (5), 1264–1270.

Modeling Solid Waste Management in Delaware: A Statewide Analysis

- Challenge: 3 counties and the funding authority does not control waste collection
- 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

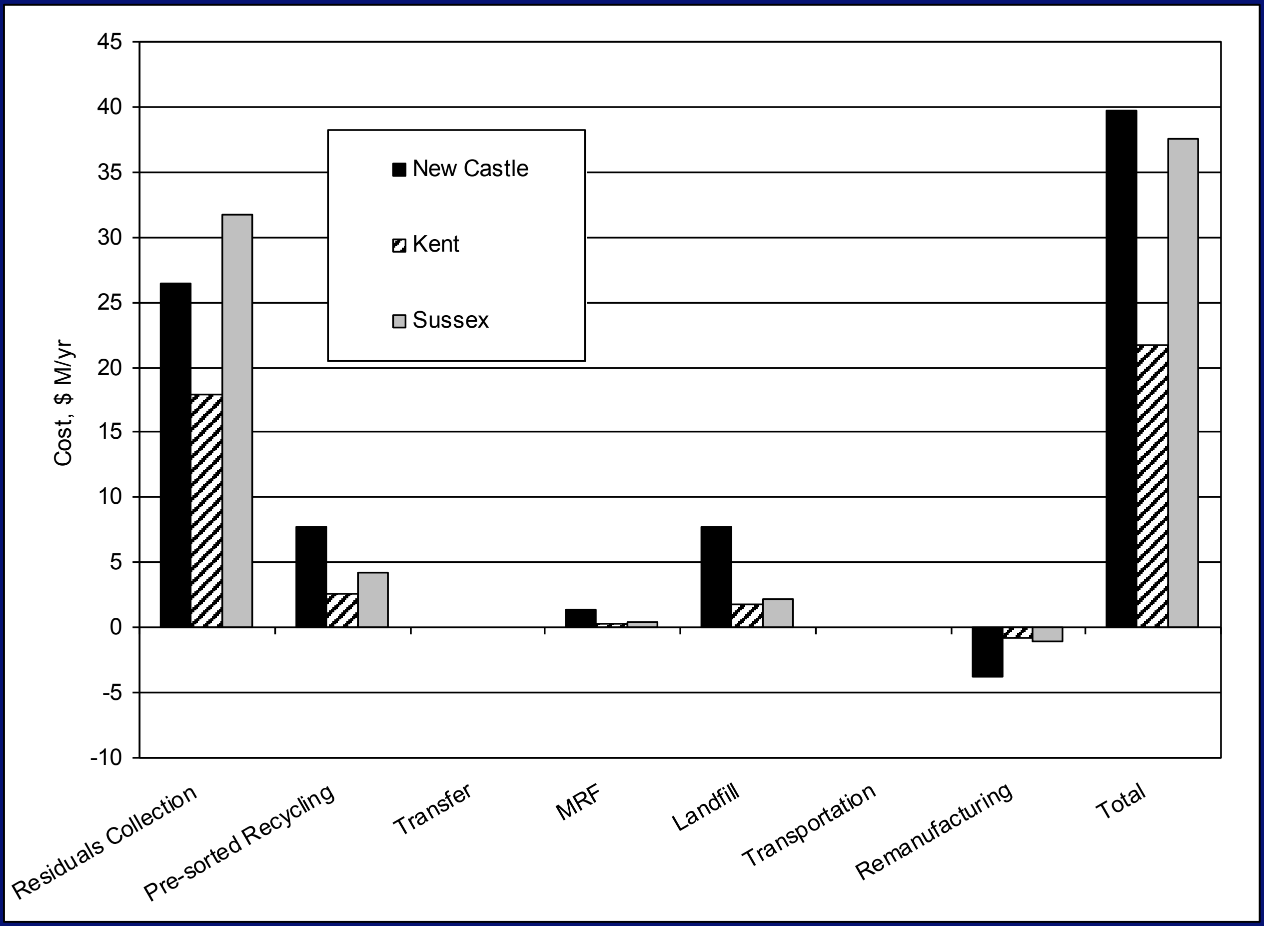


How Do we Combine Counties to Provide the State a Meaningful Roadmap?



The manner in which waste is handled is similar …

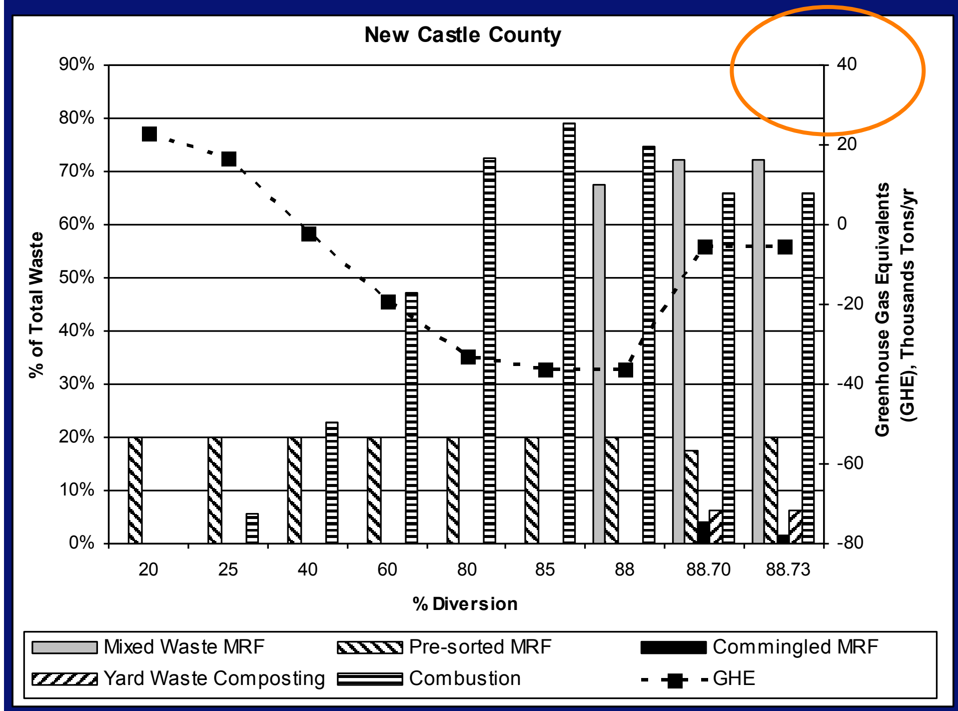
How Do we Combine Counties to Provide the State a Meaningful Roadmap?

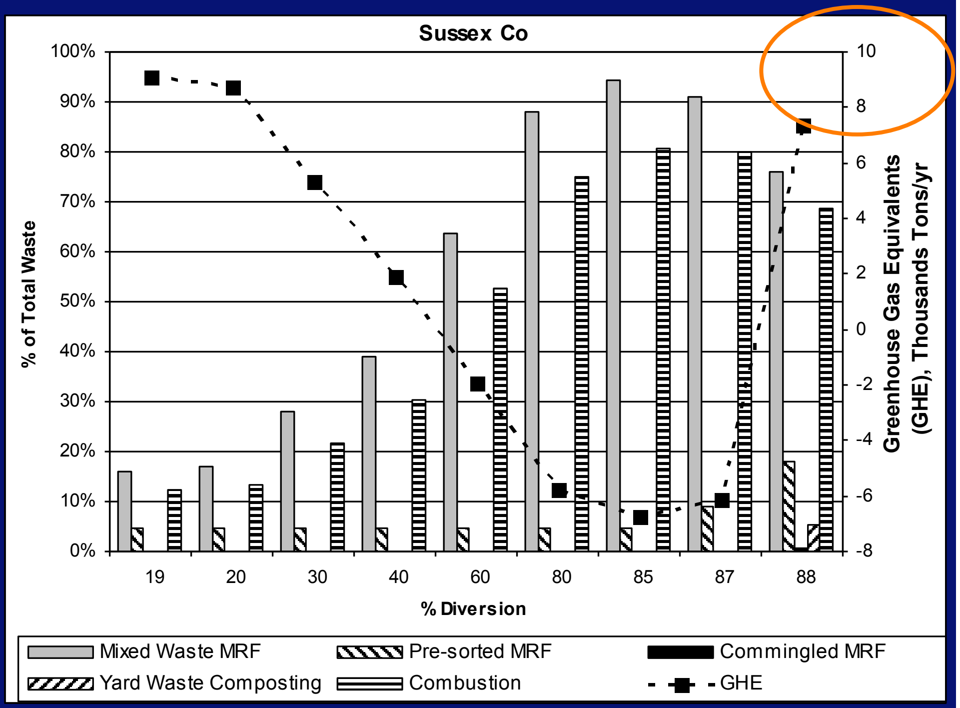


… but collection costs per Mg are higher in the rural counties

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
- Larger GHG decreases possible in New Castle County (more populated)

Using an Optimization Approach: Observations from County-Wide Summary

- Non-uniform utilization of curbside collection, combustion subject to a cost constraint
- Optimization model led to counter-intuitive results
  - MRF upstream of combustion
  - Effectiveness of recycling and yard waste composting influenced by transport distance

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	21,070,666	35,903,768	**99,024,811**
30%	35%	30%	30.7%	42,050,377	21,363,049	35,903,768	99,317,194
30%	30%	35%	30.9%	42,050,377	21,0		99,403,794
30%	40%	25%	30.5%	42,050,377	21,6		99,258,166
35%	25%	20%	30.7%	43,245,513	20,7		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
…	…	…	…	…	…		…
…	…	…	…	…	…		
…	…	…	…	…	…		

Uniform diversion is not least cost case

Least-Cost 30% Statewide Diversion

- 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
  - Combustion prohibited
- Generate alternatives that maximize differences in unit operations & waste flow choices in SWM strategies using Modeling to Generate Alternatives (MGA)

Modeling to Generate Alternatives (MGA)

Cost-effective 30% statewide diversion strategy includes:

