Bioenergy Production from MSW by Solid-State Anaerobic Digestion

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Intro to HS-AD (a.k.a. SS-AD)

- **Designed to process feedstocks with > 15% total solids content.**

**Flowchart:**
- **Organic Waste** → **Pre-Processing/Pretreatment**
  - **Inoculum**
  - **Additives**
  - **Parasitic Energy**
- **High-Solids Anaerobic Digestion** → **Biogas Processing** → **Biogas Utilization**
  - Combined heat & power
  - Compressed natural gas
  - Natural gas grid injection
- **Digestate** → **Digestate Processing** → **Digestate Utilization or Disposal**
  - Biofertilizer, compost, or soil amendment
  - Further conversion
  - Disposal in LF or WtE
- **Leachate/Digestate Recirculation**
Zero Waste Energy, Monterey
Research Motivation

- Anaerobic Digestion (AD) of OFMSW results in:
  - Energy recovery/renewable energy generation
    - Reduces fugitive GHG emissions from landfills
    - Offsets GHG emissions from fossil-fuel derived energy
  - Nutrient recovery/organic fertilizer production
    - Reduces landfill leachate volume and strength
    - Offsets impacts of inorganic fertilizer production

- High-Solids AD (HS-AD) advantages over Liquid AD:
  - Reduced parasitic energy demand
  - Reduced reactor volume requirements
  - Reduced water usage and leachate generation
Research Objectives

■ Overall Goals
  ■ Contribute to the fundamental science of HS-AD and evaluate potential for implementation in FL

■ Specific Objectives
  ■ 1. State-of-the-Art of HS-AD
    ■ Trends and drivers in the industry and appropriate technologies for FL
  ■ 2. Enhancing Bioenergy Production
    ■ Improve biodegradability of yard waste and explore co-digestion strategies
  ■ 3. Potential for HS-AD Implementation in FL
    ■ Identify promising locations for HS-AD based on existing MSW infrastructure and potential bioenergy production, GHG emissions reductions and nutrient recovery.
    ■ Evaluate economics and develop policy recommendations.
Objective 1: State-of-the-Art

- **Goals**
  - Understand trends and identify primary drivers in the industry
  - Identify appropriate technologies for implementation in FL

- **Methodology**
  - Review published and “grey” literature
  - Developed chronological database of US HS-AD projects
  - Visits to facilities in California and the Netherlands
HS-AD Technology Classifications

- Anaerobic Digestion
  - L-AD
  - HS-AD
  - Batch
  - Continuous
  - Thermophilic
  - Mesophilic
  - Single-Stage
  - Multi-Stage
  - SS-OFMSW
  - MS-OFMSW
  - Mixed MSW
  - Codigestion
  - Single-Substrate

- TS Content
- Loading Conditions
- Operating Temperature
- Number of Stages
- Feedstock
HS-AD Development in the US

Projected based on projects in planning, permitting, and construction phases.

Approximate Total Number of Full-Scale HS-AD Facilities in the US

- 2011: 0
- 2012: 0
- 2013: 1
- 2014: 5
- 2015: 9
- 2016: 18
- 2017: 30
HS-AD Locations in the US

- CleanWorld (3)
- ZWE (3)
- Orbit Energy (1)
- BIOFerm (1)
HS-AD Development Timeline

1970
- Liquid AD (L-AD) widely implemented
- Development of HS-AD begins in the EU

1980
- Sharp increase in landfill bans and taxation in the EU
- Addition of OFMSW to L-AD systems begins

1990
- Source-separation mandates increasing in number in the EU
- Development of HS-AD becomes dominant AD type for OFMSW in the EU

2000
- HS-AD becomes dominant AD type for OFMSW in the EU

2010
- Stand-alone HS-AD capacity surpasses L-AD in the US; Single-stage batch systems are dominant technology type

2020
- Accelerating development of OFMSW recycling legislation and renewable energy incentives in the US
Summary of Major Findings

- Policy promoting OFMSW recycling in the US increasing:
  - 20 states now have yard waste landfill bans, 5 have food waste bans
  - 7 have landfill diversion targets
  - Over 200 communities offer separate collection of food waste
  - *Required* source-separation in San Francisco, Seattle, VT, and CT
  - 29 states now have renewable portfolio standards

- HS-AD implementation parallels policy development
  - HS-AD has surpassed L-AD for OSFMW processing capacity
  - CA is leading the way with policy and HS-AD development

