Energy Systems Analysis

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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
  - H_2 as an energy carrier

Why is Energy Important?

Why is Energy Important?

Source: www.goodworksonearth.org

Why is Energy Important?






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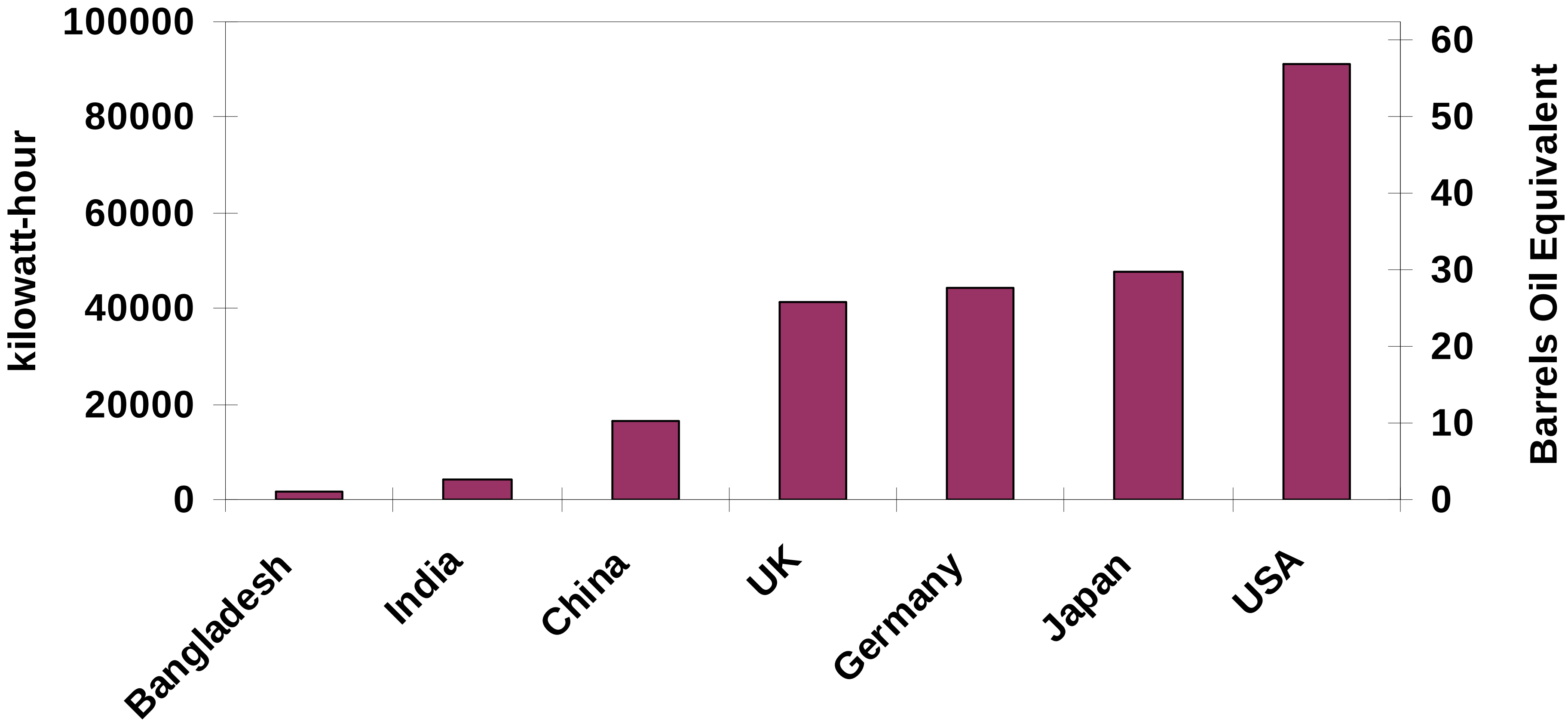
Energy Consumption is Way of Life in Industrialized Countries

2007 Primary energy consumption per capita



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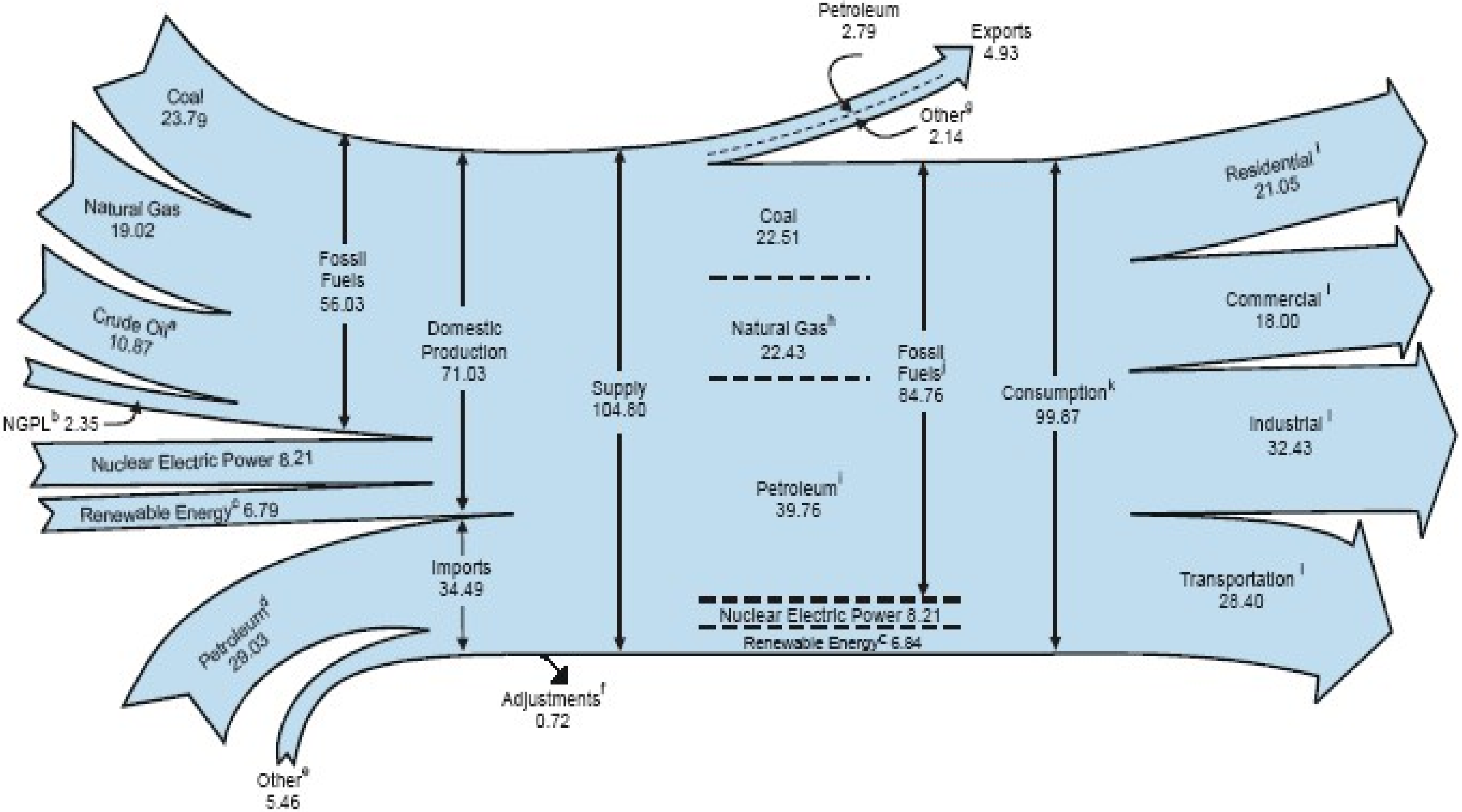
How is Energy Used?

As an Example, Consider the USA Energy Landscape

U.S. Energy Flow – 2005 (quadrillion Btu)

Energy Sources **Energy Usage**



OBSERVATION: 85% Energy from Fossil Fuels

Source :EIA

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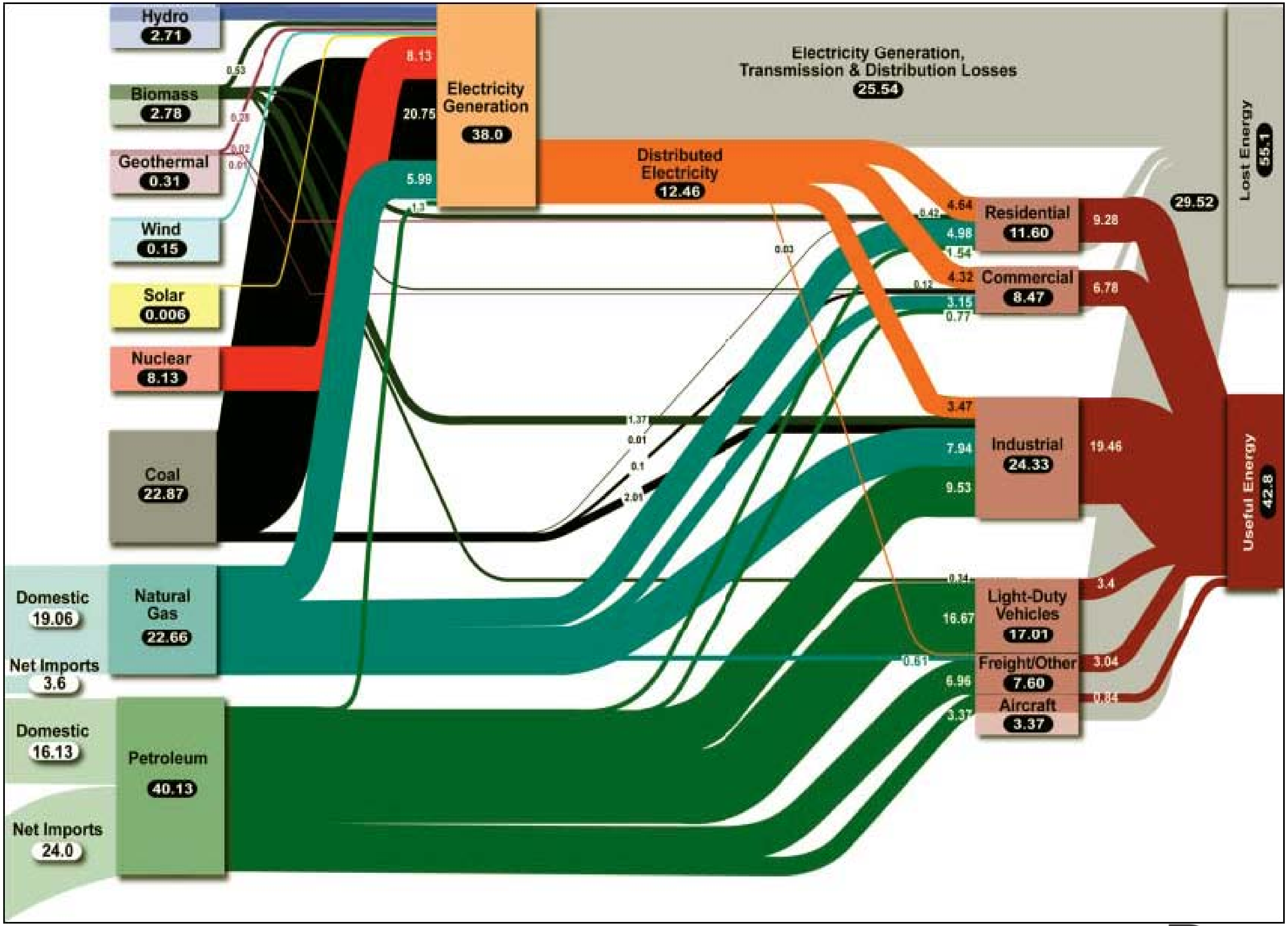
US Energy Flow – 2005



Source : LLNL

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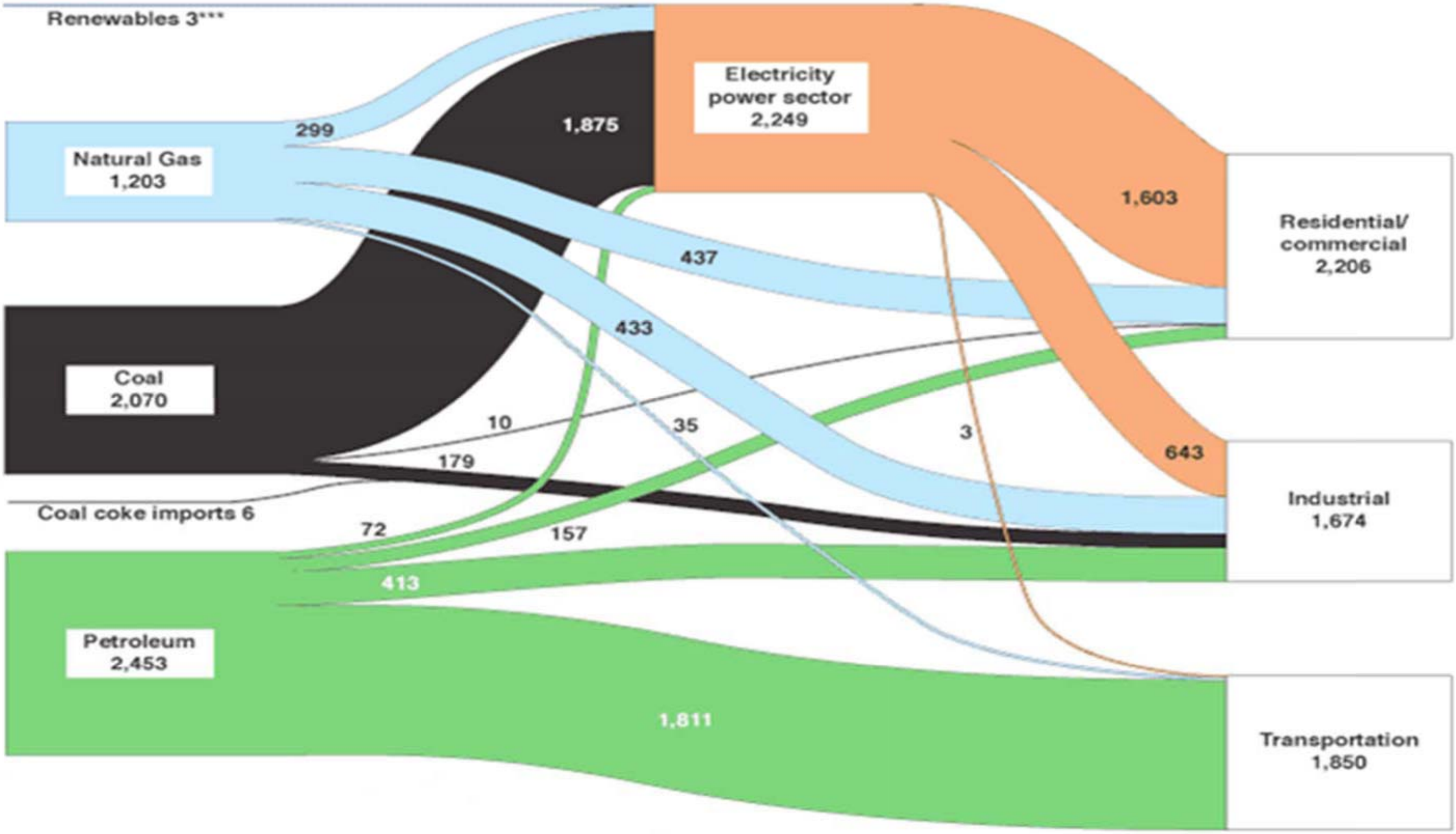
U.S. Energy Flow - 2005

- **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.**

U.S. 2002 Carbon Dioxide Emissions from Energy Consumption — 5,682* Million Metric Tons of CO_2



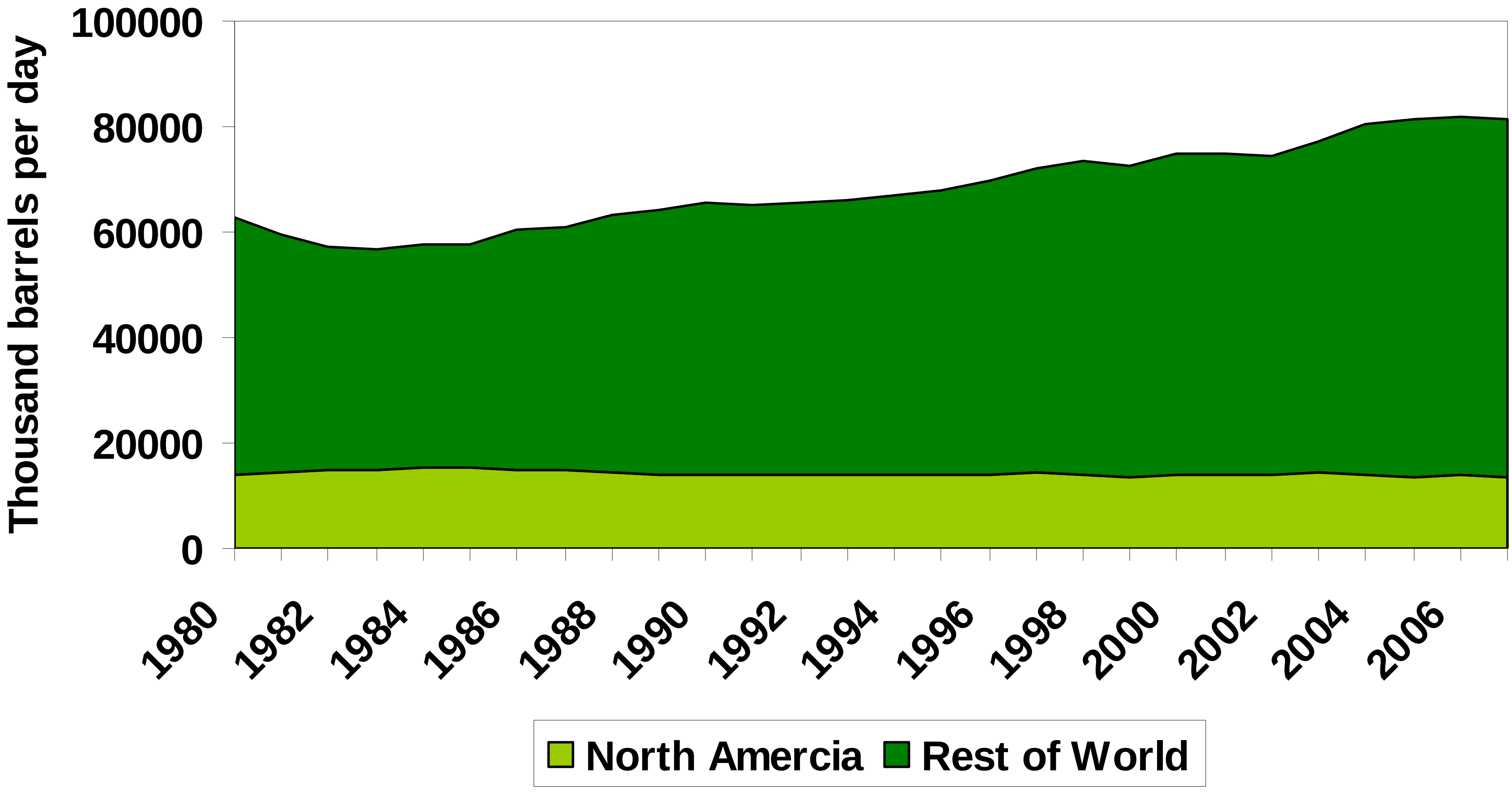
Lawrence Livermore National Laboratory, May 2004
http://eed.llnl.gov/flow/

Total World CO_2 Emissions ~ 28,000 Million Metric Tons

Availability of Primary Energy Sources

Some Energy Facts

World Oil Production



Total proven conventional oil reserve = 1238 billion bbl

Source : BP Statistical Review of world Energy 2008

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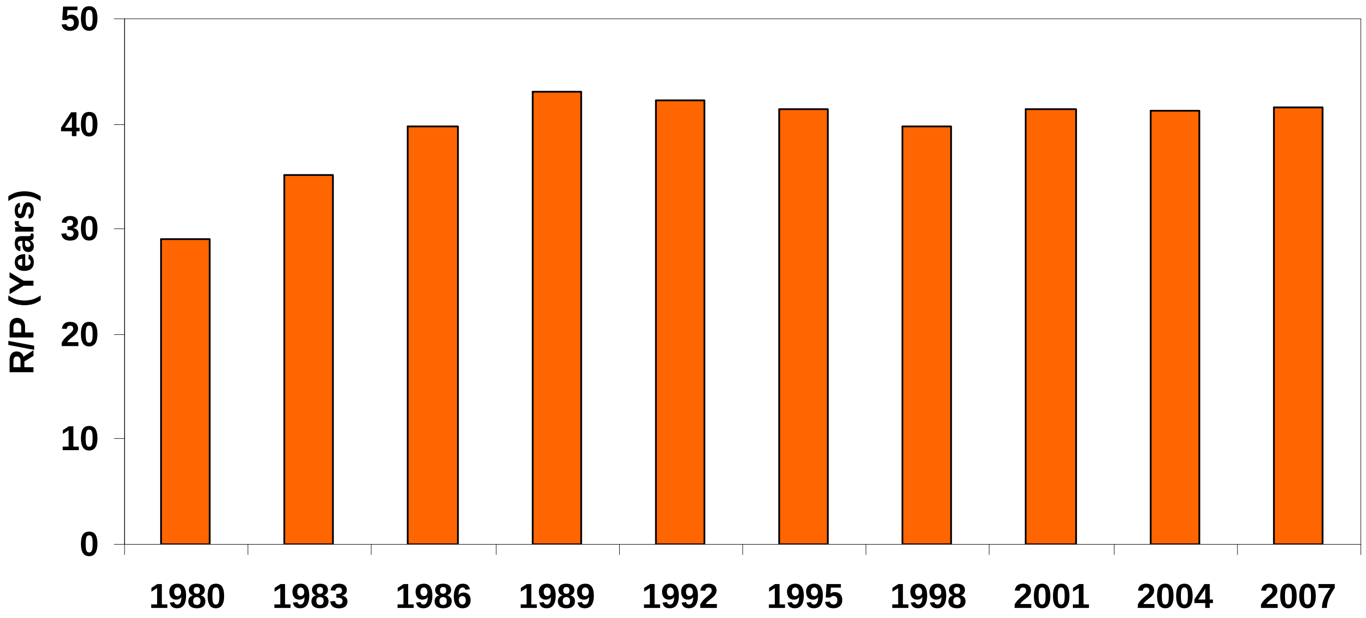
World Oil Reserves-to-Production (R/P) Ratios



