Presentation Overview

- Why is Energy Important?
- How is Energy Used?
- Availability of Primary Energy Sources?
- What will the Fossil-Fuel deprived future be?
- Fuel for the Transportation Sector
  - $\text{H}_2$ as an energy carrier
Why is Energy Important?
Why is Energy Important?

Source: www.goodworksonearth.org
Why is Energy Important?
Energy Consumption is Way of Life in Industrialized Countries

2007 Primary energy consumption per capita

- Bangladesh
- India
- China
- UK
- Germany
- Japan
- USA

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How is Energy Used?
As an Example, Consider the USA Energy Landscape

Energy Sources

Energy Usage

OBSERVATION: 85% Energy from Fossil Fuels

Source : EIA
US Energy Flow – 2005

Source: LLNL
U.S. Energy Flow - 2005

- In U.S. more than 52% Electricity from coal (also true for China & India)
- More than 55% of Energy is lost or wasted!
- Internal Compression Engines are quite inefficient.
Total World CO₂ Emissions ~ 28,000 Million Metric Tons

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Availability of Primary Energy Sources
Some Energy Facts
Total proven conventional oil reserve = 1238 billion bbl

World Oil Reserves-to-Production (R/P) Ratios

- Reserves are 16% above 1997 level
- Production is 13% higher than 1997 level
- USA R/P = 11.7 years
- USA R/Consumption = 3.9 years

Natural Gas Production

- Total proven gas reserve = 177.4 trillion m³
- Natural gas demand continues to rise

Natural Gas Reserves-to-Production Ratios

- Reserves are 21% above 1997 level
- Production is 32% higher than 1997 level
- USA R/P = 10.9 years
- In USA, natural gas production has remained flat over the last decade

Coal

- Proven World Reserve = 848 billion tons
- World Reserve-to-Production Ratio = 133 years
- USA Reserve-to-Production Ratio = 234 years
It seems that there is enough hydrocarbon fuel to last for the next fifty years!
It seems that there is enough hydrocarbon fuel to last for the next fifty years!

However.....
However…

- The world population is expected to rise
However...

- The world population is expected to rise

- **World energy consumption rate is expected to rise**
World primary energy usage rate in 2007 was 14.8 TW
By 2050, the usage rate could be 28 TW

Consumption rate could double!
However…

- The world population is expected to rise
- World energy consumption rate is expected to rise
- China’s current economic growth is expected to accelerate energy consumption
China’s Recent Energy Consumption

- Average growth rate over past quarter century > 10%!
- Current China’s primary energy consumption = 13.7 billion boe
- Current USA’s primary energy consumption = 17.3 billion boe

China could Quadruple its Energy Consumption Soon!

Development of Japan, 1940 - 2000

adaptation: Prof. M Suzuki

Energy consumption per capita ($10^7$ kcal)

GNP per capita ($10^6$ yen)
China could Quadruple its Energy Consumption Soon!

Development of Japan, 1940 - 2000

Energy consumption per capita (10⁷ kcal)

GNP per capita (10⁶ yen)

Current China (1.1×10⁷ kcal)

Current China (1.19×10⁶ yen)
China’s Recent Energy Consumption

• Average growth rate > 10%!

• Current China’s primary energy consumption = 13.7 billion boe

• Current USA’s primary energy consumption = 17.3 billion boe

• If primary energy @ per capita rate of Japan = 43.9 billion boe

• Current total world’s energy consumption = 81.4 billion boe
However…

- The world population is expected to rise
- World energy consumption rate is expected to rise
- China’s current economic growth is expected to accelerate energy consumption
- Oil production will peak during the lifetime of a child born today
However…

- The world population is expected to rise
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- China’s current economic growth is expected to accelerate energy consumption
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- For most nations it is national energy independence and security issue
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- It takes a long time to develop a new energy source and its infrastructure
However…

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- World energy consumption rate is expected to rise
- China’s current economic growth is expected to accelerate energy consumption
- Oil production will peak during the lifetime of a child born today
- For most nations it is national energy independence and security issue
- It takes a long time to develop a new energy source and infrastructure

Therefore, we must develop alternative energy sources before the current ones are nearly depleted.
Alternate Energy Sources

- Biomass
- Hydroelectricity
- Wind
- Nuclear
- Solar
Biomass: Sustainable source of carbon but...