- Single-stage, batch, thermophilic, “garage” type systems are the most suitable for Florida
  - Low cost, simple operation, reliable
Objective 2: Enhancing Bioenergy

The Lignocellulosic Challenge

- **Hydrolysis**
  - Complex Organic Matter
  - Soluble Organic Molecules

- **Acidogenesis (Fermentation)**
  - VFAs
  - Acetic Acid

- **Acetogenesis**
  - H₂ + CO₂
  - VFAs
  - Acetic Acid

- **Biogas**
  - Biogas (CH₄ + CO₂)
Objective 2: Enhancing Bioenergy

- Goals
  - Study the effects of bioaugmentation with pulp and paper mill anaerobic sludge on methane yields in batch HS-AD of yard waste
  - Determine whether enhancements can be sustained via digestate recirculation

- Hypothesis
  - Hydrolytic microorganisms in pulp and paper sludge are adapted to lignocellulosic waste and therefore have a greater capacity to degrade lignocellulosics than a conventional inoculum
Materials and Methods
## Digester Compositions

### Phase 1 Batch HS-AD

<table>
<thead>
<tr>
<th>Type</th>
<th>Wet Weight Added (g)</th>
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<tr>
<td>Bioaugmented Digesters</td>
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<tr>
<td>Control Digesters</td>
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<tr>
<td>Pulp and Paper Sludge Blank</td>
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<td>Wastewater Sludge Blank</td>
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### Phase 2 Batch HS-AD

<table>
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<tr>
<th>Type</th>
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<tbody>
<tr>
<td>Bioaugmented Digesters</td>
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<tr>
<td>Control Digesters</td>
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</tr>
<tr>
<td>Recycled Bioaugmented Digestate Blank</td>
<td></td>
</tr>
<tr>
<td>Recycled Control Digestate Blank</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- **Digestate from Phase 1 Control Digesters**
- **Digestate from Phase 1 Bioaugmented Digesters**
- **Wastewater Sludge**
- **Pulp and Paper Sludge**
- **Yard Waste**
Phase 1 Specific Methane Yields

- **Phase 1 Bioaugmentation**: Yard waste inoculated with pulp and paper sludge
- **Phase 1 Control**: Yard waste inoculated with wastewater sludge

![Graph showing the specific methane yields over time for both bioaugmentation and control phases.](image-url)
Phase 2 Specific Methane Yields

- Phase 2 Bioaugmentation: Yard waste inoculated with bioaugmented digestate
- Phase 2 Control: Yard waste inoculated with control digestate
Summary of Major Findings

- Results suggest that this strategy could serve as a low impact alternative to pretreatment
  - Significant enhancements in methane yields achieved and sustained through bioaugmentation with pulp & paper sludge

- Chemical and lignocellulosic data support hypothesis
  - VFA concentrations indicate methanogenesis was rate-limiting in bioaugmented digesters while hydrolysis was limiting in control digesters
  - 16%, 16%, and 2% less lignin, cellulose, and hemicellulose in bioaugmented digestate relative to control digestate

- Need for future research:
  - Effects of varying substrate to inocula ratios
  - Mechanisms of methane yield enhancement
  - Bioaugmentation of OFMSW co-digestion mixtures – food, yard, biosolids.
  - Pilot and full-scale testing
Objective 3: Implementation in FL

Goals

- Identify best FL counties for HS-AD implementation based on:
  - Existing MSW infrastructure
  - Potential bioenergy production & GHG emissions reductions
  - Potential for nutrient recovery.

- Evaluate economics and develop policy recommendations.

Methodology

- Review published and “grey” literature and FDEP data
- Consider findings from State-of-the-Art assessment
- Estimate potential bioenergy production, GHG reductions and nutrient recovery
Incentive for HS-AD Implementation

- **75% recycling goal by 2020**
  - Current statewide recycling rate = 50%
    - Yard and food waste recycling rates = 51% and 7%, respectively
  - 12% of waste stream is yard waste and 7% is food waste
    - *Up to 13% increase in recycling rate achievable via OFMSW recycling*

- **Renewable energy generation**
  - Up to 500MW of renewable energy could be produced
    - 175 MW electricity (~1% of FL total demand, > $120M) + 200 MW heat
    - OR: 80 million DGEs of CNG per year (~11.5% of FL total demand)
    - 660,000 MTCO$_2$E per year offset (~$3.2M - $400M)

