

# Use of Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) Models in Waste-to-Materials and Energy Pathways



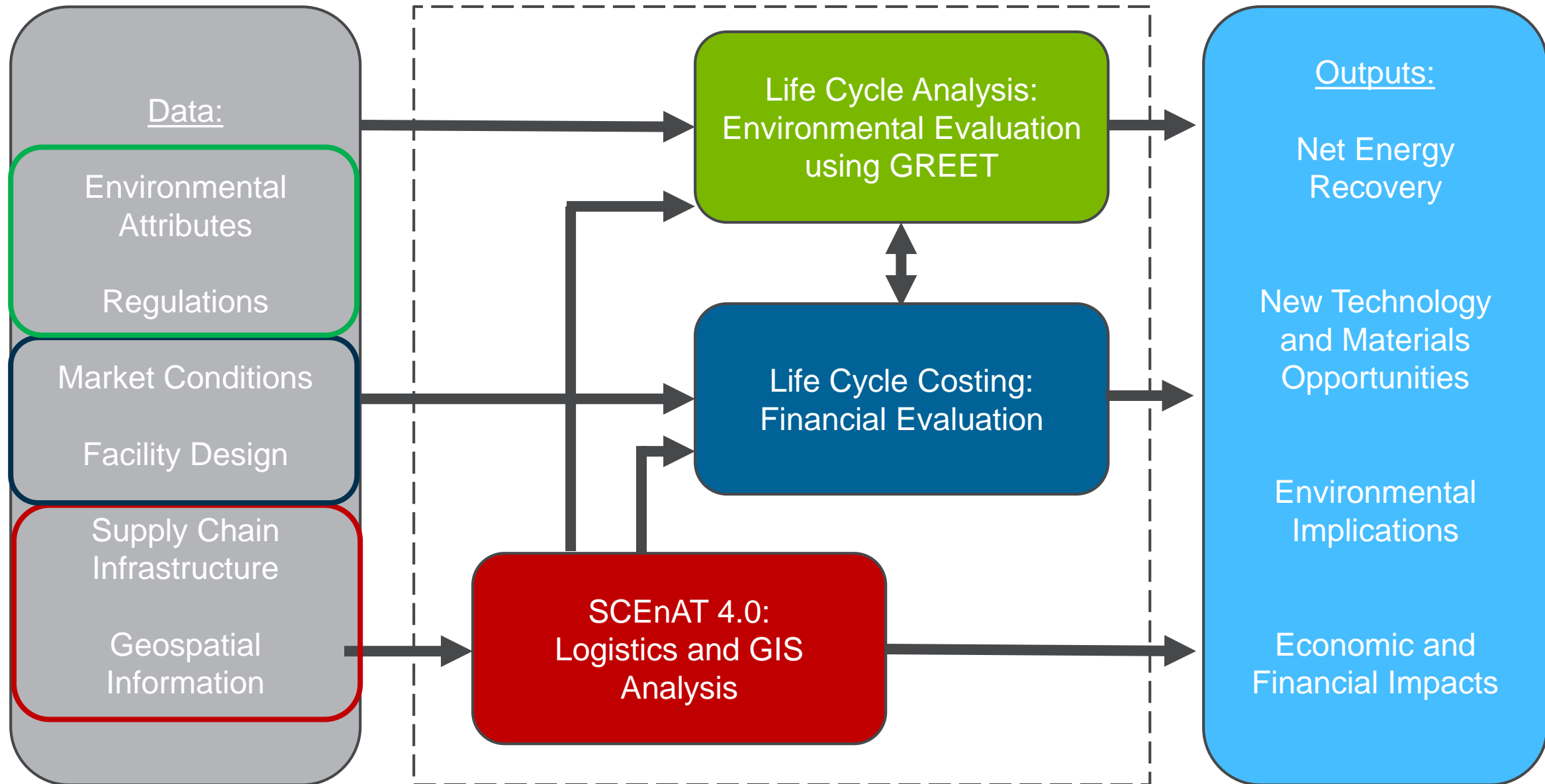
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ALICYN RHOADES + GAMINI MENDIS-  
PENN STATE BEHREND, AREC USA

ARPA-E WORKSHOP. NOVEMBER 2019

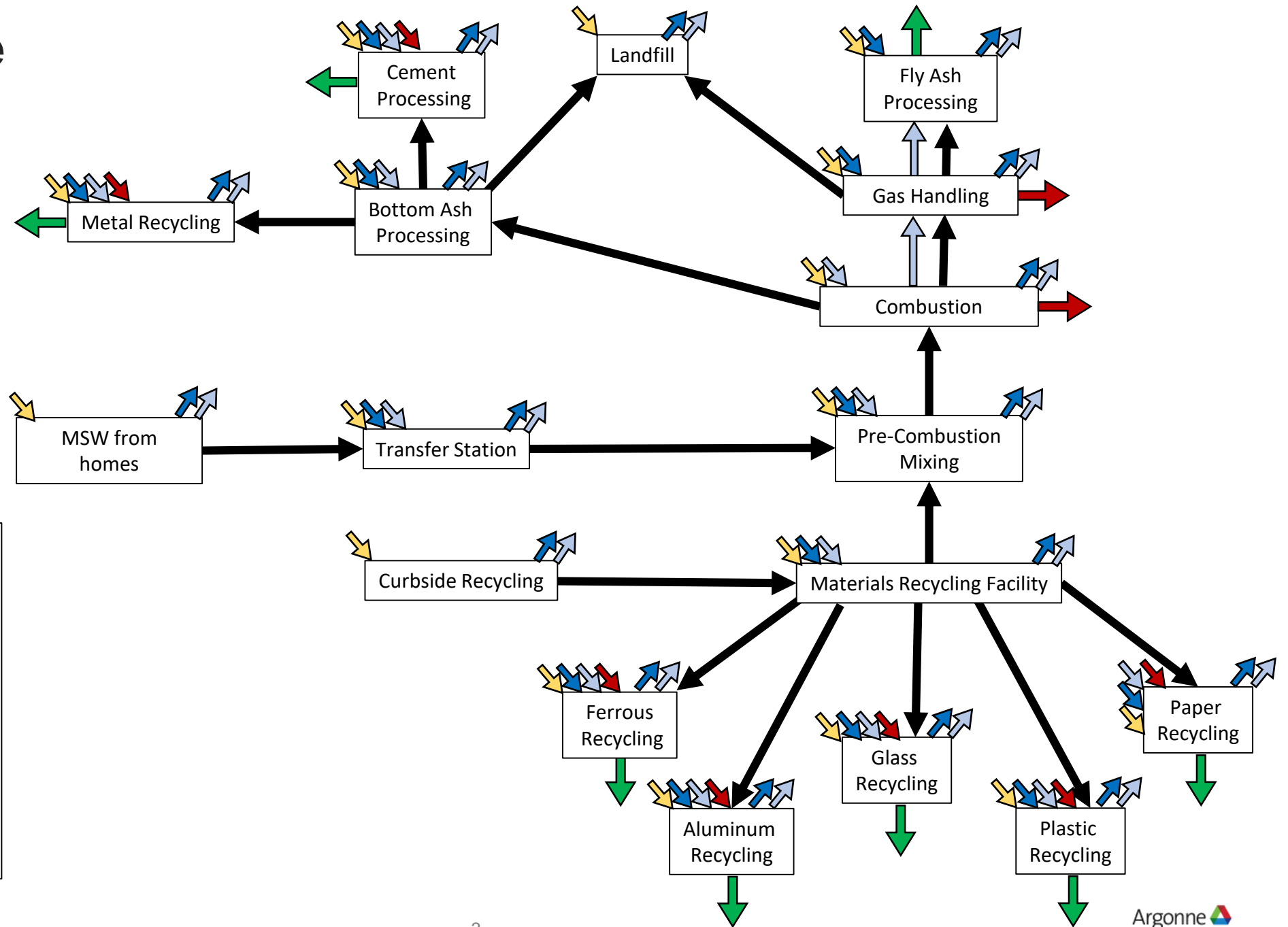
**AREC**  
Creating the Supply Chain of the Future.