- **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**

Source : BP Statistical Review of world Energy 2008

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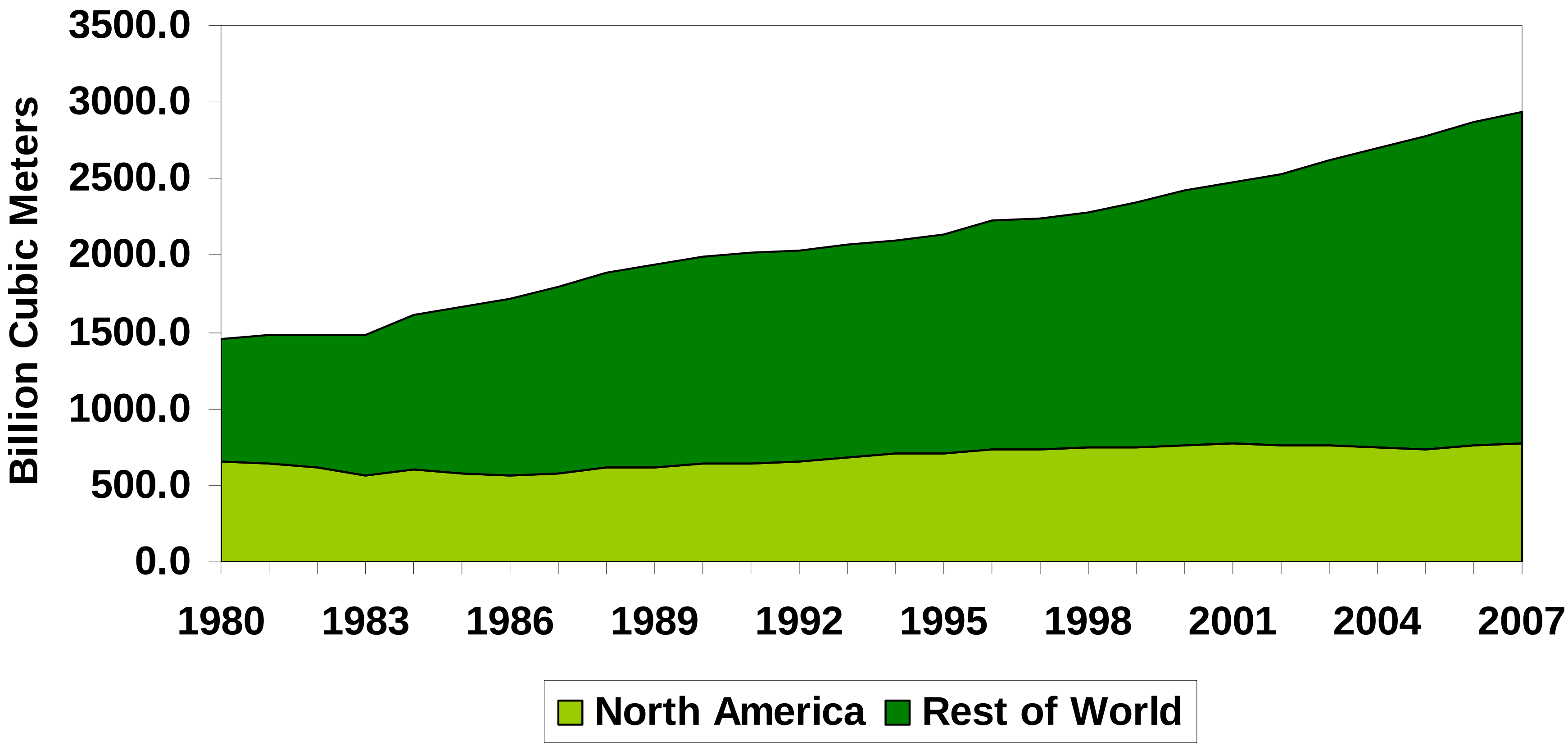
Natural Gas Production



- **Total proven gas reserve = 177.4 trillion m^3**
- **Natural gas demand continues to rise**

Source : BP Statistical Review of world Energy 2008

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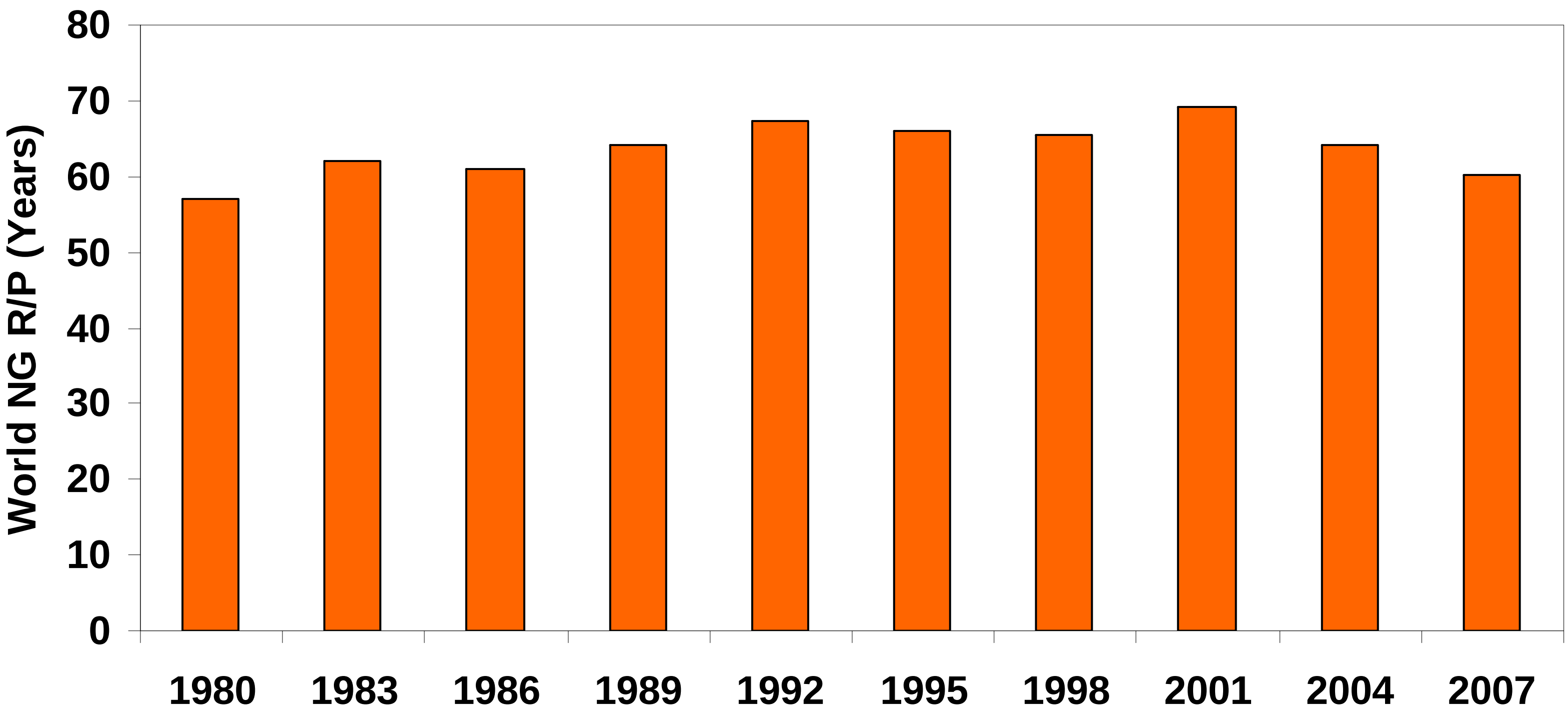
Natural Gas Reserves-to-Production Ratios



- **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**

Source : BP Statistical Review of world Energy 2008

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!

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It seems that there is enough hydrocarbon fuel to last for the next fifty years!

However…..

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However…

- The world population is expected to rise

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However…

- The world population is expected to rise
- **World energy consumption rate is expected to rise**

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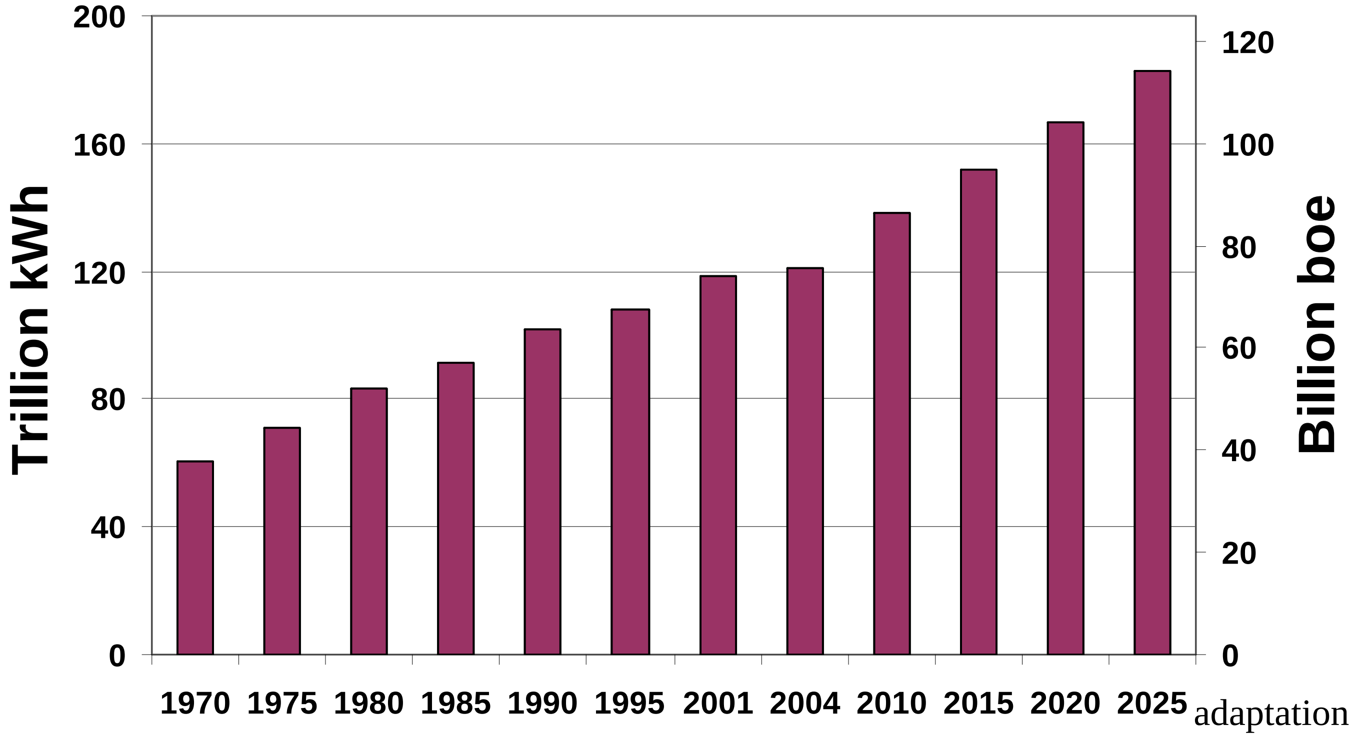
World Marketed Energy Consumption



adaptation : EIA

- **World primary energy usage rate in 2007 was 14.8 TW**
- **By 2050, the usage rate could be 28 TW**

Consumption rate could double!

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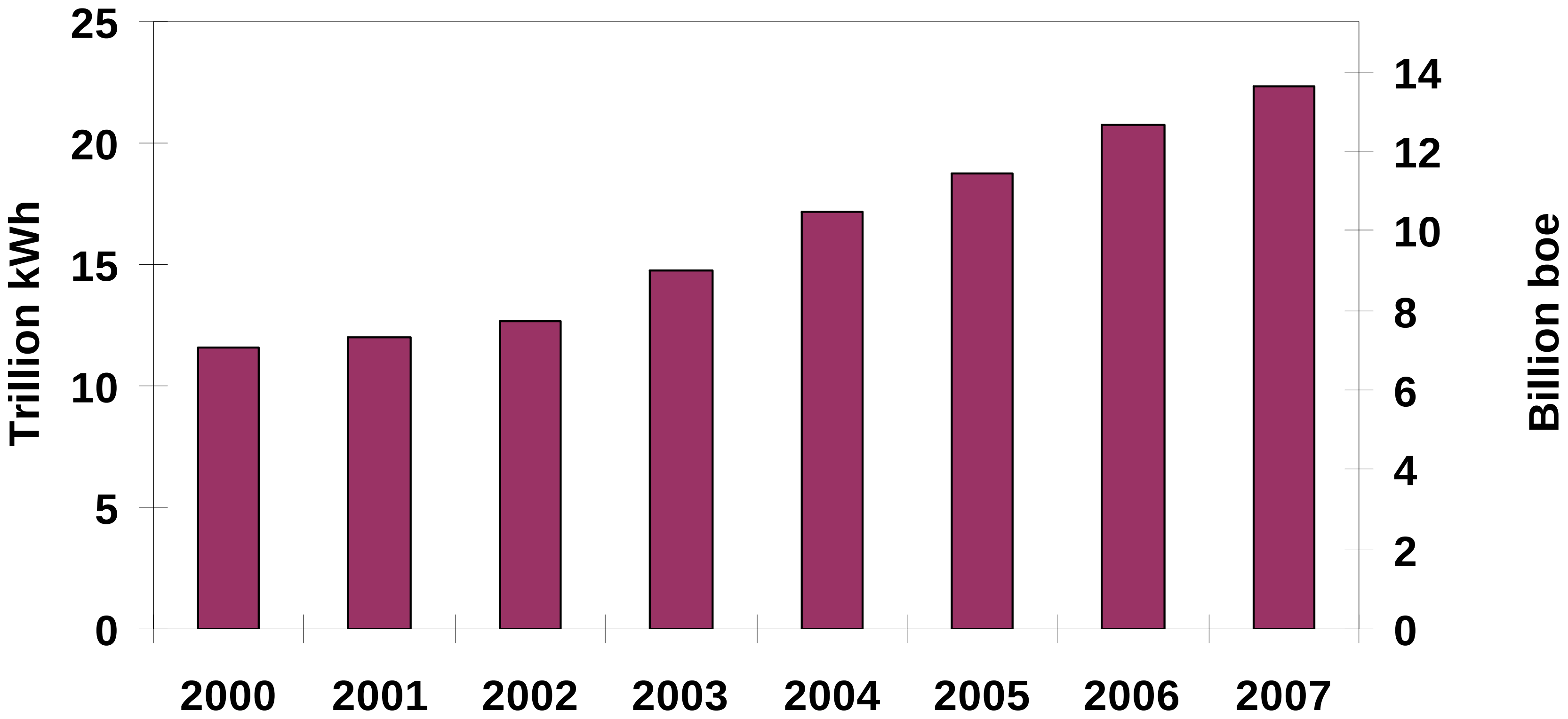
However…

- 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

Source : BP Statistical Review of world Energy 2008

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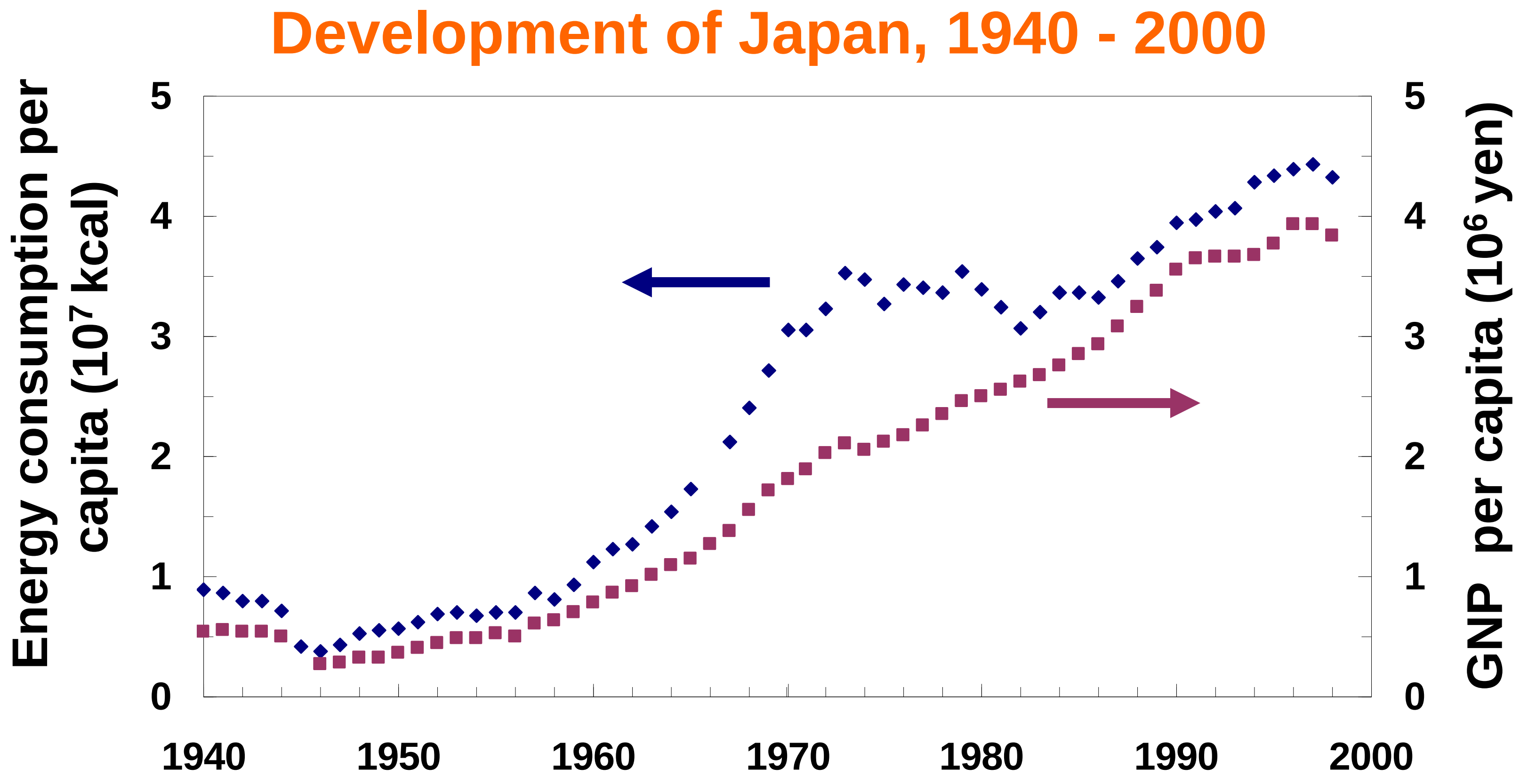
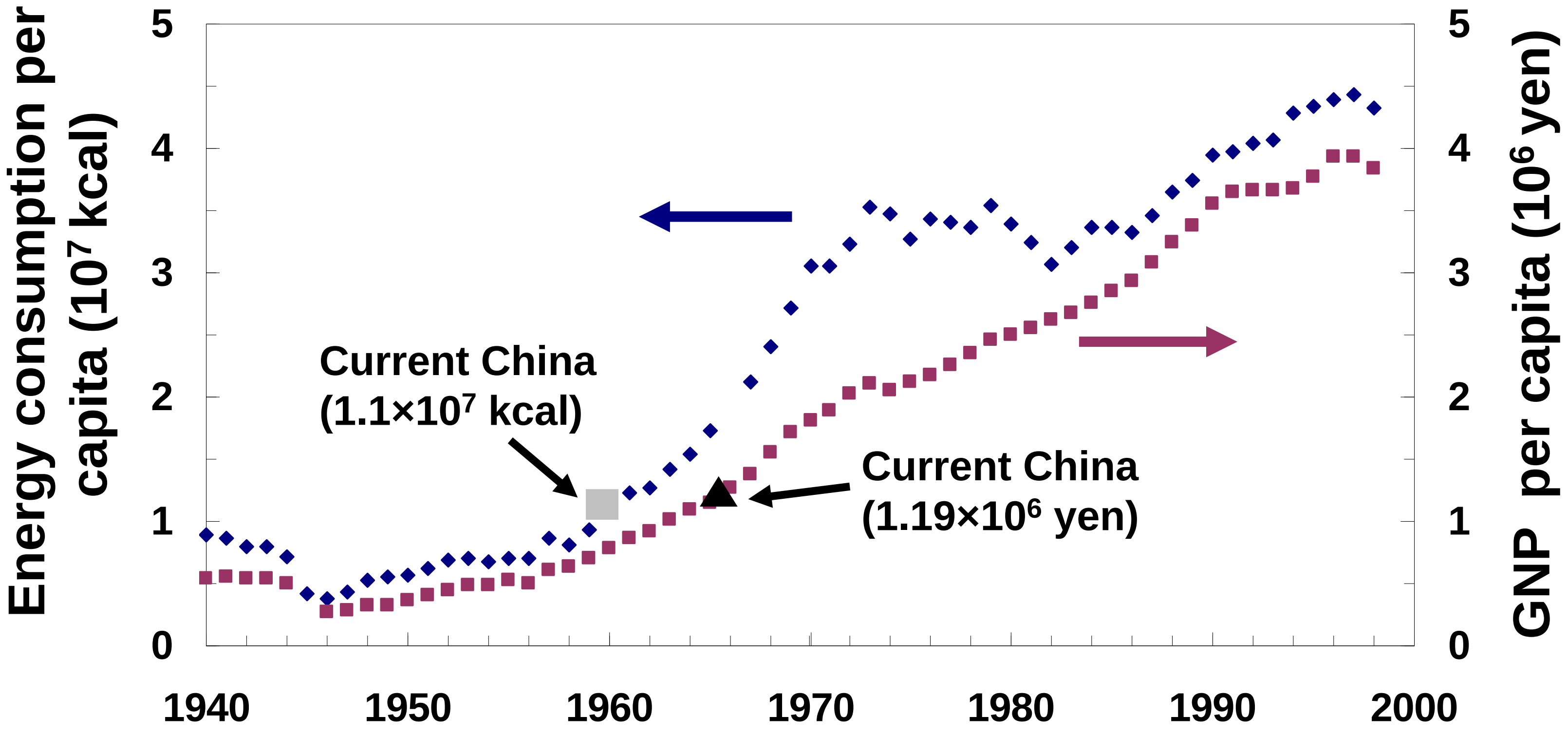
China could Quadruple its Energy Consumption Soon!



adaptation : Prof. M Suzuki

China could Quadruple its Energy Consumption Soon!