- **Nutrient recovery**
  - Up to 7,000 TPY and 3,500 TPY of N and P, respectively (~$ 2.1M)
OFMSW “Recycling” Infrastructure

Liquid AD (a)
1a - Harvest Power

Composting (b)
1b - George B. Wittmer Assoc., Inc.
2b - New River LF
3b - Watson C&D
4b - Vista LF
5b - Solorganics, Inc.
6b - 1 Stop Landscape and Brick, Inc.
7b - Bay Mulch, Inc.
8b - Mother's Organics, Inc.
9b - Busch Gardens
10b - Bay Mulch, Inc. Plant City
11b - HS Ranch and Farm, Inc.
12b - 1 Stop Landscape, Inc.
13b - Okeechobee LF
14b - FFE-Brighton McGill
15b - MW Horticulture Recycling
16b - Environmental Turnkey, LLC

Bioenergy (c)
1c - Gainesville Ren. Energy Center, 100MW wood-fired power plant
2c - Brooksville Power and Lime, 70 MW wood-fired power plant
3c - INEGIS New Plant Biorefinery, Hybrid Gasification, 3MGY eth.

WIE (d)
1d - Bay County WIE
2d - Lake County WIE
3d - Pasco County WIE

NOTES: 1. Not listed in FDEP, 2015b;
2. Yard waste composting only;
3. Permitted by Seminole Tribe;
4. Yard waste and tires WIE only

Data SI, NOAA, U.S. Navy, NGA, GEBCO
© 2015 Google Image Landsat
OFMSW Recycling Infrastructure

Liquid AD (a)  
1a - Harvest Power

Composting (b)  
1b - George B. Wittmer Assoc., Inc.\textsuperscript{12}  
2b - New River LF  
3b - Watson C&D  
4b - Vista LF  
5b - Solorganics, Inc.  
6b - 1 Stop Landscape and Brick, Inc.  
7b - Bay Mulch, Inc.  
8b - Mother’s Organics, Inc.  
9b - Busch Gardens  
10b - Bay Mulch, Inc. Plant City  
11b - BS Ranch and Farm, Inc.  
12b - 1 Stop Landscape, Inc.  
13b - Okeechobee LF  
14b - JFE-Brighton McGill\textsuperscript{13}  
15b - MW Horticulture Recycling\textsuperscript{12}  
16b - Environmental Turnkey, LLC.

NOTES:  
\textsuperscript{1}Not listed by FDEP;  
\textsuperscript{2}Yard waste composting only;  
\textsuperscript{3}Permitted by Seminole Tribe
Outlook in Florida

- Counties where implementation is most feasible:
  - Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, Lee, and Alachua

- Ideal locations for demonstration:
  - Universities, existing composting plants, or landfills with LFGTE

- Primary barrier: Economics
  - Average landfill tipping fee in FL = $43.65
  - Break-even HS-AD tipping fee without energy sales = $41 – $53
  - With energy sales = $4 – $32
  - Lack of markets for compost and lack of regulatory drivers
Summary of Major Findings

- Outlook is promising, especially in highly populated counties
- Potential environmental and economic benefits are significant
- Economic sustainability is reliant upon numerous factors
  - Local tipping fees
  - Quantity, quality, and proximity of available feedstock
  - Energy and compost markets and renewable energy incentives
  - *Public-private partnerships*
- Legislative incentive has potential to greatly improve the feasibility of HS-AD implementation; recommendations:
  - Bans on landfillsing food waste and yard waste
  - Mandated source-separation of food waste and yard waste
  - Policies promoting compost use and renewable energy generation
Additional Research

- Pilot System
  - Preliminary studies developing operation standards

- Co-digestion
  - Yard waste, food waste, biosolids

- Oyster Shells
  - Waste product, alkalinity source

- Micro-aeration
  - Improving biogas quality
Students & Postdoc

### Graduate and Postdoc

<table>
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<tr>
<th>Name</th>
<th>Rank</th>
<th>Department</th>
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<tbody>
<tr>
<td>Hinds, Gregory</td>
<td>MS</td>
<td>Civil &amp; Environmental Engineering</td>
<td>USF</td>
</tr>
<tr>
<td>Dick, George</td>
<td>MS</td>
<td>Civil &amp; Environmental Engineering</td>
<td>USF</td>
</tr>
<tr>
<td>Wang, Meng</td>
<td>Postdoctoral Researcher</td>
<td>Civil &amp; Environmental Engineering</td>
<td>USF</td>
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<tr>
<td>Anferova, Natalia</td>
<td>Visiting PhD student</td>
<td>Water Technology &amp; Environmental Eng.</td>
<td>Prague Univ. Chemistry &amp; Technology</td>
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<tr>
<td>Dixon, Phillip</td>
<td>PhD</td>
<td>Civil &amp; Environmental Engineering</td>
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### Undergraduate