All US corn and soybean can meet only 12% of gasoline and 6% of diesel demand.

Source: Hill et al., PNAS, 103, 2006
Biomass: Sustainable source of carbon but...

All US corn and soybean can meet only 12% of gasoline and 6% of diesel demand

Therefore, one must use lignocellulosic mass to increase oil production.

Still requires large land area for cultivation!
Solar Energy

Total 2007 world primary energy can be met by 8% USA land area*

U.S primary energy can be met by 1.7% of USA land area

* PV efficiency of 10%
Alternate Energy Sources

- Biomass
- Hydroelectricity
- Wind
- Nuclear
- Solar

Nuclear and solar are the only ones that can alone meet all the energy needs.
Why is Solar use not Prevalent?
Production Cost of Electricity

2005 data in cents per kilowatt-hour

Retail Cost of Electricity (Residential Rates)

- U.S: 8 ¢ per kWh
- Germany: 15 ¢ per kWh
- Japan: 21 ¢ per kWh
Photovoltaic Cost has been Declining

However, to be truly competitive, cost has to come below $1,000/kw
To Sum Up Our Discussion...

- Energy is one of the grand challenges of our time
- World is not about to run out of oil or NG
- However,
  - Demand for energy is growing rapidly
  - Conventional oil will peak out in a few decades
  - Most nations do not have enough oil or NG
- Must develop alternate energy sources
- This development must start now
- Solar can provide a long term viable option
However...

- In near future, no one primary energy source will dominate
- Primary Energy mix will change with time
- Eventually, use of renewables and nuclear will emerge and become dominant

. . . Let us examine a Future State first, and then build transition Pathways
What will the world look like in a Fossil-Fuel deprived Future?
Solar Economy vision

All uses must coexist: Use of Solar Photons must be optimized.

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How should one optimize the use of Solar Photons? (or nuclear heat)

... Let us start by examining conversion efficiencies
Efficiencies of Solar Energy Recovery
Efficiencies of Solar Energy Recovery

Challenge: Large Scale Heat Storage
Efficiencies of Solar Energy Recovery

Challenge:
Need High Energy Density Storage
Efficiencies of Solar Energy Recovery
Efficiencies of Solar Energy Recovery

- **H₂**: 5-20%
- **Biomass**
- **Liquid Fuel**
- **Electricity**: 10-40%
- **Heat**: 60-80%
Efficiencies of Solar Energy Recovery
Efficiencies of Solar Energy Recovery

- **H₂**: 5-20%
- **Heat**: 60-80%
- **Electricity**: 10-40%
- **Liquid Fuel**: 0.15-0.5%
- **Biomass**: 0.3-1%

The diagram illustrates the conversion of solar photons to various forms of energy, with traditional methods indicated by a red arrow.
Efficiencies of Solar Energy Recovery

- **H₂**: 5-20%
- **Heat**: 60-80%
- **Electricity**: 10-40%
- **Liquid Fuel**: 0.15-0.5%
- **Biomass**: 0.3-1%

Diagram shows the flow of solar photons to various energy forms with traditional method.
Preferred Ranking on the basis of Recovery Efficiencies

- Heat
- Electricity
- H₂
- Biomass/Liquid Fuel

However, challenges involved with:
- Intermittency/Storage
- Transmission/Long distances
- Cost

... Of all the end uses most challenging is transportation.
The transportation sector constitutes

- Cars (Light Duty Vehicles)
- Trucks
- Busses
- Trains
- Airplanes

And needs:

- High energy density fuel ~ 33 kWh/gallon of gasoline
- Ease of use/handling
- Safe in the hands of a common man
Energy Systems Analysis of the U.S. Transportation Sector
Transportation Fuels

Current State

- Liquid Hydrocarbons from Crude Petroleum

Future State

- Crude oil scarce
- Coal to Liquid
- Gas to Liquid
- Nuclear
- Sun to Fuel
Sun to Wheels

Option #1: Sun to biofuels

Question:
How much land area to support the entire US transportation sector?
Land area for 13.8 mbbl/d = 25-55% of the total US land area
Total US land area: 3.6 million mi²
Sun to Wheels

