Energy Analysis of Energy Systems

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Outline

- Context
  - Why Energy Analysis of Energy Systems?
  - What is Energy Analysis?

- Hydrogen Energy
  - Options
  - Comparison of Biohydrogen processes

- Other Examples
  - Jatropha/ Karanj
  - Solar Thermal Power
  - Buildings
  - Hydrogen Storage
  - Photo Electrochemical Cells
Hydrogen – Future?

- We are at the peak of the oil age and the beginning of the hydrogen age. The transition will be messy and take many competing technological paths but the long term future will be in hydrogen and fuel cells

   Herman Kulpers, Shell Global
Hydrogen Energy

- Can hydrogen energy mitigate the energy problem?
- Can hydrogen energy reduce Green House Gas emissions?
- Is this a sustainable solution?
Hydrogen pathways

- Solar Energy
- Nuclear Energy
- Wind
- Bio-Energy
- Fossil-Fuel

- Thermal
- Electricity
- Gasification
- Fermentation

- Thermo chemical
- Photo chemical

- Electrolysis

- Photo biological

- Hydrogen

- Cracking + Shift Reaction
Steam Methane Reforming

\[ \text{CH}_4 + 2\text{H}_2\text{O} \longrightarrow 4\text{H}_2 + \text{CO}_2 \]

Industrial Process
Renewable Hydrogen

- Current methods of hydrogen production
  - Steam methane reforming (SMR)
  - Coal gasification
  - Electrolysis
- Based on fossil fuels, Not sustainable
- Need for hydrogen production from renewable energy sources like wind, solar, biomass etc.
Biological methods of hydrogen production

- Operates at ambient temperature and pressure – expected to be less energy intensive.
- Variety of feedstocks as carbon source like sugars, lignocellulosic material, wastewater etc.
- Several reactions – substrate, bacteria

\[ \text{C}_6\text{H}_{12}\text{O}_6 + 2\text{H}_2\text{O} \rightarrow 4\text{H}_2 + 2\text{CO}_2 + 2\text{CH}_3\text{COOH} \]
Comparison of biohydrogen production processes

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Available online 10 September 2007
Biohydrogen - Issues

- Production at commercial level is not reported.
- Pretreatment methods and hydrogen production depends on feedstock
  - Which feedstock is viable, which is not?
- Analysis of different feedstocks/processes is necessary before scaling up the process.
Biomass to Hydrogen Conversion

Biomass to hydrogen conversion routes

Thermochemical
- Pyrolysis/Gasification

Biological
- Biophotolysis (direct/indirect)
- Dark fermentation
- Photofermentation
Processes compared

- #1 Dark Fermentation
- #2 Photo Fermentation
- #3 Two-stage fermentation process
- #4 Biocatalysed Electrolysis

Input feedstock – Sugarcane juice
Net energy analysis

- Functional unit – 1 kg hydrogen at 25°C temperature and 1 atm pressure.
- Base case – steam methane reforming
- Criteria
  - Net energy ratio (output/non-renewable energy input) NER > 1
  - Greenhouse gases (GHG) emissions (kg CO₂ eq / kg H₂)
  - Energy Efficiency
- LCA software SimaPro 6
Impact Assessment

- SimaPro 6 Life Cycle Analysis (LCA) software
- Assumptions
  - Heat derived from diesel with 90% combustion efficiency
  - Indian electricity mix (60% coal, 12% gas and oil, 25% hydropower, 3% nuclear)
  - 100% carbon closure for biomass derived CO$_2$
  - Methane (Natural gas), Ligneous residue (Bagasse)
Electricity Supply Mix

- Coal: 60%
- Hydro: 25%
- Gas & Oil: 12%
- Nuclear & Oth.: 3%
# Steam methane reforming

