Municipal Solid Waste: A Solution to the Growing Problem

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Purpose

- Investigate and select an alternative method of MSW disposal
- Design a waste processing plant
- Advance the previous deterministic model to optimize a construction and expansion timeline
- Select a feasible investment strategy
Today’s Agenda

1. MSW in the United States
   - City selection
   - Waste disposal methods
2. Pyrolysis Processing Plant
3. Producing Hydrogen from Synthetic Gas
   - Other possible end products
4. MSW Processing Plant Capital Costs
5. Deterministic Model
6. Results
7. Ownership
Background

- Municipal Solid Waste in the United States
  - Composition
  - Waste Disposal

MSW Production and Disposal, 1960-2001

- MSW Produced
- MSW Disposed
Waste Disposal in the U.S.

- Close to 210 million tons of MSW per year
- Methods
  - Landfilling
  - Incineration
  - Pyrolysis
  - Recycling
City Selection

• Cities Considered:
  – New York City, New York
  – Los Angeles, California
  – Detroit, Michigan
  – Hilo, Hawaii

• Basis of Analysis
  – Amount of MSW produced
  – Population and Population growth
  – Cost of current disposal method
Municipal Solid Waste Produced

- Total MSW Generation
- Recycling Rates
- Waste Disposal Methods
  - NYC—Transporting MSW
  - Detroit—Incineration and Landfilling
  - Hilo—Transporting MSW and Landfilling
  - Los Angeles—Landfilling

![Bar Chart: Municipal Solid Waste Produced](chart.png)

- New York City
- Los Angeles
- Detroit
- Hilo
Population

- Metropolitan Area Populations
- NYC has largest metropolitan population
- Hilo has a population under a million
• Hilo has the largest population growth but very small population
• New York also has large population growth
• Detroit has smallest population growth
Price to Dispose of MSW

- Average Prices
- New York Fresh Kills Landfill Closed—Transporting Waste Out of State
- Cost of Incineration High
- Hilo Running Out of Space
- West Coast Has More Space than East Coast
Location Choice...

- **New York City:**
  - Price to Dispose of MSW: $63.30
  - Population of Metropolitan Area: 22 million
  - Amount of MSW in Metro: 46,000 tons/day
  - Landfilling in NYC
    - Prevention of landfilling in high density NYC
    - 9 private and 23 public landfills—capacity of 60 million tons
    - 17 companies with three year base contracts and two 1 year extensions
Disposal Methods

• Methods Considered
  – Landfilling
  – Incineration
  – Pyrolysis

• Basis of Analysis
  – Cost to build and operate
  – Environmental Concerns
  – Production of Products
Landfilling

• Advantages
  – Small Capital Investment
  – Little Maintenance
  – Cheaper Disposal Fees

• Disadvantages
  – Environmental Pollution
    • Methane Carbon Dioxide
    • Leachate
  – Property Decrease in Value

Source: http://www.zerowasteamerica.org/Landfills.htm
Incineration

- **Advantages**
  - Minimizes Landfill Volume
  - Recovery of Energy

- **Disadvantages**
  - High Building and Operation Costs
  - Air Emissions
  - Toxic Ash

Source: http://www.meniscusclients.com/portfolio/cwa/tech_info.htm
Pyrolysis

• Advantages
  – Minimizes Landfill Volume
  – Recovery of Energy
  – Production of Synthetic Gas

• Disadvantages
  – Air Emissions—
  – Leachate
  – Slag—Landfilled or used in road foundations
Method Choice...

• Pyrolysis
  – Land Constraints in NYC
  – Production of Syngas
    • Mixture of CO, CO₂ and H₂
    • Can lead to production of synthetic fuels, hydrogen, ammonia, alcohols, aldehydes, carboxylic acids
Pyrolysis Process

• Why Separate Before Pyrolysis?
  – Enhance Profit / Reduce Costs
    • Sell Recyclable Metals; Low Heat Value
    • Reduce Wear and Tear on Equipment
    • Easier Than Separation After Pyrolysis
  – Control Refuse Properties
    • Slag Seals Refuse if Proper Proportions
Front End Separation

Waste Energy
13.9x10^9 Btu/D

Purox Feed Energy
13.8x10^9 Btu/D

2 EQPT LINES - PER LINE:
16 HPD
6 DPW
60 TPH

180,000 CFM

BAGHOUSE DUST COLLECTION

new york municipal solid waste
Purox Pyrolysis Facility

- RAM Feed
- Purox Reactor
- Off Gas
- 40% Water

New York Municipal Solid Waste
Wastewater Plant

O₂ FEED
40 TPD

WASTE WATER
480 TPD

SURFACE AERATORS

50,000 mg/L BOD
Oxygen Plant
Oxygen Plant (cont.)