Development of Japan, 1940 - 2000



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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…

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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**

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- 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%**

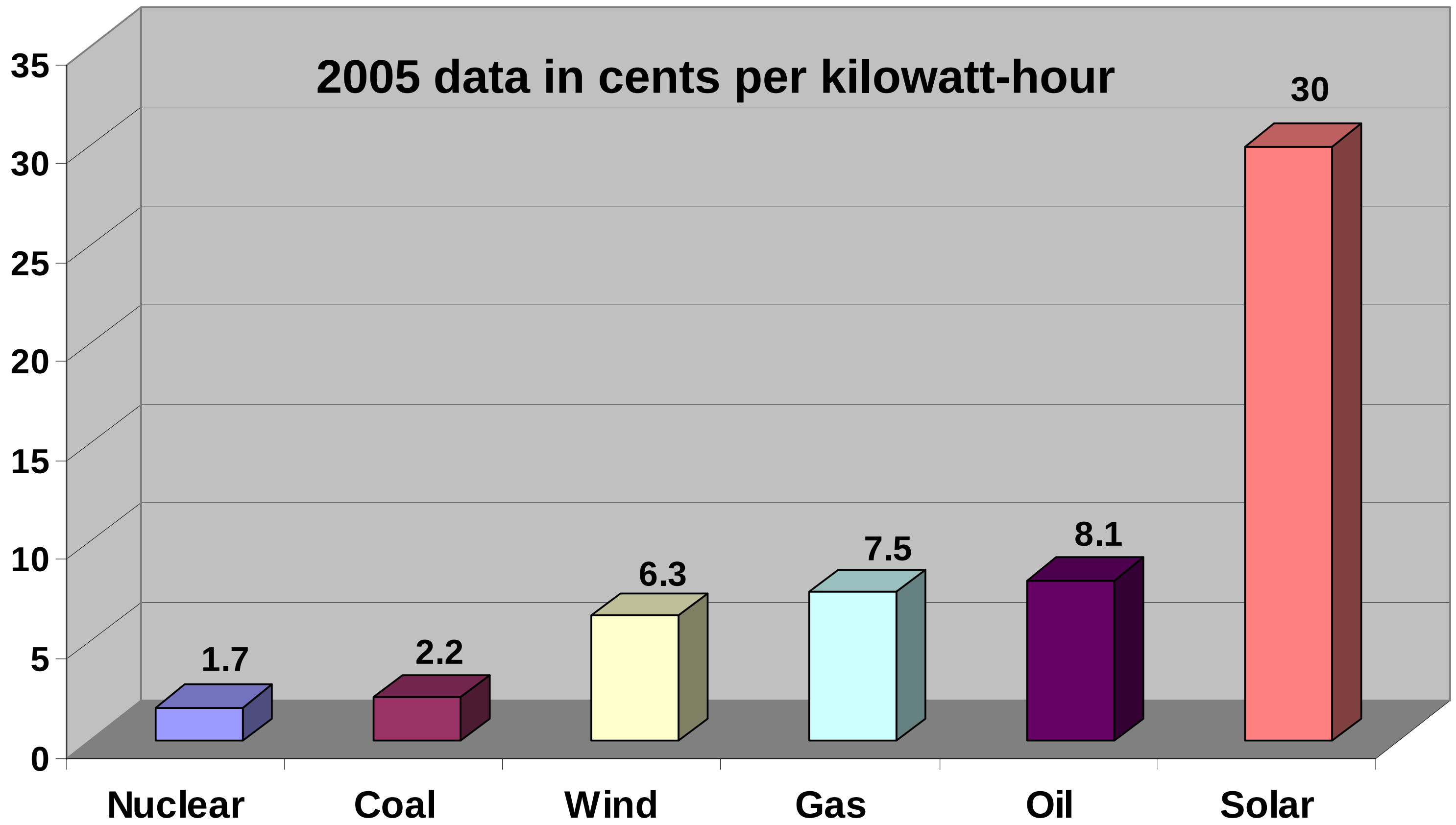
Alternate Energy Sources

- 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



Retail Cost of Electricity (Residential Rates)

U.S	8 ¢ per kWh
Germany	15 ¢ per kWh
Japan	21 ¢ per kWh

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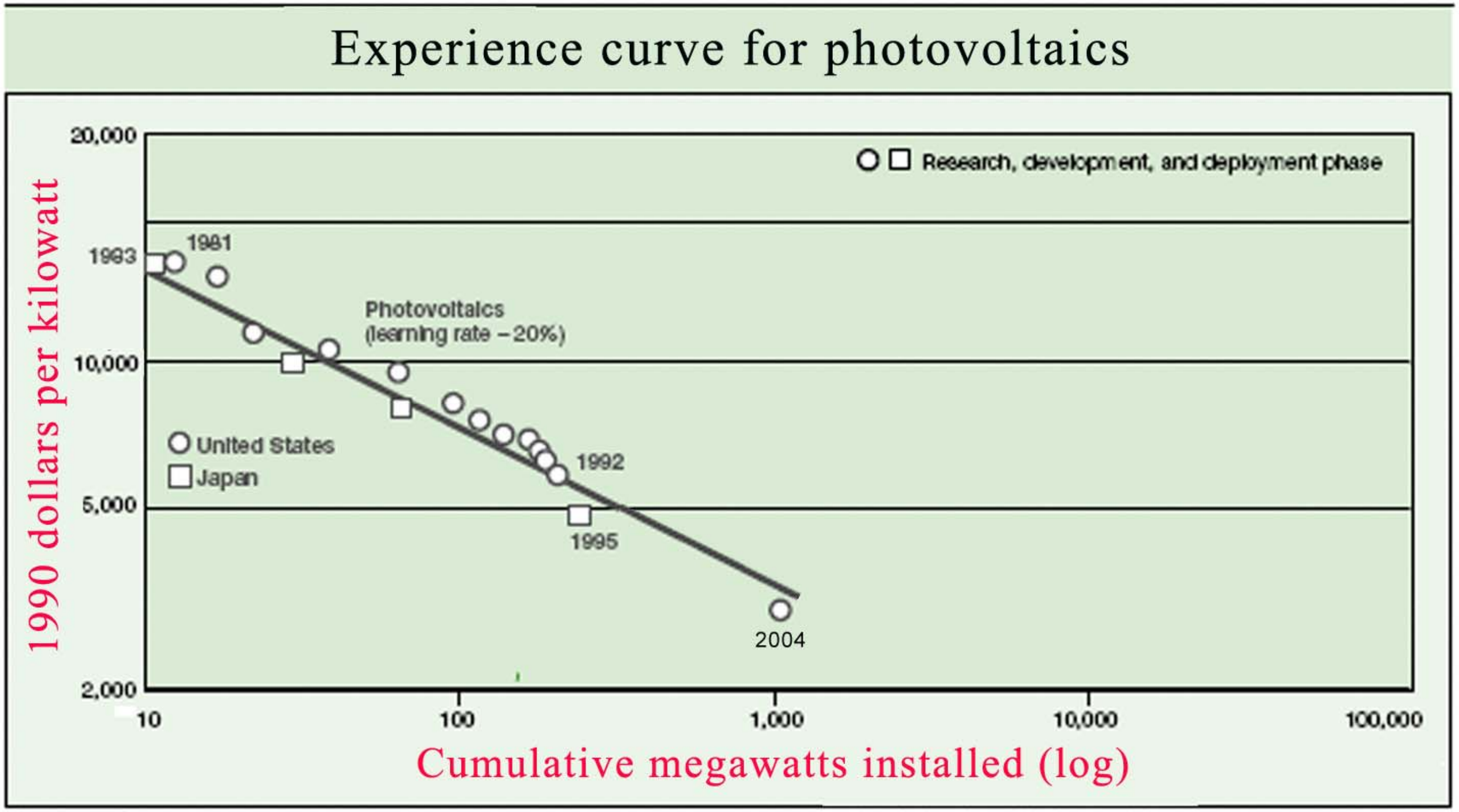
Photovoltaic Cost has been Declining



adaptation : UN report

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

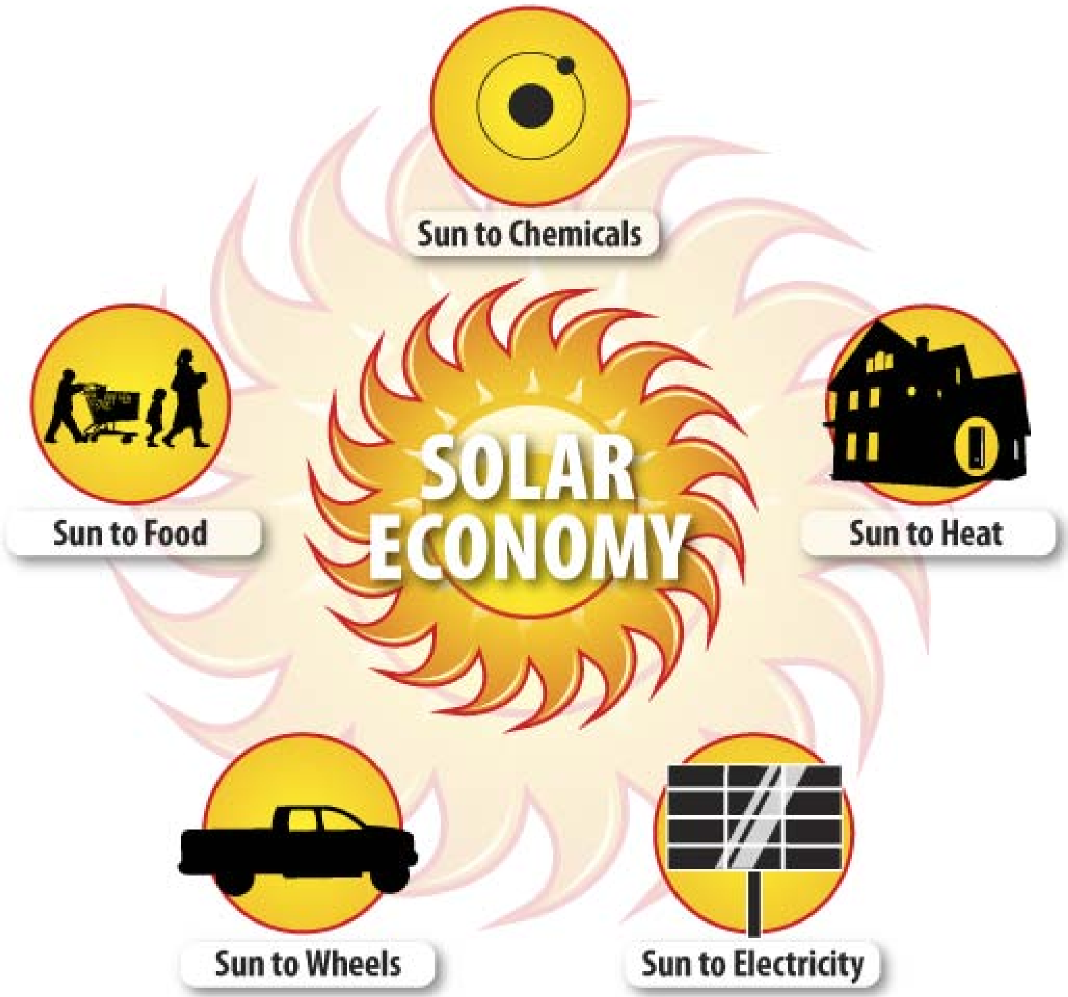
However…

- 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

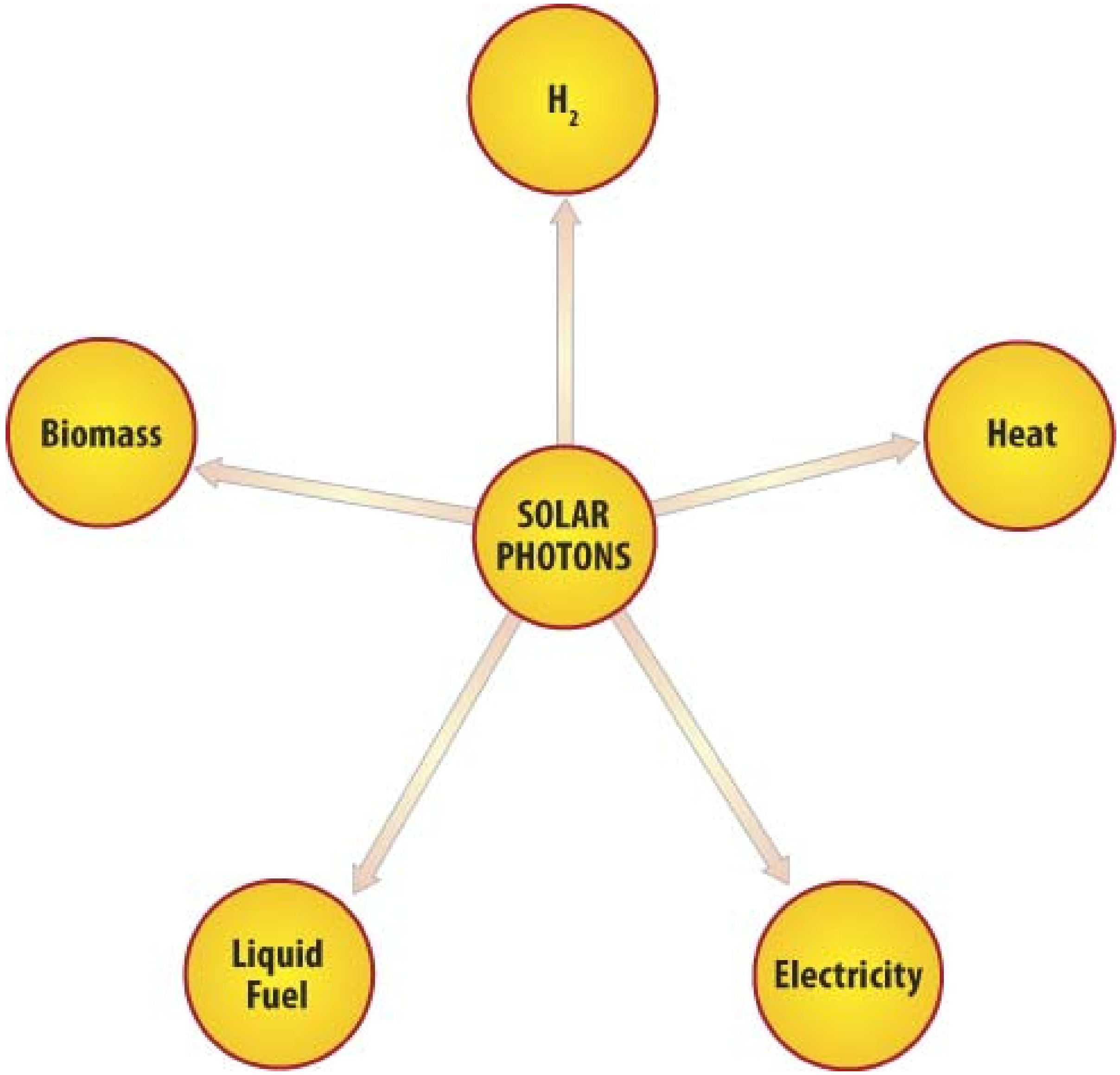


All uses must coexist: Use of Solar Photons must be optimized.

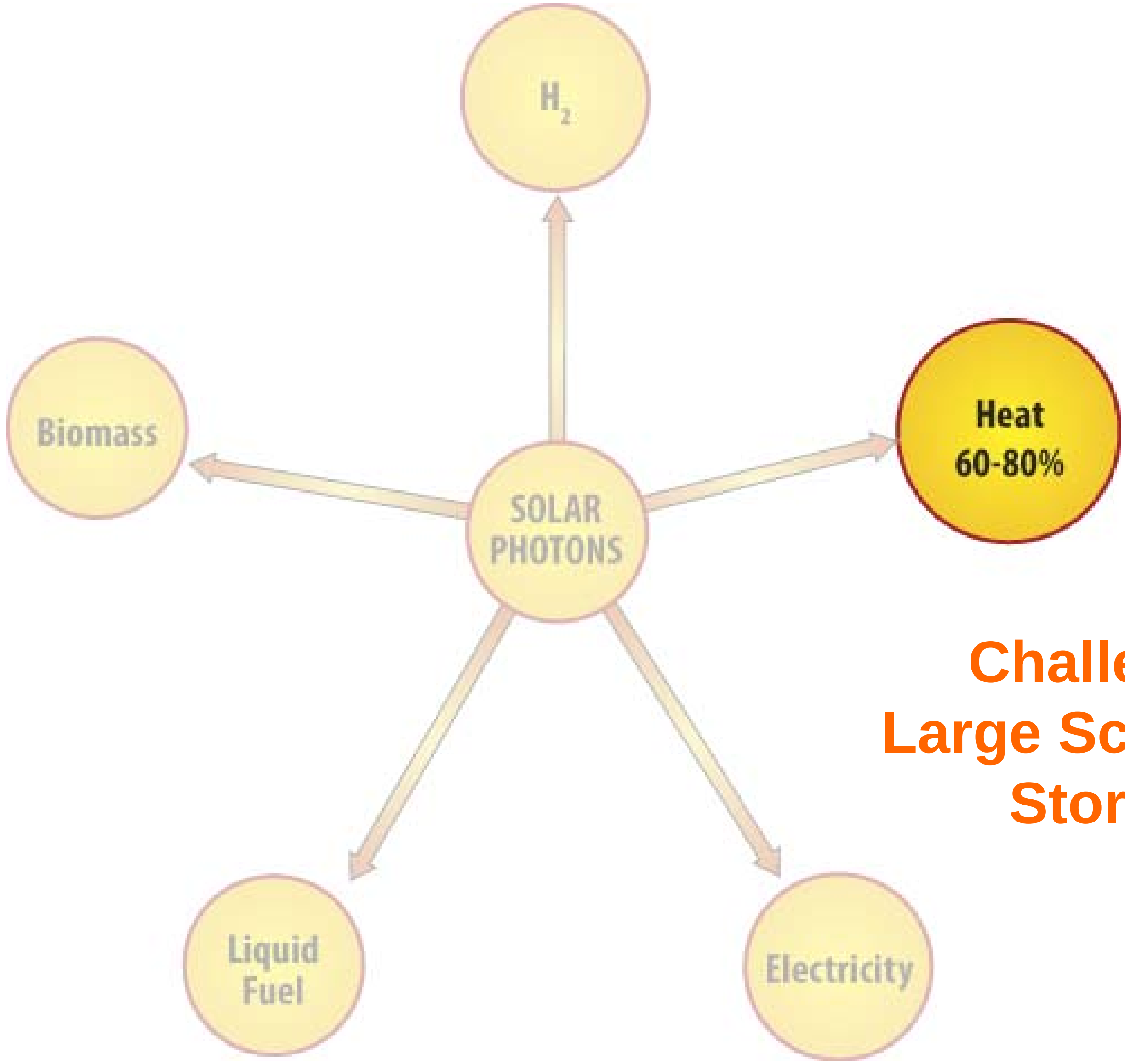
How should one optimize the use of Solar Photons? (or nuclear heat)

. . . Let us start by examining conversion efficiencies

Efficiencies of Solar Energy Recovery



Efficiencies of Solar Energy Recovery



Challenge: Large Scale Heat Storage

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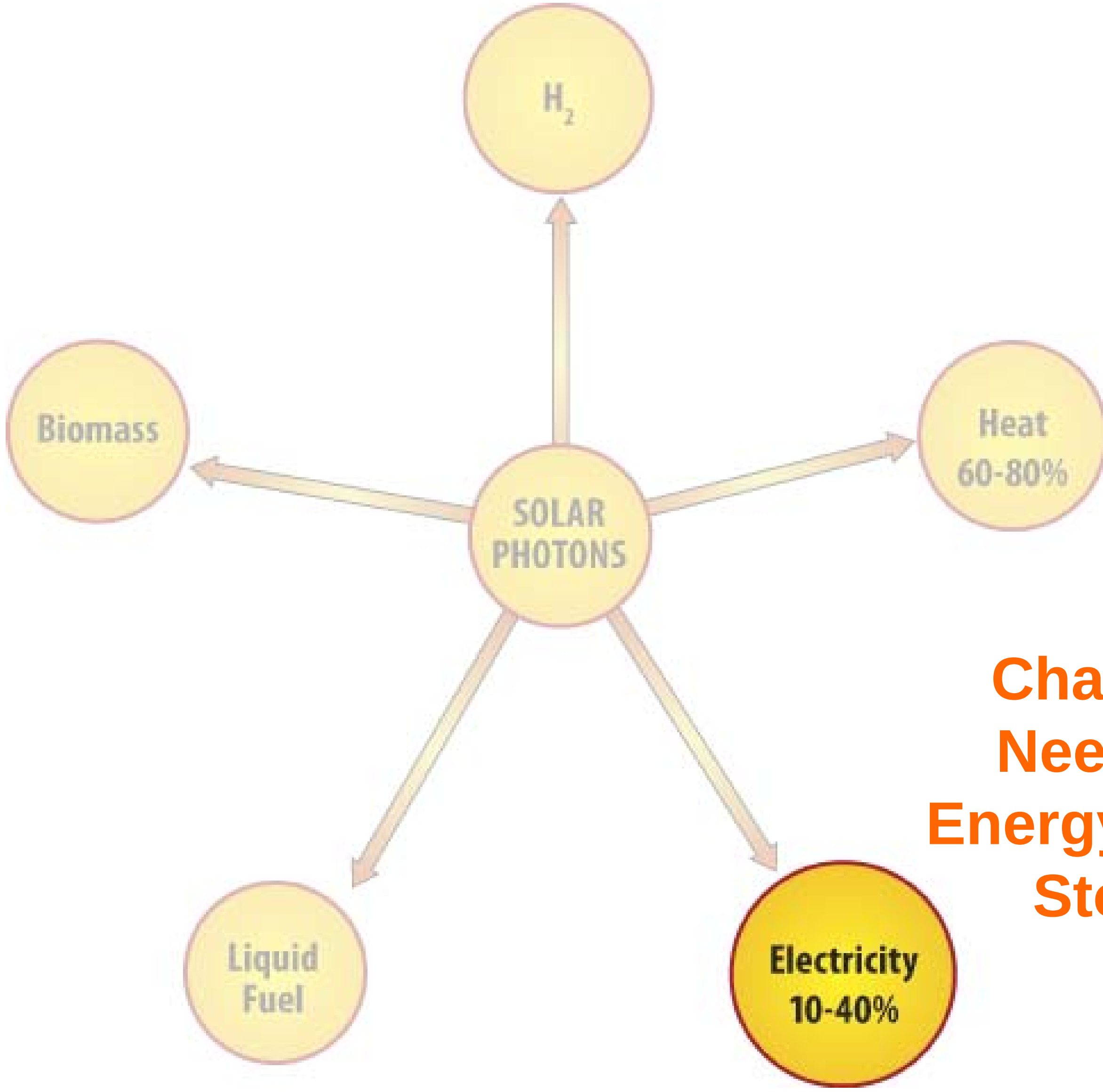
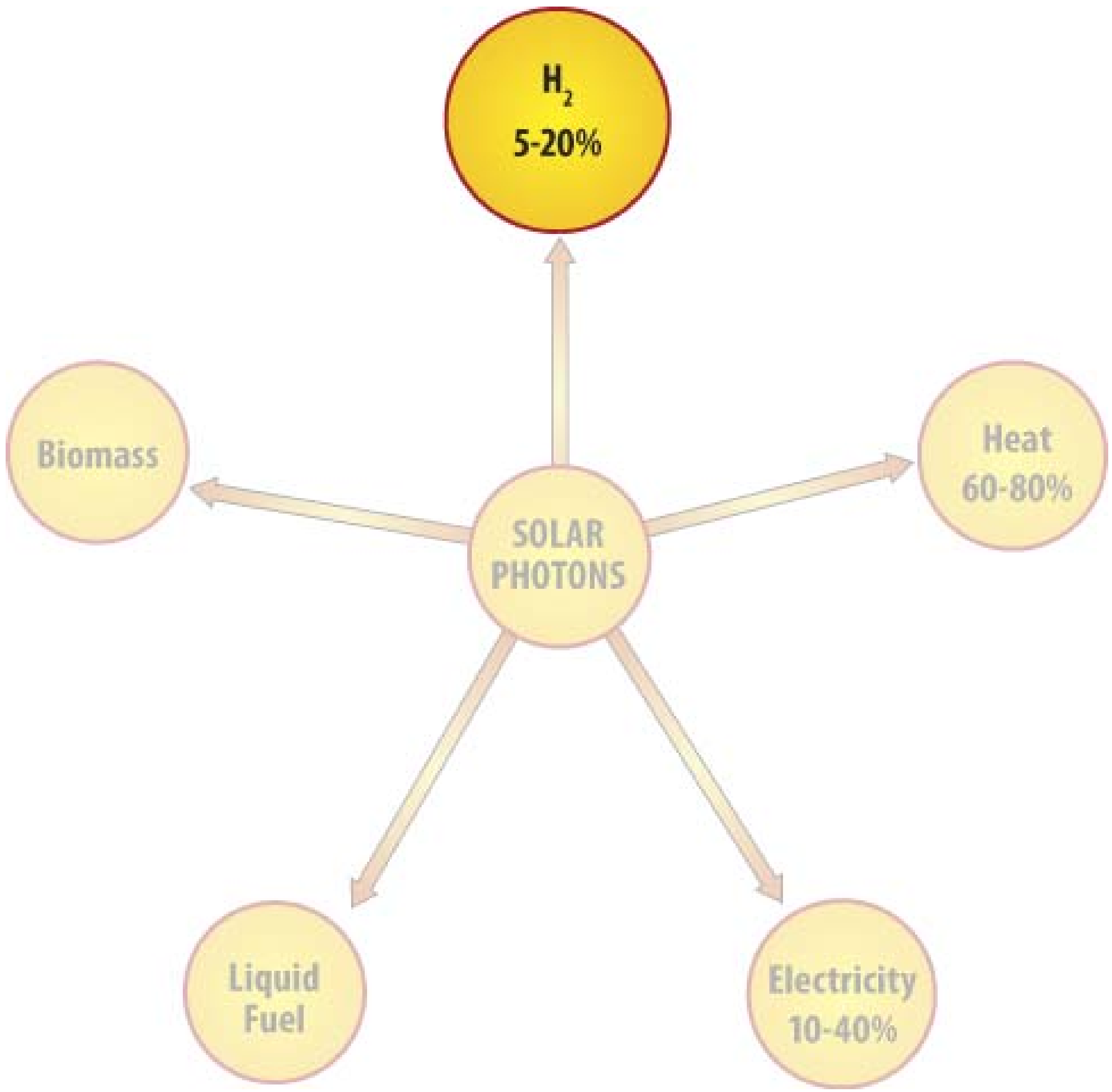
Efficiencies of Solar Energy Recovery