- cost-effective 35% diversion from New Castle

  Cost: $43.2 M/yr relax the cost → $48 M/yr

- cost-effective 20% diversion from Kent

  Cost: $20.2 M/yr relax the cost → $22.5 M/yr

- cost-effective 20% diversion from Sussex

  Cost: $34.6 M/yr 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**

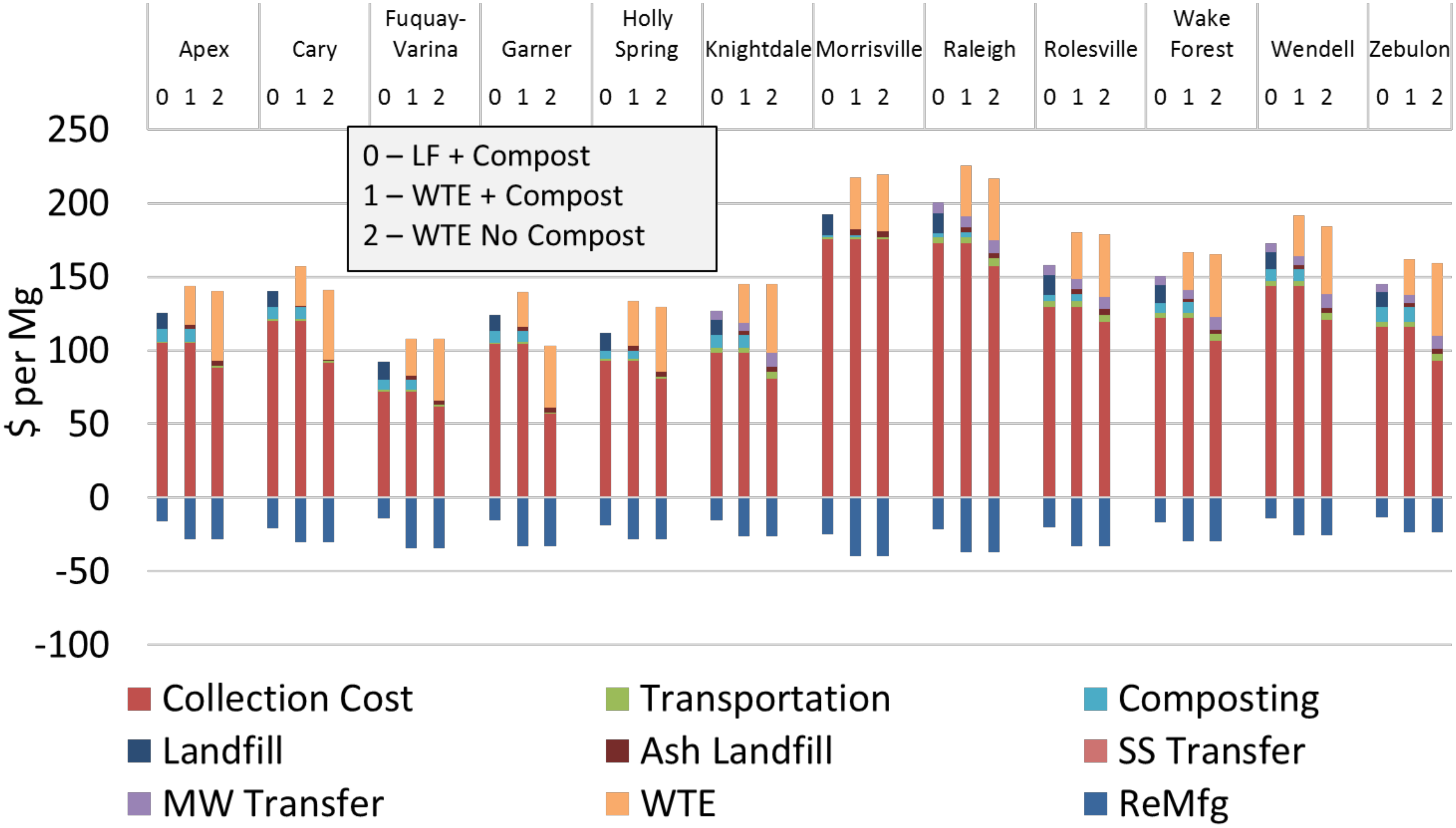
Case Study for Wake County, North Carolina, USA

- 12 independent cities with their own collection systems
  - Each city contracts with county for some solid waste services, primarily the landfill
  - The cities control residential but not commercial waste
    - Commercial waste must be considered for capital investments
  - Substantial data development

Waste Generation Sectors

- Single-family (SF) residential waste generators
  - Waste generation, composition, and collection details specified for each municipality (12)
- Multi-family (MF) residential waste generators
  - Waste generation, composition, and collection details specified for 2 MF sectors: 1) Raleigh 2) other cities
- Convenience centers (CC)
  - Generation at city and county sites combined
- Commercial waste generators (COM)
  - Only includes residual waste – excludes any source-separated recyclables or food waste
  - Residual waste split between 2 landfills

Wake County: Single Family Costs



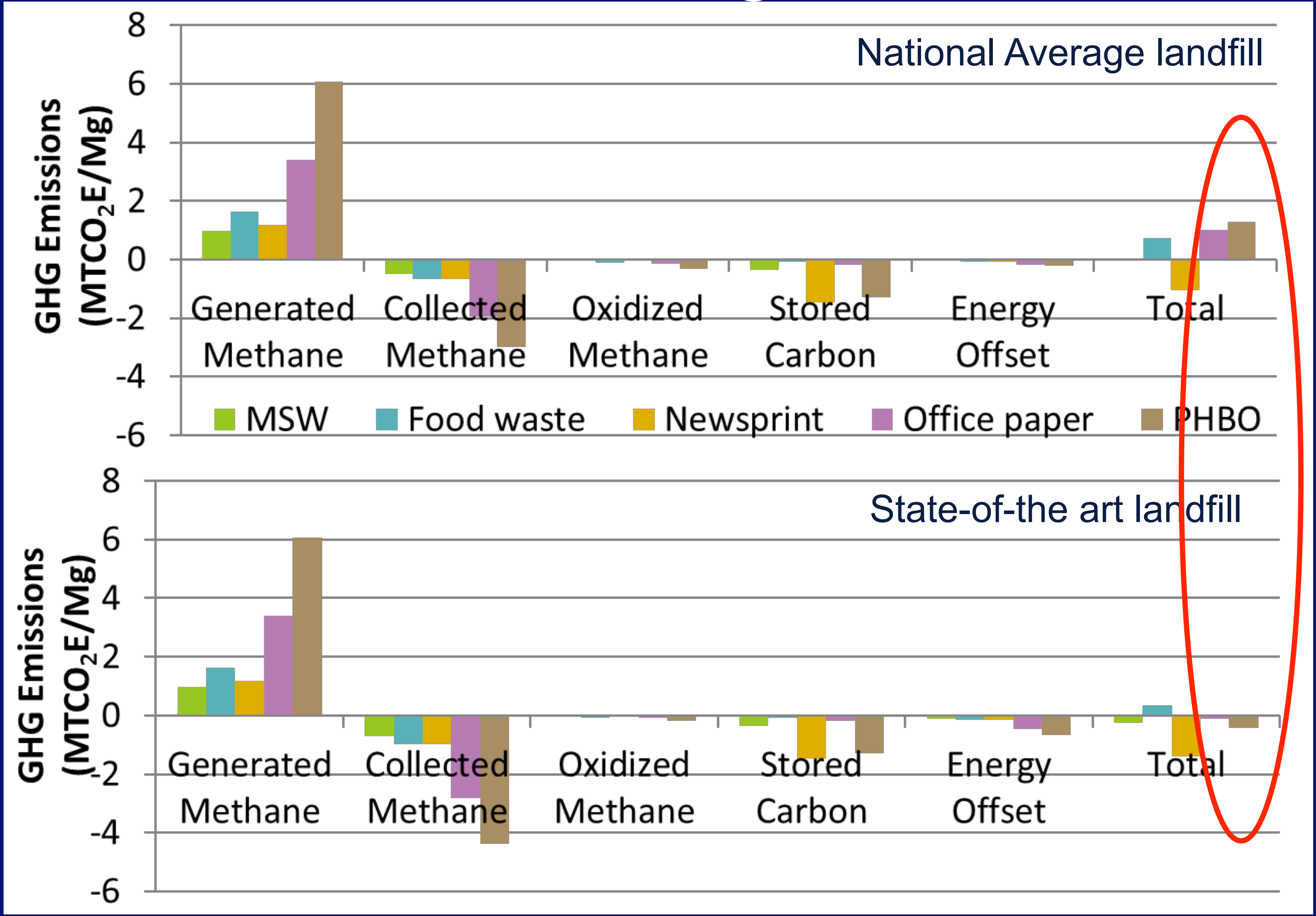
Next Steps

- We have represented the current system and have reasonable agreement to mass flows and costs with actual data
- Consider population growth and changes in waste composition over a 30 year time horizon
- Develop optimal scenarios for each city and combine

Consumer Packaging Study: Is biodegradability a desirable attribute for discarded solid waste ?