# Framework Organization



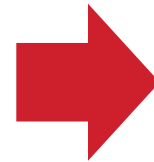
# System Scope



# ***Objective: Develop a framework to enable evaluating quantitative environmental and economic benefits of ARPA-E projects***

## **Potential Results**

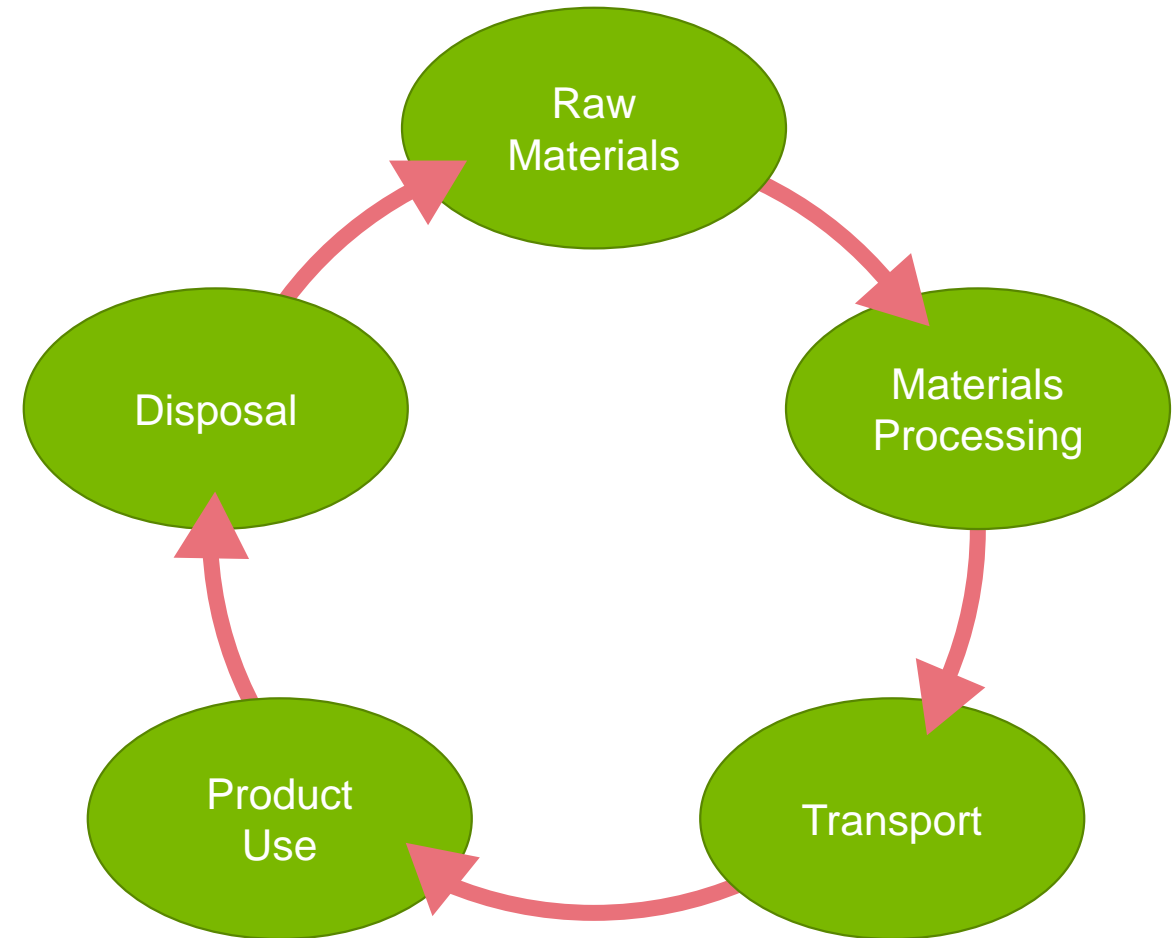
- ❑ **Functional unit:** ton of waste used
- ❑ **LCA results:**
  - Greenhouse gas (GHG) emissions
  - Air pollutant emissions (VOC, CO, NOx, PM10, PM2.5, and SOx)
  - Energy use (fossil energy and renewable energy)
  - Net energy recovery
  - Water consumption
- ❑ **Life Cycle Costing (LCC)**
  - ❑ Return on Investment (ROI), Fixed and Variable Costs



- Can compare the environmental and economic benefits of ARPA-E projects in a consistent manner.
- Can provide quantitative environmental and economic benefits of WTM&E technologies that help improve public perception.

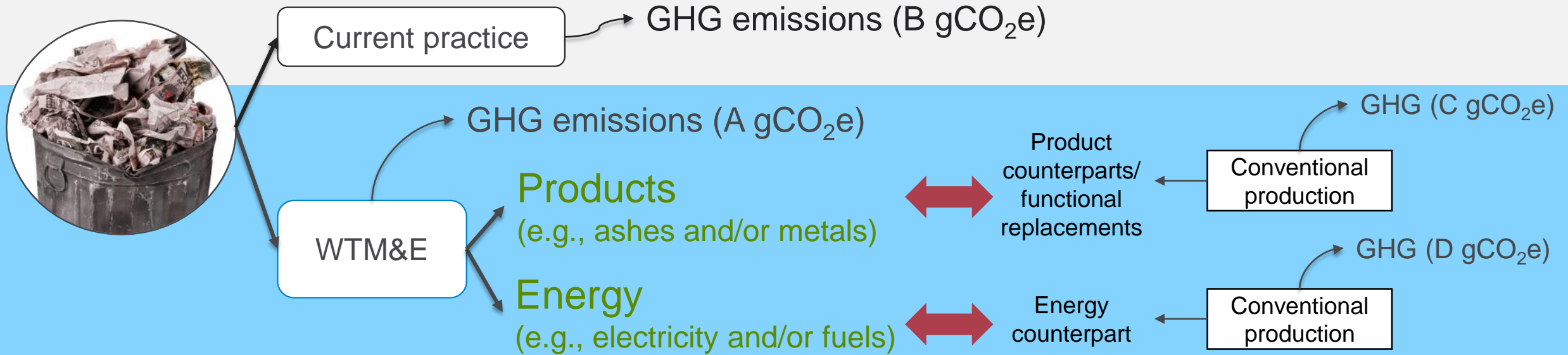
# Life Cycle Analysis (LCA)

- Examines environmental impacts (GHG emissions, ozone depletion, etc.) over entire life cycle
- Cradle-to-grave or cradle-to-cradle
- Comparative LCA: Evaluate environmental impacts of multiple systems, i.e. recycling vs landfilling vs combustion
- Total environmental impacts may not be intuitive, i.e. transportation distance for recycling may have high fuel use
- **Identify opportunities to minimize negative environmental impacts of plastics through industry partnerships**



# The system boundary of the LCA of WTM&E in the GREET LCA model

- Using waste avoids emissions from conventional waste management practices.
  - Waste is not intentionally produced / Waste management is regulated.



- Waste-To-Materials and Energy (WTM&E) pathway emissions:  $A \text{ gCO}_2\text{e}$ .
- By diverting waste, emissions associated with current waste management ( $B \text{ gCO}_2\text{e}$ ) can be avoided.
- WTM&E products displace counterparts and avoid emissions from conventional products ( $C$  and  $D \text{ gCO}_2\text{e}$ ).