Challenge: Need High Energy Density Storage

Efficiencies of Solar Energy Recovery



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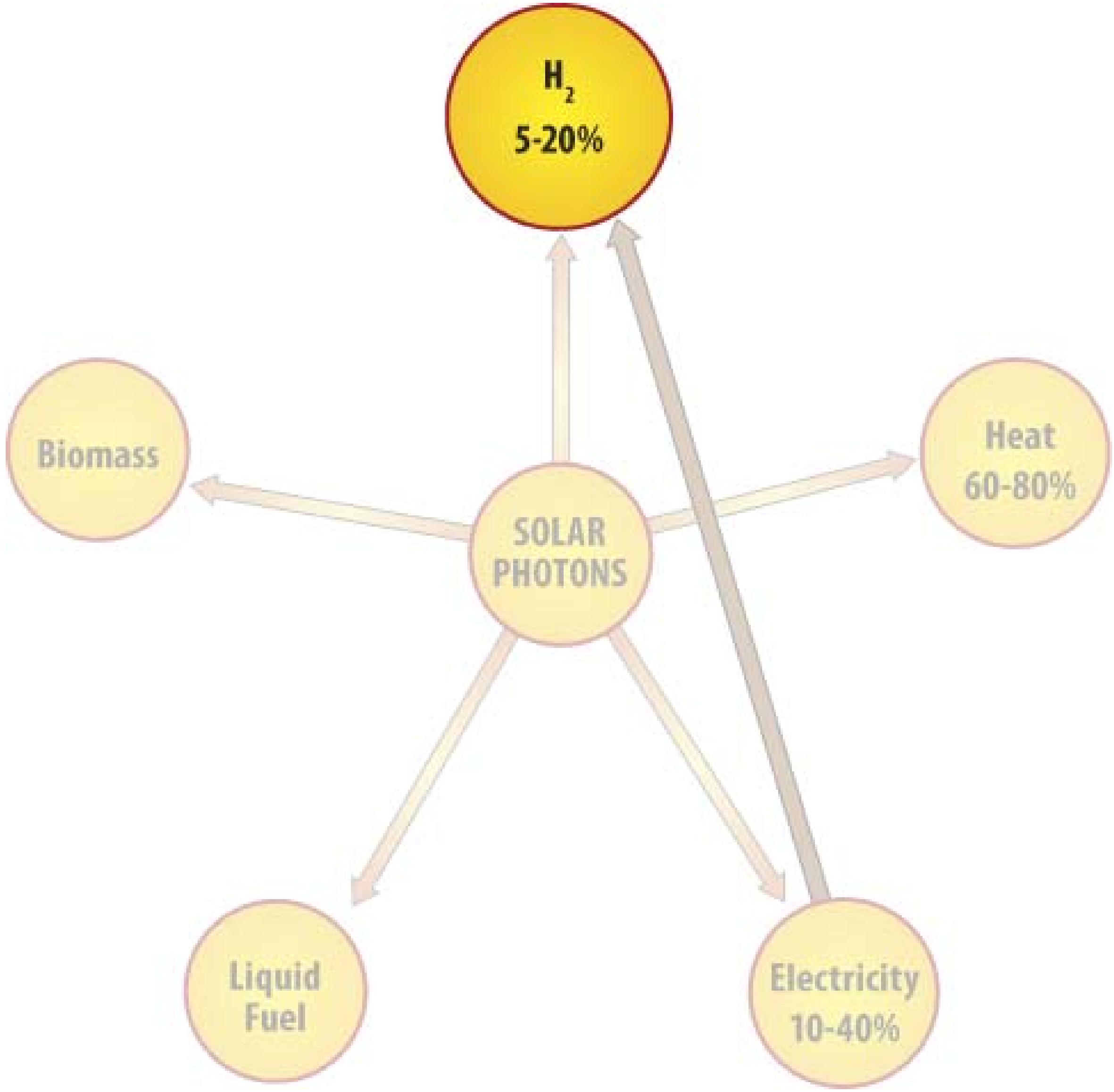

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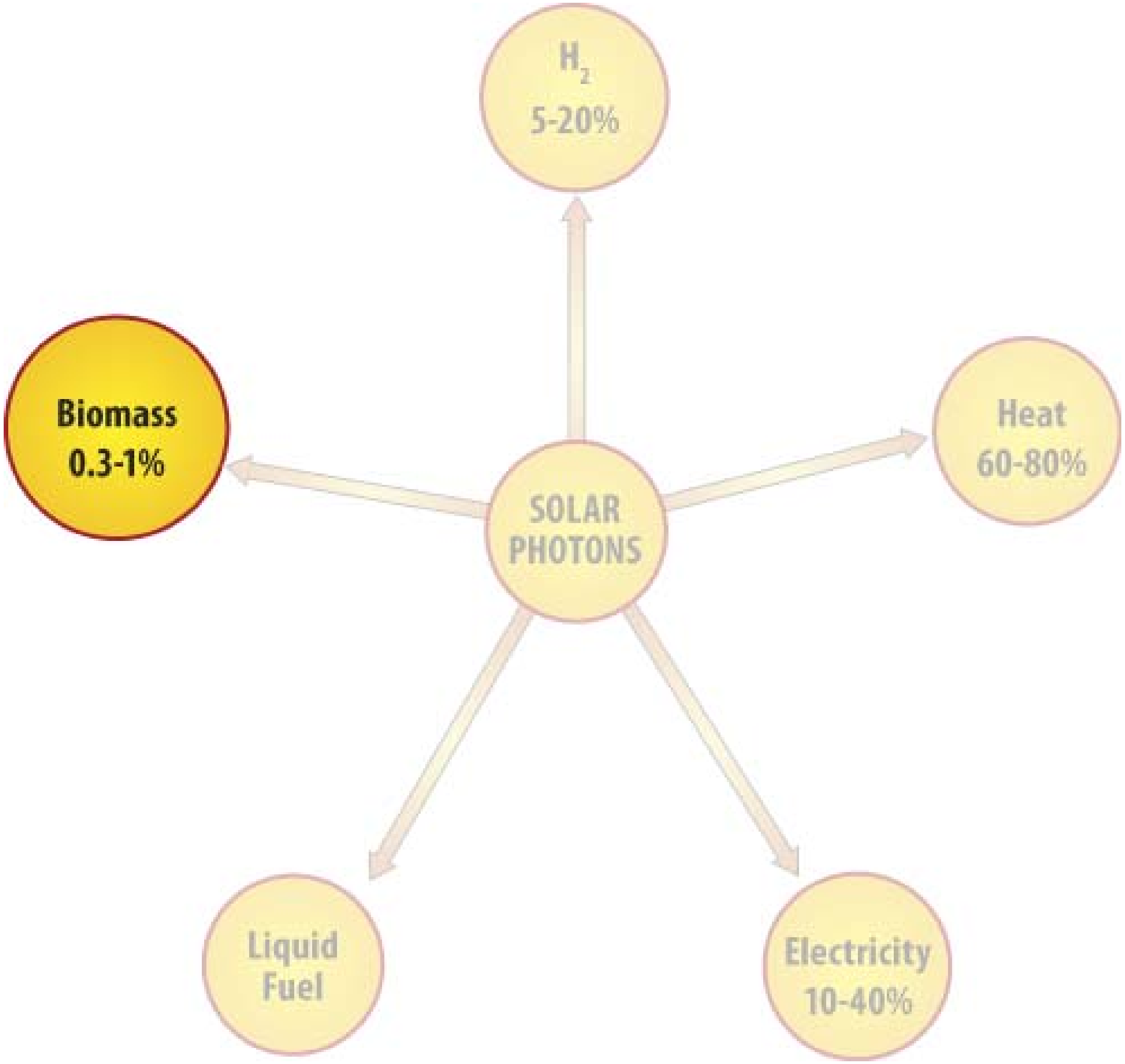

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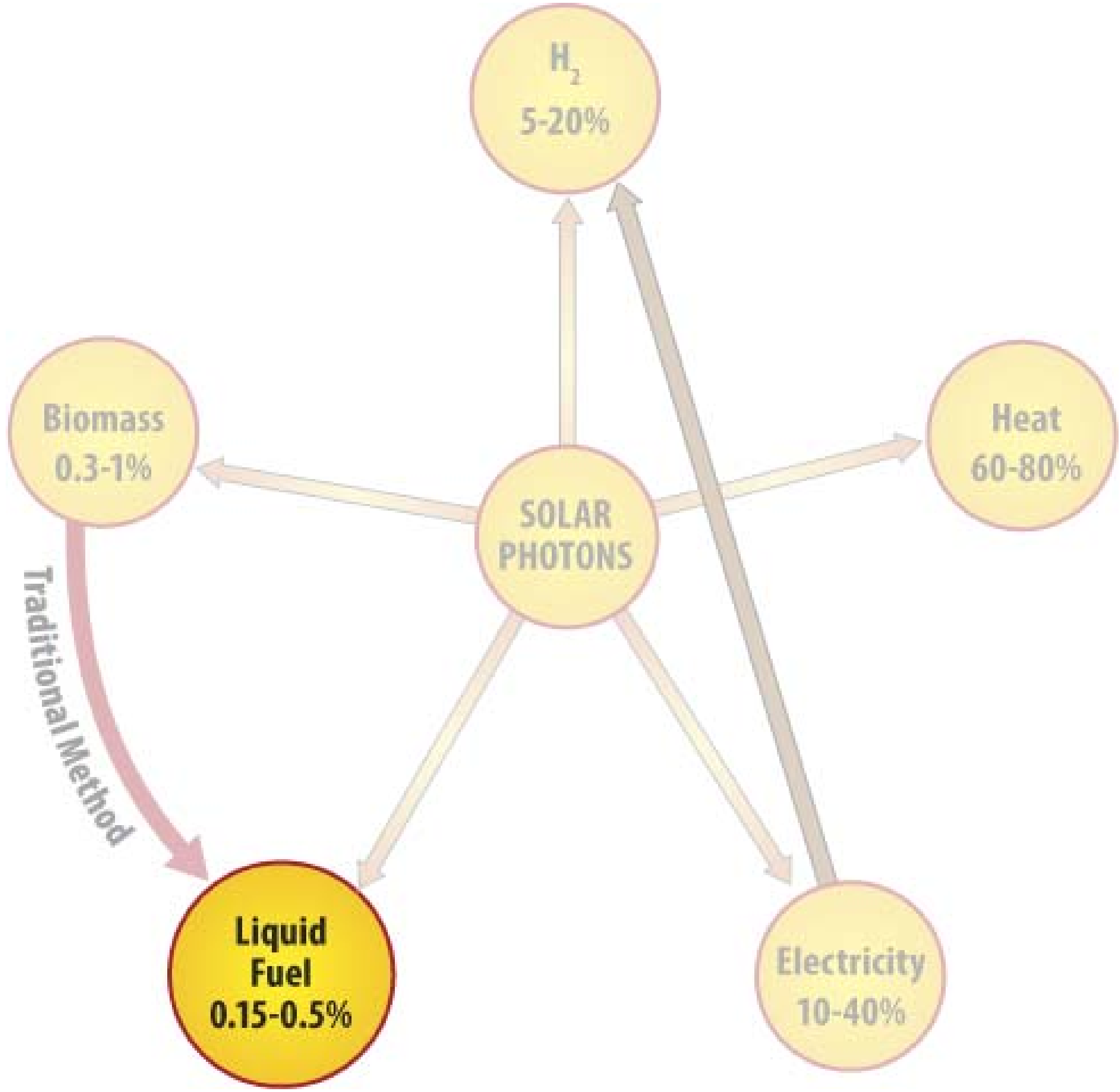

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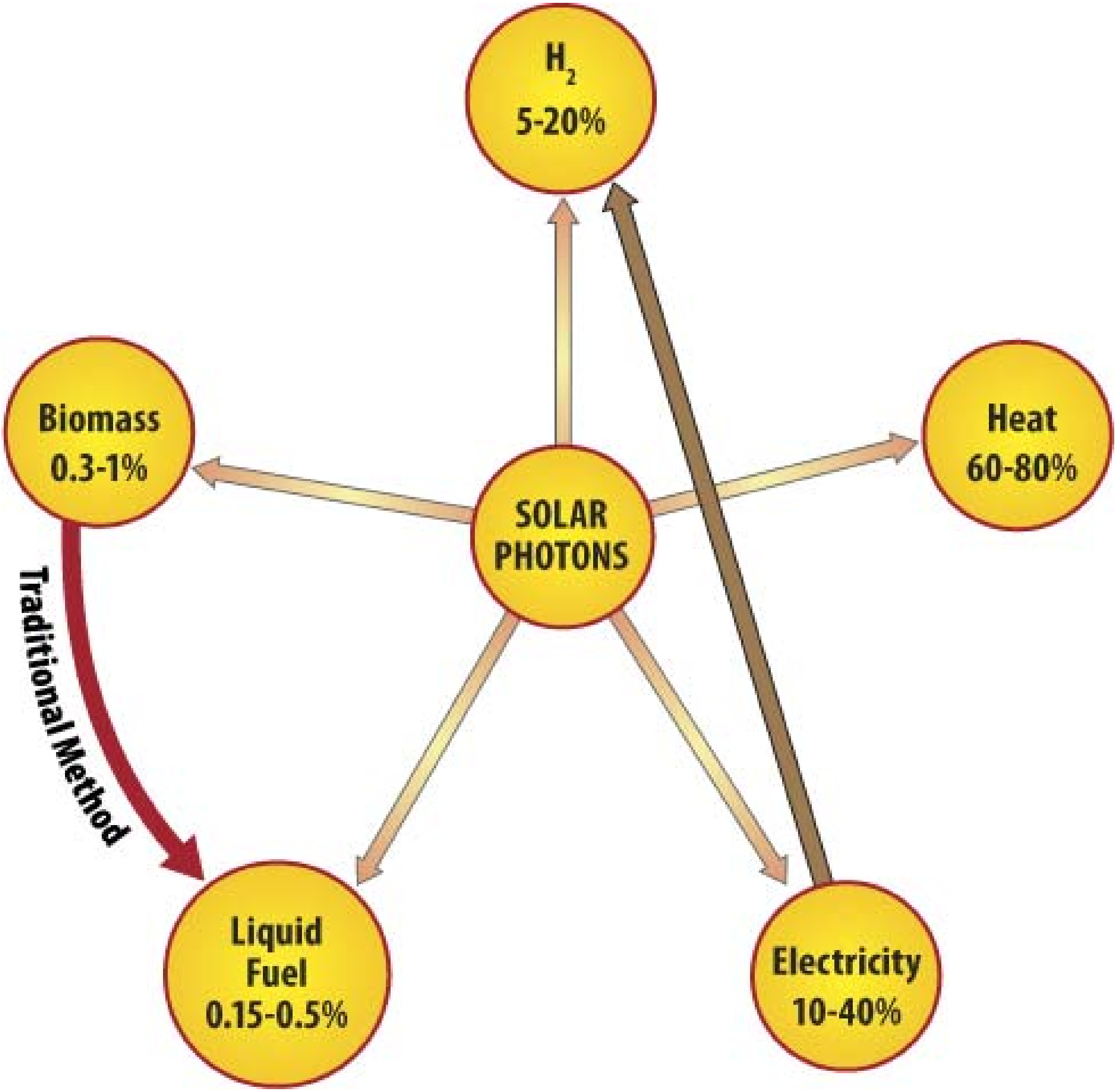

Preferred Ranking on the basis of Recovery Efficiencies

- Heat
- Electricity
- H_2
- Biomass/Liquid Fuel

However, challenges involved with:

- Intermittency/Storage
- Transmission/Long distances
- Cost

… Of all the end uses most challenging is transportation.

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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

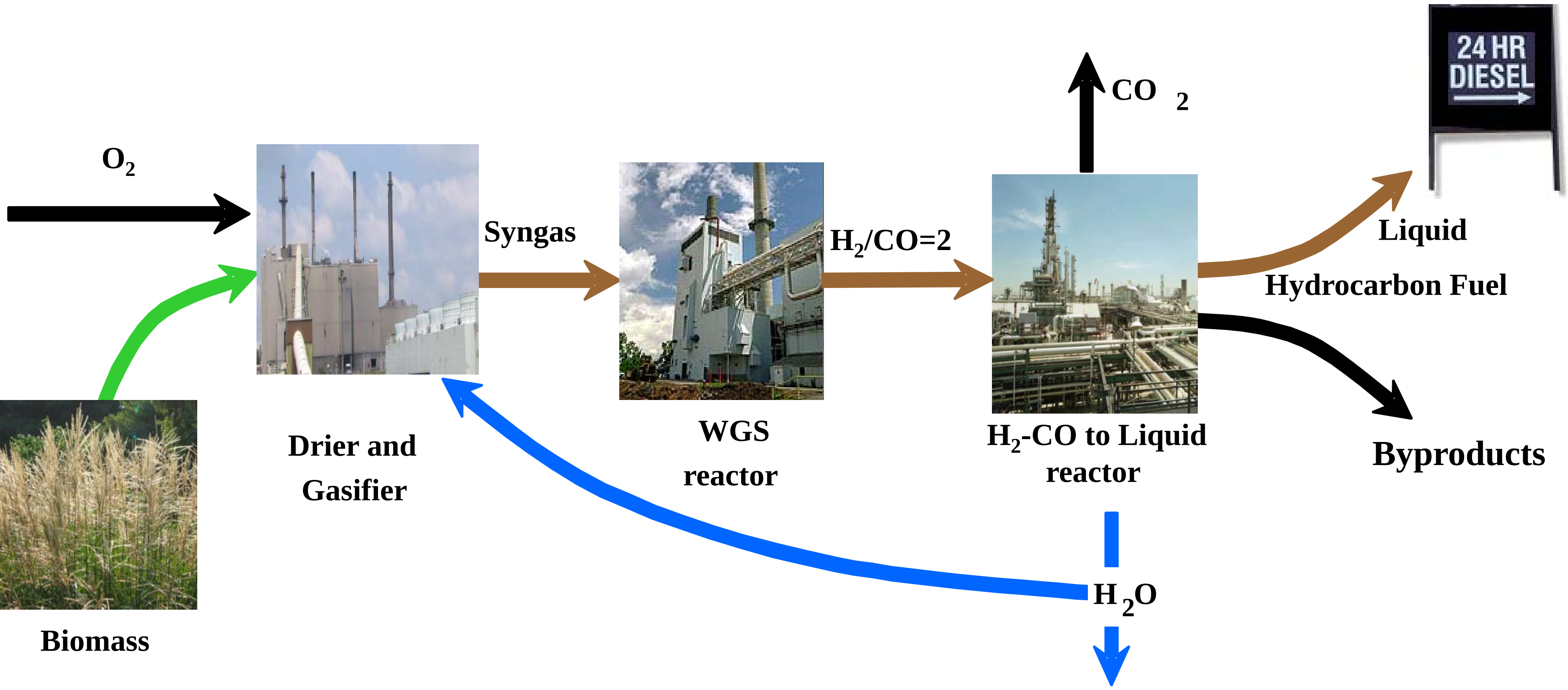
Sun to Wheels

Option #1: Sun to biofuels

Question:

How much land area to support the entire US transportation sector?

Biomass to Synthetic Oil by Conventional Gasification Route



Land area for 13.8 mbbl/d = 25-55% of the total US land area

Total US land area: 3.6 million mi^2

Sun to Wheels

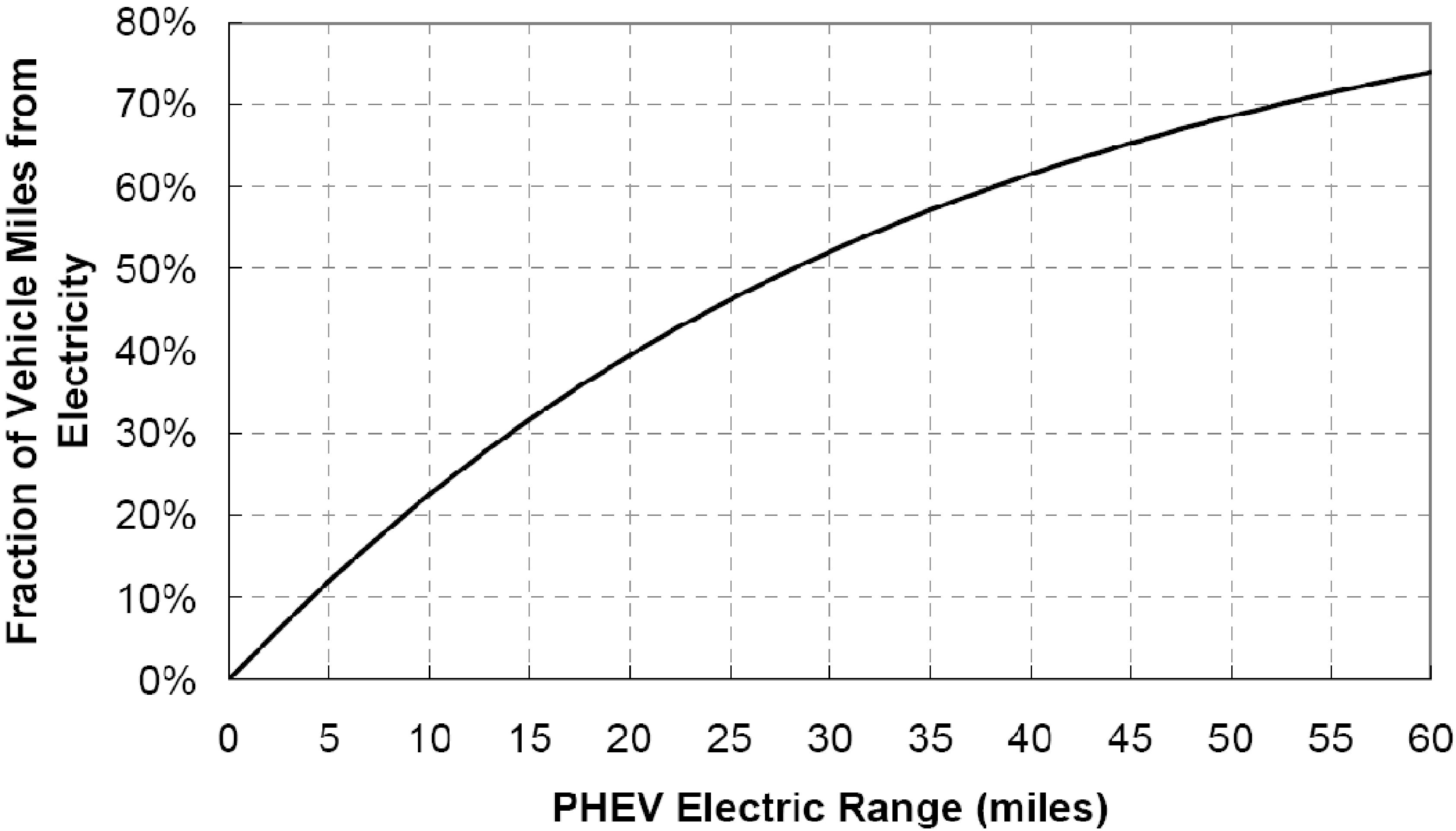
Biomass alone can not meet the need for the entire US transportation sector

Sun to Wheels

Option #2: Sun to electricity

- To travel 350 miles, amount of electricity needed = 105 kWh
- However, battery storage ≤ 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)