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit (/kg H(_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resource consumption</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas (in ground), input</td>
<td>3.64</td>
<td>kg</td>
</tr>
<tr>
<td>Coal (in ground), input</td>
<td>159.2</td>
<td>g</td>
</tr>
<tr>
<td>Iron (Fe, ore), input</td>
<td>10.3</td>
<td>g</td>
</tr>
<tr>
<td>Iron scrap, input</td>
<td>11.2</td>
<td>g</td>
</tr>
<tr>
<td>Limestone (CaCO(_3), in ground)</td>
<td>16.0</td>
<td>g</td>
</tr>
<tr>
<td>Oil (in ground)</td>
<td>16.4</td>
<td>g</td>
</tr>
<tr>
<td><strong>Average air emissions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td>1.4</td>
<td>g</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>10.62</td>
<td>kg</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>5.7</td>
<td>g</td>
</tr>
<tr>
<td>Methane</td>
<td>59.8</td>
<td>g</td>
</tr>
<tr>
<td>Nitrogen oxides (as NO(_2))</td>
<td>12.3</td>
<td>g</td>
</tr>
<tr>
<td>Nitrous oxide (N(_2)O)</td>
<td>0.04</td>
<td>g</td>
</tr>
<tr>
<td>Non-methane hydrocarbons (NMHCs)</td>
<td>16.8</td>
<td>g</td>
</tr>
<tr>
<td>Particulates</td>
<td>2.0</td>
<td>g</td>
</tr>
<tr>
<td>Sulfur oxides (as SO(_2))</td>
<td>9.5</td>
<td>g</td>
</tr>
</tbody>
</table>
#1 Dark Fermentation

Sugarcane → Milling → Dark fermentation

Bagasse → Anaerobic digester

Methane

Pressure swing adsorption

Hydrogen
#2 Photo Fermentation

Sugarcane → Milling → Photo fermentation → Anaerobic digester → Pressure swing adsorption

Bagasse → Methane

Hydrogen
#3 Two-stage fermentation process

Sugarcane → Milling → Bagasse → Dark fermentation → Photo fermentation → Anaerobic digester → Hydrogen

Pressure swing Adsorption → Hydrogen

Methane
#4 Biocatalysed Electrolysis

- Sugarcane → Milling → Bagasse → Dark fermentation
  - Carbon dioxide → Biocatalyzed electrolyzer
- Anaerobic digester → Methane
  - Hydrogen
- Pressure swing Adsorption → Hydrogen
#4 Biocatalysed Electrolysis

![Diagram of a biocatalysed electrolysis system]

- **CO₂** enters the system at the anode, where it is converted to **H⁺**.
- Bacteria catalyse the reaction at the anode.
- **e⁻** flow is directed through the power supply.
- **H₂** is produced at the cathode.
- **H⁺** ions are transported through the **PEM** (Polymer Electrolyte Membrane).
## Input data used in the analysis

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Value</th>
<th>Unit</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity use in sugarcane crushing</td>
<td>37.8</td>
<td>kJ/kg of sugarcane</td>
<td>[20]</td>
</tr>
<tr>
<td>Sucrose output</td>
<td>10.45</td>
<td>% of sugarcane</td>
<td>[21]</td>
</tr>
<tr>
<td>Dry bagasse output</td>
<td>17.34</td>
<td>% of sugarcane</td>
<td>[21]</td>
</tr>
<tr>
<td>Optimum sugar concentration in fermentation</td>
<td>2</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>Optimum C/N ratio</td>
<td>47</td>
<td>–</td>
<td>[22]</td>
</tr>
<tr>
<td>H₂ production in dark-fermentation</td>
<td>3.4</td>
<td>mol/mol C₆</td>
<td>[23]</td>
</tr>
<tr>
<td>CO₂ production in dark-fermentation</td>
<td>1.7</td>
<td>mol/mol C₆</td>
<td>-</td>
</tr>
<tr>
<td>H₂ production in photo-fermentation</td>
<td>9.6</td>
<td>mol/mol C₆</td>
<td>[11]</td>
</tr>
<tr>
<td>CO₂ production in photo-fermentation</td>
<td>4.8</td>
<td>mol/mol C₆</td>
<td>-</td>
</tr>
<tr>
<td>Methane/CO₂ molar ratio in biogas</td>
<td>60/40</td>
<td>–</td>
<td>-</td>
</tr>
<tr>
<td>Hydrogen recovery in PSA</td>
<td>90</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>Isothermal efficiency of compressor</td>
<td>65</td>
<td>%</td>
<td>-</td>
</tr>
<tr>
<td>Electricity requirement in biocatalyzed electrolysis</td>
<td>0.6</td>
<td>kWh/m³ H₂</td>
<td>[16]</td>
</tr>
<tr>
<td>Platinum loading in biocatalyzed electrolysis</td>
<td>0.5</td>
<td>mg/cm²</td>
<td>[16]</td>
</tr>
</tbody>
</table>
## Results of mass and energy balance