- Air Separation
  - 78.1% N₂, 20.9% O₂, 0.934% Ar, 0.035% CO₂
- 280 TPD O₂ = 1 Purox Reactor
- Equipment: Compressor, Heat Exchanger, Distillation Columns
Oxygen Plant (cont.)

• Purpose:
  – Eliminate Nitrous Oxides
    • Environmental aspects
  – Increases concentration of reactants
  – Raise reactor temperature to effectively destroy toxins
End Product Possibilities

- Hydrogen
- Ammonia
- Polycarbonates
- Synthetic Fuel
- Methanol
- Dimethyl Ether
- Acetic Acid
End Product Possibilities

• Hydrogen

  Uses: fuel cells, alternative fuels, petroleum industry applications

(1) $\text{CH}_4 + 2 \text{H}_2\text{O} \leftrightarrow 4 \text{H}_2 + \text{CO}_2$

(2) $\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$

Sale Price: $2500/\text{ton}$
End Product Possibilities

• Ammonia

  Uses: fertilizers, refrigeration, processing

  \[ N_2 + H_2 \rightarrow 2 \text{NH}_3 \]

  Sale Price: $200/ton
  -using \( H_2 \) ($2500/ton) and \( N_2 \) ($160/ton)
End Product Possibilities

- Polycarbonates
  Uses: drink bottles, CD/DVD substrates, audio/video cassettes

  \[(1) \text{CO}_2 + \text{H}_2 \rightarrow \text{CO} + \text{H}_2\text{O}\]
  \[(2) 2 \text{NaCl} + \text{CO} \rightarrow 2 \text{Na} + \text{Phosgene}\]
  \[(3) \text{Phosgene} + \text{bisphenyl-}A \rightarrow \text{Polycarbonate} + 2 \text{HCl}\]

Sale Price: $66/ton (HCl $72/ton)
- using H₂ ($2500/ton)
- using bisphenyl-A ($2000/ton) and NaCl ($46/ton)
End Product Possibilities

• **Synthetic Fuel**
  
  Uses: diesel fuel, waxes

  \[ \text{CO} + 2 \text{H}_2 \rightarrow \text{CH}_2 + \text{H}_2\text{O} \]

  Sale Price: $630/ton
  - using \( \text{H}_2 \) ($2500/ton)
End Product Possibilities

- Methanol

Potential Uses: MTBE, DME,

(1) $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$
(2) $\text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH}$
(3) $\text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$

Sale Price: $254/\text{ton}$
- using $\text{H}_2$ ($2500/\text{ton}$)
End Product Possibilities

- **Dimethyl Ether**
  
  Uses: alternative fuel (developing countries)
  
  (1) $3 \text{CO} + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + \text{CO}_2$
  
  (2) $2 \text{CO} + 4 \text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + \text{H}_2\text{O}$
  
  Sale Price: $109/\text{ton}$
  
  - using $\text{H}_2$ ($2500/\text{ton}$)
End Product Possibilities

- **Acetic Acid**
  
  Uses: photo film, vinyl acetate, vinegar

  \[
  \text{CH}_3\text{OH} + \text{CO} \rightarrow \text{CH}_3\text{COOH}
  \]

  Sale Price: $800/ton
  - results from CH\(_3\)OH that results from H\(_2\) ($2500/ton)
End Product Comparison