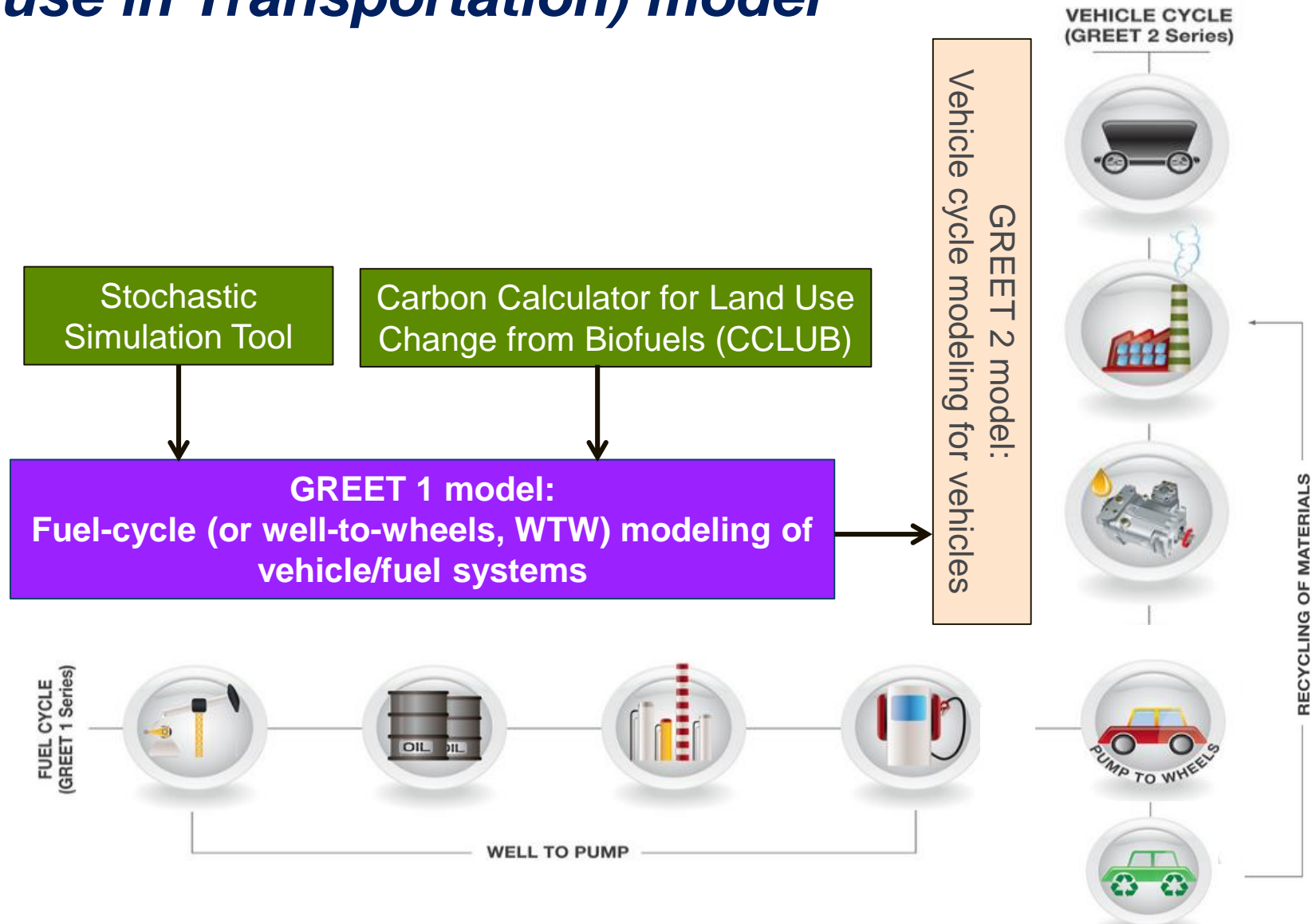
$A \text{ gCO}_2\text{e}$   
 $- B \text{ gCO}_2\text{e}$   
 $- C \text{ gCO}_2\text{e}$   
 $- D \text{ gCO}_2\text{e}$

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Life Cycle Emissions

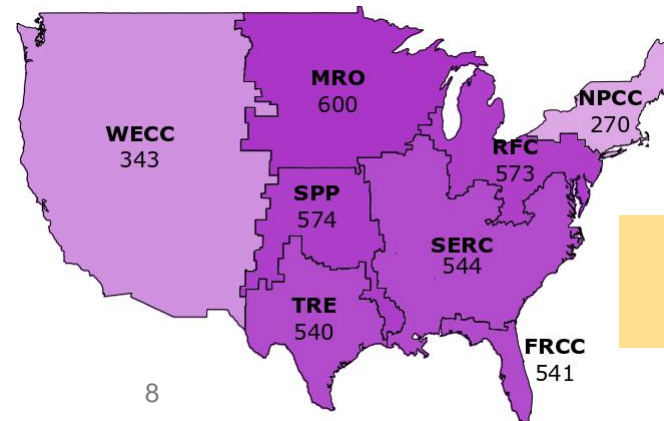


# The GREET<sup>®</sup> (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model



# GREET Database

	Aluminum (Virgin)	Cast Iron	Cement	Copper	Glass	LDPE	HDPE	Polypropylene	PVC	Rubber	Silicon	Average Steel	Nickel	Zinc	Magnesium	Platinum
Energy Use (mmBtu/ton)																
Total energy	127	30	4	38	13	74	69	67	50	47	3,169	26	71	37	113	983
Fossil fuels	81	29	4	33	12	72	67	66	48	46	2,301	24	65	30	102	958
Coal	29	21	2	11	3	5	5	4	5	2	952	17	14	14	24	885
Natural gas	37	6	1	15	9	58	54	46	39	26	1,267	7	39	14	77	13
Petroleum	15	2	1	7	0	8	8	16	4	18	83	0	12	1	1	60
Water consumption (gal/ton)																
	63,528	307	279	3,118	781	1,404	1,384	1,171	1,115	911	688,244	1,285	18,341	6,378	5,354	49,256
Total Emissions (grams/ton)																
VOC	966	2,015	100	327	138	1,357	1,284	1,151	799	5,708	22,219	2,379	747	289	1,069	8,649
CO	2,718	890	1,143	2,303	595	4,997	4,772	7,643	3,053	2,037	77,504	17,139	7,761	930	4,285	14,204
NOx	5,861	1,449	1,246	6,045	1,614	3,392	3,113	2,882	2,935	4,579	154,173	2,162	21,258	1,805	7,152	63,264
PM10	4,791	1,003	213	576	99	311	310	259	234	751	21,887	1,368	7,210	1,929	684	13,863
PM2.5	2,382	458	116	310	66	133	127	105	124	399	10,686	652	3,645	949	418	5,506
SOx	29,307	2,954	379	131,837	1,090	23,729	23,319	21,309	12,057	12,514	315,951	8,412	595,110	3,895	6,944	243,889
BC	49	7	4	85	8	22	19	18	26	38	1,086	10	394	11	67	349
OC	80	18	14	56	16	40	34	31	39	58	2,281	23	159	26	126	632
CH4	12,628	4,234	337	5,131	2,194	25,952	24,854	23,238	14,965	6,995	382,856	3,877	10,846	4,800	18,476	138,024
N2O	114	15	6	48	19	94	85	76	69	82	3,656	22	102	38	167	1,409
CO2	7,085,341	797,544	855,909	2,570,491	1,065,870	2,071,651	1,835,912	1,527,024	1,971,802	3,294,338	177,494,631	2,236,042	4,681,093	2,400,421	7,842,467	94,038,262
GHGs	8,144,349	936,140	869,795	2,741,759	1,138,132	2,887,287	2,615,597	2,260,010	2,446,304	3,546,809	190,140,203	2,392,589	5,047,935	2,556,816	27,710,579	98,601,677