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<tr>
<td>Ariane Rosario</td>
<td>Third Year</td>
<td>Civil &amp; Environmental Engineering</td>
<td>USF</td>
</tr>
<tr>
<td>Lensey Casimir</td>
<td>Fourth Year</td>
<td>Civil &amp; Environmental Engineering</td>
<td>USF</td>
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Students & Postdoc
Feedback on Final Report
Suggestions for Future Research
This material is based upon work supported by the William W. “Bill” Hinkley Center for Solid and Hazardous Waste Management (Subcontract No. UFOER00010286), the National Science Foundation S-STEM Graduate Scholarship (Grant No. DUE-0965743), and the USF Richard Ian Stessel Fellowship. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the funding agencies.

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<td>Gresham, Smith and Partners</td>
<td><a href="mailto:juan_oquendo@gspnet.com">juan_oquendo@gspnet.com</a></td>
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<td>Ramin Yazdani</td>
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</tr>
<tr>
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<td>Las Angeles County, CA</td>
<td><a href="mailto:cskye@dpw.lacounty.gov">cskye@dpw.lacounty.gov</a></td>
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# HS-AD Vendors in the US

<table>
<thead>
<tr>
<th>Vendor Name</th>
<th>Main Office Location</th>
<th>Founding Year</th>
<th>Primary Partnerships</th>
<th># of Facilities in Operation in the US</th>
<th># of Facilities in Development in the US</th>
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<tr>
<td>Zero Waste Energy, LLC</td>
<td>California</td>
<td>2009</td>
<td>Eggersmann Group, Bulk Handling Systems, Environmental Solutions Group</td>
<td>≥ 3</td>
<td>≥ 7</td>
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<tr>
<td>CleanWorld Corporation</td>
<td>California</td>
<td>2009</td>
<td>UC Davis, Synergex</td>
<td>≥ 3</td>
<td>≥ 1</td>
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<tr>
<td>Orbit Energy, Inc.</td>
<td>North Carolina</td>
<td>2002</td>
<td>McGill Environmental</td>
<td>≥ 1</td>
<td>≥ 5</td>
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<tr>
<td>BIOFerm Energy Systems</td>
<td>Wisconsin</td>
<td>2007</td>
<td>Viessmann Group, Schmack Biogas</td>
<td>≥ 1</td>
<td>≥ 1</td>
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<td>Organic Waste Systems, Inc.</td>
<td>Belgium (subsidiary in Ohio)</td>
<td>1988</td>
<td>NR</td>
<td>≥ 0</td>
<td>≥ 1</td>
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<tr>
<td>Harvest Power, Inc.</td>
<td>Massachusetts</td>
<td>2008</td>
<td>GICON Bioenergie GmbH</td>
<td>≥ 0</td>
<td>≥ 1</td>
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<td>Eisenmann Corporation</td>
<td>Germany (subsidiary in Illinois)</td>
<td>1977</td>
<td>NR</td>
<td>≥ 0</td>
<td>≥ 2</td>
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<td>Turning Earth, LLC.</td>
<td>Denmark (subsidiary in Georgia)</td>
<td>2009</td>
<td>Solum Group, Aikan A/S</td>
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<td>Maryland</td>
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<td>Vendor Name</td>
<td>Operating Temperature</td>
<td>TS Content</td>
<td>Loading Conditions</td>
<td>Number of Stages</td>
<td>Retention Time</td>
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<tr>
<td>Zero Waste Energy, LLC</td>
<td>Thermophilic</td>
<td>&lt; 50%</td>
<td>Batch</td>
<td>1</td>
<td>21 days</td>
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<tr>
<td>CleanWorld Corporation (formerly CleanWorld Partners, LLC)</td>
<td>Thermophilic</td>
<td>~10%</td>
<td>Continuous</td>
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<td>BIOFerm Energy Systems</td>
<td>Mesophilic</td>
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<td>Batch</td>
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<td>28 days</td>
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<td>20 days</td>
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NR = Not Reported; Information reported here was derived from technology vendor websites and personal communications.
Materials and Methods Cont’d
## Inocula and Substrate Characterization