- **Sale Price ($/ton)**
- **Price ($/ton MSW)**
- **Revenue ($ MM/yr)**

<table>
<thead>
<tr>
<th>Product</th>
<th>Hydrogen</th>
<th>Ammonia</th>
<th>Synthetic Fuel</th>
<th>Methanol</th>
<th>Polycarbonates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sale Price</strong></td>
<td>2500</td>
<td>200</td>
<td>750</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td><strong>Revenue</strong></td>
<td>1000</td>
<td>500</td>
<td>1000</td>
<td>500</td>
<td>1000</td>
</tr>
</tbody>
</table>
Product Possibilities

- Ammonia
- Polycarbonates
- Synthetic Fuel
- Methanol
- Dimethyl Ether
- Acetic Acid
- Hydrogen
### Synthetic Gas

<table>
<thead>
<tr>
<th>Component</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>12.5%</td>
</tr>
<tr>
<td>CO</td>
<td>20.8%</td>
</tr>
<tr>
<td>CH₄</td>
<td>5.7%</td>
</tr>
<tr>
<td>H₂O</td>
<td>47.9%</td>
</tr>
<tr>
<td>CO₂</td>
<td>12.5%</td>
</tr>
<tr>
<td>N₂</td>
<td>0.6%</td>
</tr>
</tbody>
</table>
Hydrogen Plant

Steam Reformation

Water-Gas Shift

CO₂ Removal

Pressure Swing Adsorption

Syngas → H₂O → H₂O → CO₂ → CO, CO₂, CH₄, N₂ → 99.999% Pure H₂
Steam Reformation

- Coal fired furnace
- Heat Load of 140 Million Btu/hr
- Steam:Methane = 8
- 170 tubes, 5-in ID, 40 ft. long
- 380,000 lbs Nickel-Alumina Catalyst

\[
\begin{align*}
\text{CH}_4 + \text{H}_2\text{O} & \rightarrow 3\text{H}_2 + \text{CO} \\
\text{CO} + \text{H}_2\text{O} & \rightarrow \text{CO}_2 + \text{H}_2 \\
\text{OVERALL REACTION:} & \quad \text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2 \\
\Delta HR_X & = 84,000 \text{ Btu/lbmol} \\
T & = 1600 \degree \text{F} \\
P & = 20 \text{ atm}
\end{align*}
\]

33.8 MM Btu/hr
Hydrogen Plant

Syngas:
- 24% H₂
- 39.9% CO
- 10.9% CH₄
- 24% CO₂
- 1.2% N₂

3050 lbmol/hr

Steam Reformation

56% H₂
15.8% CO
0.1% CH₄
26.9% CO₂
0.9% N₂

4380 lbmol/hr

new york municipal solid waste
Water-Gas Shift

- 300,000 lbs Chromia-promoted iron catalyst
- Steam:CO = 8
- 4 X 36ft reactors
  - 100 tubes
  - 3-in ID
- 2 X Heat Exchangers
- Flash Drum

\[
\text{CO + H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2
\]

36.8 MM Btu/hr

9.8 MM Btu/hr
Hydrogen Plant

Water-Gas Shift

- 56% H₂
- 15.8% CO
- 0.1% CH₄
- 26.9% CO₂
- 0.9% N₂
- 4380 lbmol/hr

- 62.3% H₂
- 1.5% CO
- 0.1% CH₄
- 0.2% H₂O
- 35.2% CO₂
- 0.8% N₂
- 4960 lbmol/hr
CO₂ Removal

Diagram showing a process flow for CO₂ removal.
Hydrogen Plant

62.3% H₂
1.5% CO
0.1% CH₄
0.2% H₂O
35.2% CO₂
0.8% N₂

4960 lbmol/hr

CO₂ Removal

96.4% H₂
2.3% CO
0.2% CH₄
0.2% H₂O
0% CO₂
1.2% N₂

3203 lbmol/hr

new york municipal solid waste
Pressure Swing Adsorption

$W = 1022.2 \text{ HP}$

$W = 5551.58 \text{ HP}$
Hydrogen Plant

Pressure Swing Adsorption

96.4% H₂
2.3% CO
0.2% CH₄
0.2% H₂O
0% CO₂
1.2% N₂

3203 lbmol/hr

99.99% Pure Hydrogen

3090 lbmol/hr
MSW Processing Plant
Capital Costs

• Based on plant processing 1500 TPD MSW

• Capital Investment
  – Purox Pyrolysis Plant
  – Hydrogen Production Plant

• Production Costs
  – Operating Costs
  – Transportation Costs
## Purox Pyrolysis Capital Costs