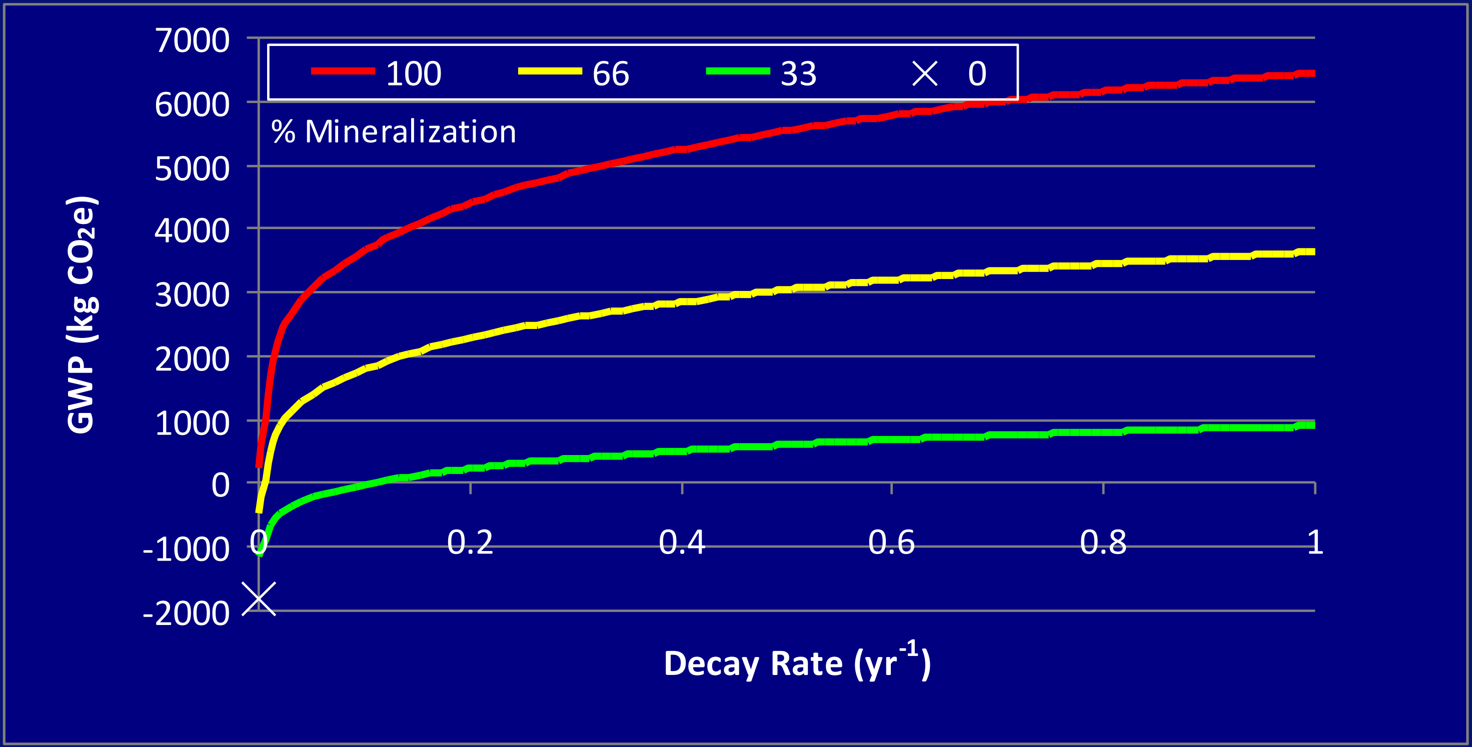
- Interest in the environmental footprint of consumer products
  - Many disposed in landfills
  - U.S. and globally
  - Work to represent the national average landfill
    - Weighted average of landfills that
      1. Collect gas and use beneficially
      2. Collect gas and flare
      3. Do not collect gas

Material modeling in landfills



Observations

- Slower biodegradation is better (national average)
- Recalcitrant biogenic carbon is optimal based on disposal
  - Must now integrate this with the production process



Levis, J. W.; Barlaz, M. A. Is biodegradability a desirable attribute for discarded solid waste ? *Environ. Sci. Technol.* **2011**, *45* (11), 5470–5476.

Observations

- Consider a developing country and disposal of a specific material in an uncontrolled landfill (open dump)
  - allocation methodology now becomes critical
  - plastic packaging may not leach or biodegrade
    - Residual contents will

Uncertainty in Solid Waste LCA

Process	Model Uncertainty	Scenario Uncertainty	Parameter Uncertainty
General	Linearity	System boundaries, Spatial and temporal variation, Allocation	
Impact Assessment	Modeling fate and effects	Normalization and weighting methods	Characterization factors
Composition		Choice of composition	Waste fraction distribution, material properties
Collection	Collection model	Choice of collection scheme	Fuel efficiency, emission factors
Treatment	Process models and sub-process models (e.g., landfill gas)	Choice of technology (e.g.,state-of-the art vs. average)	Emission factors
Beneficial recovery	Process model	Choice of offsets and technologies	Substitution rate, emission factors
Energy System		Choice of marginal fuel(s)	Emission factors, fuel efficiency

Adopted from Clavreul, J.; Baumeister, H.; Christensen, T. H.; Damgaard, A. An environmental assessment system for environmental technologies. *Environ. Model. Softw.* **2014**, *60*, 18–30.

Intrinsic LCA Modeling Uncertainties

- Lack of spatial/temporal information on environmental impacts
- Assumption of linearity
- Characterization factor choices and uncertainties
  - Can be related to spatial/temporal uncertainty
  - GWP for methane is 72, 25, or 7.6 kg CO_2e/kg CH_4 using 20, 100, or 500 year horizons (static case)

Tools to evaluate uncertainty and sensitivity

- Scenario analysis
  - What significant parts of the analysis are likely to differ from what was modeled?
- Contribution analysis
  - What processes, materials or emission have the largest effect on results?
- Parametric perturbation analysis
  - How do results change if you change parameter values?
- Uncertainty propagation
  - What is the actual distribution of result values and how are they correlated with parameter uncertainty?

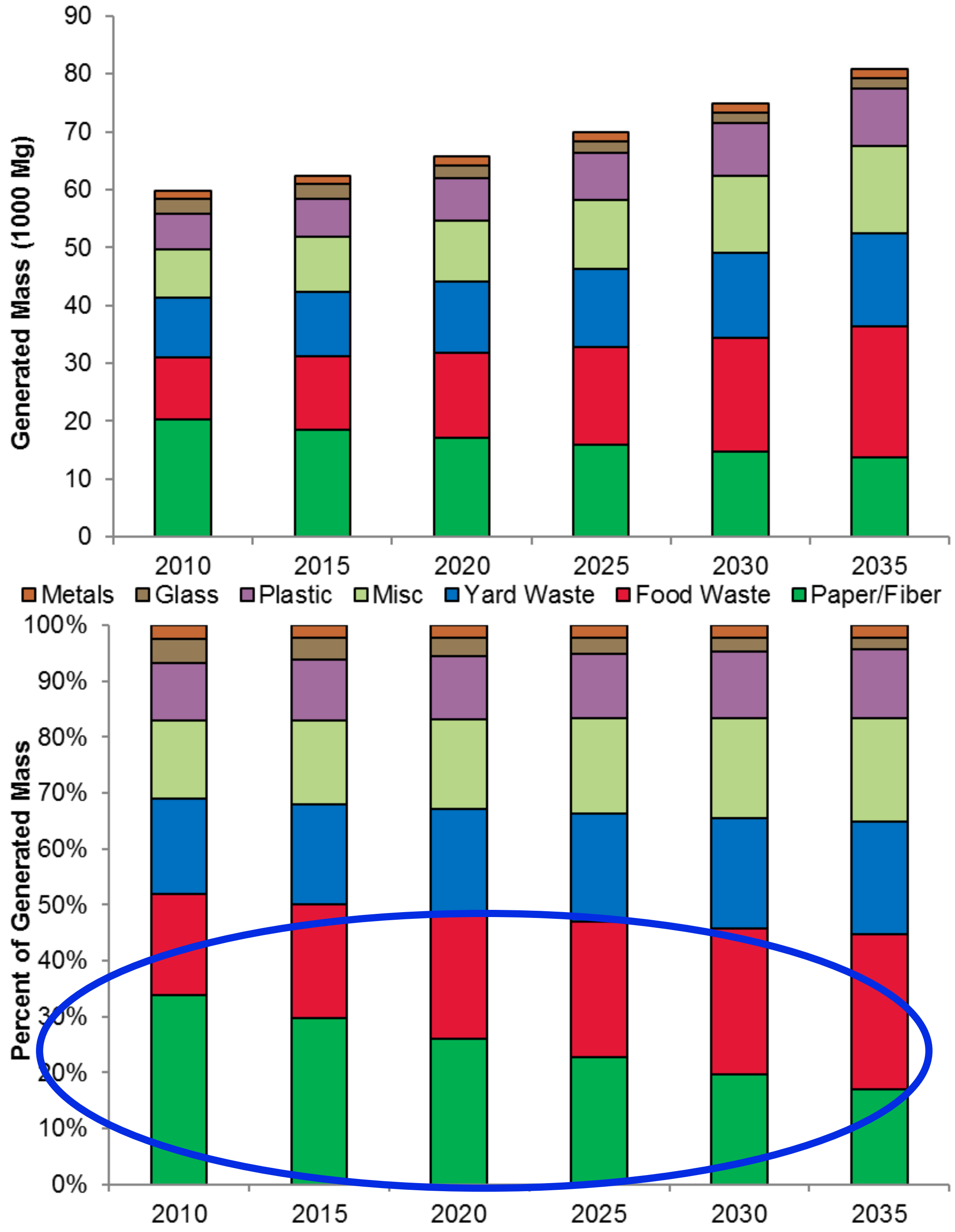
Scenario Analysis

- Useful for modeling alternative possibilities
  - Use different allocation method(s)
  - Use different offset(s)
  - Use different fuel/electricity sources
- Provide a broad look at how changes to the system affect results
- Provides information on the robustness of the results