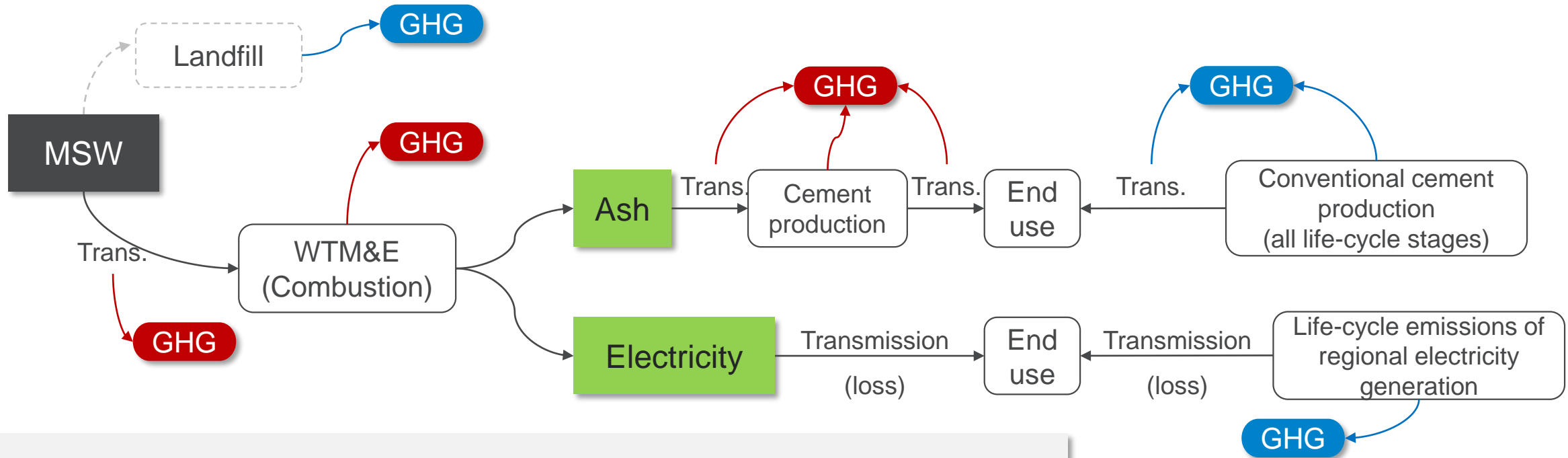


Unit: grams g\_CO<sub>2e</sub>/kWh

2019 U.S. electricity generation mix  
483 g\_CO<sub>2e</sub>/kWh at the plug



# The example of the proposed LCA framework system boundary



## Information we need to conduct LCAs:

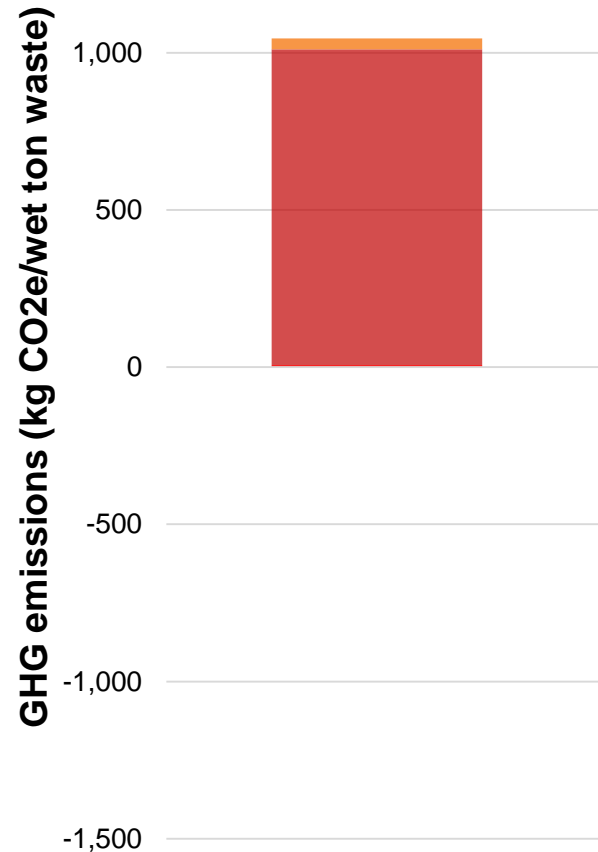
- Waste composition
- Estimated emissions from current waste management practices
- Logistics (waste and products) and associated energy use and emissions
- Inputs/outputs of the WTM&E (material and energy production per unit waste) and additional processes (e.g., cement from ash)
- Life-cycle results of the corresponding counterparts.

**GHG** (blue oval) Avoided GHG emissions (negative)

**GHG** (red oval) Positive GHG emissions

# Preliminary results of the case study

Case 1	
Cement production (ton/ton waste)	0.1
Electricity generation (kWh/ton waste)	700

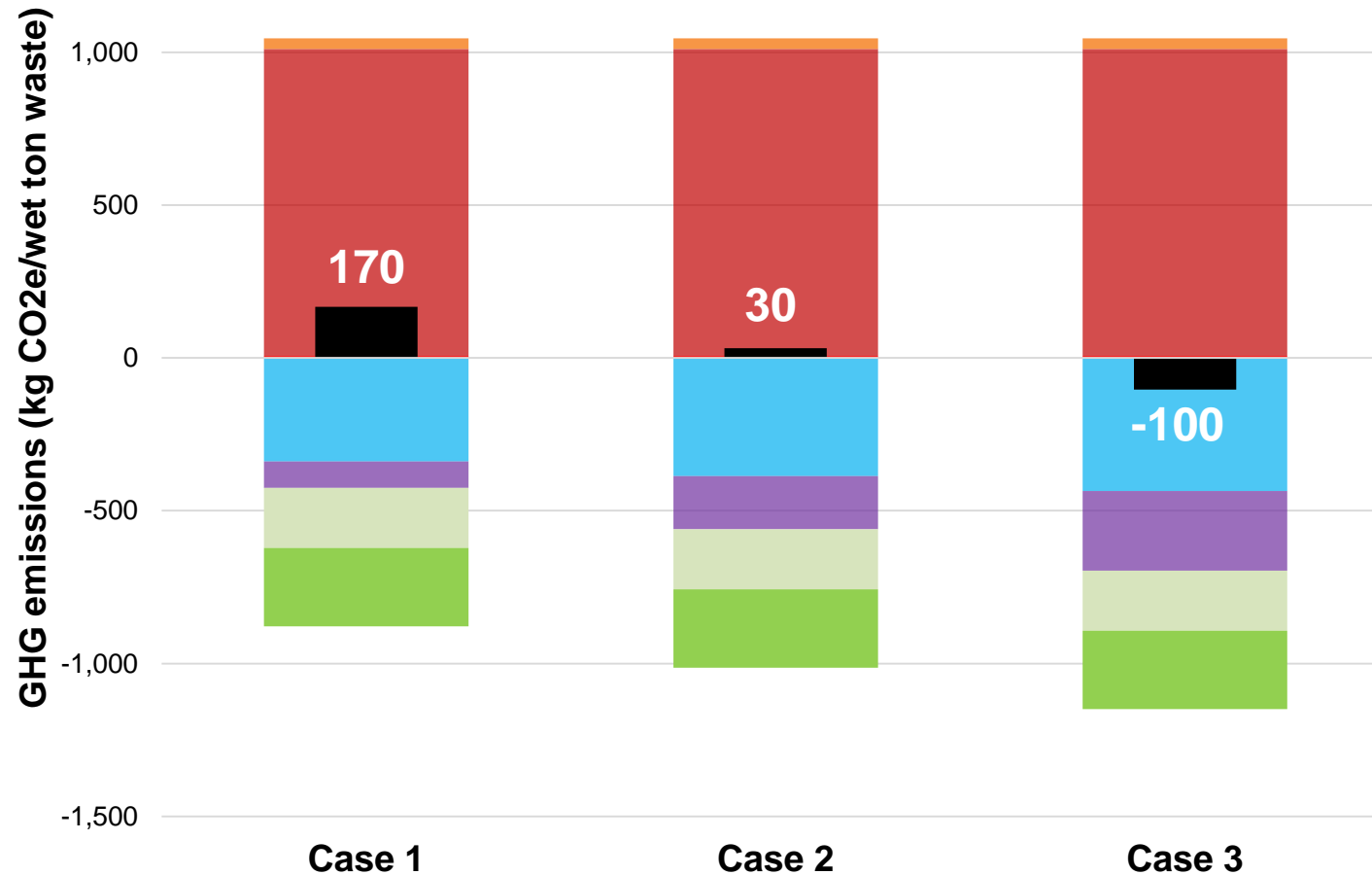


Generating cement and electricity from MSW combustion

- A - Waste transportation (30 mi)
- A - Emissions from waste incineration
- A - Ash transportation (45mi)