<table>
<thead>
<tr>
<th>Particular</th>
<th>Unit (/kg H2)</th>
<th>Dark-fermentation</th>
<th>Photo-fermentation</th>
<th>Two-stage process</th>
<th>Electrochemically assisted process</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sugarcane input</td>
<td>kg</td>
<td>281.45</td>
<td>99.68</td>
<td>93.09</td>
<td>90.56</td>
</tr>
<tr>
<td>Electricity input</td>
<td>kWh</td>
<td>5.8</td>
<td>3.89</td>
<td>3.82</td>
<td>6.42</td>
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<tr>
<td>Ammonia</td>
<td>kg</td>
<td>0.35</td>
<td>0.13</td>
<td>0.12</td>
<td>0.11</td>
</tr>
<tr>
<td>Platinum</td>
<td>mg</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Output</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bagasse (dry)</td>
<td>kg</td>
<td>46.06</td>
<td>16.31</td>
<td>15.23</td>
<td>14.82</td>
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<tr>
<td>Carbon dioxide</td>
<td>kg</td>
<td>24.59</td>
<td>13.44</td>
<td>13.04</td>
<td>12.39</td>
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<tr>
<td>Methane</td>
<td>kg</td>
<td>6.75</td>
<td>0.67</td>
<td>0.45</td>
<td>0.54</td>
</tr>
<tr>
<td>Process</td>
<td>Case 1: Without by-products</td>
<td>GHG (kg CO₂)</td>
<td>Non-renewable energy use (MJ)</td>
<td>Energy efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------</td>
<td>--------------</td>
<td>-------------------------------</td>
<td>-----------------------</td>
<td></td>
</tr>
<tr>
<td>Steam methane reforming</td>
<td></td>
<td>12.8</td>
<td>188</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Dark-fermentation</td>
<td></td>
<td>5.5</td>
<td>61.7</td>
<td>9.6</td>
<td></td>
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<td>Photo-fermentation</td>
<td></td>
<td>3.5</td>
<td>40.1</td>
<td>25.6</td>
<td></td>
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<tr>
<td>Two-stage process</td>
<td></td>
<td>3.4</td>
<td>39.3</td>
<td>27.2</td>
<td></td>
</tr>
<tr>
<td>Biocatalyzed electrolysis</td>
<td></td>
<td>5.3</td>
<td>64.8</td>
<td>25.7</td>
<td></td>
</tr>
</tbody>
</table>
Results (with by product use)

<table>
<thead>
<tr>
<th>Process</th>
<th>Case 2: With by-products</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GHG (kg CO₂)</td>
<td>Non-renewable energy use (MJ)</td>
<td>Energy efficiency (%)</td>
<td></td>
</tr>
<tr>
<td>Steam methane reforming</td>
<td>12.8</td>
<td>188</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Dark-fermentation</td>
<td>-87</td>
<td>-1060</td>
<td>89.1</td>
<td></td>
</tr>
<tr>
<td>Photo-fermentation</td>
<td>-21.9</td>
<td>-247.5</td>
<td>82.3</td>
<td></td>
</tr>
<tr>
<td>Two-stage process</td>
<td>-19.5</td>
<td>-218.2</td>
<td>81.6</td>
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<tr>
<td>Biocatalyzed electrolysis</td>
<td>-17.5</td>
<td>-180</td>
<td>76.8</td>
<td></td>
</tr>
</tbody>
</table>
Life cycle inventory

Seed bed preparation, Sowing

Karanja Seeds

Irrigation

Fossil diesel, electricity

Fertilizer, herbicide

Agricultural Cultivation stage

Fossil diesel, electricity

Transportation

Fossil diesel, Electricity, and NaOH, MeOH

Conversion stage

Vehicle operation with fuel combustion stage

Karanja Bio-diesel (NER, MJ/km vehicle driven), cost (ALCC, per ha, per tonne and per km basis)