Biomass alone can not meet the need for the entire US transportation sector
Option #2: Sun to electricity

- To travel 350 miles, amount of electricity needed = 105 kWh
- However, battery storage $\leq$ 100 Wh/kg
- On-board electric storage is a challenge
- Plug-in hybrids vehicle (PHEV) will have a role to play
Plug-in hybrid vehicles (PHEV)

5.5 Mbbl/d replaced with PHEVs of 40 miles per charge batteries

Parks et al., NREL/TP-640-41410, May 2007
Sun to Wheels

Option #3: $H_2$ Fuel Cell Vehicles
Hydrogen
Hydrogen as an Energy Carrier – Its Promises and Challenges
The Promise of Hydrogen

Fuel Cell

Clean and efficient conversion to power
No pollutants – only water as byproduct
The Challenge of Hydrogen

- It is just an energy carrier
- Must be produced from an energy source
- Inefficiencies in the steps of production, transportation and delivery
Committee on Alternatives and Strategies for Future Hydrogen Production and Use

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1 NAE = Member, National Academy of Engineering

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Focus of the Study

Transportation

Light Duty Vehicles (LDVs)

Source: General Motors
Focus of the H₂ Systems Analysis

- Estimated current and future
  - Projected costs
  - Energy efficiencies
  - Carbon dioxide (CO₂) emissions

- Addressed national security issues
  - Availability of each feed stock
  - Impact on oil import

- Addressed infrastructure issues
H$_2$ Production Technologies

- Natural Gas
- Coal
- Nuclear
- Biomass
- Electrolysis
- Wind
- Solar (PV)

Both current and potential future technologies considered
Production Sizes

1. Central Station
   ▪ Production capacity ~ 1.2 MM kg/d
   ▪ Supports ~ 2 MM cars

2. Midsize plant
   ▪ Production capacity ~ 24,000 kg/d
   ▪ Supports ~ 40,000 cars

3. Distributed Plant
   ▪ Production capacity ~ 480 kg/d
   ▪ Supports ~ 800 cars
Performance Assumptions

Efficiency of Fuel Cell Vehicles (FCV) = \(1.66 \times\) Efficiency of Gasoline Hybrid Electric Vehicles (GHEV)
Delivered $H_2$ Costs of Various Technologies

GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency

Source: NRC
Delivered H₂ Costs of Various Technologies

GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency

Source: NRC
Delivered H$_2$ Costs of Various Technologies

- Natural gas, coal and nuclear can provide H$_2$ at comparable cost to gasoline
- In future, wind has a potential to provide comparable cost
- Solar requires breakthrough technology to compete
However, there are other issues besides cost

- Overall system efficiency
- Carbon release to atmosphere
- Availability of feedstock
However, there are other issues besides cost:

- Overall system efficiency
- Carbon release to atmosphere
- Availability of feedstock
Well-To-Wheels Energy Use

Energy use (kWh/km)

Technology

- Central station
- Mid-size
- Distributed

Energy use:
- Current
- Future

Source: NRC
Well-To-Wheels Energy Use

Most Technologies Have Overall Efficiency Comparable to Gasoline
However, there are other issues besides cost

- Overall system efficiency
- Carbon release to atmosphere
- Availability of feedstock
Carbon Released During H₂ Production, Dispensing & Delivery (Future Technologies)

Source: NRC

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Carbon Released During H₂ Production, Dispensing & Delivery (Future Technologies)

For All Sources, Carbon Emission is Not More Than Gasoline

Source: NRC
However, there are other issues besides cost

- Overall system efficiency
- Carbon release to atmosphere
- Availability of feedstock
Penetration Curves for Fuel Cell Vehicles (USA)  
**Optimistic Case Postulated by Committee**

Complete replacement of ICE vehicles with fuel cell vehicles in 2050

Source: NRC
Hydrogen Penetration Scenario (USA)

The diagram shows the projected hydrogen penetration scenario in the USA from the years 2000 to 2050. The x-axis represents the year, ranging from 2000 to 2050, while the y-axis represents the hydrogen production in billions of kilograms per year and millions of tons per year.