# Preliminary results of the case study

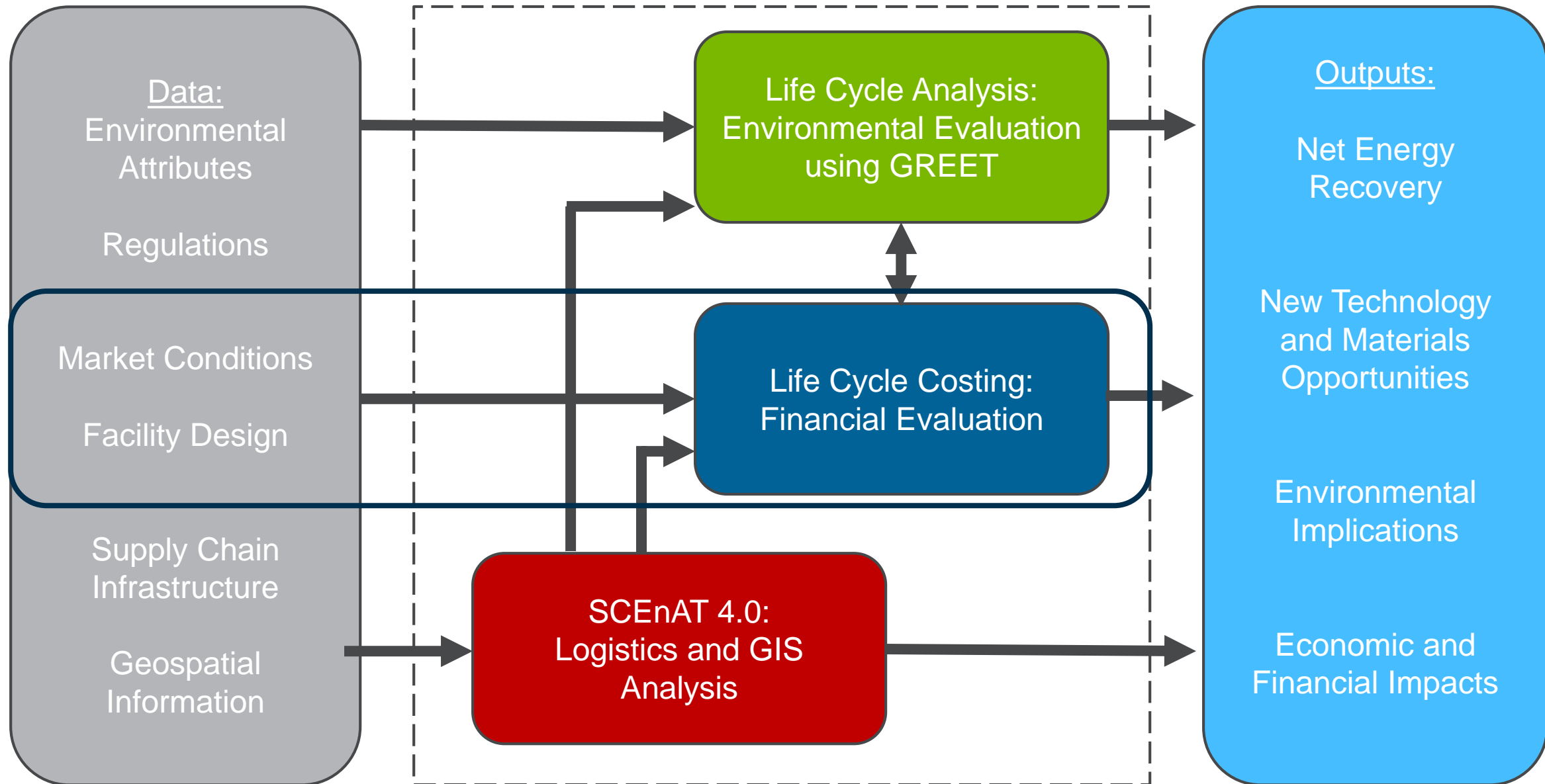
	Case 1	Case 2	Case 3
Cement production (ton/ton waste)	0.1	0.2	0.3
Electricity generation (kWh/ton waste)	700	800	900



Generating cement and electricity from MSW combustion

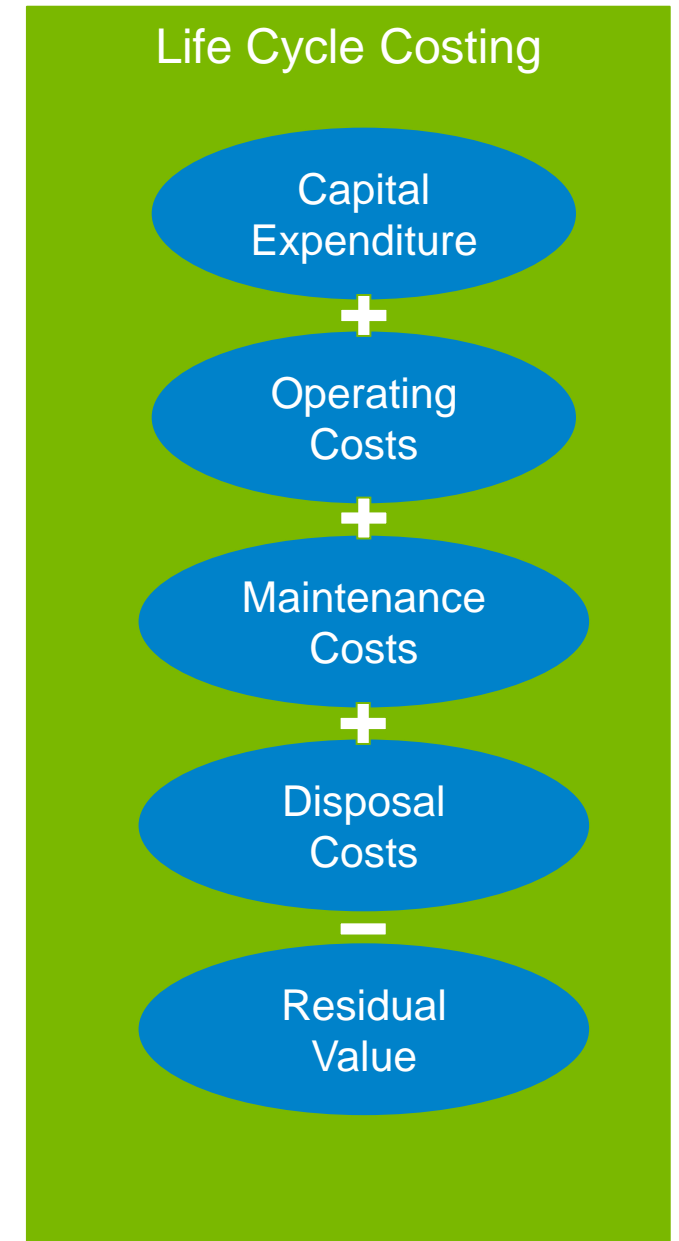
- A - Waste transportation (30 mi)
- A - Emissions from waste incineration
- A - Ash transportation (45mi)
- B - Avoided landfill gas emissions (CH<sub>4</sub>)
- B - Avoided landfill gas emissions (CO<sub>2</sub>)
- C - Displaced cement production
- D - Displaced electricity generation
- Net GHG

# Framework Organization



# Life Cycle Costing (LCC)

- Similar to LCA, LCC evaluates costs over the lifetime of a system
  - Includes cost of facility creation, useful life of equipment and facilities, maintenance, revenue, etc.
- LCC methods will be informed by the system boundaries determined by the LCA approach
- Develop Life Cycle Costing to act alongside GREET framework
  - Costing models for:
    - Collection
    - Sorting
    - Combustion
    - Landfilling
    - Other End-of-Life processes, as needed
      - Thoughts?



# Potential Costs and Revenues from MSW management

## Collection

### Fixed Costs

- Vehicle fixed costs
  - Purchasing
- Vehicle storage site
  - Construction, etc.

### Variable Costs

- Utilities
- Maintenance
- Labor
- Vehicle variable costs
  - Gas
  - Travel distance
  - Maintenance

### Revenues

- Collection Fee
- Municipal Subsidy

## Recycling

### Fixed Costs

- Permitting
- Land cost
- Construction
- Equipment

### Variable Costs

- Utilities
- Maintenance
- Labor
- Landfill Tipping Fees

### Revenues

- Collection Fee
- Municipal Subsidy
- Sale of Metals, Plastics, Glass, etc.