Cracking

Pressing

Filtration

Transesterification
Methodology for analysis

- Life cycle Approach
- NER = E_{out}/E_{in}

*If NER > 1, Replacement viable*

*NER < 1, Replacement not viable*

- CRF (d, n)=[d*(1+d)^n]/[(1+d)^n-1]
- ALCC = AC + C_0*CRF (d, n)
- NER (Net Energy Ratio)
- ALCC (Annualized cost)
- CRF (Cash recovery factor)

**Secondary Energy**

**Primary Energy**

**Renewable Energy**

- Seed bed preparation, Sowing, diesel
- Jatropha/Karanja Seeds
- Irrigation

Agricultural Cultivation stage

- Fossil diesel, electricity
- Fertilizer, herbicide, fossil

Transportation and conversion stage

- Fossil diesel, MeOH, NaOH
- Vehicle operation with fuel combustion stage

Cracking

- Pressing
- Filtration
- Trans-esterification

Jatropha/karanja Bio-diesel (NER, MJ/km vehicle driven, cost (Rs/kg), Renewable Energy
Jatropha and Karanja Analysis results

Rs. 33-36/kg  2007 values

Rs. 21-25/kg
## Energy Analysis – Hydrogen Storage

Comparison of different storage options for 1 km ride

<table>
<thead>
<tr>
<th></th>
<th>Compressed tank</th>
<th>Cryogenic tank</th>
<th>FeTi hydride</th>
<th>Mg hydride</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂ consumption (gms)</td>
<td>6.24</td>
<td>6.4</td>
<td>8.04</td>
<td>9.7</td>
</tr>
<tr>
<td>Direct energy required to travel (kJ)</td>
<td>749</td>
<td>768</td>
<td>965.4</td>
<td>1164</td>
</tr>
<tr>
<td>Energy required to produce and store H₂ (kJ)</td>
<td>1260.7</td>
<td>2172.7</td>
<td>1473.7</td>
<td>1777</td>
</tr>
<tr>
<td>Energy required to produce tank (kJ)</td>
<td>34.2</td>
<td>15.6</td>
<td>177.3</td>
<td>60</td>
</tr>
<tr>
<td>Total energy required (kJ)</td>
<td>2043.9</td>
<td>2956.3</td>
<td>2616.4</td>
<td>3001.5</td>
</tr>
</tbody>
</table>
Energy Analysis - PEC

[Graph showing the efficiency and stability of different materials with various symbols and lines representing different materials such as InP, CuP, TiO₂, Fe₂O₃, WO₃, and TiO₂. The x-axis represents stability (days) and the y-axis represents efficiency (%).]
Energy Analysis Of Buildings

Lifecycle energy analysis of an air-conditioned residential building

Daylighting Simulation
Sustainability Analysis

1. Process flow charts
2. Sizing of different equipment required
3. Inventory (process energy and material) to produce one unit of output
   - Total primary energy required to produce required process energy and materials
     - Total GHG emissions in producing process energy and materials (using emission factors)
       - GHG emissions
     - Classification of total primary energy into non-renewable and renewable energy
       - Non-renewable energy use
     - Cost of different equipment and material required, discount rate, life of the equipment
       - Life cycle cost
   - Materials and other resources such as water, land etc required to produce 1 kg of hydrogen
3. Resource constraint
4. Amount of material and other resources required to meet the current demand
Resource constraint

- Material supply constraint
  - Annual requirement/Reserve
  - Area
    - Area required/Available land area
  - Material constraint
    - Annual requirement/Reserve
  - Other constraint
    - Technical constraint, water for biomass based systems etc.
  - No constraint
Summing Up

Energy Analysis – useful for new, emerging energy systems

- Rational basis for target setting – guiding material, design choices – as a screening tool
- Energy analysis, environmental emissions
- Energy analysis – also useful for product and process redesign – for energy intensive products/ processes
- Sustainability – materials, water, land – apart from energy
Acknowledgments

Manish S. Ph.D. - 2008
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Prof. K.V. Venkatesh
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Uttam Sen M.Sc.-Ph.D 2007
Priyanka DD 2013
Venkateshwaran Summer Intern-2008
Ajay V Summer Intern-2008
References


Thank you