Source: NRC
Land Use in Biomass Gasification Option (USA)

Currently available: 700,000 mi² cropland, 900,000 mi² pasture land

Source: NRC
NATURAL GAS SMR

Natural Gas Use Due to Use of $H_2$ in FCVs

- CS NG-F
- EIA forecast: Net imports

©2008 R. Agrawal
NATURAL GAS SMR

Natural Gas Use Due to Use of H₂ in FCVs

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All Natural Gas will Have To Be Imported!!
How about CO$_2$ Sequestration?
Cumulative Carbon Sequestration (USA)

- Capacity of depleted U.S. oil and gas reservoirs = 150+ billion metric tons CO₂
- Capacity of unminable U.S. coal seams = 55 billion metric tons CO₂

Source: NRC
To Sum Up Hydrogen Discussion So Far…

For fossil fuels:

- Cost of $H_2$ is no greater than gasoline
- Well to wheel efficiency is no worse than gasoline
- Carbon emission is not increased
- Enough space to sequester $CO_2$
...So What are the Major Challenges to Hydrogen Use for the Light Duty Vehicles?
Major Challenges

Fuel cell

- Cost needs reduction (greater than $2000/kW to less than $100/kW)
- Efficiency needs improvement (from less than 50% to greater than 65%)
- Lifetime must be increased (from less than 1000 hrs to 4000-5000 hrs)
- Operating temperature issues
Major Challenges

On board storage

- High pressure or cryogenic tanks take up too much space
- Safety perception with high pressure tanks
## Major Challenges

### Energy density of hydrogen

<table>
<thead>
<tr>
<th></th>
<th>kWh/kg</th>
<th>kWh/gal</th>
<th>Eq. vol.(gal) (5 kg $H_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$ @ 10,000 psi</td>
<td>33.3</td>
<td>5.0</td>
<td>33</td>
</tr>
<tr>
<td>Liquid $H_2$</td>
<td>33.3</td>
<td>8.9</td>
<td>18</td>
</tr>
<tr>
<td>Gasoline</td>
<td>11</td>
<td>33.6</td>
<td>8.3</td>
</tr>
</tbody>
</table>
Major Challenges

Development of infrastructure to provide H\textsubscript{2} for LDV use

- ‘Chicken and Egg’ problem
- For fossil fuel H\textsubscript{2}, distribution and dispensing costs compete with production cost
- Transition path not clear
- Cost and efficiency of current distributed H\textsubscript{2} generator are unacceptable
Major Challenges

$H_2$ could be provided from fossil fuels

- Might need viable $CO_2$ capture and storage
- Reservoir studies
- Long-term risk analysis
- Requires successful collection/disposal of other pollutants
Major Challenges

In the long run H\textsubscript{2} needs to be produced from renewable or nuclear

- Current cost is too high
- Major breakthroughs are needed
  - Wind (electrolysis)
  - Solar
  - Nuclear
Summary for option #3 (H₂ FCV)

- Need for a common energy carrier such as H₂?
- H₂ economy will not happen “soon”
- In the transition period, H₂ can be produced from fossil fuels without much negative consequences
- Although H₂ can be produced from fossil fuels without much negative consequences, following major challenges must be met first
  - Cost effective and durable FC systems
  - H₂ storage
  - Safety in the hands of general population
- However, the final solution must use renewables or nuclear
Sun to Wheels

Option #4: Electricity & Biofuels

- 5.5 Mbbl/d replaced with PHEVs of 40 miles per charge of batteries
- 8.3 Mbbl/d still needed

Question: Can we get 8.3 Mbbl/d sustainably from biomass?
Option #4: Electricity & Biofuels

- Explore alternative synergistically integrated processes to produce 8.3 Mbbl/d.
Novel synergistic integration for fuel

Integrative processes can produce more fuel
A Novel Biomass and $\text{H}_2$ from Carbon-free energy source partnership

A Hybrid Hydrogen-Carbon ($\text{H}_2\text{CAR}^\text{TM}$) Economy!
H₂CAR™ economy

- Biomass primarily supplier of carbon atoms
- H₂ from a sustainable carbon-free source
- H₂ converts every carbon atom to liquid fuel
- No release of CO₂ during conversion process
- CO₂ release only at end use
- A solution to store H₂ as a high density fuel
- A sustainable open-loop cycle for carbon
An Example of a synergistic Solution
Novel H$_2$CAR™ Process