<table>
<thead>
<tr>
<th></th>
<th>Pulp and Paper Sludge</th>
<th>Wastewater Sludge</th>
<th>Yard Waste for Phase 1 Batch HS-AD</th>
<th>Digestate from Phase 1 Bioaugmented Digesters</th>
<th>Digestate from Phase 1 Control Digesters</th>
<th>Yard Waste for Phase 2 Batch HS-AD</th>
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<tr>
<td><strong>Alkalinity</strong> (mg/L as CaCO$_3$)</td>
<td>2,100</td>
<td>580</td>
<td>50</td>
<td>400</td>
<td>140</td>
<td>25</td>
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<td><strong>TS</strong> (% of wet weight)</td>
<td>10.0 ± 0.2</td>
<td>0.6 ± 0.0</td>
<td>50.8 ± 3.4</td>
<td>18.5 ± 0.1</td>
<td>23.7 ± 0.3</td>
<td>64.2 ± 0.5</td>
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<tr>
<td><strong>VS</strong> (% of wet weight)</td>
<td>8.4 ± 0.1</td>
<td>0.4 ± 0.0</td>
<td>46.4 ± 2.9</td>
<td>16.6 ± 0.1</td>
<td>21.7 ± 0.2</td>
<td>60.1 ± 0.4</td>
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Biogas Quality

- Phase 1 Bioaugmentated Digesters
- Phase 1 Control Digesters
- Phase 2 Bioaugmented Digesters
- Phase 2 Control Digesters

Biogas Quality (% Methane) vs. Time (Days)
Chemical Analysis

**Phase 1 Bioaugmented Digesters**

- **sCOD (mg/L)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 4000 mg/L.

- **VFA (mg/L as Acetate)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 1200 mg/L.

- **Total Ammonia Nitrogen (mg/L)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 250 mg/L.

- **Alkalinity (mg/L as CaCO₃)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 1000 mg/L.

**Phase 1 Control Digesters**

- **sCOD (mg/L)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 3500 mg/L.

- **VFA (mg/L as Acetate)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 800 mg/L.

- **Total Ammonia Nitrogen (mg/L)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 150 mg/L.

- **Alkalinity (mg/L as CaCO₃)**
  - Days: 1, 7, 21, 42, 63, 106
  - Values range from 0 to 800 mg/L.

**pH** = 7.1-8.4 (in bioaugmented digesters); 6.3-8.0 (in control digesters)
Lignocellulosic Analysis

- Lignin, cellulose, and hemicellulose contents in the bioaugmented digestate were 2%, 16%, and 16% less, respectively, than in the control digestate.
Methane Yield Enhancements

Enhancement Achieved in Phase 1 of Batch HS-AD
Enhancement Achieved in Phase 2 of Batch HS-AD
### Benefits of HS-AD Implementation in FL

<table>
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<tr>
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<th>Yard Waste</th>
<th>Food Waste</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Assumed Generation Rate (short tons/year) =</td>
<td>3,700,000</td>
<td>2,200,000</td>
<td>5,900,000</td>
</tr>
<tr>
<td>Assumed Volatile Solids Fraction (% by wet weight) =</td>
<td>0.60</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Assumed Biogas Generation (m$^3$/kg VS) =</td>
<td>0.30</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Total Energy Content (GWh/year) =</td>
<td>3,520</td>
<td>870</td>
<td>4,390</td>
</tr>
<tr>
<td><strong>Total Electricity Generation Potential (GWh/year)</strong> =</td>
<td>1,230</td>
<td>300</td>
<td>1,530</td>
</tr>
<tr>
<td>Total Electricity Generation in Florida (GWh/year) =</td>
<td></td>
<td></td>
<td>246,200</td>
</tr>
<tr>
<td>Fraction of Florida Electricity Demand Fulfilled =</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

**OR:**

| CNG Generation (DGE/year) = | 63,400,000 | 15,700,000 | 79,100,000 |
| Total CNG Consumption in Florida (DGE/year) = | | | 688,000,000 |
| **Fraction of Florida CNG Demand Fulfilled** = | 9.2%       | 2.3%       | 11.5%     |