Effect of composition

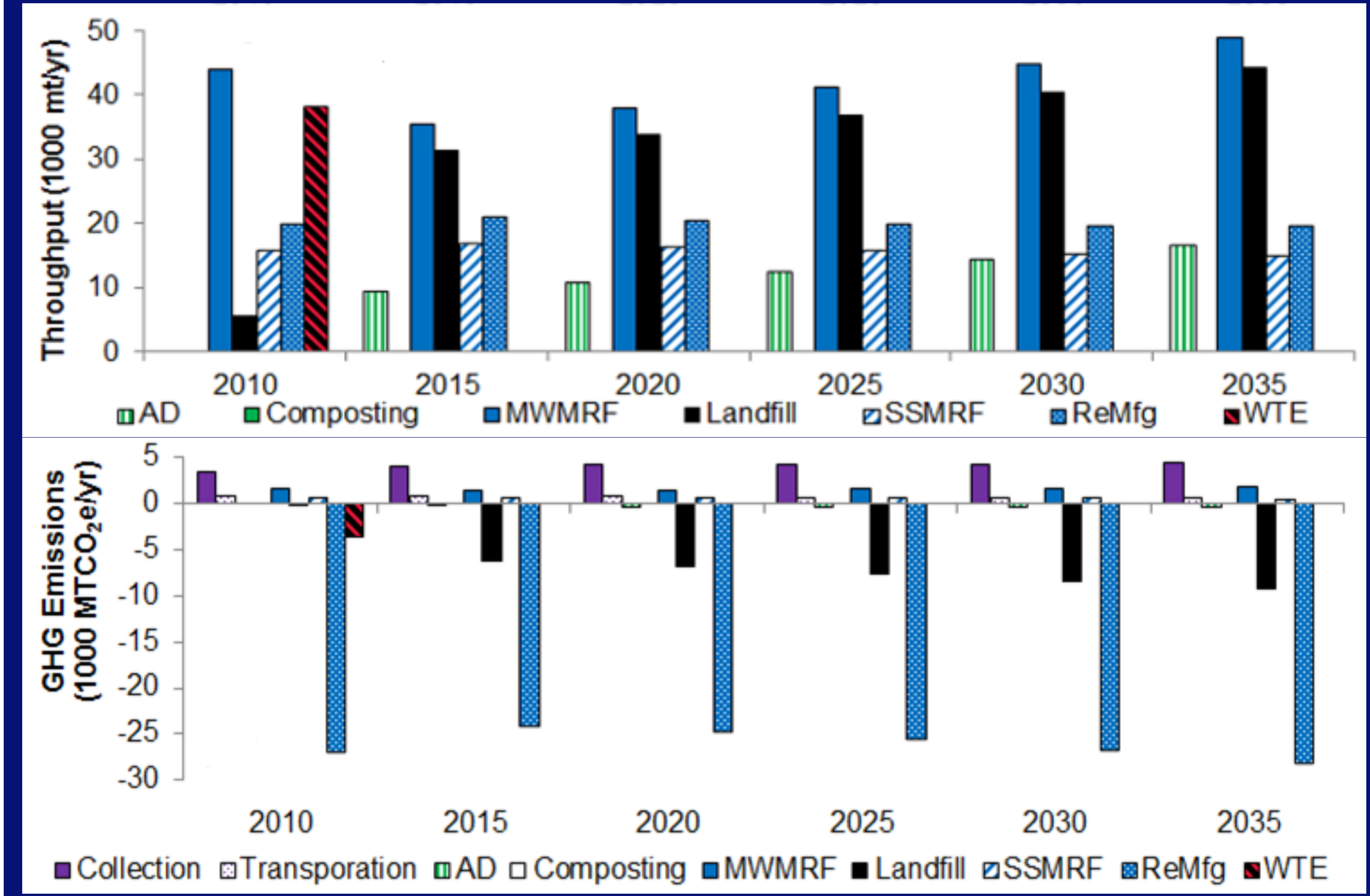
- Developed per capita generation trends for 30 waste materials based on EPA 2012 MSW Facts and Figures data.

Municipal solid waste generation, recycling, and disposal in the United States: Tables and figures 2010; United State Environmental Protection Agency: Washington, DC, 2011.



Levis, J. W.; Barlaz, M. A; Decarolis, J. F.; Ranjithan, S. R. A Systematic Exploration of Efficient Strategies to Manage Solid Waste in U.S. Municipalities: Perspectives from the Solid Waste Optimization Life-Cycle Framework (SWOLF). *Environ. Sci. Technol.* **2014**.

Effects of Composition

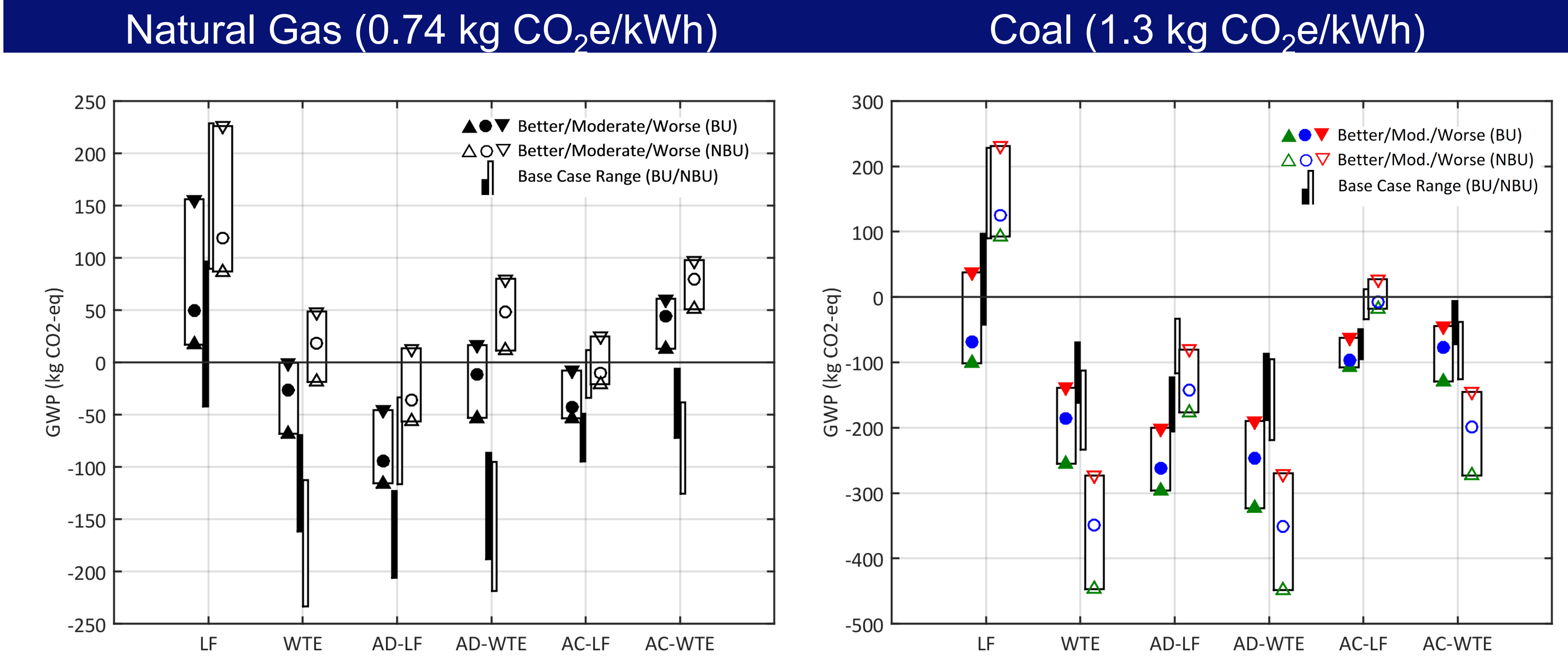


- The WTE facility is used only in the first stage because there is more paper and less plastic than in the following stages and because of the decrease in electricity GHG intensity
- AD use over time increases as more food waste is generated

Levis, J. W.; Barlaz, M. A; Decarolis, J. F.; Ranjithan, S. R. A Systematic Exploration of Efficient Strategies to Manage Solid Waste in U.S. Municipalities: Perspectives from the Solid Waste Optimization Life-Cycle Framework (SWOLF). *Environ. Sci. Technol.* **2014**.

Electricity GHG Intensity

Food Waste Management Example

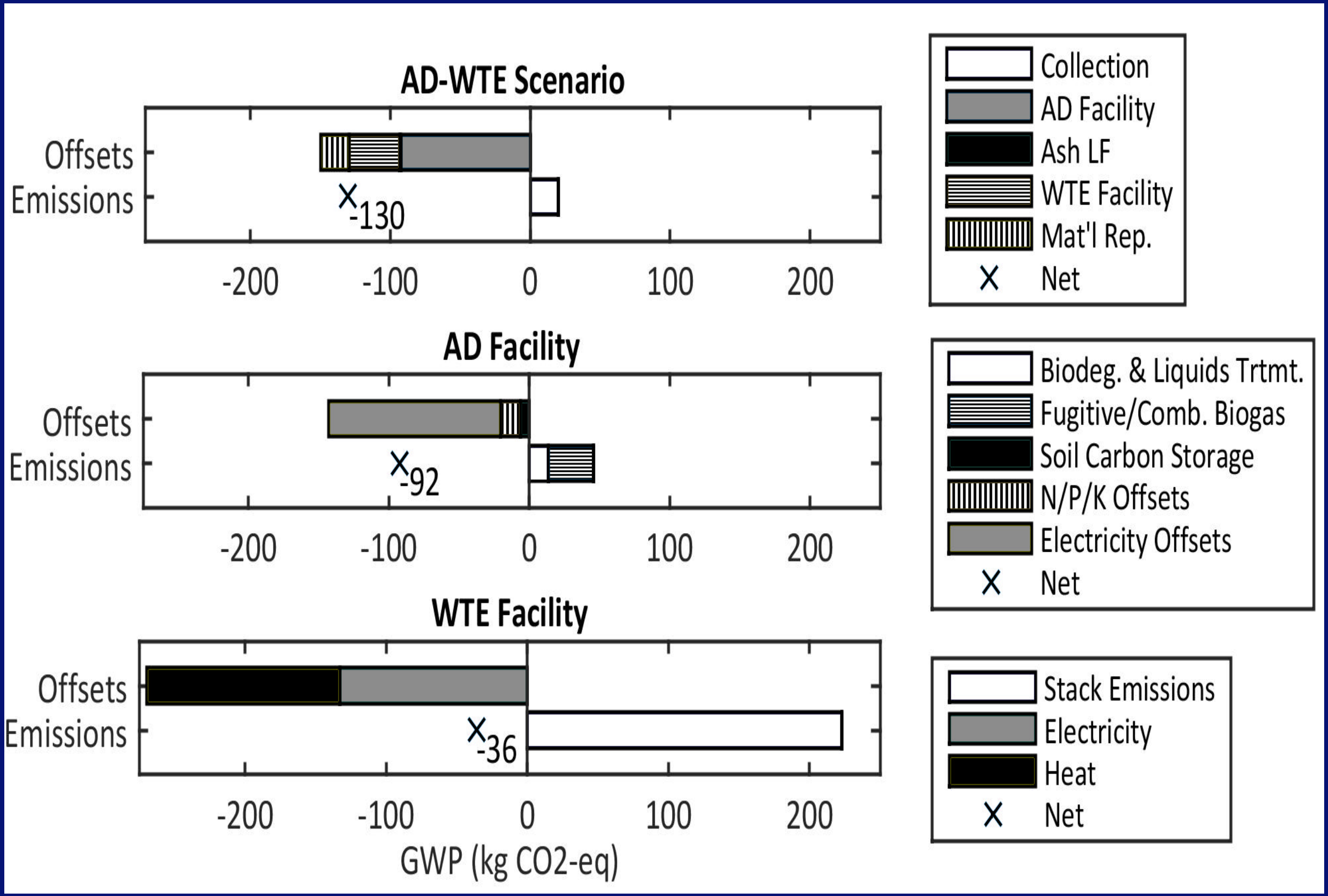


Base case used 55/45 Coal/Natural Gas split based on marginal split
in the Southeastern Electricity Reliability Council (SERC) grid (0.89 kg CO_2e/kWh)