Biomass

O$_2$

H$_2$

Gasifier

CO$_2$ Recycle

Syngas

Unreacted H$_2$,CO Recycle

H$_2$-CO to Liquid reactor

H$_2$O

Liquid Hydrocarbon Fuel

Byproducts

Carbon-free Energy source

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Agrawal et al., PNAS, 104, 2007
## Requirements for 8.3 Mbbl/d

<table>
<thead>
<tr>
<th>Process</th>
<th>Biomass Requirement (Billion Ton)</th>
<th>Land area (million km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>2.26</td>
<td>1.51</td>
</tr>
<tr>
<td>H₂CAR™</td>
<td>0.85</td>
<td>0.57</td>
</tr>
</tbody>
</table>
Production of 13.84 million bbl/d of synthetic oil using Biomass

Future Case¹:
Gasifier Efficiency = 70%
Biomass growth rate = 1.5 kg dry mass/m²/yr

<table>
<thead>
<tr>
<th>Case</th>
<th>Land area (million km²)</th>
<th>Required H₂ (Billion kg/yr)</th>
<th>Carbon Efficiency (%)</th>
<th>Energy Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biomass</td>
<td>H₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional</td>
<td>2.5</td>
<td>0</td>
<td>0</td>
<td>36.7</td>
</tr>
<tr>
<td>(\text{H}_2\text{CAR}^{\text{TM}})</td>
<td>0.92*</td>
<td>0.046*</td>
<td>239</td>
<td>~100</td>
</tr>
</tbody>
</table>

¹Needs only 10% of the US land area or half of current cropland area!
Currently available: 1.8 million km² cropland, 2.3 million km² pasture land

¹ NRC H₂ Report
Effect of Biomass growth rate on land area

Gasifier Efficiency = 70%
Total US land area = 9.2 million km²
Advantages of Biomass H₂CAR™

- Crop Diversity (Biodiversity vs Monocultures)
- Tailor biomass to maximize carbon pickup
- Reduction in land area radius to support a plant
- Reduction in biomass storage space
- Reduced energy input
Advantages of Biomass $H_2$CAR™ (contd.)

- Decreased use of fertilizer and pesticides
- Decreased wear and tear to land
- Plausible use of carbonaceous municipal waste
- Synthesis of desired hydrocarbon molecules
Challenges for the Proposed H$_2$CAR™ process

- Cost-effective production of H$_2$ from carbon-free energy source
- Biomass growth rate and yield
- Design and operation of Novel Gasifier
- More selective conversion to desired synthetic liquid fuel
- Efficient Internal Combustion Engine
Why Concept Works?
Energy source for a barrel of oil

Gasifier Efficiency = 70%

<table>
<thead>
<tr>
<th></th>
<th>Biomass (MJ)</th>
<th>Hydrogen (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>8779</td>
<td>-</td>
</tr>
<tr>
<td>H₂CAR™</td>
<td>3193</td>
<td>3799</td>
</tr>
</tbody>
</table>

Nearly 55% energy in final barrel of oil comes from H₂!
Problems with current gasification processes

Carbon efficiency of 30-40% results in large land area requirements
How 60-70% carbon is lost in biomass case?

<table>
<thead>
<tr>
<th>Syngas composition normalized to 100 moles carbon in biomass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_2$</td>
</tr>
<tr>
<td>$CO$</td>
</tr>
<tr>
<td>$CO_2$</td>
</tr>
<tr>
<td>$H_2O$</td>
</tr>
<tr>
<td>$T \ (°C)$</td>
</tr>
<tr>
<td>$H_2/CO$</td>
</tr>
</tbody>
</table>

To obtain $H_2/CO = 2$, additional 16 $CO_2$ are lost due to WGS reaction $CO + H_2O \rightarrow CO_2 + H_2$.