<table>
<thead>
<tr>
<th>Item</th>
<th>1975</th>
<th>2004</th>
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</thead>
<tbody>
<tr>
<td>Construction</td>
<td>47.1</td>
<td>126.9</td>
</tr>
<tr>
<td>Interest during construction</td>
<td>4.30</td>
<td>11.59</td>
</tr>
<tr>
<td>Startup Costs</td>
<td>2.56</td>
<td>6.90</td>
</tr>
<tr>
<td>Working Capital</td>
<td>1.56</td>
<td>4.21</td>
</tr>
<tr>
<td><strong>TOTAL CAPITAL INVESTMENT</strong></td>
<td>55.5</td>
<td>149.6</td>
</tr>
</tbody>
</table>
## Hydrogen Capital Costs

<table>
<thead>
<tr>
<th>Process</th>
<th>Equipment</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Reformation</td>
<td>Compressor</td>
<td>$5,727,400</td>
</tr>
<tr>
<td></td>
<td>Steam Reformer</td>
<td>$2,000,000</td>
</tr>
<tr>
<td>Water-Gas Shift</td>
<td>High Temp. Reactor X 4</td>
<td>$1,029,776</td>
</tr>
<tr>
<td></td>
<td>Heat Exchanger</td>
<td>$8,000</td>
</tr>
<tr>
<td></td>
<td>Flash Drum</td>
<td>$112,000</td>
</tr>
<tr>
<td>CO2 Removal</td>
<td>Stripper</td>
<td>$1,694,000</td>
</tr>
<tr>
<td></td>
<td>Turbine</td>
<td>$312,000</td>
</tr>
<tr>
<td></td>
<td>Slump Tank</td>
<td>$26,000</td>
</tr>
<tr>
<td></td>
<td>Compressor X 4</td>
<td>$964,000</td>
</tr>
<tr>
<td></td>
<td>Flash Drum X 3</td>
<td>$126,000</td>
</tr>
<tr>
<td></td>
<td>CO2 Storage Tank</td>
<td>$3,400,000</td>
</tr>
<tr>
<td></td>
<td>Pump</td>
<td>$114,000</td>
</tr>
<tr>
<td></td>
<td>Refrigerator</td>
<td>$485,000</td>
</tr>
<tr>
<td>PSA stuff</td>
<td>PSA</td>
<td>$2,201,000</td>
</tr>
<tr>
<td>Storage/Production</td>
<td>Compressor</td>
<td>$3,000,000</td>
</tr>
<tr>
<td></td>
<td>Heat Exchanger</td>
<td>$1,500</td>
</tr>
<tr>
<td></td>
<td>Storage Tanks X 12</td>
<td>$3,700,000</td>
</tr>
</tbody>
</table>

**Total Equipment Costs**: $24,900,676
Waste to Hydrogen TCI & Production Costs

- **TCI of Plant**
  - $300 million

- **Production Costs**
  - $56 million/year
  - Utilities, Catalysts, Labor
  - Do not account for transportation costs
Deterministic Model

• Advance the previous deterministic model
• New additions:
  – Refined Plant Investment & Production Costs
  – Allowed plants to expand by incorporating new capital costs
  – Updated contracts and locations
  – Developed new transportation costs

new york municipal solid waste
Refined Plant Investment & Production Costs

Scaled Up TCI

Scaled Up Operating Costs

y = 0.0358x - 3.9913

y = 0.1356x - 20.722
Contracts & Locations

- Updated contracts
  - Many contracts recently expired

- Reconfigured mileage
  - Account for highways and driving times
  - More accurate mileage from transfer location to possible facilities
Plant Transportation Costs

- **MSW Semi-Dump Trucks**
  - Capacity = 15 tons of waste
  - $80,000 each
  - Mileage = 6 miles/gallon
  - Lifetime = 1MM miles

\[
\text{Cost}_{MSW} = \frac{\text{(waste/day)}}{(\text{Capacity}_{MSW} \times \text{(#trips/day))}}
\]