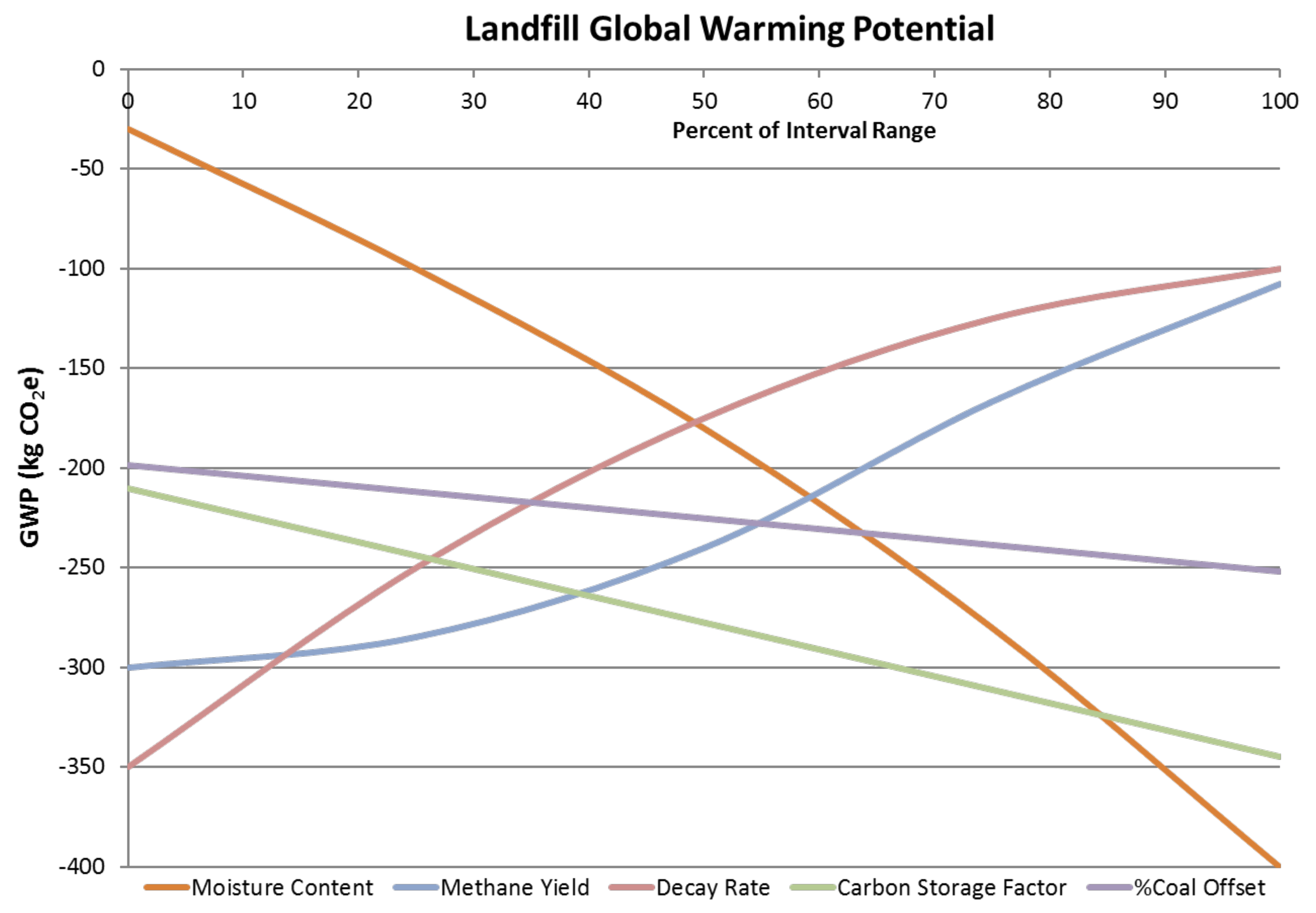
Hodge, K. L.; Levis, J. W.; Barlaz, M. A; DeCarolis, A Systematic Evaluation of Industrial, Commercial, and Institutional Food Waste Management Strategies in the U.S.. *Environ. Sci. Technol.* (Submitted).

Contribution Analysis

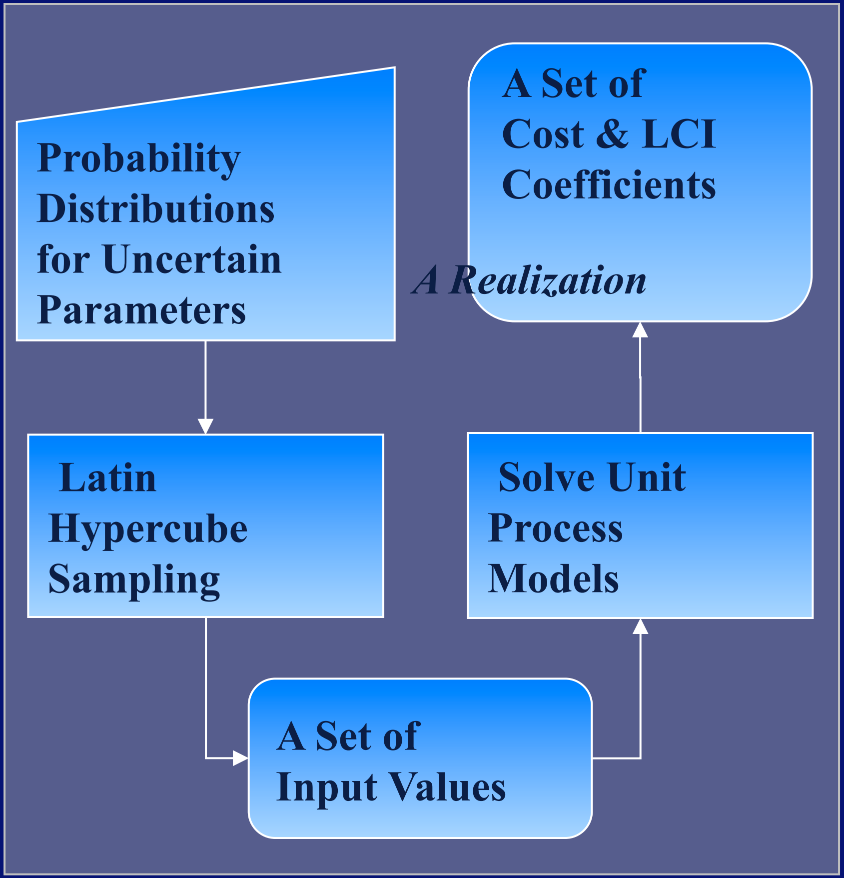
- Compare the contributions of the various sub-processes and/or materials involved in your process or product to various impacts.