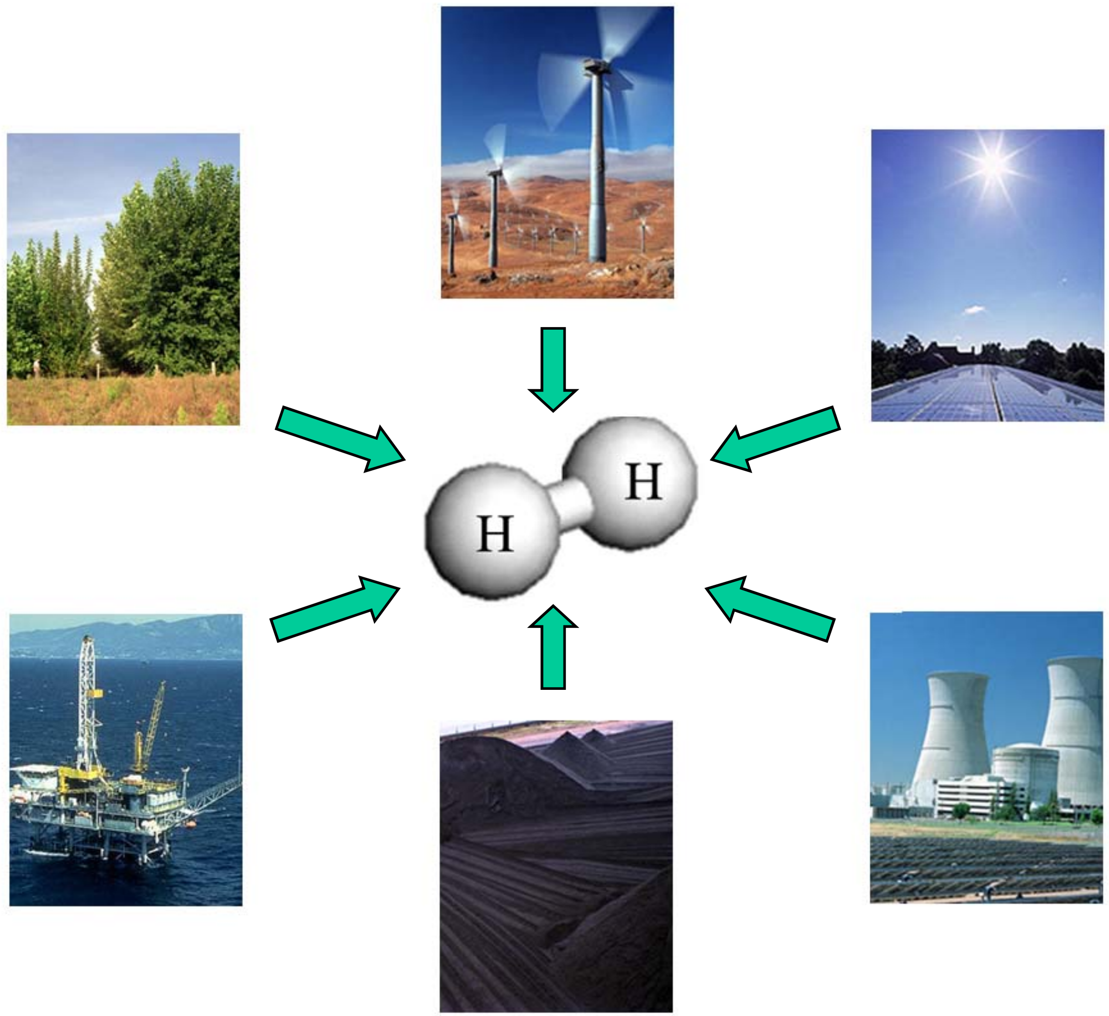
5.5 Mbbl/d replaced with PHEVs of 40 miles per charge batteries

Parks *et al.*, NREL/TP-640-41410, May 2007

Sun to Wheels

Option #3: H_2 Fuel Cell Vehicles

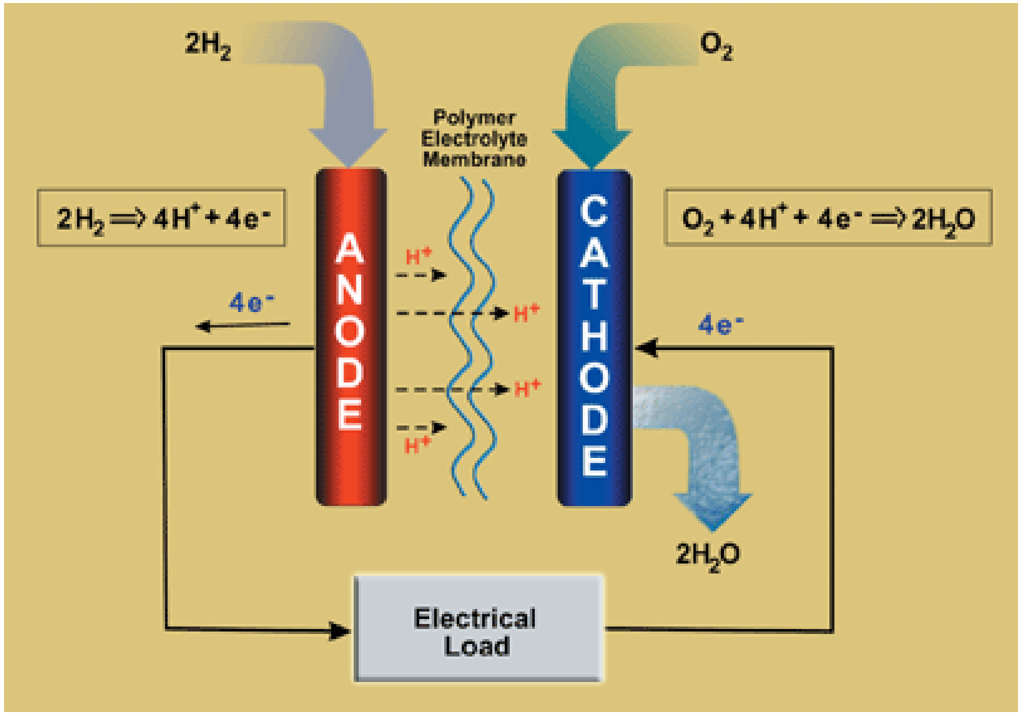
Hydrogen



Hydrogen as an Energy Carrier – Its Promises and Challenges

The Promise of Hydrogen

Fuel Cell



Source: EPA

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

MICHAEL P. RAMAGE, NAE,1 Chair, ExxonMobil Research and Engineering Company (retired), Moorestown, New Jersey

RAKESH AGRAWAL, NAE, Air Products and Chemicals, Inc., Allentown, Pennsylvania
Now at Purdue University, West Lafayette, Indiana

DAVID L. BODDE, University of Missouri, Kansas City

ROBERT EPPERLY, Consultant, Mountain View, California

ANTONIA V. HERZOG, Natural Resources Defense Council, Washington, D.C.

ROBERT L. HIRSCH, Scientific Applications International Corporation, Alexandria, Virginia

MUJID S. KAZIMI, Massachusetts Institute of Technology, Cambridge

ALEXANDER MacLACHLAN, NAE, E.I. du Pont de Nemours & Company (retired), Wilmington, Delaware

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DANIEL SPERLING, University of California, Davis

ALFRED M. SPORMANN, Stanford University, Stanford, California

JAMES L. SWEENEY, Stanford University, Stanford, California

1 NAE = Member, National Academy of Engineering

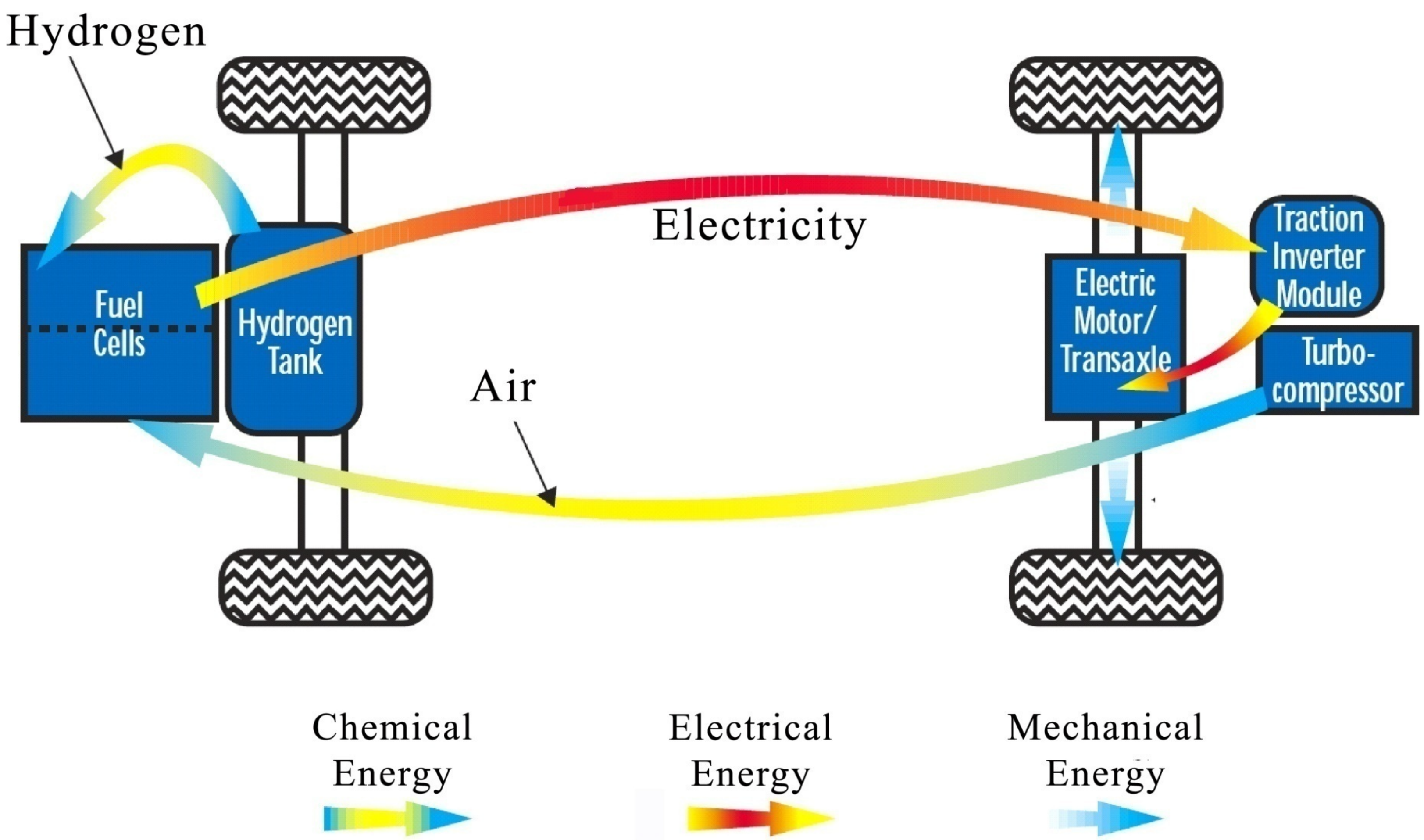
Focus of the Study

Transportation

Light Duty Vehicles (LDVs)

Source: General Motors

Hydrogen Fuel Cell Car



adaptation : Ford Motors

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Focus of the H_2 Systems Analysis

- Estimated current and future
  - Projected costs
  - Energy efficiencies
  - Carbon dioxide (CO_2) 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

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Production Sizes

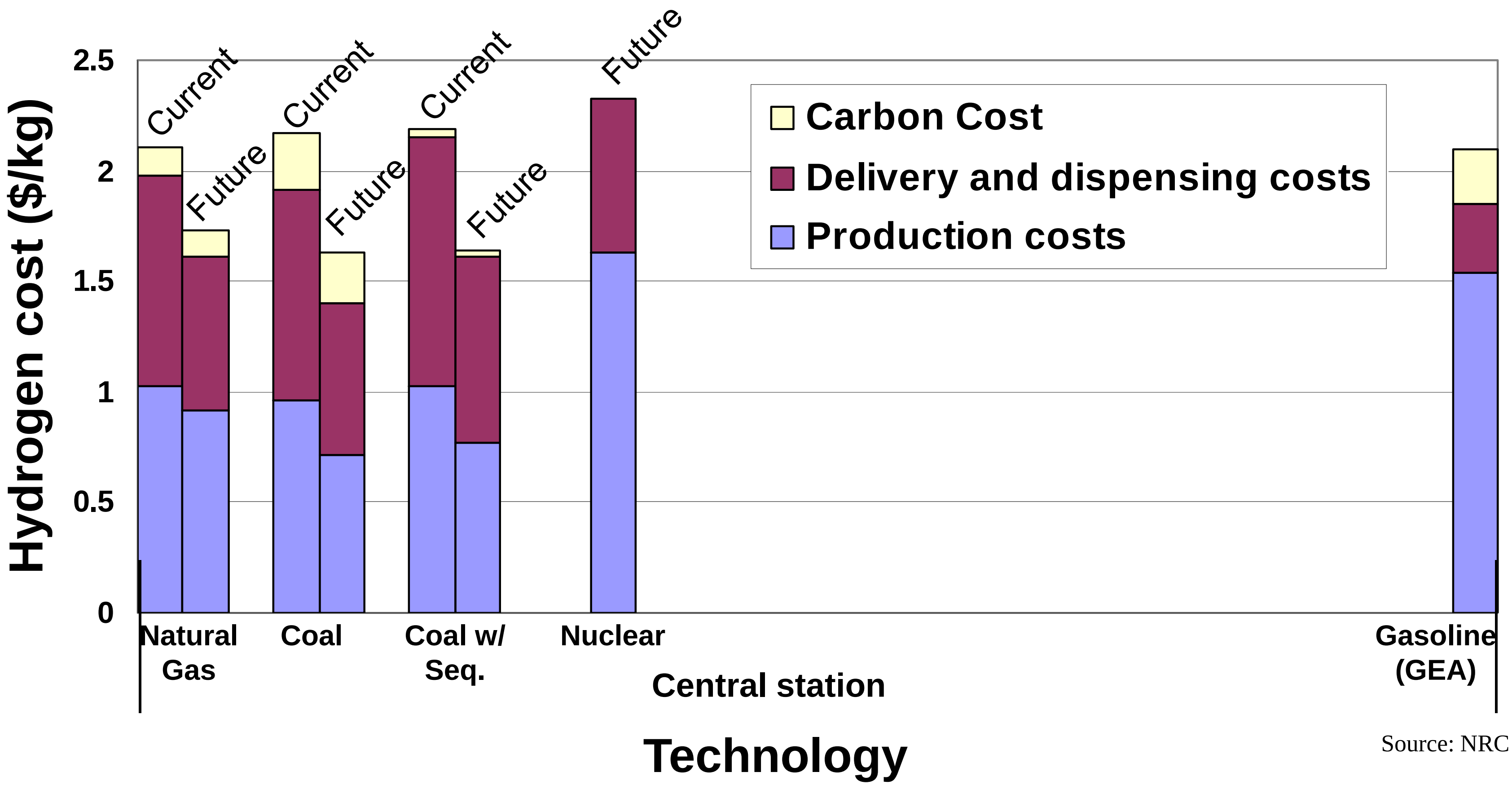
1. Central Station
   - Production capacity ~ 1.2 MM kg/d
   - Supports ~ 2 MM cars
2. Midsize plant
   - Production capacity ~ 24,000 kg/d
   - Supports ~ 40,000 cars
3. Distributed Plant
   - Production capacity ~480 kg/d
   - Supports ~ 800 cars

Performance Assumptions

Efficiency of Fuel Cell Vehicles (FCV) =

1.66 × Efficiency of Gasoline Hybrid Electric Vehicles (GHEV)

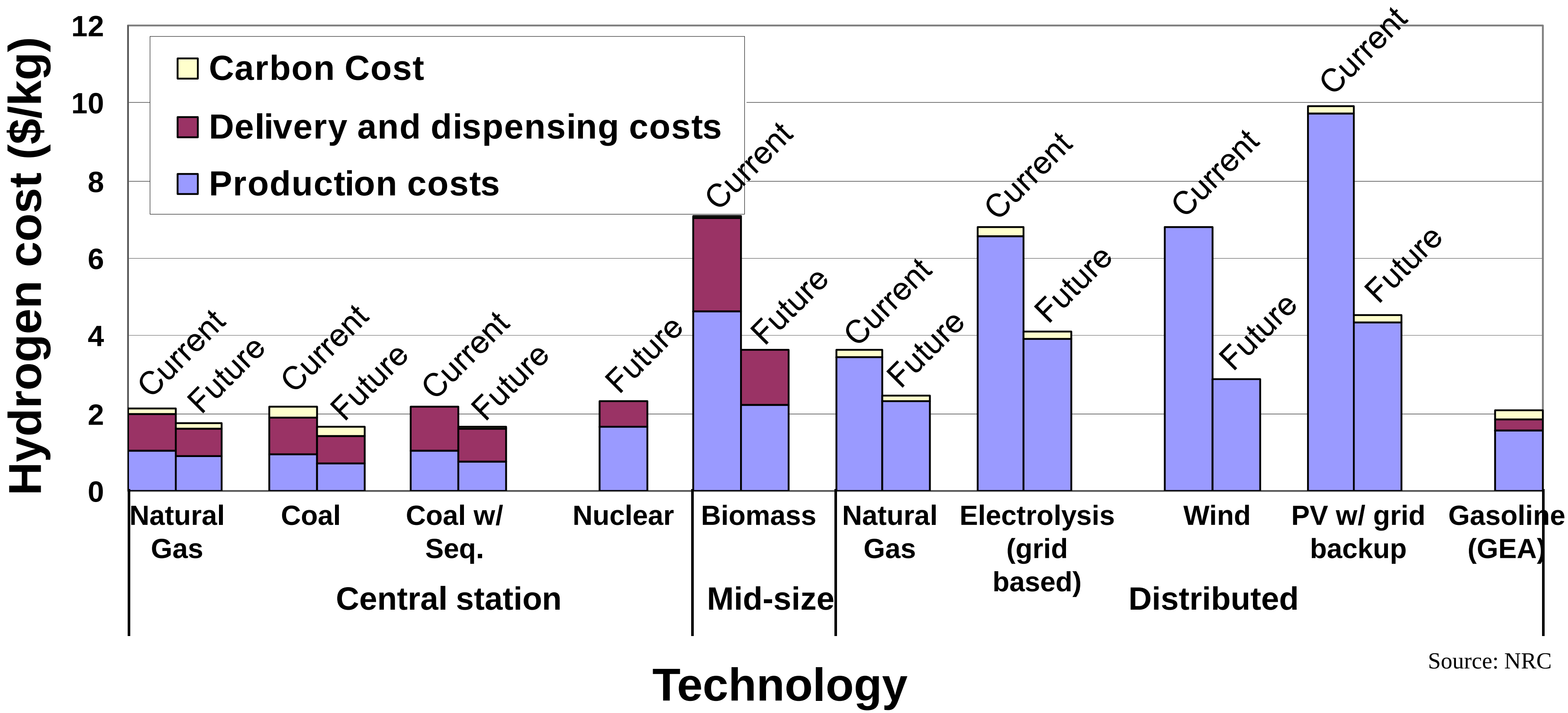
Delivered H_2 Costs of Various Technologies



Source: NRC

GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency

Delivered H_2 Costs of Various Technologies



GEA = Gasoline Efficiency Adjusted – scaled to hybrid vehicle efficiency

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**

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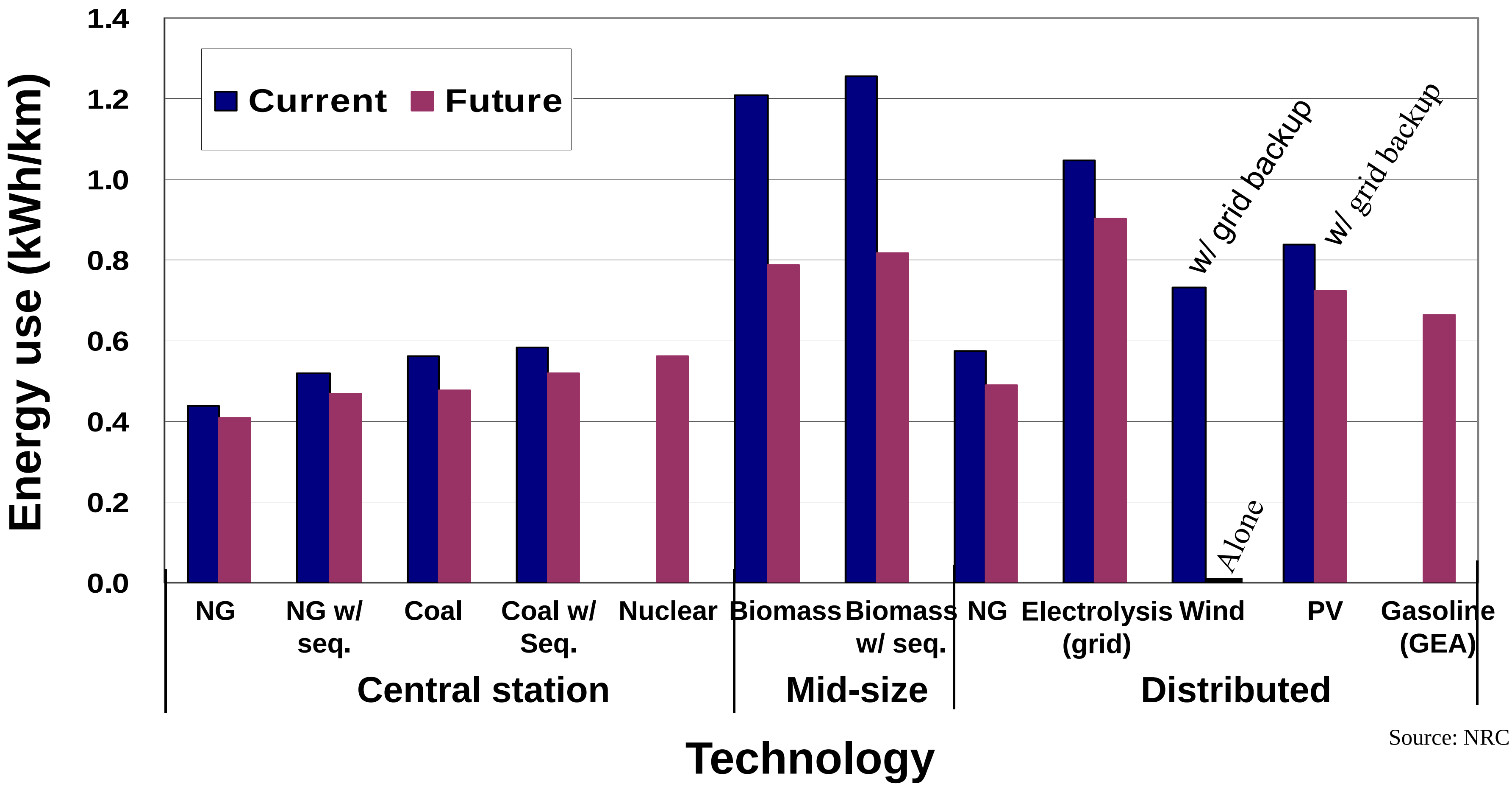
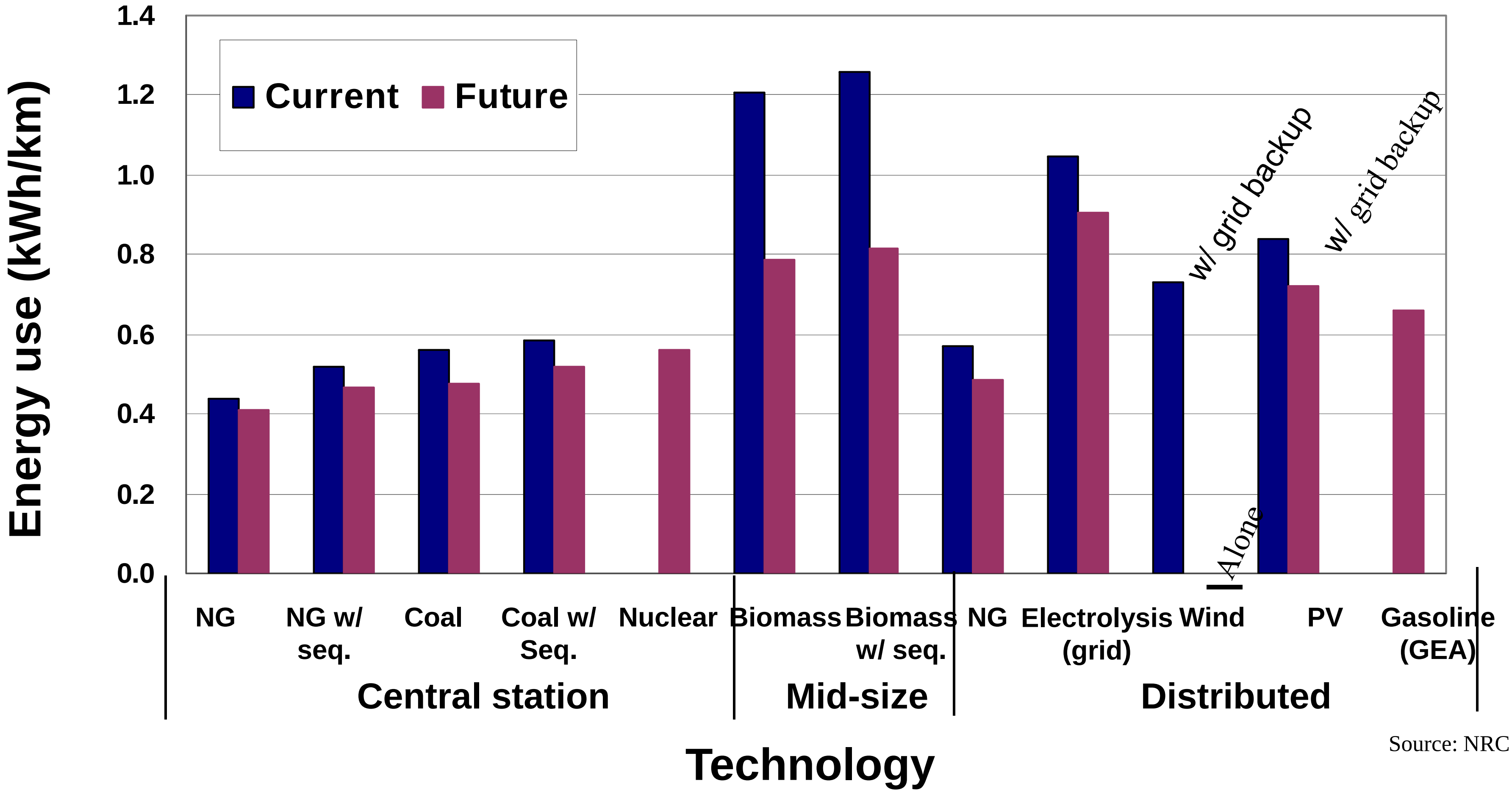
Well-To-Wheels Energy Use