Note: Assumes 9.7 kWh-m$^{-3}$ CH$_4$, 9.8 kWh-L$^{-1}$ diesel, 35% electrical conversion efficiency, and 67% CNG conversion efficiency; mass conversion factor = 907 kg per short ton

<table>
<thead>
<tr>
<th></th>
<th>Nitrogen</th>
<th>Phosphorous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed Digestate Generation Rate (short tons/year) =</td>
<td>3,540,000</td>
<td>3,540,000</td>
</tr>
<tr>
<td>Assumed Total Solids Content (%) =</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Assumed Available Fraction (%) =</td>
<td>1.0%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Nutrient Recovery Potential (short tons/year) =</td>
<td>7,080</td>
<td>3,540</td>
</tr>
</tbody>
</table>

Note: Assumes 40% mass reduction in HS-AD; mass conversion factor = 907 kg per short ton
Preliminary Codigestion Study

Specific Methane Production (L CH₄/kg VS)

- Yard Waste, Food Waste, Biosolids + Pulp and Paper Sludge as Inoculum
- Yard Waste, Food Waste, Biosolids + Wastewater Sludge as Inoculum
- Yard Waste, Food Waste + Wastewater Sludge as Inoculum

Day 6: 1 g/L Crushed Oyster Shell Addition

Time (days)
## Preliminary Codigestion Study

<table>
<thead>
<tr>
<th></th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>B1</th>
<th>B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yard Waste (g)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Food Waste (g)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Biosolids (g)</td>
<td>15</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wastewater Sludge (g)</td>
<td>0</td>
<td>90</td>
<td>67.5</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>Paper Mill Sludge (g)</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>Total mass</td>
<td>150</td>
<td>150</td>
<td>112.5</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

### Percent Enhancement vs. Time (days)

- **Enhancement by P&P**
- **Enhancement by Biosolids**

-100% | 0% | 100% | 200% | 300% | 400% | 500% | 600%
---|---|---|---|---|---|---|---
0 | 10 | 20 | 30 | 40 | 50 | 60 | Time (days)

---

Figure showing percent enhancement over time for different waste streams. The categories include Yard Waste, Food Waste, Biosolids, Wastewater Sludge, Paper Mill Sludge, and Total mass. The graph plots percent enhancement against time in days, with data points indicating the enhancement by P&P and biosolids.
Orbit Energy Process

- Developed by the DOE
- Uses proprietary microbial consortium
Clean World Technology

Diagram:

- Liquid Feed
- Solids Feed
- Grinder
- Hydrolysis Reactor (HR)
- Wet Grind
- Biogasification Reactor (BGR)
- Separator
- Solids
- Biostabilization Reactor (BSR)
- Water Recycle
- Ammonia and/or Salt
- Biogas
- Liquid Effluent
Clean World UC Davis
BIOFerm Dry Fermentation Technology and UW Oshkosh Facility
BIOFerm EUCO Technology
DRANCO Diagram, Sordisep Process, and Brecht I and II Facilities
DRANCO Pohlsche Heide with Partial Steam Digestion
Harvest Power HS-AD in BC
Aikan North America Technology
Aikan North America Hartford, CT
EcoCorp Process Diagram

1. Green/Food/Paper Waste Municipal Solid Waste
2. Sewage/Mannure Sludge
3. Industrial Waste Construction Waste
4. Removal of Iron
5. Biogas
6. Aerobic Composting
7. Recycling Inineration Landfilling

EcoCorp DIGESTER
1,200 m³ (x2)

Gas Filtering
Gas Storage
Desulphurization/Dewatering
Gas Separation
Biomethane

CO₂

Gas Turbine

Facility Steam Generation
Facility Electricity Generation

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35,000</td>
<td>12,000</td>
<td>3,000</td>
<td>20,000</td>
<td>3,500</td>
<td>18,000</td>
<td>8,500</td>
</tr>
</tbody>
</table>
ZWE San Jose Process Diagram

1. SOLID WASTE → MATERIAL RECOVERY
2. FOOD & YARD WASTE → ORGANIC RECOVERY
3. ANAEROBIC DIGESTION
4. IN-VEssel COMPOSTING → HIGH-GRADE COMPOST
5. IN-VEssel COMPOSTING → ELECTRIC POWER
6. BIOGAS → CHP