Parameter Perturbation Analysis



Methodology for Uncertainty Propagation: Monte Carlo Analysis



Probability Distributions for Uncertain Parameters

Latin Hypercube Sampling

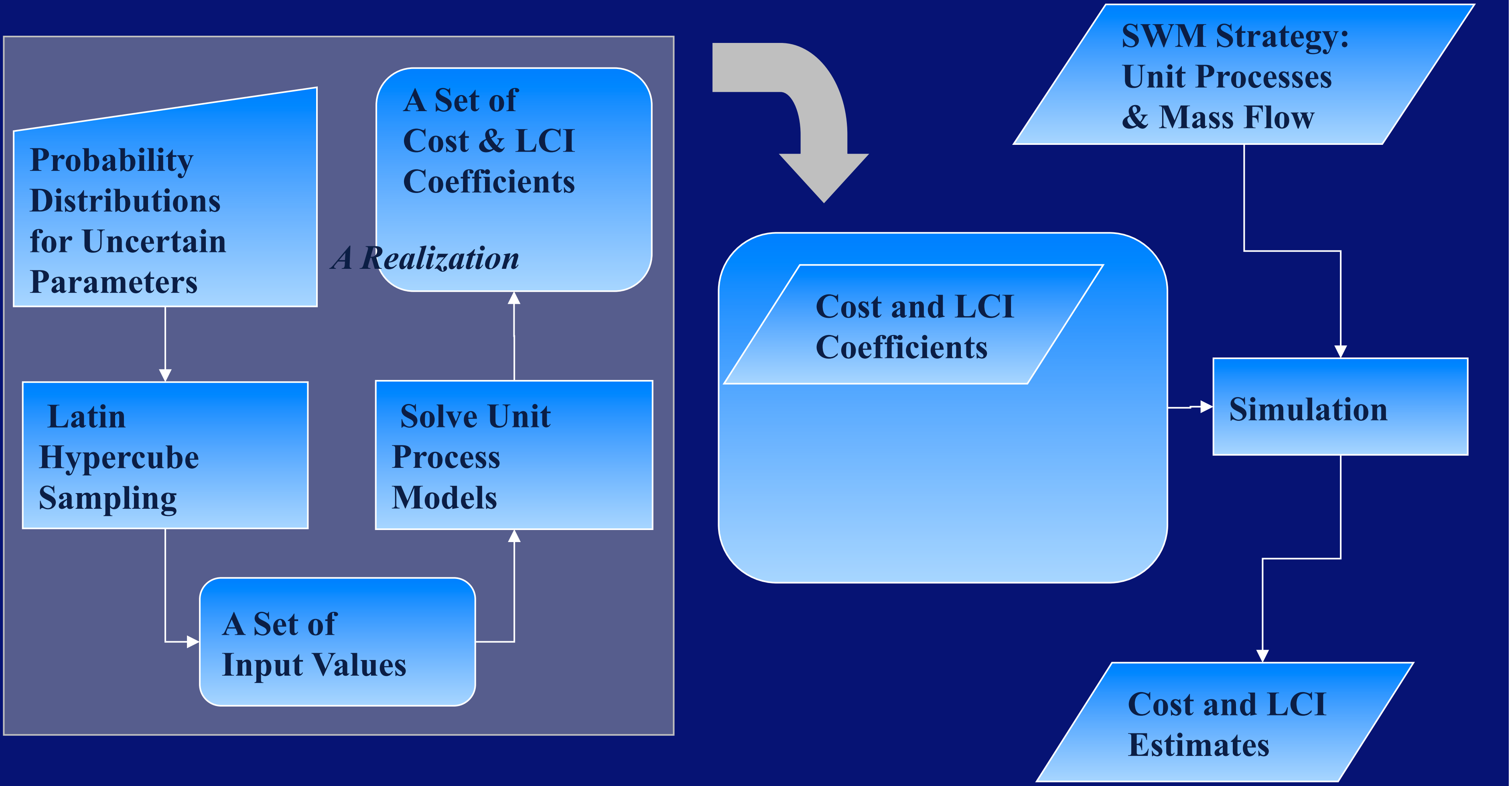
A Set of Input Values

Solve Unit Process Models

A Set of Cost & LCI Coefficients

A Realization

Methodology for Uncertainty Propagation



Probability Distributions for Uncertain Parameters

Latin Hypercube Sampling

A Set of Input Values

Solve Unit Process Models

A Set of Cost & LCI Coefficients

A Realization

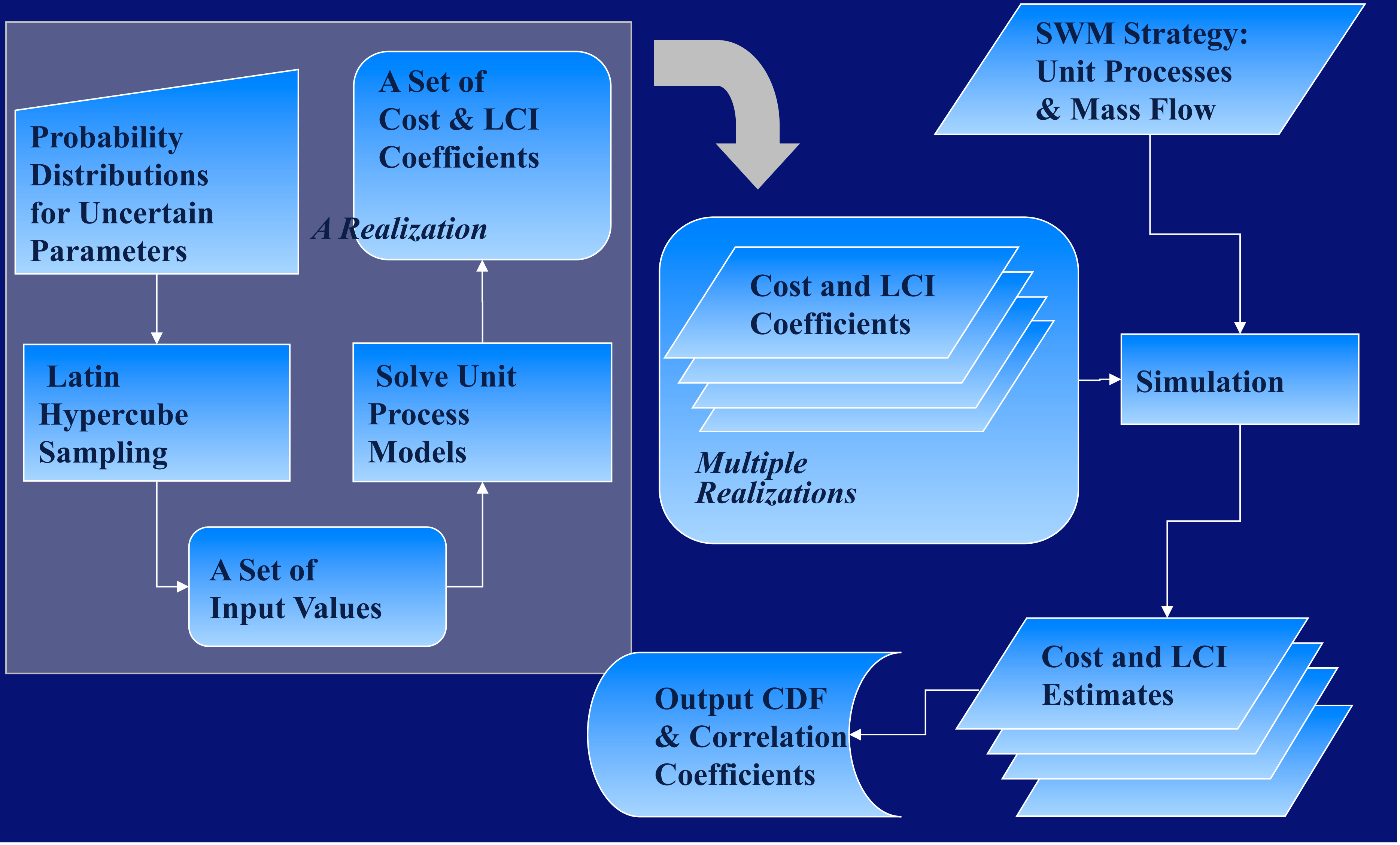
Cost and LCI Coefficients

SWM Strategy: Unit Processes & Mass Flow

Simulation

Cost and LCI Estimates

Methodology for Uncertainty Propagation



Probability Distributions for Uncertain Parameters

Latin Hypercube Sampling

A Set of Input Values

Solve Unit Process Models

A Set of Cost & LCI Coefficients

A Realization

Cost and LCI Coefficients

Multiple Realizations

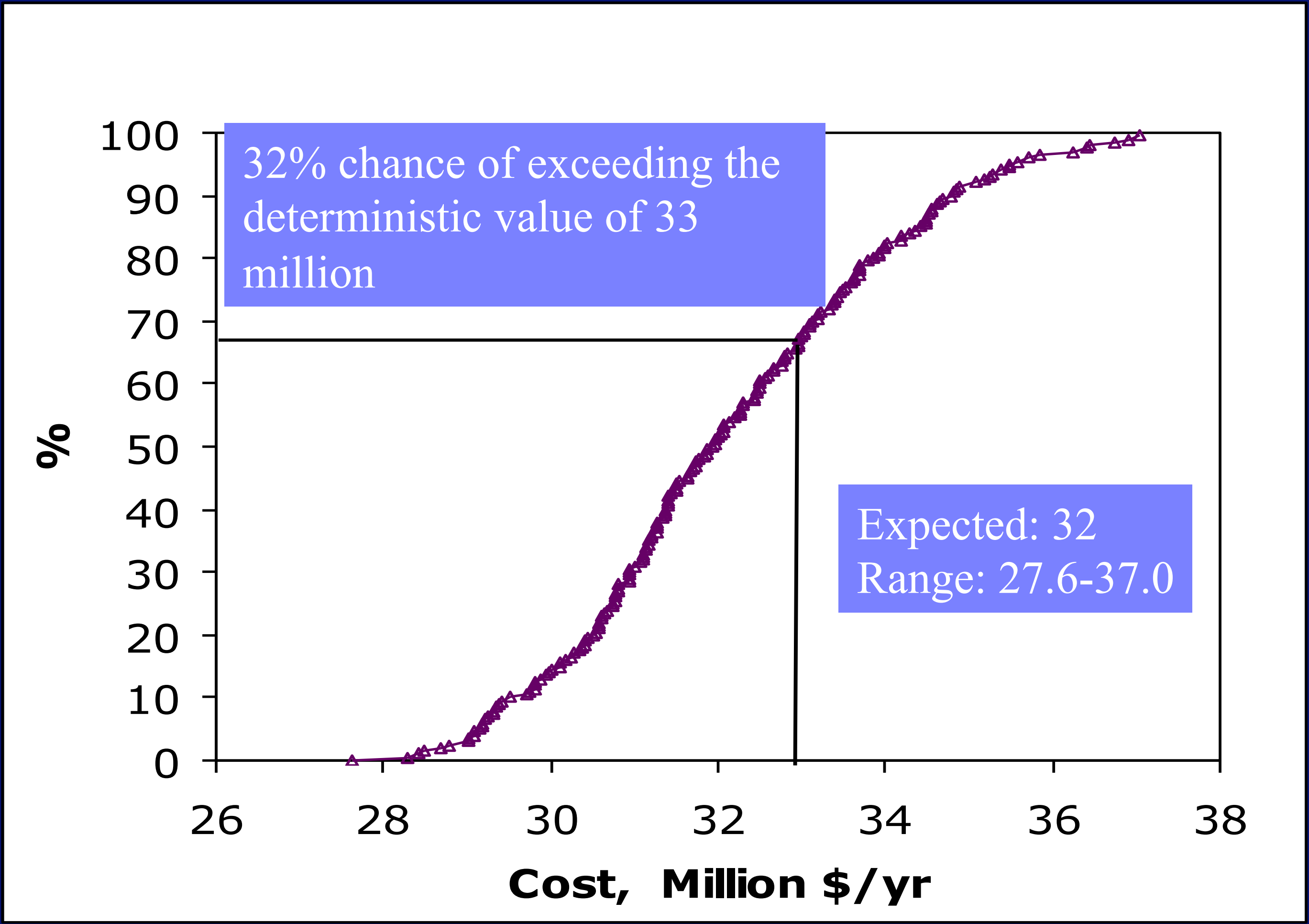
SWM Strategy: Unit Processes & Mass Flow