## Combustion

### Fixed Costs

- Permitting
- Land cost
- Construction
- Equipment

### Variable Costs

- Utilities
- Maintenance
- Labor
- Landfill Tipping Fees

### Revenues

- Waste Disposal
- Fly Ash and Bottom Ash
- Metals
- Energy
- Heat

## Landfilling

### Fixed Costs

- Permitting
- Land cost
- Equipment
- Labor
- Landfill capping

### Variable Costs

- Utilities
- Maintenance
- Labor

### Revenues

- Tipping/Host Fee
- Gas Sale



**Instructions:**

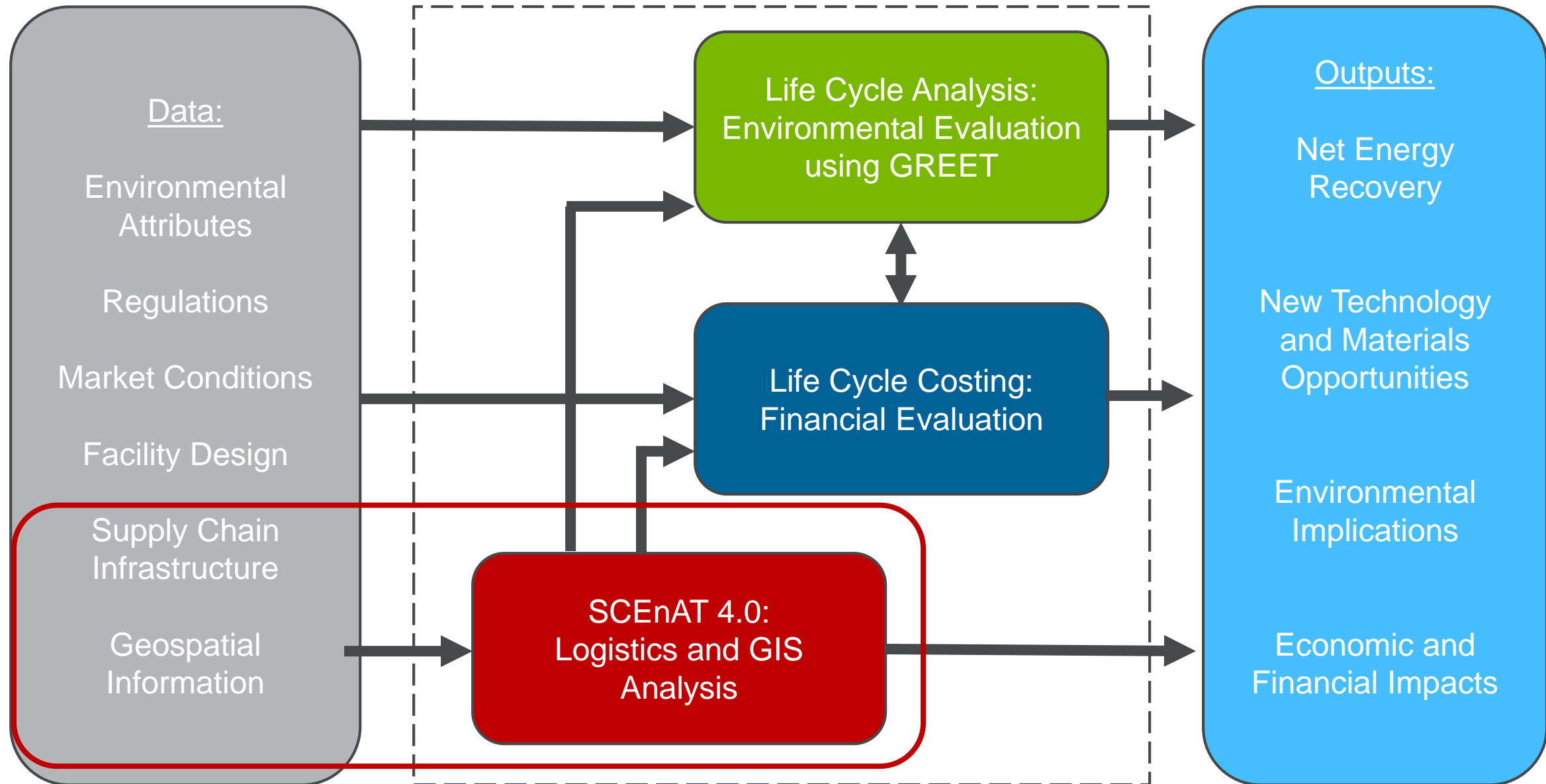
Please identify (X) which categories are particularly important for the analysis.  
 If something is missing, please write it in. If more space is required, or you would like to comment, please use the back of the document.  
 If you or your company/institution would be willing to partner with us to collect information, please circle the category

**Optional**

Name: \_\_\_\_\_  
 Company: \_\_\_\_\_  
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<p><b>Economic Drivers</b>                  What factors drive economic decision making?</p> <p><input type="checkbox"/> Price of Produced Materials (Metal, etc.)</p> <p><input type="checkbox"/> Fixed Costs/Variable Costs for Facilities</p> <p><input type="checkbox"/> Geographic Cost Factors</p> <p><input type="checkbox"/> Price of Fuel/Electricity</p> <p><input type="checkbox"/> Permitting/Compliance Costs</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>	<p style="text-align: center;"><b>Collection</b></p> <p style="text-align: center;"><u>Fixed Costs</u></p> <p>Vehicle Fixed Costs</p> <p><input type="checkbox"/> Purchasing</p> <p>Vehicle Storage Site</p> <p><input type="checkbox"/> Construction, Permitting, etc.</p> <p><input type="checkbox"/></p> <p style="text-align: center;"><u>Variable Costs</u></p> <p>Vehicle variable costs</p> <p><input type="checkbox"/> Gas/Travel Distance</p> <p><input type="checkbox"/> Maintenance</p> <p><input type="checkbox"/> Insurance</p> <p><input type="checkbox"/></p>	<p style="text-align: center;"><b>Combustion, Recycling, Landfilling</b></p> <table border="1" style="width: 100%;"> <tr> <td> <p style="text-align: center;"><u>Fixed Costs</u></p> <p><input type="checkbox"/> Permitting</p> <p><input type="checkbox"/> Land cost</p> <p><input type="checkbox"/> Construction</p> <p><input type="checkbox"/> Equipment</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> </td> <td> <p style="text-align: center;"><u>Variable Costs</u></p> <p><input type="checkbox"/> Utilities</p> <p><input type="checkbox"/> Maintenance</p> <p><input type="checkbox"/> Labor</p> <p><input type="checkbox"/> Landfill Tipping Fees</p> <p><input type="checkbox"/> Wastewater and Gas Treatment</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> </td> </tr> </table>		<p style="text-align: center;"><u>Fixed Costs</u></p> <p><input type="checkbox"/> Permitting</p> <p><input type="checkbox"/> Land cost</p> <p><input type="checkbox"/> Construction</p> <p><input type="checkbox"/> Equipment</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>	<p style="text-align: center;"><u>Variable Costs</u></p> <p><input type="checkbox"/> Utilities</p> <p><input type="checkbox"/> Maintenance</p> <p><input type="checkbox"/> Labor</p> <p><input type="checkbox"/> Landfill Tipping Fees</p> <p><input type="checkbox"/> Wastewater and Gas Treatment</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>
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<p><b>Economic Outputs</b>                  What economic information would be useful for analysis and decision making?</p> <p><input type="checkbox"/> Return on Investment (ROI)</p> <p><input type="checkbox"/> Cost Breakdown for Processes in MSW Supply Chain (Collection, Combustion, etc.)</p> <p><input type="checkbox"/> Cost Breakdown for Unit Operations</p> <p><input type="checkbox"/> Revenue from Sources (Fees, Recycled Materials, Energy Generation, etc.)</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>	<p style="text-align: center;"><u>Revenues</u></p> <p><input type="checkbox"/> Collection Fee</p> <p><input type="checkbox"/> Municipal Subsidies</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>	<p style="text-align: center;"><u>Revenues</u></p> <table border="1" style="width: 100%;"> <tr> <td> <p><input type="checkbox"/> Waste Disposal Fees</p> <p><input type="checkbox"/> Fly Ash and Bottom Ash</p> <p><input type="checkbox"/> Recycled Product Sales</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> </td> <td> <p><input type="checkbox"/> Energy</p> <p><input type="checkbox"/> Heat</p> <p><input type="checkbox"/> Tipping Fees</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p> </td> </tr> </table>		<p><input type="checkbox"/> Waste Disposal Fees</p> <p><input type="checkbox"/> Fly Ash and Bottom Ash</p> <p><input type="checkbox"/> Recycled Product Sales</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>	<p><input type="checkbox"/> Energy</p> <p><input type="checkbox"/> Heat</p> <p><input type="checkbox"/> Tipping Fees</p> <p><input type="checkbox"/></p> <p><input type="checkbox"/></p>
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# Framework Organization