Source: NRC

Well-To-Wheels Energy Use



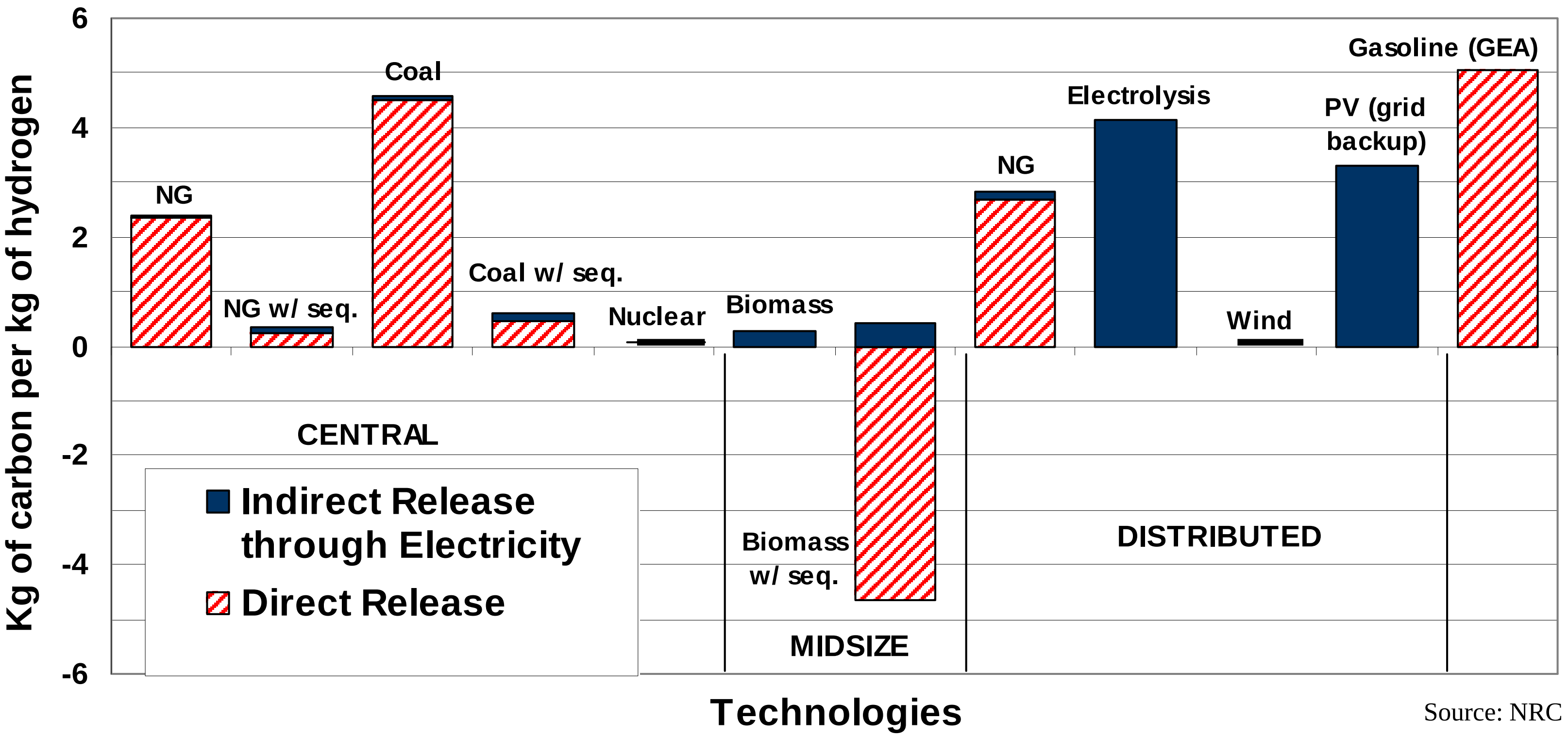
Source: NRC

Most Technologies Have Overall Efficiency Comparable to Gasoline

However, there are other issues besides cost

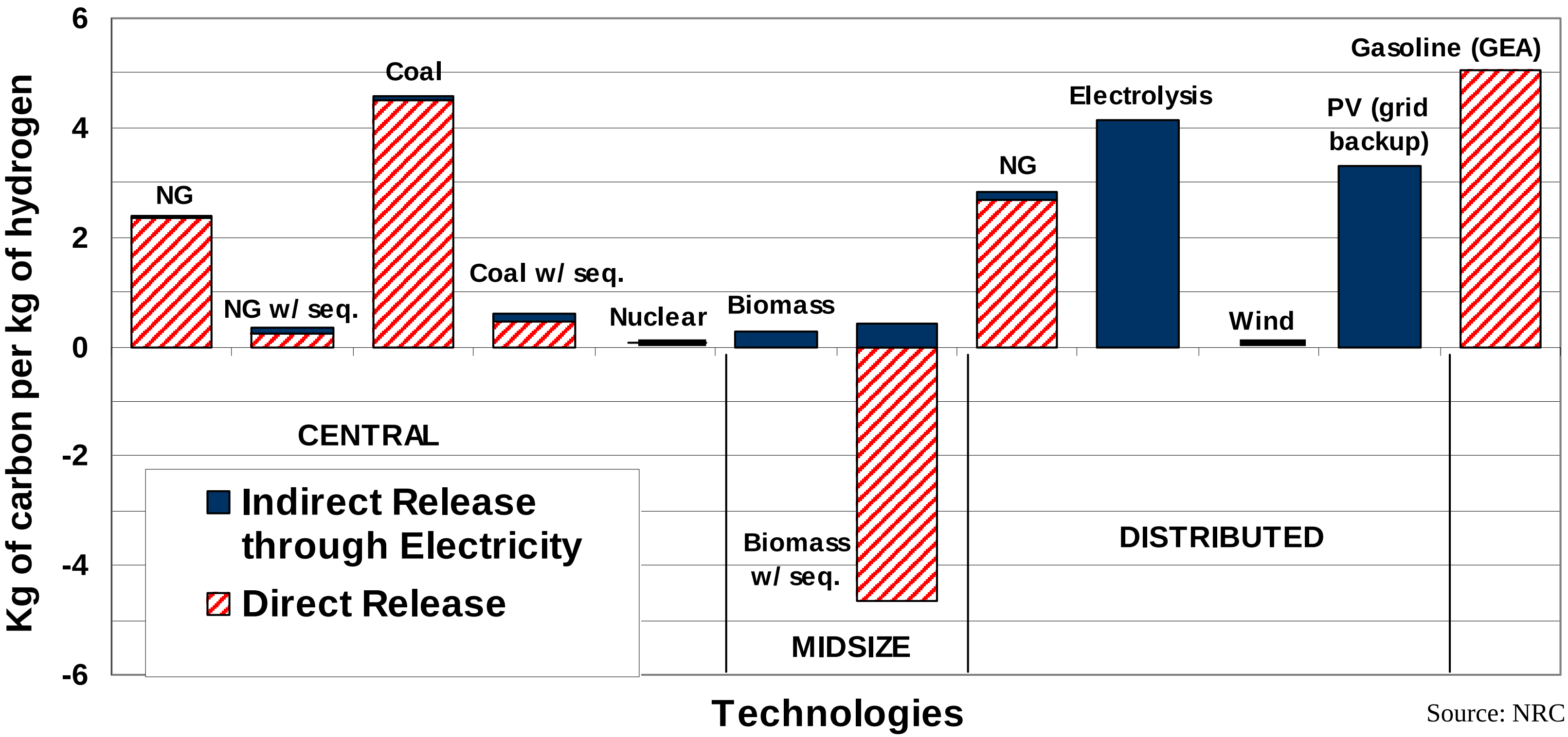
- Overall system efficiency
- **Carbon release to atmosphere**
- Availability of feedstock

Carbon Released During H_2 Production, Dispensing & Delivery (Future Technologies)



Source: NRC

Carbon Released During H_2 Production, Dispensing & Delivery (Future Technologies)



Source: NRC

For All Sources, Carbon Emission is Not More Than Gasoline

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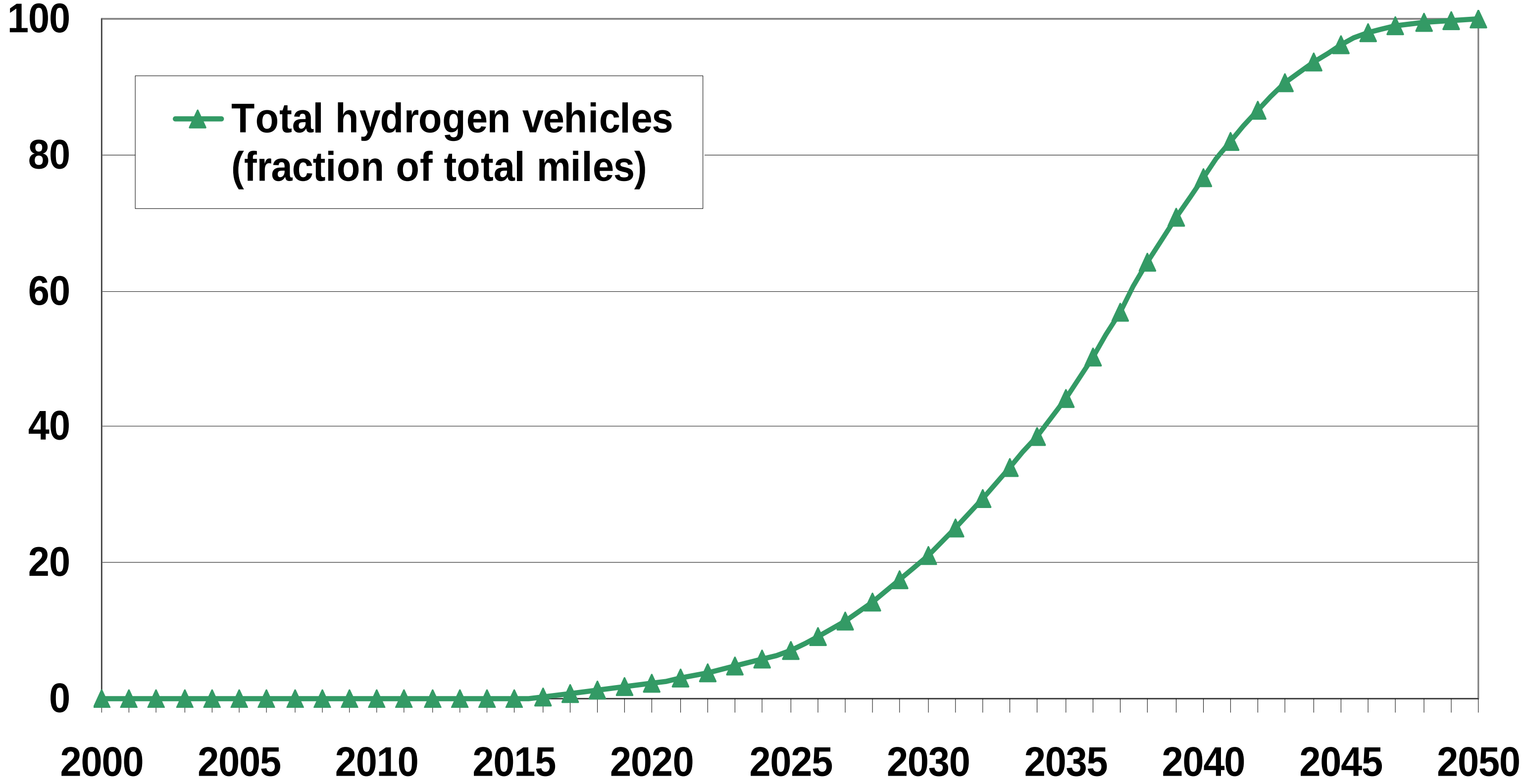
However, there are other issues besides cost

- Overall system efficiency
- Carbon release to atmosphere
- **Availability of feedstock**

Penetration Curves for Fuel Cell Vehicles (USA)
Optimistic Case Postulated by Committee



Source: NRC

Complete replacement of ICE vehicles with fuel cell vehicles in 2050

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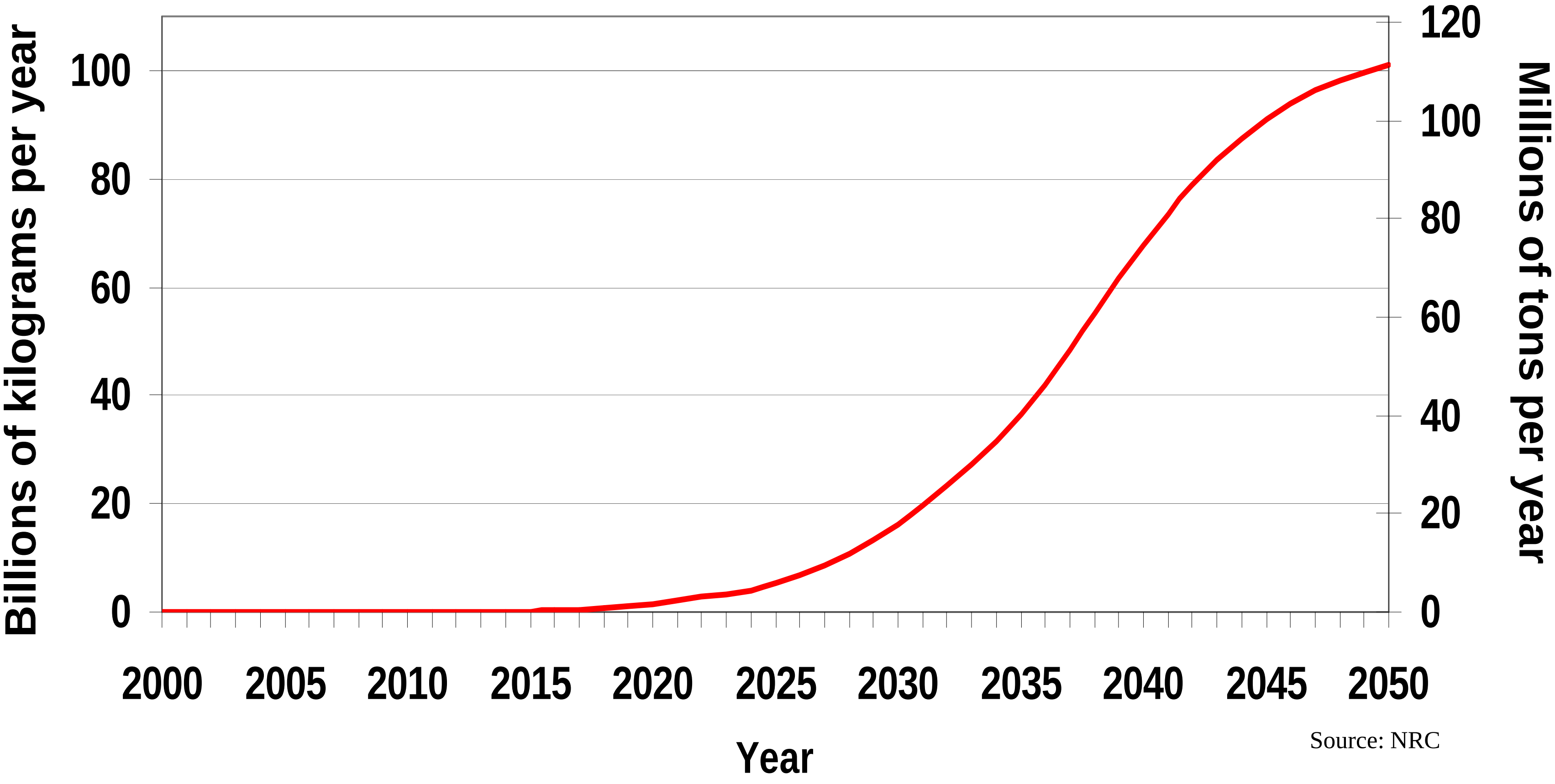
Hydrogen Penetration Scenario (USA)



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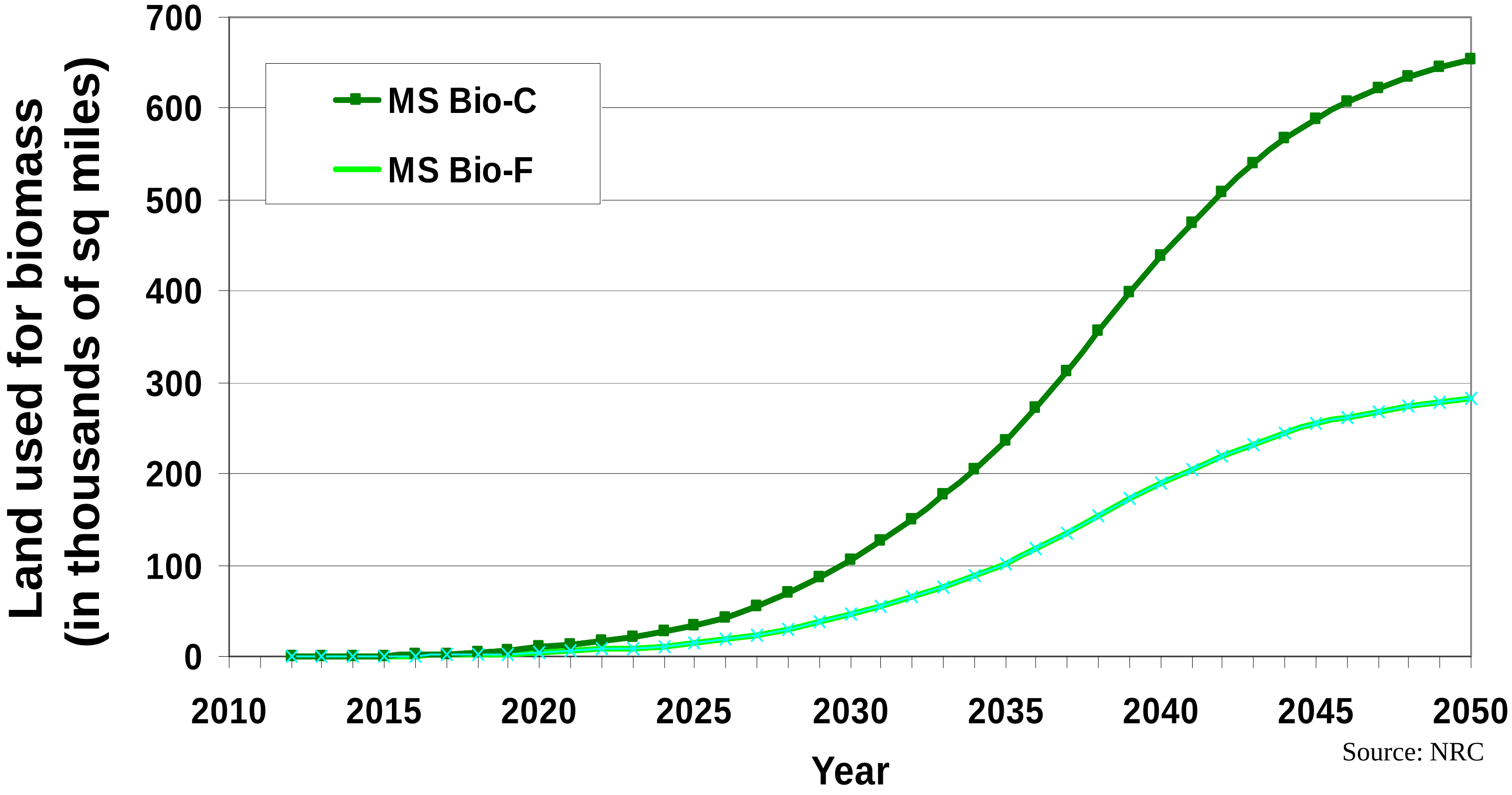
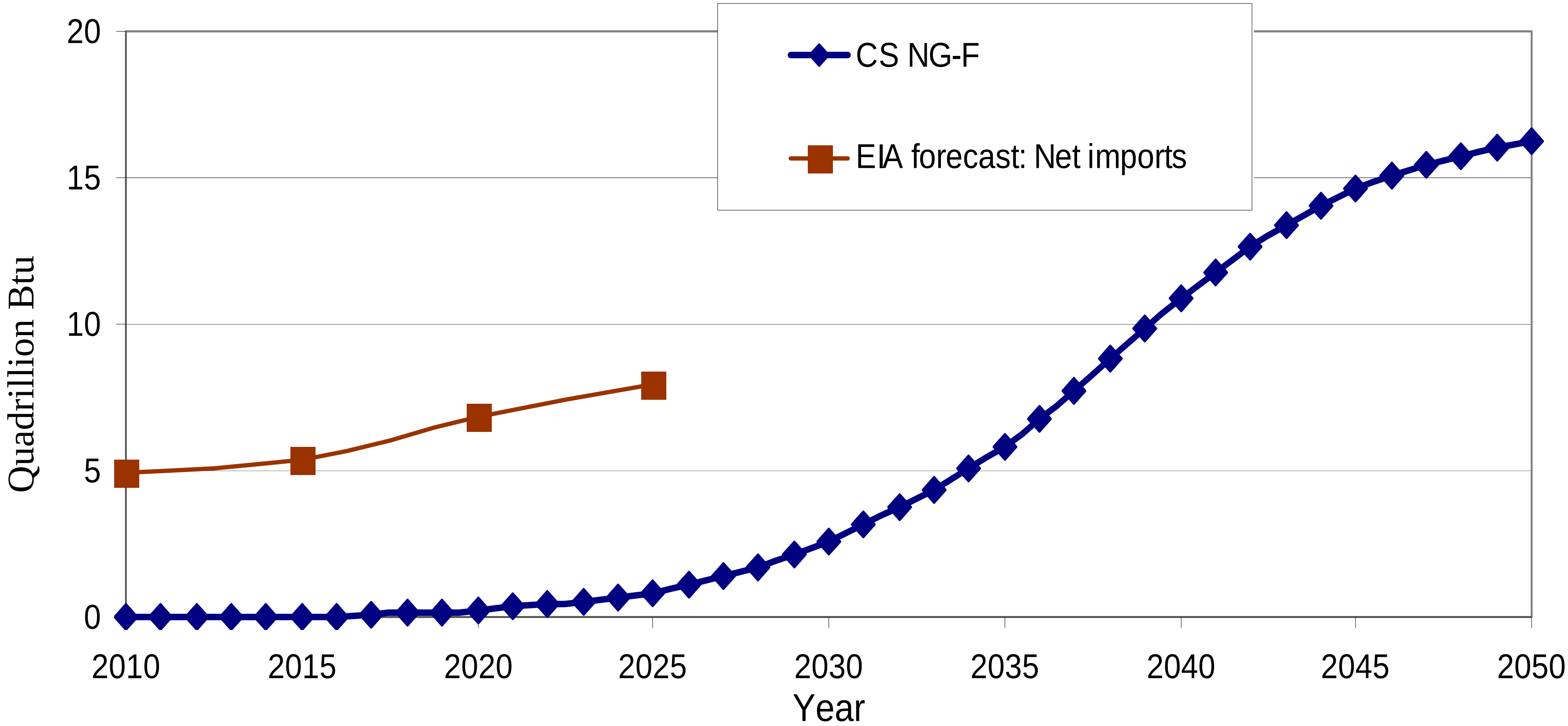
Land Use in Biomass Gasification Option (USA)