- **H}_2\text{ Tanker Trucks**
  - Capacity = 4.5 tons hydrogen
  - Tube Trailer = $340,000
  - Truck Cab = $110,000

\[
\text{Cost}_{H}_2\text{truck} = \frac{\text{(H}_2\text{tons/day)}}{(\text{Capacity}_{H}_2\text{trucks} \times \text{(#trips/day))}}
\]
Private Enterprise

• **Private**
  – Model will determine profitability based on NPW
  – Determine if ROI is greater than 10%
  – Raise money through investors
• **Public as an alternative**
  – Raise money through municipal bonds
  – Model will determine minimum disposal fee without process losing money
Mathematical Model

• Pre-determined Factors
  – Process: Pyrolysis
  – Final Product: Hydrogen

• Implement deterministic, stochastic mathematical model for logistic planning
Deterministic Model

- Pyrolysis- TCI & Operating Cost
- Material Balances, Objectives, & Constraints
- Hydrogen- TCI

Ownership
- Private
- Public

Processing/Production Plant
- Size/Capacity
- Expansions at time t, plant j

Location

Transportation
- Transfer of wastes from transfer station to plant
- Transfer of products to consumers

Consumers
Importance of Model

- Aid in planning of process
  - Implement and control the most efficient and cost-effective flow of materials in relation to time
  - Account for current MSW disposal contracts
  - Encompass transport of MSW and final products
  - Execute the right number, location, and capacity of plants
  - Incorporate expansions in relation to time, money, and the amount of trash
Private: Annual Waste Processed compared to Waste Available

- By 2014, 86% of MSW is processed.
- Over a 20-year span, 78% of MSW available is processed.
- 197 MSW Semi-Trucks

![Graph showing annual waste processed compared to waste available.](chart.png)
Private: Waste Processed/Expansions at Each Plant

- Amount of Waste Processed (tons/day)
- Year:
  - Oxford, NJ
  - Hempstead, NY
  - Islip, NY
  - Babylon, NY
  - Huntington, NY
  - Charlespoint, NY

**Graph Details:**
- Y-axis: Amount of Waste Processed (tons/day)
- Color Legend:
  - Green: Oxford, NJ
  - Red: Hempstead, NY
  - Yellow: Babylon, NY
  - Blue: Huntington, NY
  - Orange: Charlespoint, NY
- Total Capital Investment (20 years) = $2.0 MMM
- NPW (20 years) = $198 MM
- Return on Investment = 12.5%
- 508 Hydrogen Tankers
- Disposal Fee $45/ton
- Saves City of New York over $54MM/y
Investment Strategy

- Private Feasible
  - Total Capital Investment (20 years) = $2.0 MMM
  - NPW (20 years) = $198 MM
  - Return on Investment = 12.5%
Public as an Alternative
Public: Cumulative Cash

Year:
- $1.50
- $1.00
- $0.50
- $0.00
- $0.50
- $1.00
- $1.50
- $2.00
- $2.50
- $3.00
- $3.50

Year:
- 2007
- 2012
- 2017
- 2022
- 2027

New York Municipal Solid Waste

CEMS
Public: Cumulative Cash with Bonds

Year:
- 2007
- 2012
- 2017
- 2022
- 2027

Cash Savings ($MM/year):
- $3.00
- $2.50
- $2.00
- $1.50
- $1.00
- $0.50
- $0.00
- -$0.50
- -$1.00

B1, B2, B3 markers.
Public: Bonds

All bonds are 10 year bonds at 4% interest

- Total Amount In Bonds = $1.14 MMM
- Total Interest Paid = $5.5MM
  - Amount issued in 2007 = $974 MM
  - Pay off amount (w/interest) = $1.44 MMM
- Bond 1
- Bond 2
  - Amount issued in 2011 = $136 MM
  - Pay off amount (w/interest) = $201 MM
- Bond 3
  - Amount issued in 2014 = $30 MM
  - Pay off amount (w/interest) = $44 MM
Public: Annual Waste Processed compared to Waste Available

- By 2015, 84% of MSW is processed
- Lifetime: 69% waste processed
- No tax
- Fee charged to city $35/ton saves city $75 MM/y
- TCI = $1.9 MMM
Questions