Simulation

Cost and LCI Estimates

Output CDF & Correlation Coefficients

Example Result: Monte Carolo Analysis

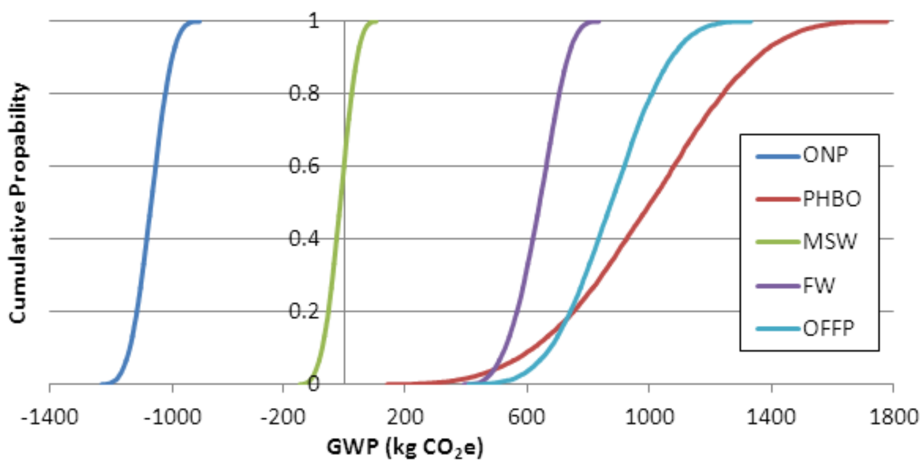


32% chance of exceeding the deterministic value of 33 million

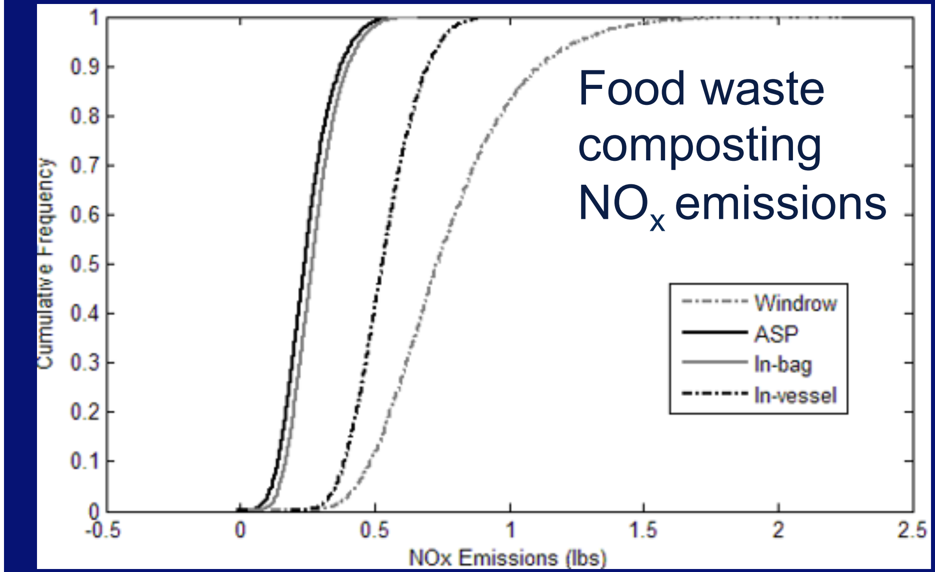
Expected: 32
Range: 27.6-37.0

Monte Carlo Analysis

Landfill GHG Emissions

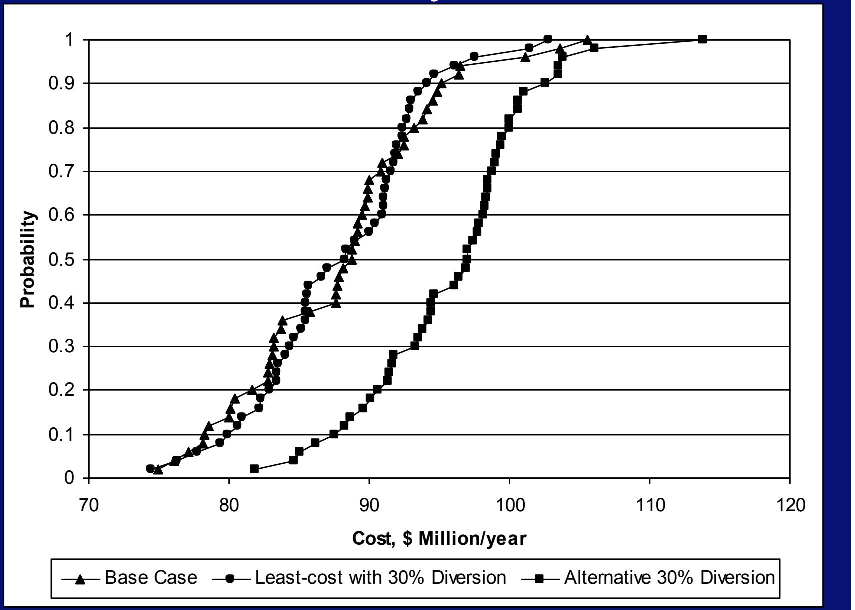


Levis, J. W.; Barlaz, M. A. Is biodegradability a desirable attribute for discarded solid waste ? Supporting Information. *Environ. Sci. Technol.* **2011**, *45* (11), 5470–5476.


Food waste composting NO_x emissions

Levis, J. W.; Barlaz, M. a. What is the most environmentally beneficial way to treat commercial food waste? *Environ. Sci. Technol.* **2011**, *45* (17), 7438–7444.

Delaware system costs



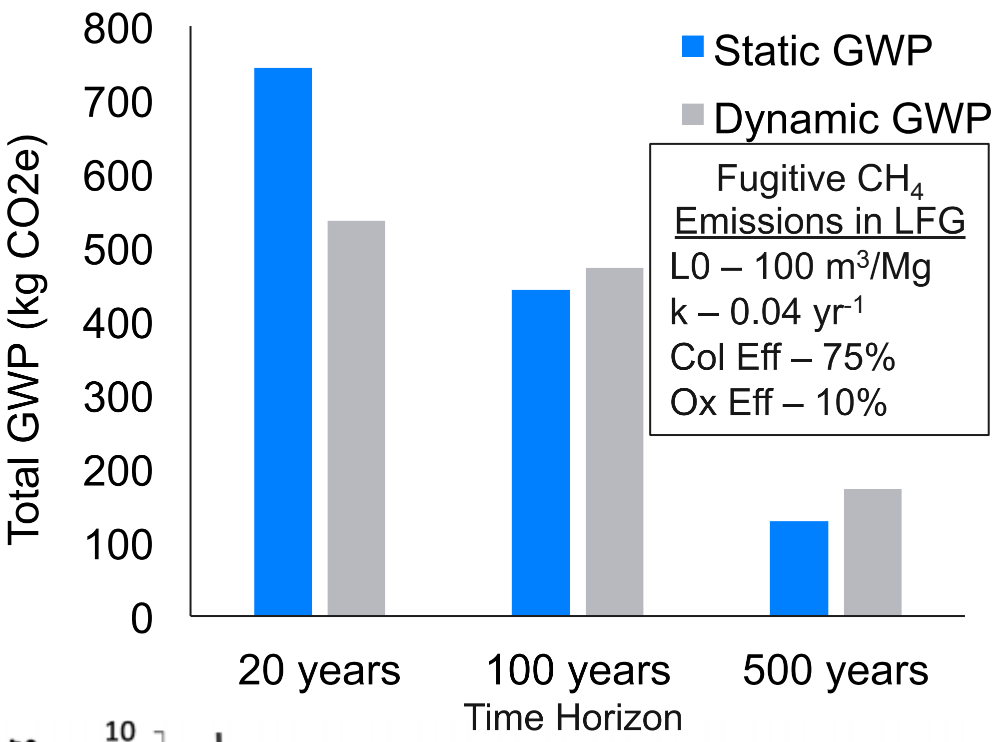
Kaplan, P. O.; Ranjithan, S. R.; Barlaz, M. a. Use of life-cycle analysis to support solid waste management planning for Delaware. *Environ. Sci. Technol.* **2009**, *43* (5), 1264–1270.

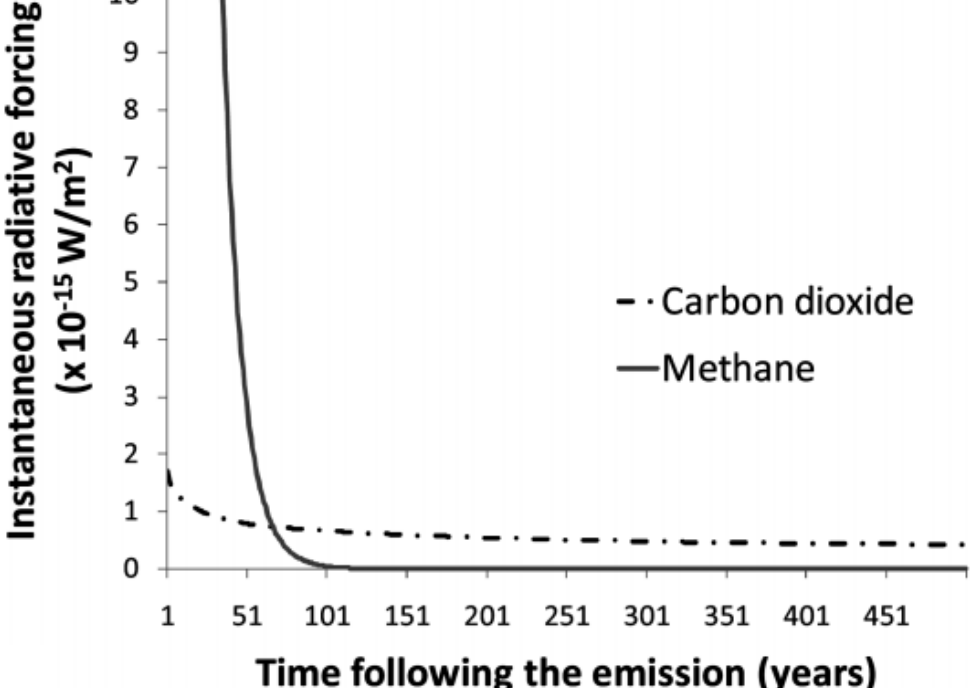
Are differences between scenarios robust?