Additional losses occur in FT reactor.
An Alternative Interim Solution

Synthetic oil from Coal
Novel H$_2$CARTM Process for Coal
Production of 13.84 million bbl/d of synthetic oil using Coal

Gasifier Efficiency = 75%

<table>
<thead>
<tr>
<th>Case</th>
<th>Amt of Coal (Billion tons/yr)</th>
<th>Required H₂ (Billion kg/yr)</th>
<th>CO₂ sequestered (Gtc/yr)</th>
<th>Carbon efficiency (%)</th>
<th>Energy efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>1.97</td>
<td>--</td>
<td>0.9</td>
<td>39.9</td>
<td>50.7</td>
</tr>
<tr>
<td>H₂CAR™</td>
<td>0.83</td>
<td>211.46</td>
<td>0</td>
<td>~100</td>
<td>65.2</td>
</tr>
</tbody>
</table>

No Need for CO₂ sequestration!
Longevity of Coal Reserves in USA*

- At current consumption rate of 1.13 billion tons/yr ~ 244 yrs
- With Additional production of 13.8 mbbl/d using conventional process ~ 89 yrs
- With Additional production of 13.8 mbbl/d using H₂CAR™ ~ 144 yrs

*US Coal Reserves ~ 275 billion tons
Challenges for the Proposed H₂CAR™ Coal process

- Cost-effective production of H₂ from carbon-free energy source
- Design and operation of Novel Gasifier
- More selective conversion to desired synthetic liquid fuel
- Efficient Internal Combustion Engine
A Detour to Explore more Process Integration . . .
Search For Synergy Between Thermochemical and Biological Processes
Proposed Framework for Biofuels

Biomass

Micro-organisms based Processes

CO$_2$ + H$_2$O

Biomass

CO$_2$ and Carbonaceous By-products

Fuel

Heat

Complex Biomass

Energy

H$_2$

Chemical Processing System

Other Raw Materials

Non-carbonaceous Waste & Byproducts

Biomass Processing

Carbon-free energy source

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Detail Schematic of the proposed Framework for Biofuels

Biomass Processing

Biomass

Micro-organisms based Processes

CO₂ and Carbonaceous By-products

Heat

CO₂ recycle

Gasifier

CO/H₂/CO₂/H₂O

Unreacted H₂, CO recycle

Fischer-Tropsch & Associated Processes

Liquid Hydrocarbon Fuel

24 HR DIESEL

Byproducts

Biomass

Complex Biomass

Carbon-free Energy sources

H₂

H₂O

H₂O
Detailed Schematic of an Integrated Framework for Biofuels
**H₂CAR-fermentation integration**

<table>
<thead>
<tr>
<th>Case</th>
<th>Carbon Efficiency (%)</th>
<th>Energy Efficiency (%)</th>
<th>H₂ requirement (billion kg/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn Ethanol</td>
<td>67</td>
<td>57</td>
<td>-</td>
</tr>
<tr>
<td>H₂CAR</td>
<td>~100</td>
<td>57</td>
<td>250</td>
</tr>
<tr>
<td>H₂CAR + Fermentation (Heat and CO₂ integration)</td>
<td>~100</td>
<td>66</td>
<td>200</td>
</tr>
</tbody>
</table>

* In all cases, mass equivalent to DDGS is subtracted
Potential benefits of the Biomass Integrated Processes

- Integrated process leads to increased energy efficiency (65% vs 57%)

- No CO₂ release during the conversion process decreases land area requirements significantly
In Summary

- Energy is one of the grand challenges of our time
- World is not about to run out of oil or NG
- However,
  - Demand for energy is growing rapidly
  - Conventional oil will peak out in a few decades
  - Most nations do not have enough oil or NG
- Must develop alternate energy sources
- This development must start now
In Summary

- Solar/Nuclear hold the future promise
- Multiple Challenges with the use of solar
  - Cost
  - Intermittency/Storage
  - Transmission
- System approach needed to optimize use of solar photons
- Biomass predominantly a carbon source
In Summary

For Transportation Fuel:

- The picture continues to evolve
- Electricity likely to play a significant role
- Liquid fuels will continue to dominate
  - However, carbon source will be sustainable
  - Integration with carbon-free energy sources likely e.g. Nuclear or solar
  - Need for creativity and innovation
- H$_2$ could play a role if associated challenges could be met
- Multiple energy careers will be used.
Energy System Analysis

“A Great time to be a Chemical Engineer”
Acknowledgement

- Navneet Singh
- Qijie Guo
- NRC H$_2$ Committee
....Thank you