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

NATURAL GAS SMR

Natural Gas Use Due to Use of H_2 in FCVs



NATURAL GAS SMR

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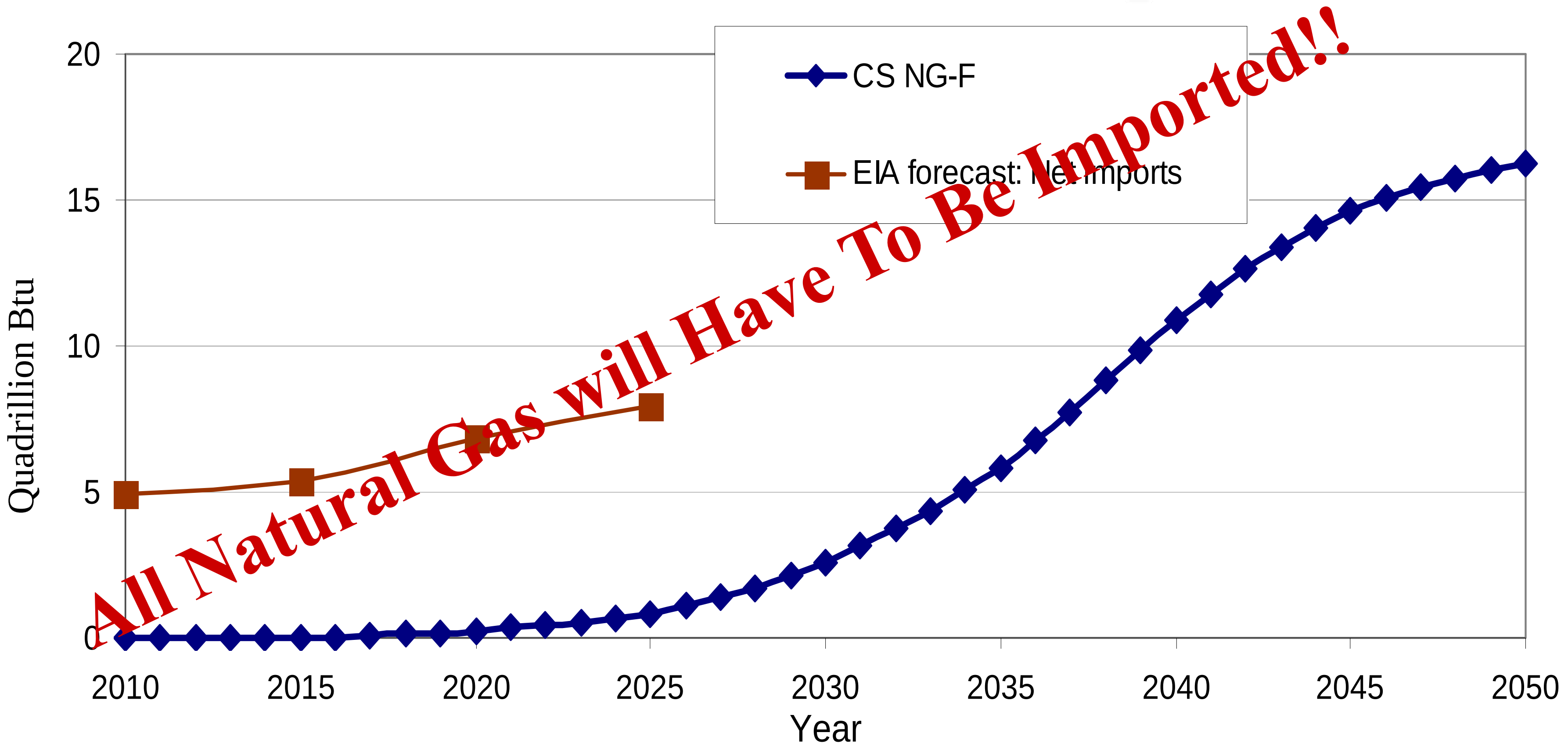

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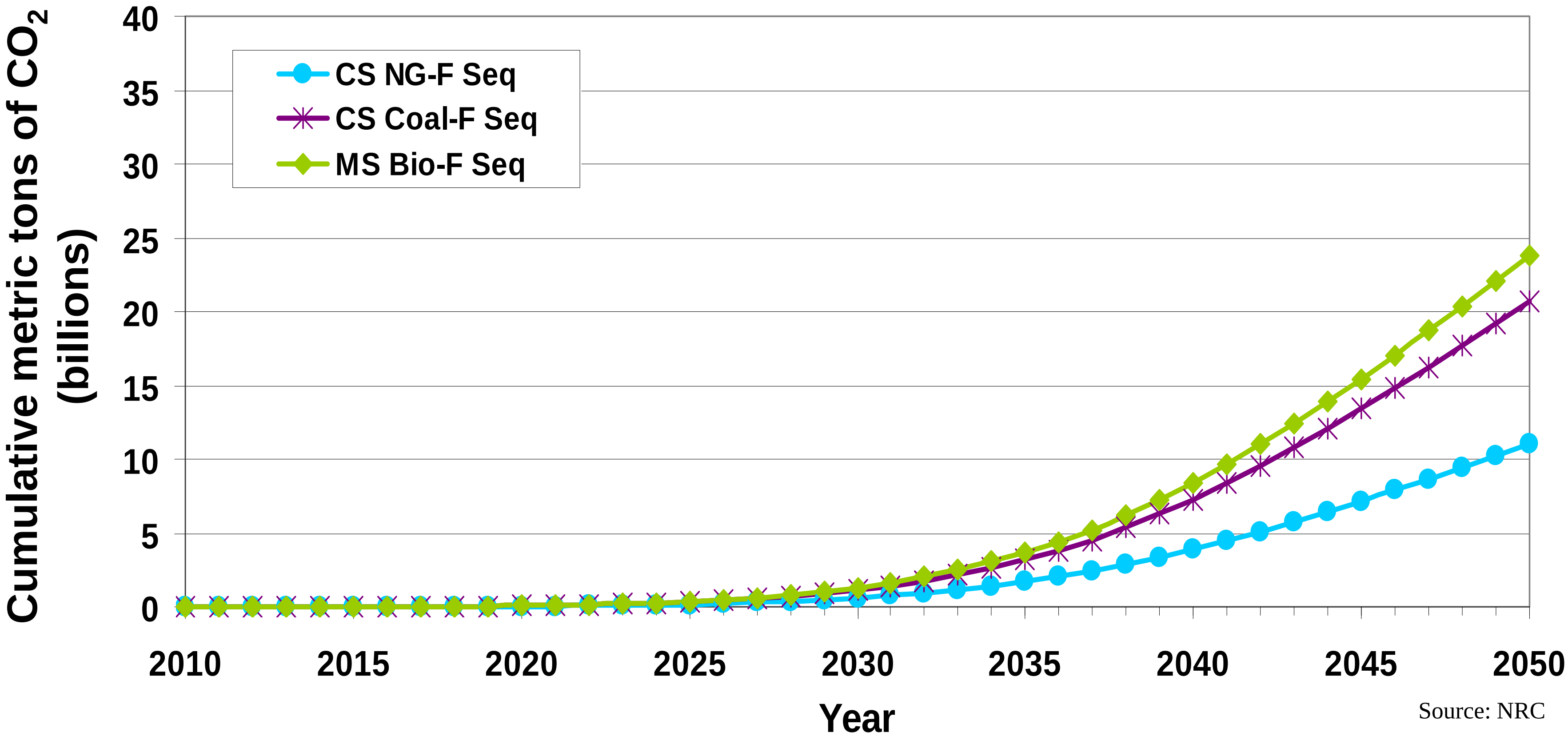
How about CO_2 Sequestration?

Cumulative Carbon Sequestration (USA)



Source: NRC

- Capacity of depleted U.S. oil and gas reservoirs = 150+ billion metric tons CO_2
- Capacity of unminable U.S. coal seams = 55 billion metric tons CO_2

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

	kWh/kg	kWh/gal	Eq. vol.(gal) (5 kg H_2)
H_2@ 10,000 psi	33.3	5.0	33
Liquid H_2	33.3	8.9	18
Gasoline	11	33.6	8.3

Major Challenges

Development of infrastructure to provide H_2 for LDV use

- **'Chicken and Egg' problem**
- **For fossil fuel H_2, distribution and dispensing costs compete with production cost**
- **Transition path not clear**
- **Cost and efficiency of current distributed H_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_2 needs to be produced from renewable or nuclear

- **Current cost is too high**
- **Major breakthroughs are needed**
  - **Wind (electrolysis)**
  - **Solar**
  - **Nuclear**

Sun to Wheels

Summary for option #3 (H_2 FCV)

- Need for a common energy carrier such as H_2?
- H_2 economy will not happen “soon”
- In the transition period, H_2 can be produced from fossil fuels without much negative consequences
- Although H_2 can be produced from fossil fuels without much negative consequences, following major challenges must be met first
  - Cost effective and durable FC systems
  - H_2 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**

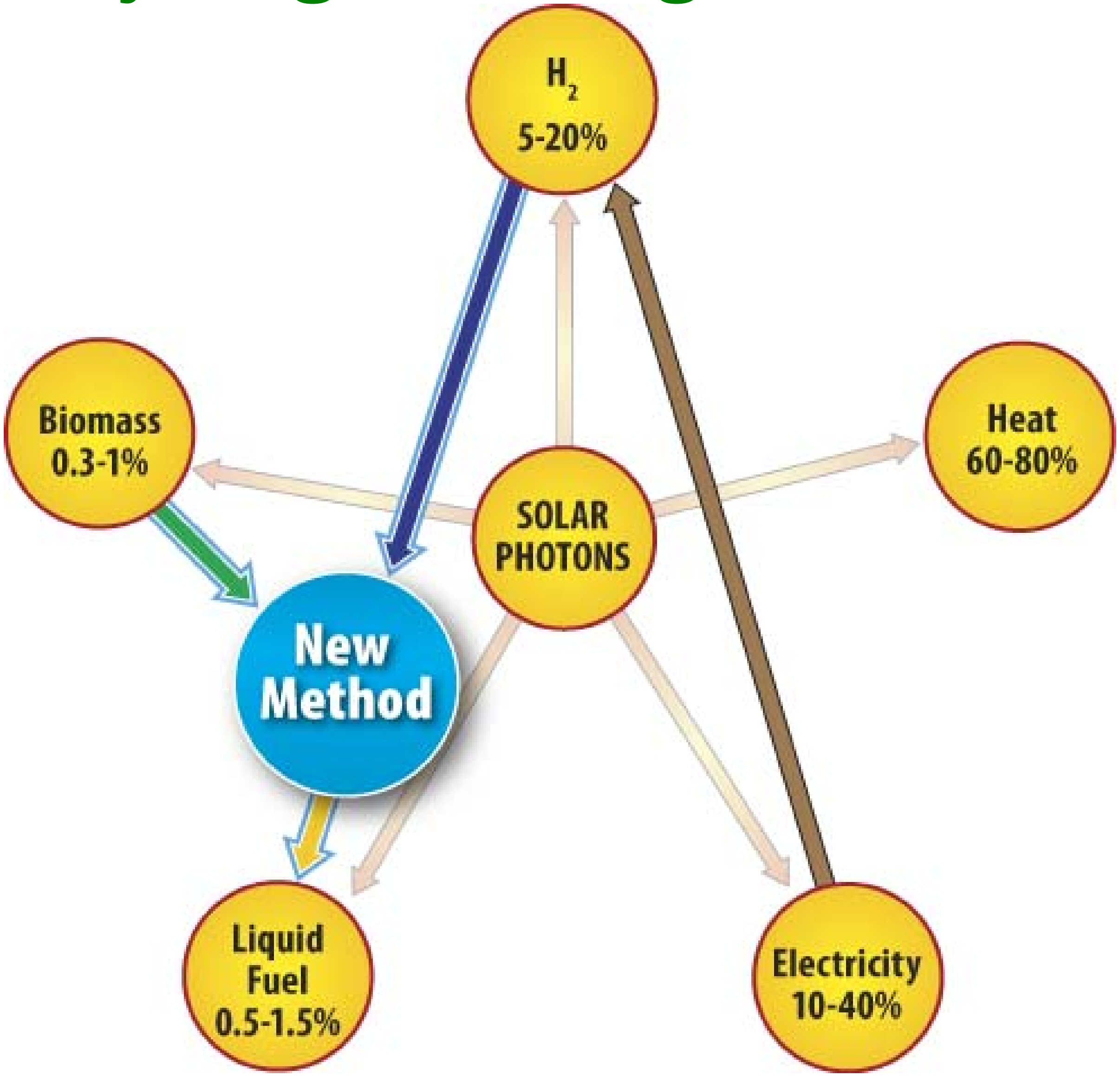
Question: Can we get 8.3 Mbbl/d sustainably from biomass?

Sun to Wheels

Option #4: Electricity & Biofuels

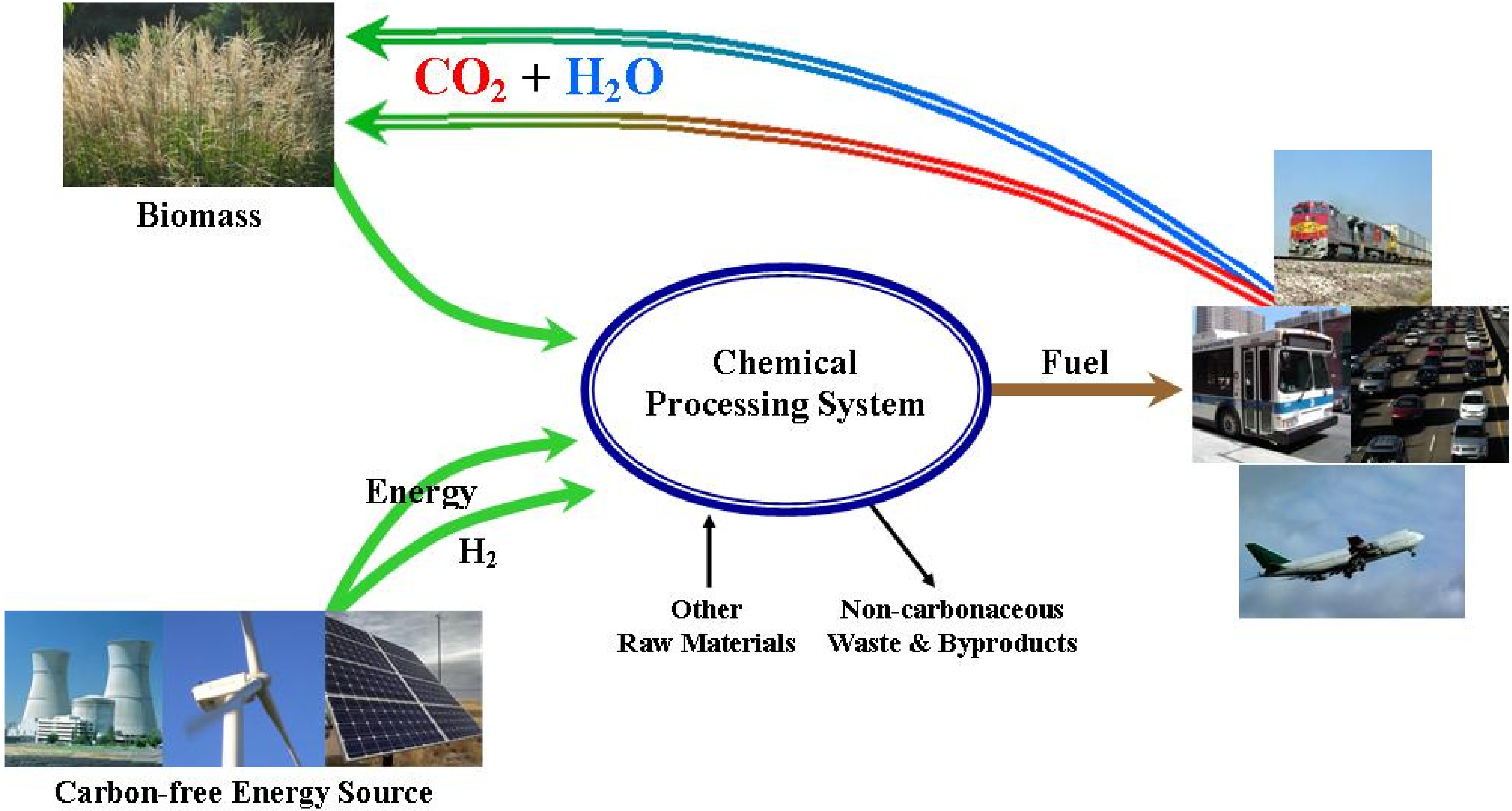
- **Explore alternative synergistically integrated processes to produce 8.3 Mbbl/d.**

Novel synergistic integration for fuel



Integrative processes can produce more fuel

A Novel Biomass and H_2 from Carbon-free energy source partnership



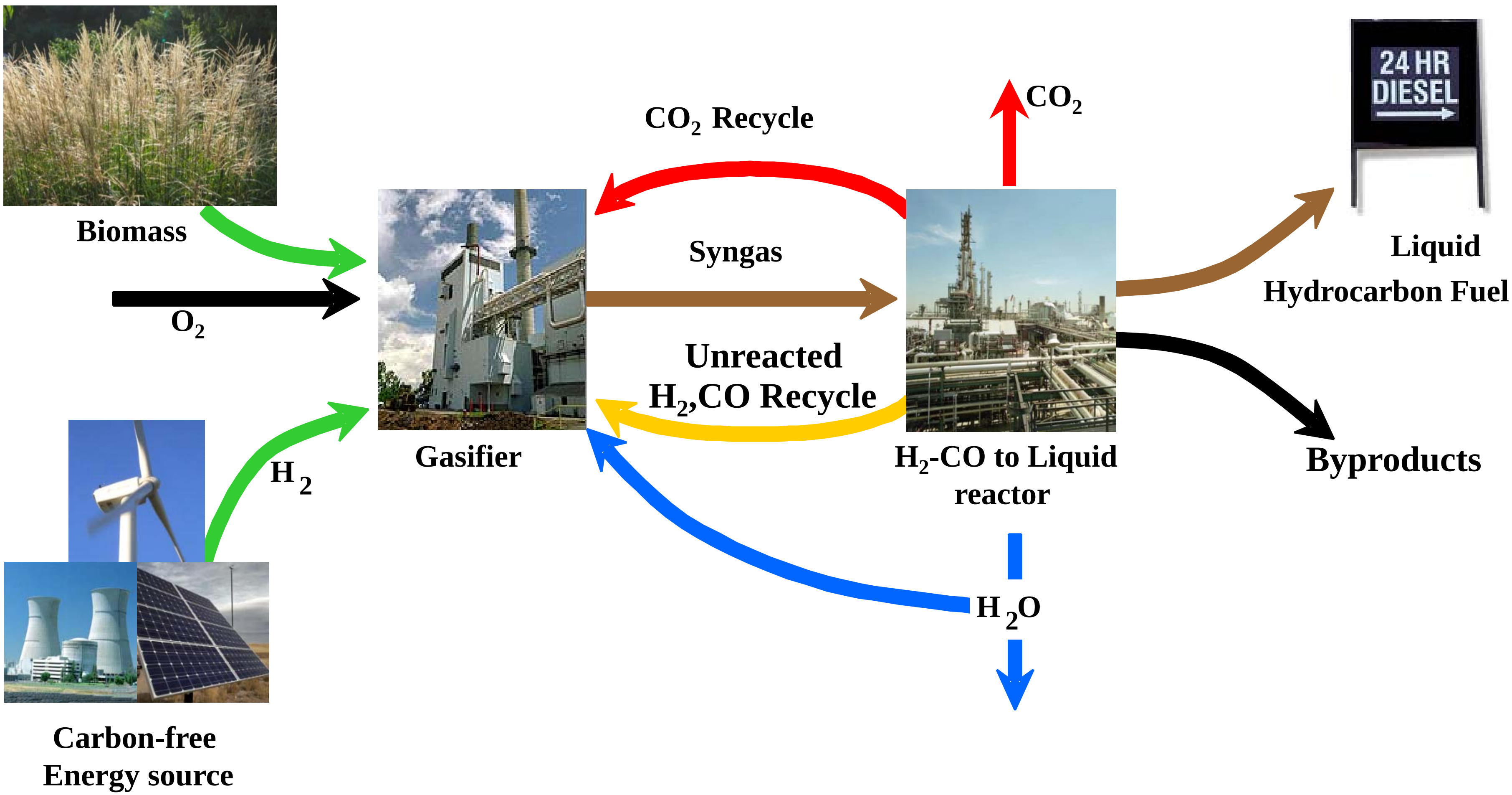
A Hybrid Hydrogen-Carbon (H_2CAR^{TM}) Economy!

Agrawal *et al.*, *PNAS*, 104, 2007

H_2CAR[TM] economy

- Biomass primarily supplier of carbon atoms
- H_2 from a sustainable carbon-free source
- H_2 converts every carbon atom to liquid fuel
- No release of CO_2 during conversion process
- CO_2 release only at end use
- A solution to store H_2 as a high density fuel
- A sustainable open-loop cycle for carbon

An Example of a synergistic Solution Novel H_2CAR^{TM} Process



Agrawal *et al.*, *PNAS*, 104, 2007

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Requirements for 8.3 Mbbl/d

Process	Biomass Requirement (Billion Ton)	Land area (million km^2)
Conventional	2.26	1.51
H_2CAR^{TM}	0.85	0.57

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Production of 13.84 million bbl/d of synthetic oil using Biomass

Future Case[1]:

Gasifier Efficiency = 70%

Biomass growth rate = 1.5 kg dry mass/m^2/yr

Case	Land area (million km^2)		Required H_2 (Billion kg/yr)	Carbon Efficiency (%)	Energy Efficiency (%)
	Biomass	H_2			
Conventional	2.5	0	0	36.7	40.6
H_2CAR™	0.92*	0.046*	239	~100	58

*Needs only 10% of the US land area or half of current cropland area!