# Geospatial Analytics using SCEnAT 4.0

SCEnAT 4.0 contains a suite of Geographic Information System (GIS), Machine Learning (ML), and Artificial Intelligence (AI) tools

Combine LCA, LCC, and spatial data  
– EPA, DOE, NASA, etc.

Develop capabilities to analyze logistics in MSW system  
– Identify alternate supply chains  
– Enable multi-objective optimization



Instructions:

Please identify (X) which categories are most interested in/foresee the most potential in.

If something is missing, please write it in. If more space is required, or you would like to comment, please use the back of the document.

If you or your company/institution would be willing to partner with us to collect information, please circle the category

Optional

Name: \_\_\_\_\_

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### New Technologies

What alternative technology scenarios are important?

- Emissions Control
- Bottom Ash Value Recovery
- Fly Ash Value Recovery
- Sorting Methods
- Rare Earth Extraction
- 
- 

### Challenging Data

What data is difficult to find, measure, or predict?

- Input waste mass, composition, and moisture content
- Effects of additives on combustion products (bottom ash, gas emissions, chemical segregation)
- 
- 
- 
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- 

### Environmental Outputs

What environmental information would be useful for public analysis and decision making?

- Energy Use (total/fossil/NG/petroleum/coal/renewable)
- GHG Emissions (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O)
- Criteria Air Pollutant Emissions
- Water Consumption and Quality
- Air Ozone Depletion
- Heavy Metal Emissions (As, Pb, Hg)
- Persistent Organic Pollutant Emissions
- Recycled Mass and Composition
- Fly and Bottom Ash Mass
- 
- 
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### Valuable By/Coproducts

What value recovery opportunities are most important to further develop?

- Electricity
- Iron/Steel
- Aluminum
- Other Metals:  
\_\_\_\_\_
- HDPE/PET
- Other Plastics:  
\_\_\_\_\_
- Cement
- Fuels:  
\_\_\_\_\_
- Rare Earth Elements:  
\_\_\_\_\_
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# Future work

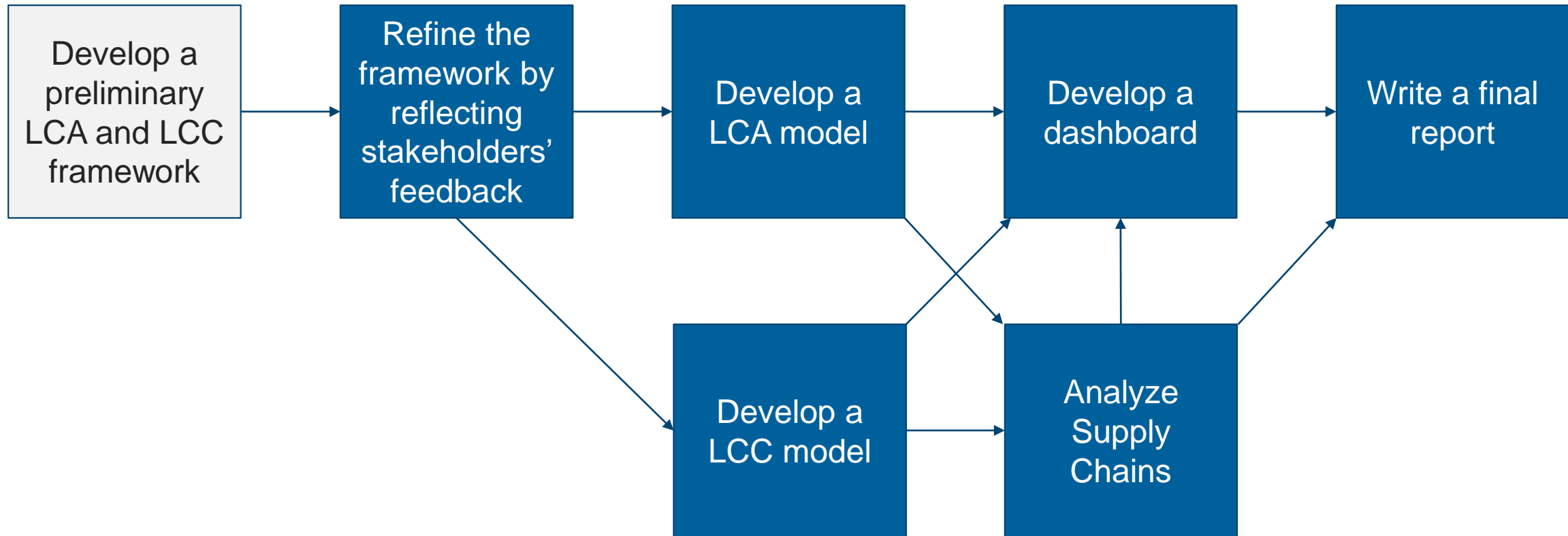
Project start  
(Oct 2019)

ARPA-E Workshop  
(Nov 2019)

Dec 2019

Feb 2020

Mar 2020



# Breakdown of Unit Processes in a Combustion Facility

Questions:

What unit processes are most important?

What unit processes are missing?