Time Dependent impact of GHGs

- The effect a GHG emission has on radiative forcing varies with time and with existing atmospheric concentrations of GHGs (which also vary with time).
- Dynamic GWIs reduce the impact of future emissions based on the change in radiative forcing of those future emissions.
  - Requires dynamic LCIs
  - May include explicit discounting

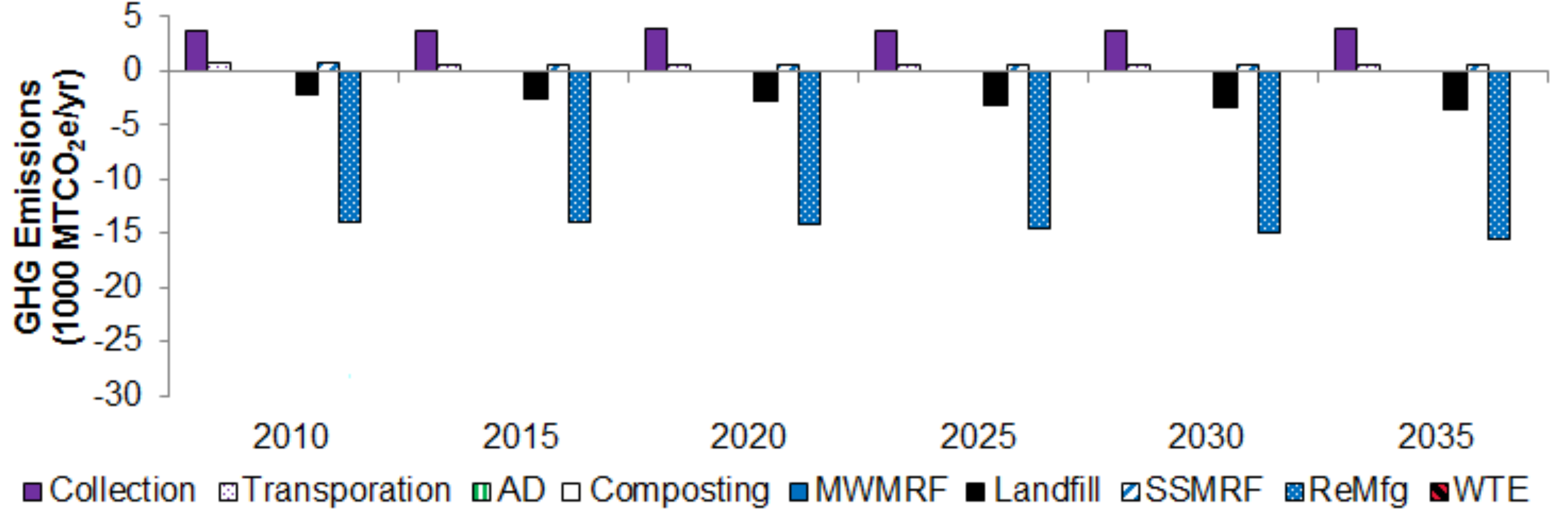
  - DNYCO2 Dynamic Carbon Footprinter - http://www.ciraig.org/en/dynco2.php





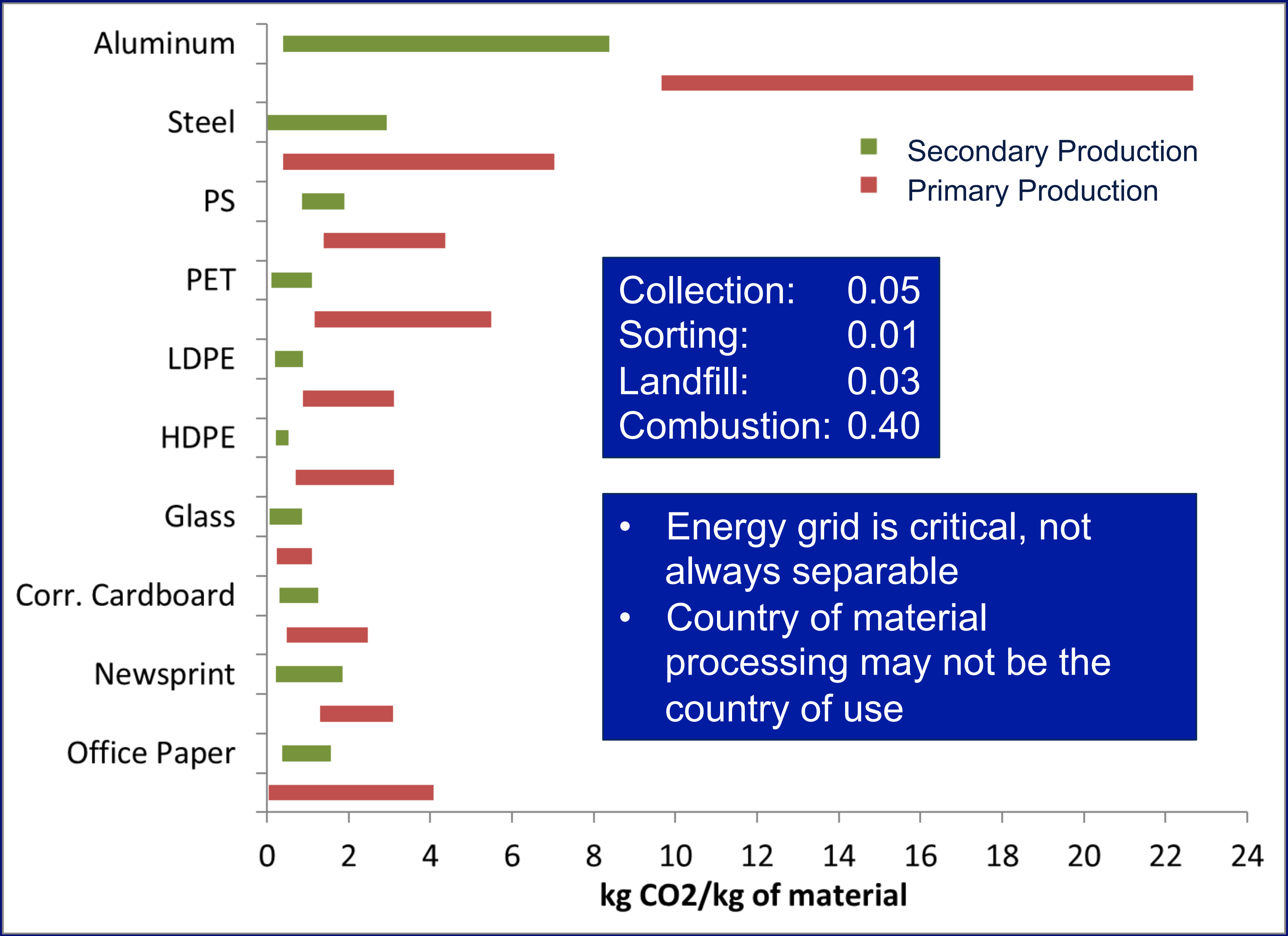
Levasseur, A.; Lesage, P.; Margni, M.; Deschěnes, L.; Samson, R. Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environ. Sci. Technol.* **2010**, *44* (8), 3169–3174.

Material Reprocessing Offsets: Important but …



Levis, J. W.; Barlaz, M. a; Decarolis, J. F.; Ranjithan, S. R. A Systematic Exploration of Efficient Strategies to Manage Solid Waste in U.S. Municipalities: Perspectives from the Solid Waste Optimization Life-Cycle Framework (SWOLF). *Environ. Sci. Technol.* **2014**.

… Uncertain

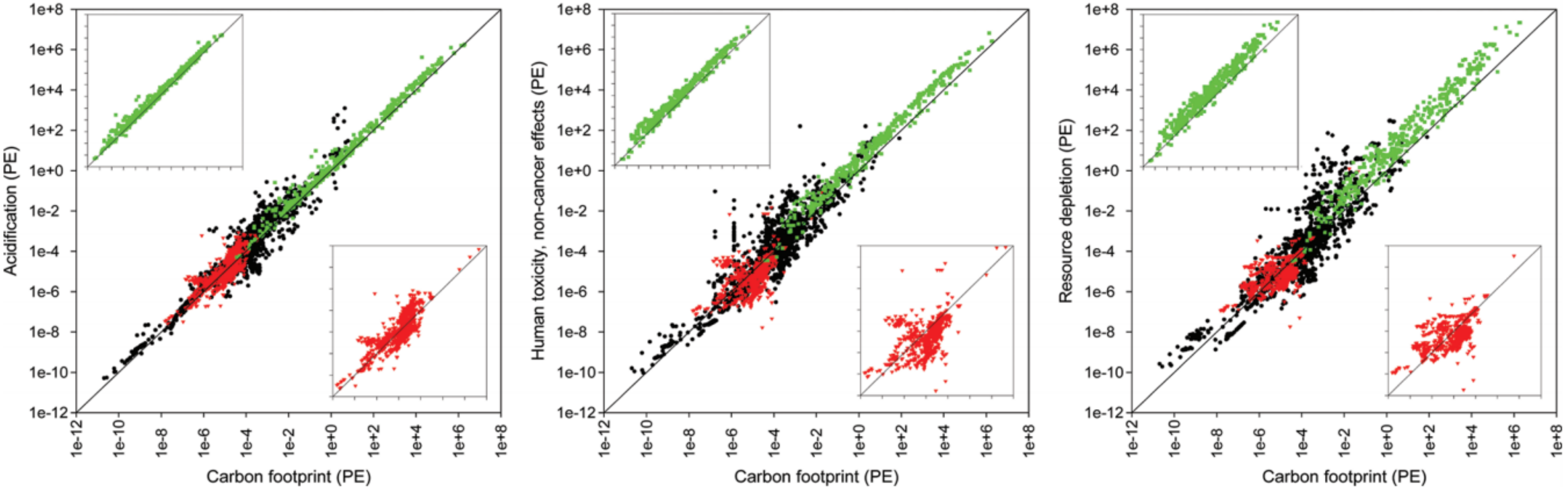


Collection: 0.05
Sorting: 0.01
Landfill: 0.03
Combustion: 0.40

- Energy grid is critical, not always separable
- Country of material processing may not be the country of use

Brogaard, L. K.; Damgaard, A.; Jensen, M. B.; Barlaz, M.; Christensen, T. H. Evaluation of life cycle inventory data for recycling systems, Rs. Cons. Recycling, 2014, 87, p. 30-45.

Impacts and trade-offs



Laurent, A.; Olsen, S. I.; Hauschild, M. Z. Limitations of carbon footprint as indicator of environmental sustainability. *Environ. Sci. Technol.* **2012**, *46* (7), 4100–4108.

- Laurent et al. (2012) found climate change was generally a reasonable proxy for impacts primarily affected by fossil energy use (e.g., acidification, photochemical oxidation) and potentially poor proxy for toxicity and non-fossil resource use impacts.
- Steinmann et al. (2016) found that marine ecotoxicity and climate change indicators covered 84% of the variance in life-cycle product rankings.
  - The addition of land use and ozone depletion accounted for 90.1%

Steinmann, Z. J. N.; Schipper, A. M.; Hauck, M.; Huijbregts, M. A. J. How Many Environmental Impact Indicators Are Needed in the Evaluation of Product Life Cycles? *Environ. Sci. Technol.* **2016**, *50* (7), 3913–3919.

Conclusions and Challenges

- Every study is different and will require different applications of available models
- The optimal system may require coordination between several cities or cities and commercial companies
  - This may not be possible
- How do we express results simplistically so that non-LCA experts can use?
  - Expressing uncertainty is critical to our collective credibility
- As LCA and waste experts, we are best prepared to analyze and interpret
- Do not forget that no one steals garbage, but some people will steal sorted aluminum cans

Acknowledgements

- Ranji Ranjithan, Joe DeCarolis
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- Waste Management Inc.