Currently available: 1.8 million km^2 cropland, 2.3 million km^2 pasture land

[1] NRC H_2 Report

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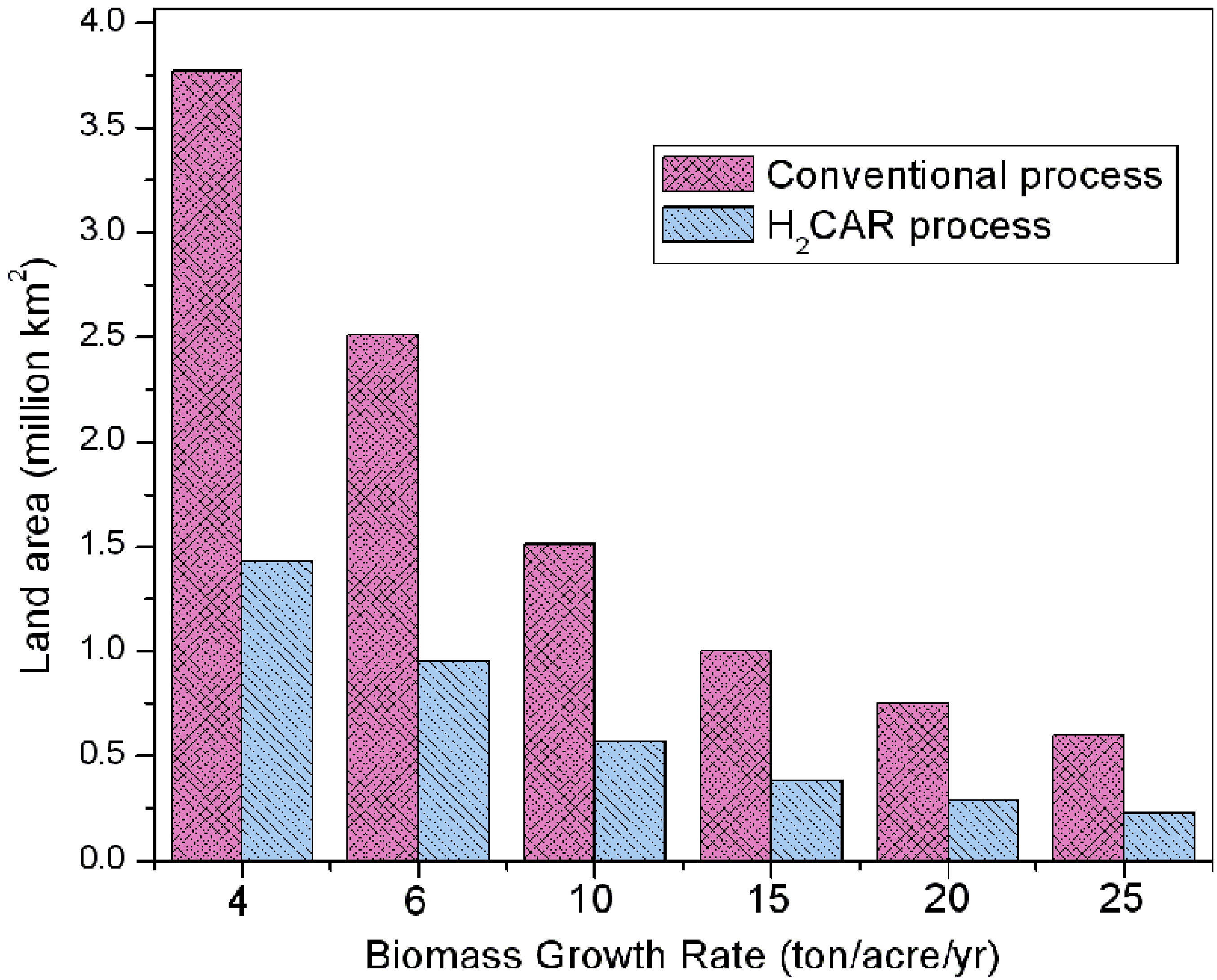
Effect of Biomass growth rate on land area



Gasifier Efficiency = 70%
Total US land area = 9.2 million km^2

Advantages of Biomass H_2CAR™

- 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

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Advantages of Biomass H_2CAR^{TM} (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_2CAR^{TM} 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%

	Biomass (MJ)	Hydrogen (MJ)
Conventional	8779	-
H_2CAR^{TM}	3193	3799

Nearly 55% energy in final barrel of oil comes from H_2!

Problems with current gasification processes

Carbon efficiency of 30-40% results in large land area requirements

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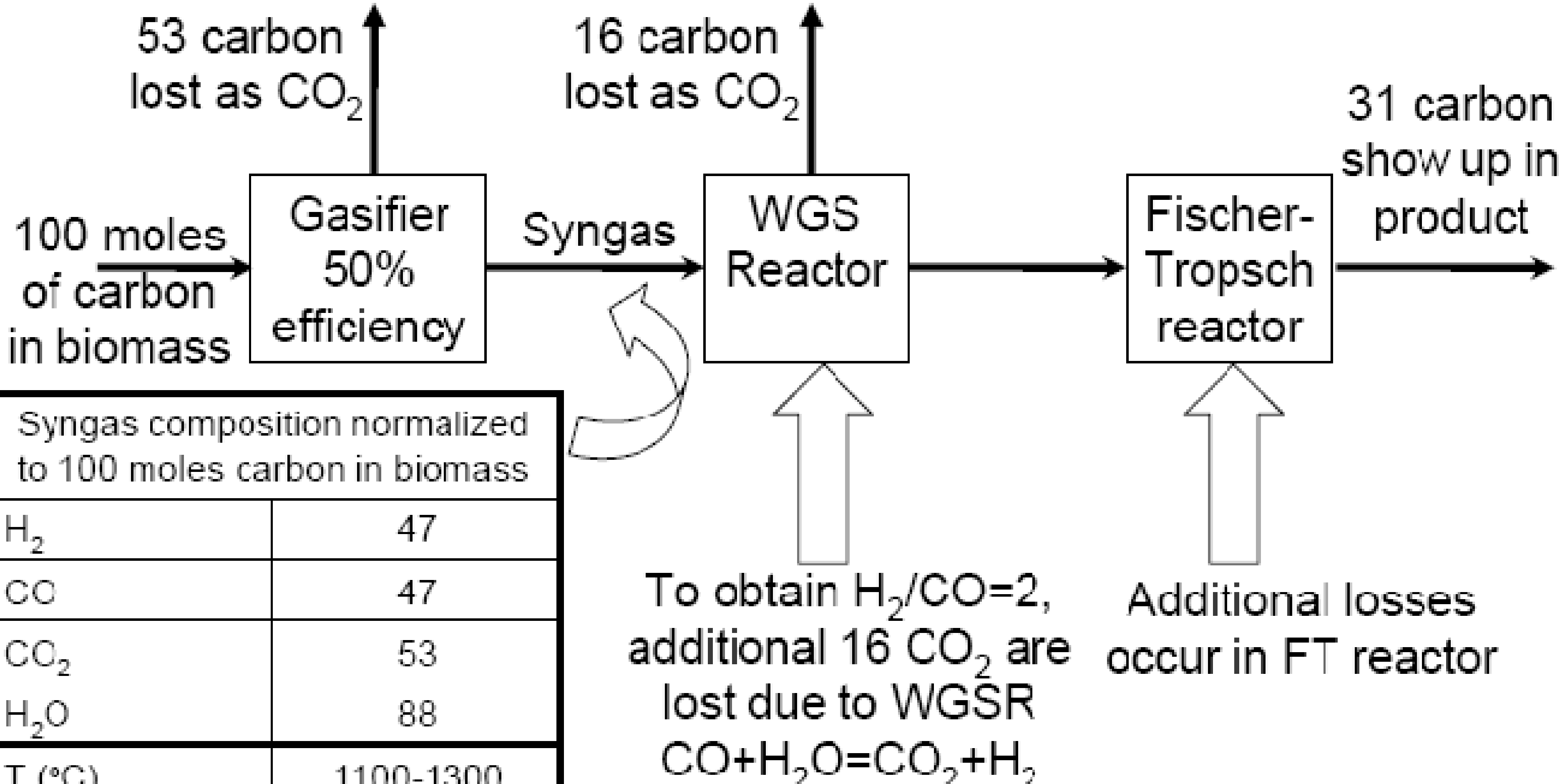
How 60-70% carbon is lost in biomass case?



Syngas composition normalized to 100 moles carbon in biomass	
H_2	47
CO	47
CO_2	53
H_2O	88
T (°C)	1100-1300
H_2/CO	1

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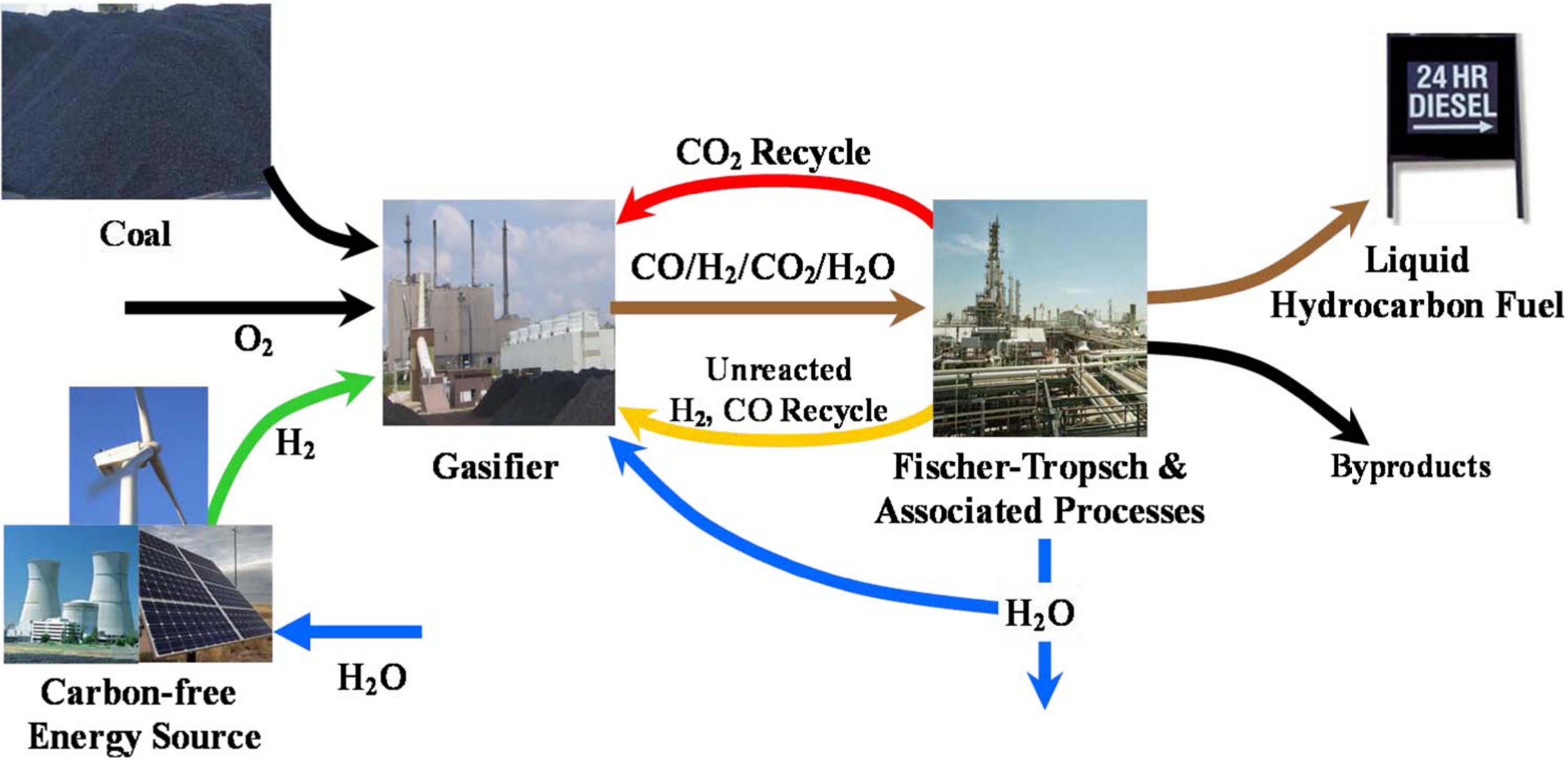
An Alternative Interim Solution

Synthetic oil from Coal

Novel H_2CAR^{TM} Process for Coal



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Production of 13.84 million bbl/d of synthetic oil using Coal

Gasifier Efficiency = 75%

Case	Amt of Coal (Billion tons/yr)	Required H_2 (Billion kg/yr)	CO_2 sequestered (Gtc/yr)	Carbon efficiency (%)	Energy efficiency (%)
Conventional	1.97	--	0.9	39.9	50.7
H_2CAR^{TM}	0.83	211.46	0	~100	65.2

No Need for CO_2 sequestration!

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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 H_2CAR^{TM} ~ 144 yrs

*US Coal Reserves ~ 275 billion tons

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Challenges for the Proposed H_2CAR^{TM} Coal process

- Cost-effective production of H_2 from carbon-free energy source
- Design and operation of Novel Gasifier
- More selective conversion to desired synthetic liquid fuel
- Efficient Internal Combustion Engine

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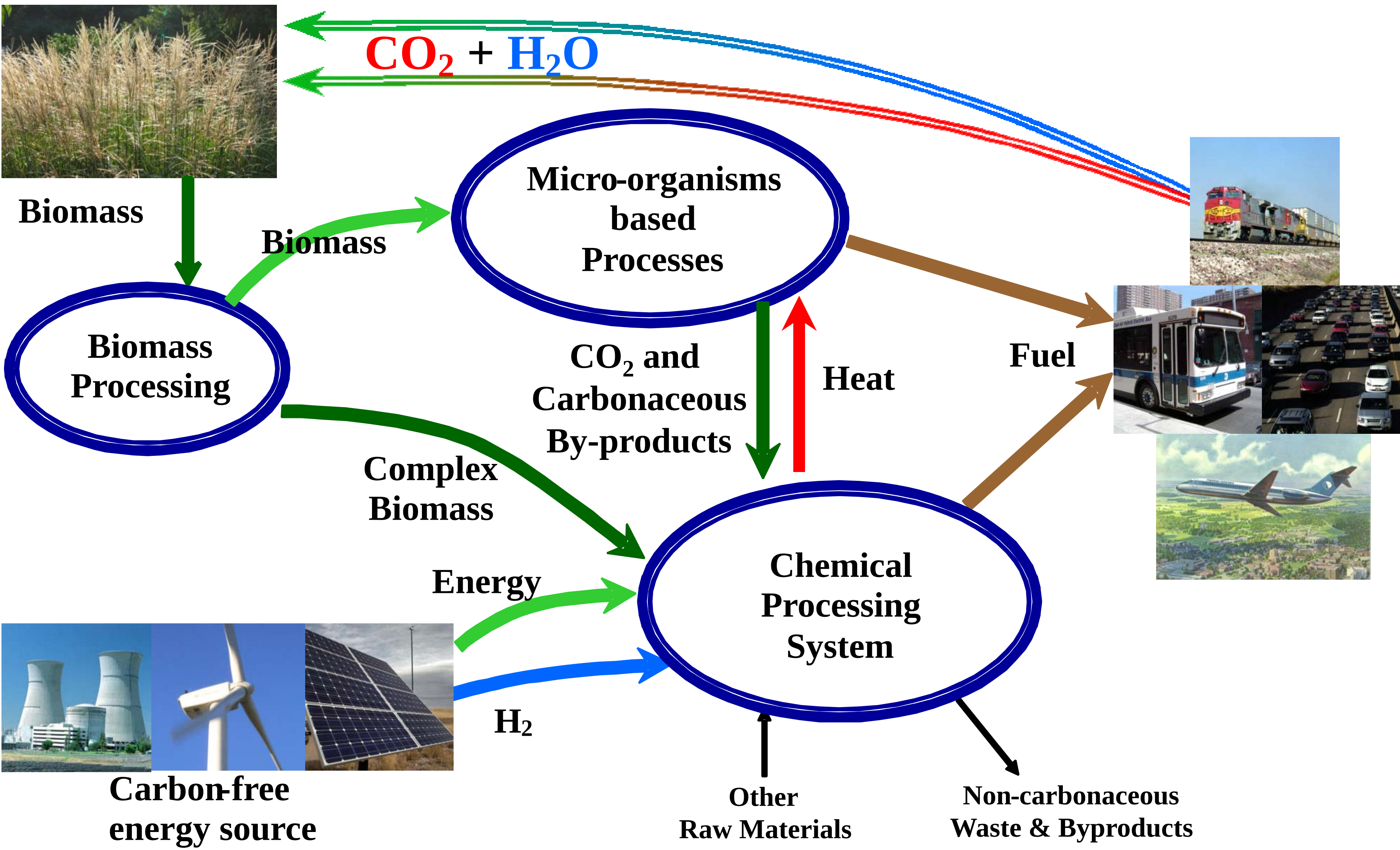
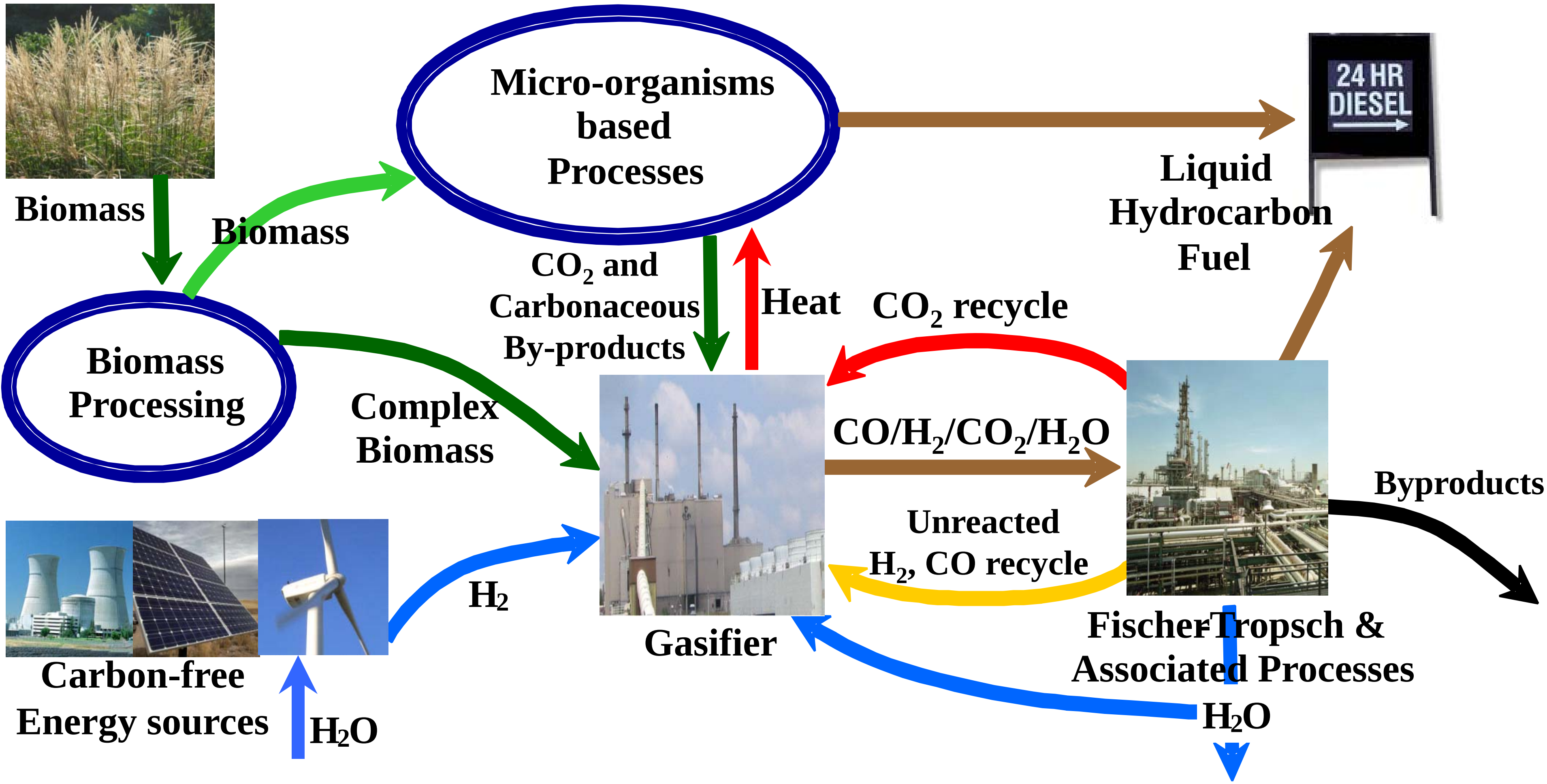
A Detour to Explore more Process Integration . . .

Search For Synergy Between Thermochemical and Biological Processes

Proposed Framework for Biofuels



Detail Schematic of the proposed Framework for Biofuels



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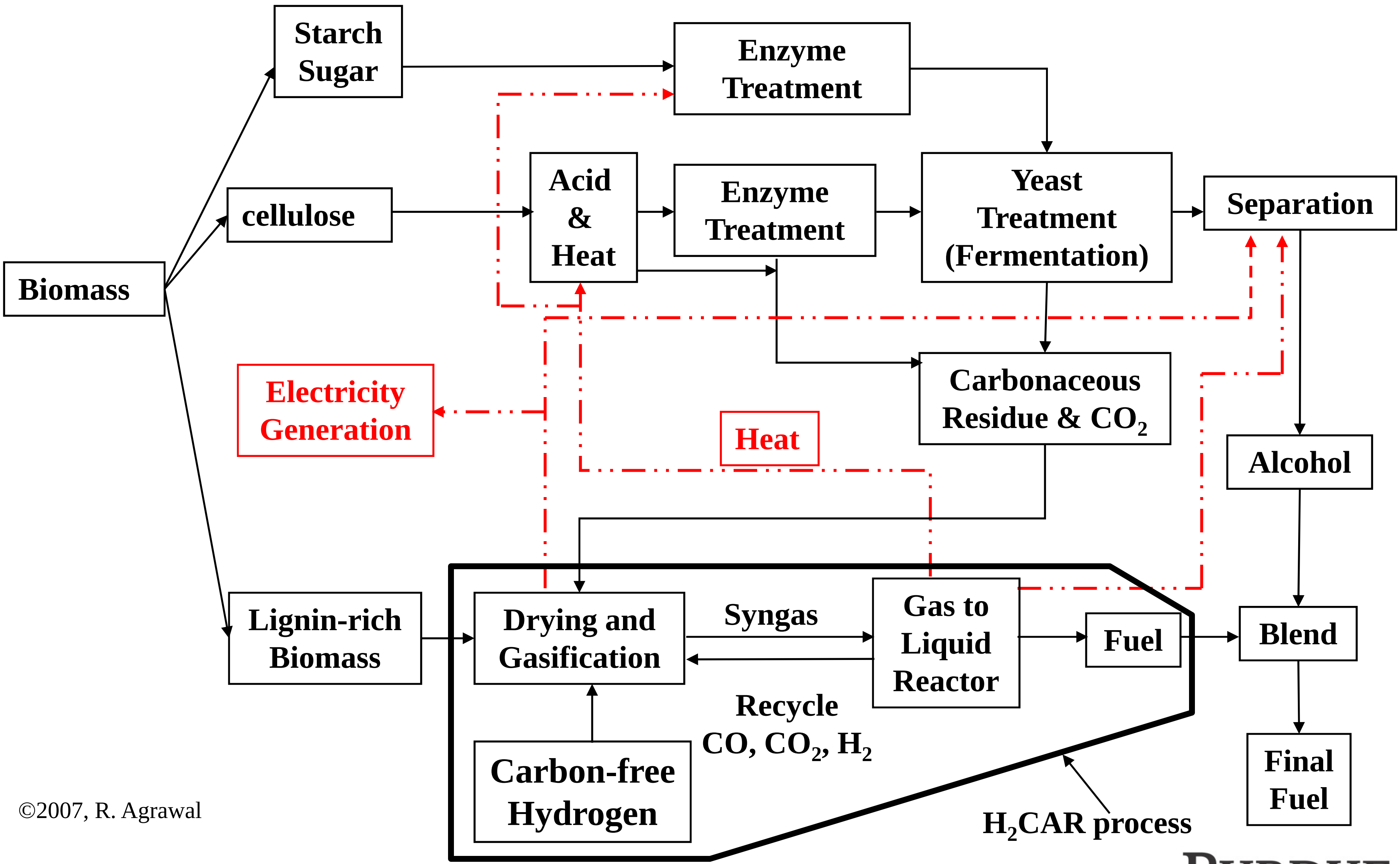
Detailed Schematic of an Integrated Framework for Biofuels



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H_2CAR-fermentation integration*

Case	Carbon Efficiency (%)	Energy Efficiency (%)	H_2 requirement(billion kg/yr)
Corn Ethanol	67	57	-
H_2CAR	~100	57	250
H_2CAR + Fermentation (Heat and CO_2 integration)	~100	66	200

* 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 CO_2 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