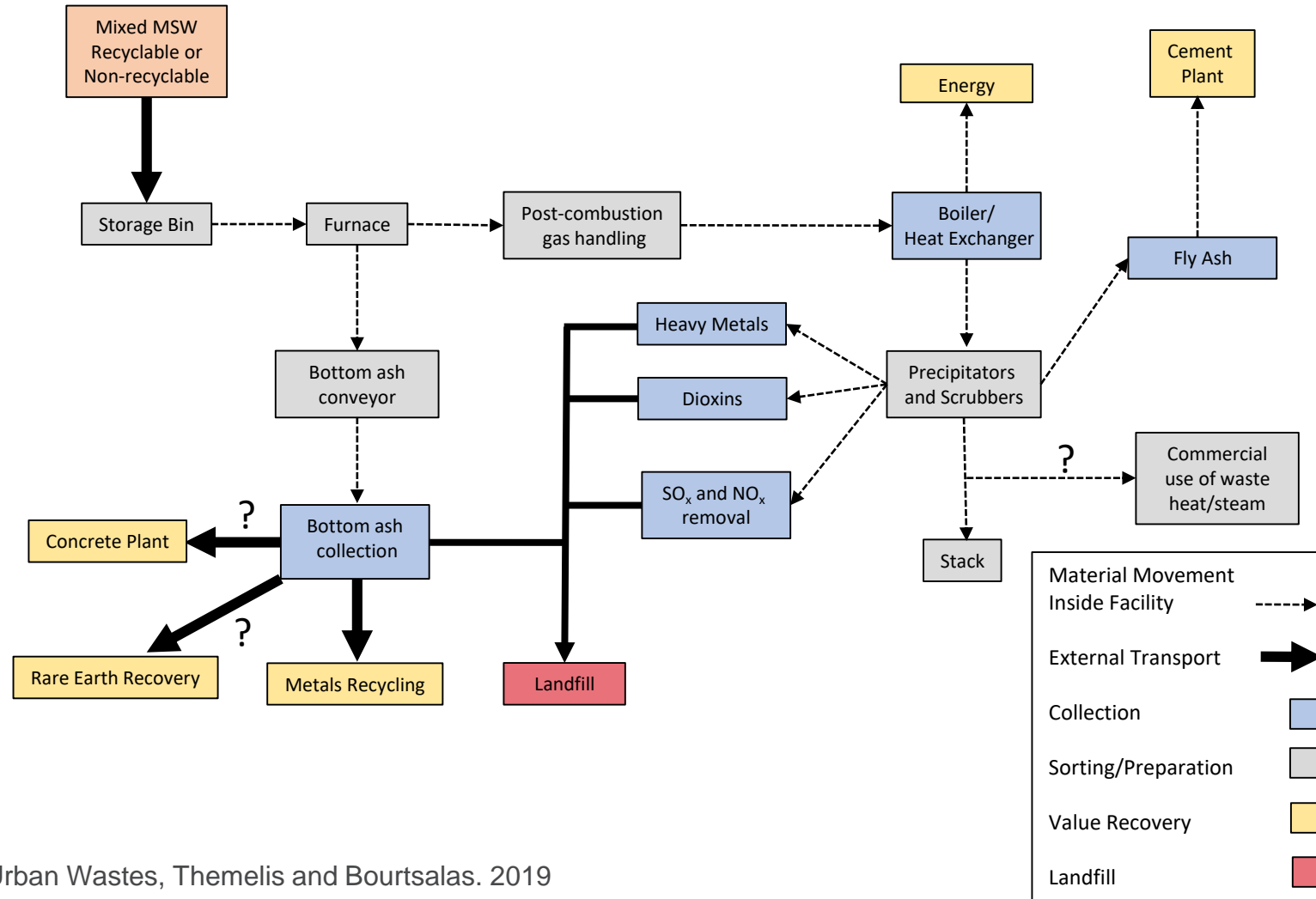


Figure adapted from Recovery of Materials and Energy from Urban Wastes, Themelis and Bourtsalas. 2019



# Breakdown of Unit Processes in a Combustion Facility

Questions:

What opportunities exist for value recovery?

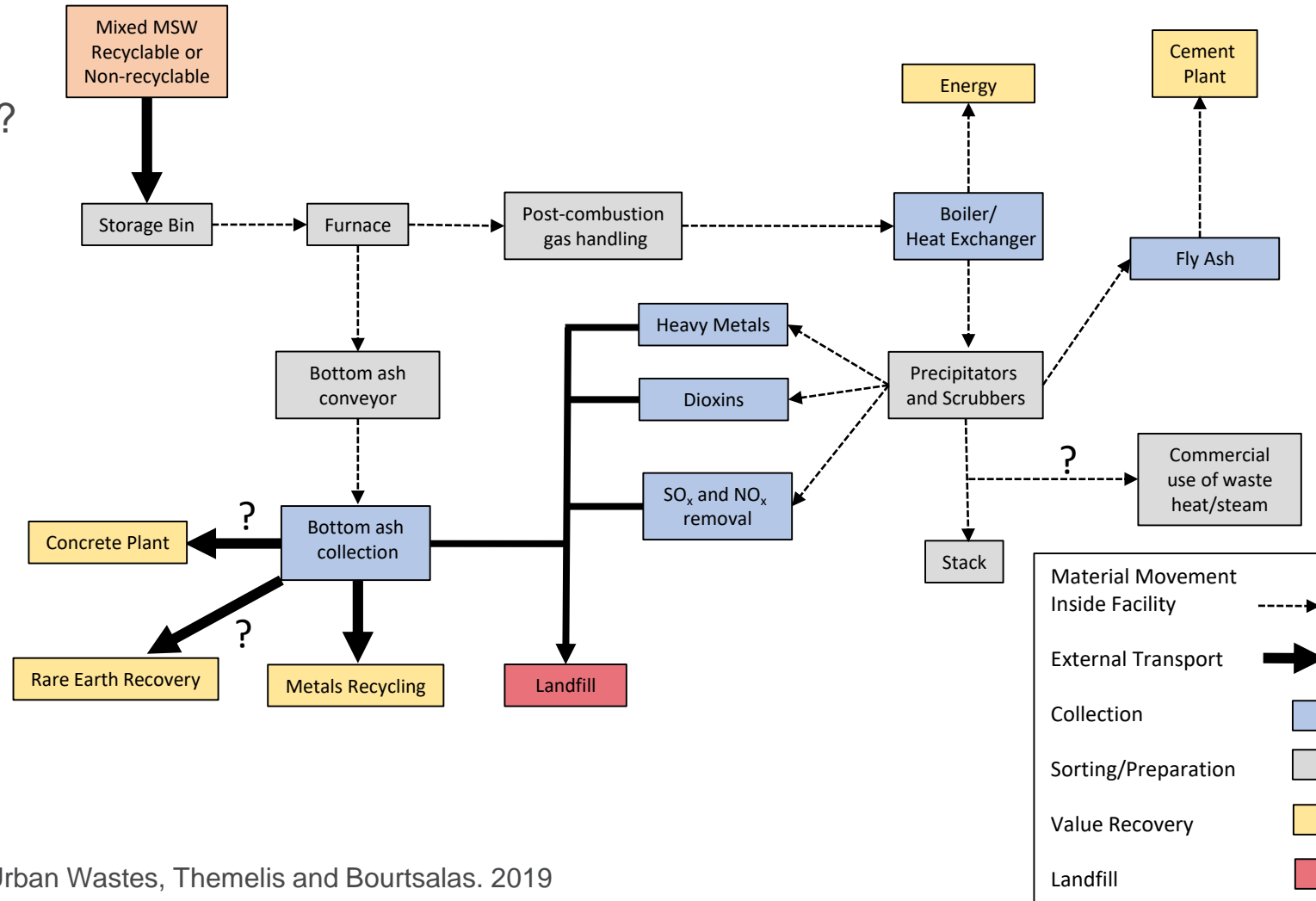


Figure adapted from Recovery of Materials and Energy from Urban Wastes, Themelis and Bourtsalas. 2019

# References

- Mintz, M., Han, J., Wang, M., & Saricks, C. (2010). Well-to-Wheels analysis of landfill gas-based pathways and their addition to the GREET model (No.ANL/ESD/10-3).Argonne National Lab.(ANL),Argonne, IL (United States).
- Han, J., Mintz, M., & Wang, M. (2011). Waste-to-wheel analysis of anaerobic-digestion-based renewable natural gas pathways with the GREET model (No.ANL/ESD/11-6).Argonne National Lab.(ANL),Argonne, IL (United States).
- Lee, U., Han, J., & Wang, M. (2017). Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *Journal of cleaner production*, 166, 335-342.
- Lee, U., Han, J., & Wang, M. (2016). Well-to-Wheels Analysis of Compressed Natural Gas and Ethanol from Municipal Solid Waste (No.ANL/ESD-16/20).Argonne National Lab.(ANL),Argonne, IL (United States).
- Benavides, P.T., Sun, P., Han, J., Dunn, J. B., & Wang, M. (2017). Life-cycle analysis of fuels from post-use non-recycled plastics. *Fuel*, 203, 11-22.
- Benavides, P.T., Dunn, J. B., Han, J., Bidy, M., & Markham, J. (2018). Exploring Comparative Energy and Environmental Benefits of Virgin, Recycled, and Bio-Derived PET Bottles. *ACS Sustainable Chemistry & Engineering*, 6(8), 9725-9733.
- Elgowainy et al., "Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at US Refineries," *Environ. Sci. Technol.* 48, 7612-7624, 2014
- Dunn, J. B., Adom, F., Sather, N., Han, J., Snyder, S., He, C., ... & You, F. (2015). Life-cycle analysis of bioproducts and their conventional counterparts in GREET (No.ANL/ESD-14/9 Rev.).Argonne National Lab.(ANL),Argonne, IL (United States).
- Themelis, N. J., Bourtsalas, A. C. (2019) *Recovery of Materials and Energy from Urban Wastes*. Springer. New York, NY (United States).