Solar Economy-Is it Feasible?

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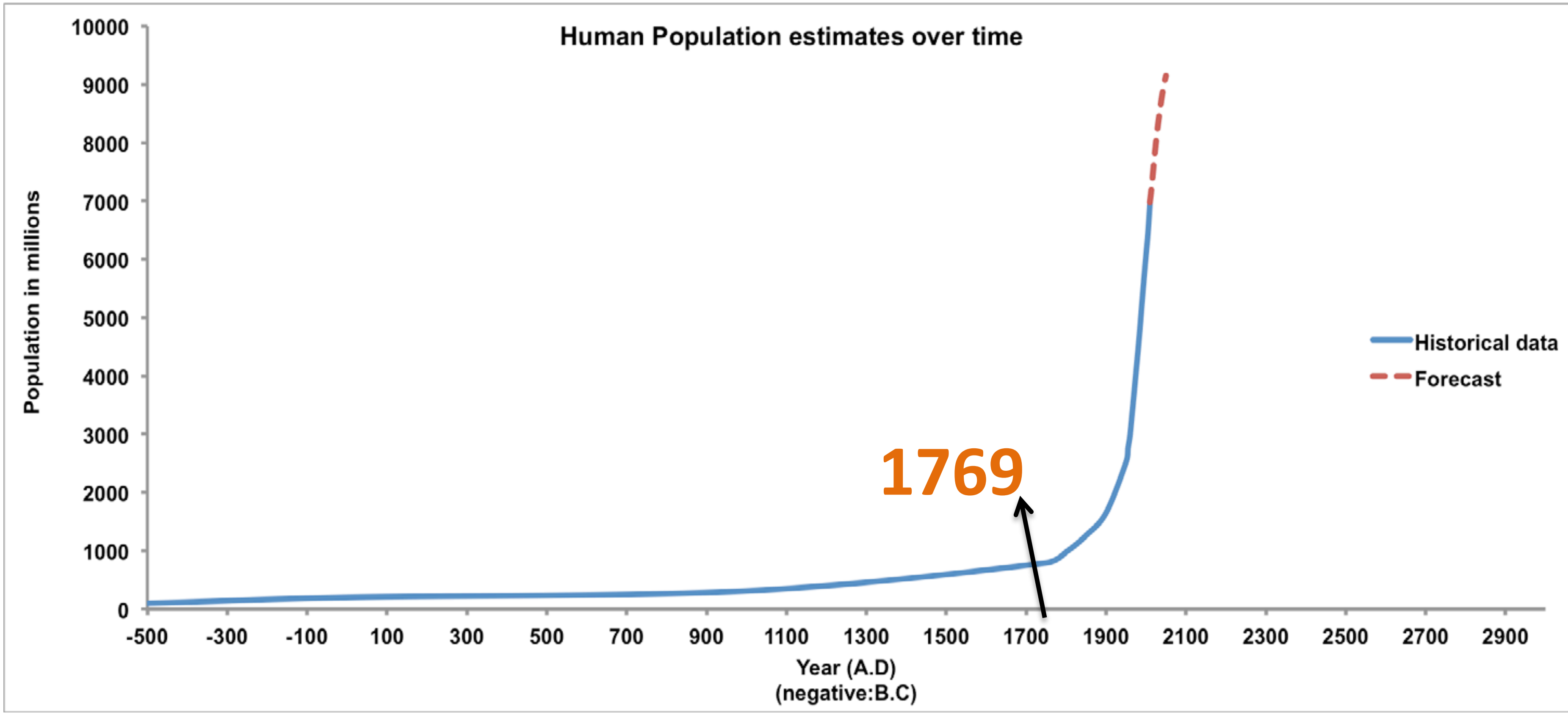
Why is Energy Important?

World Population



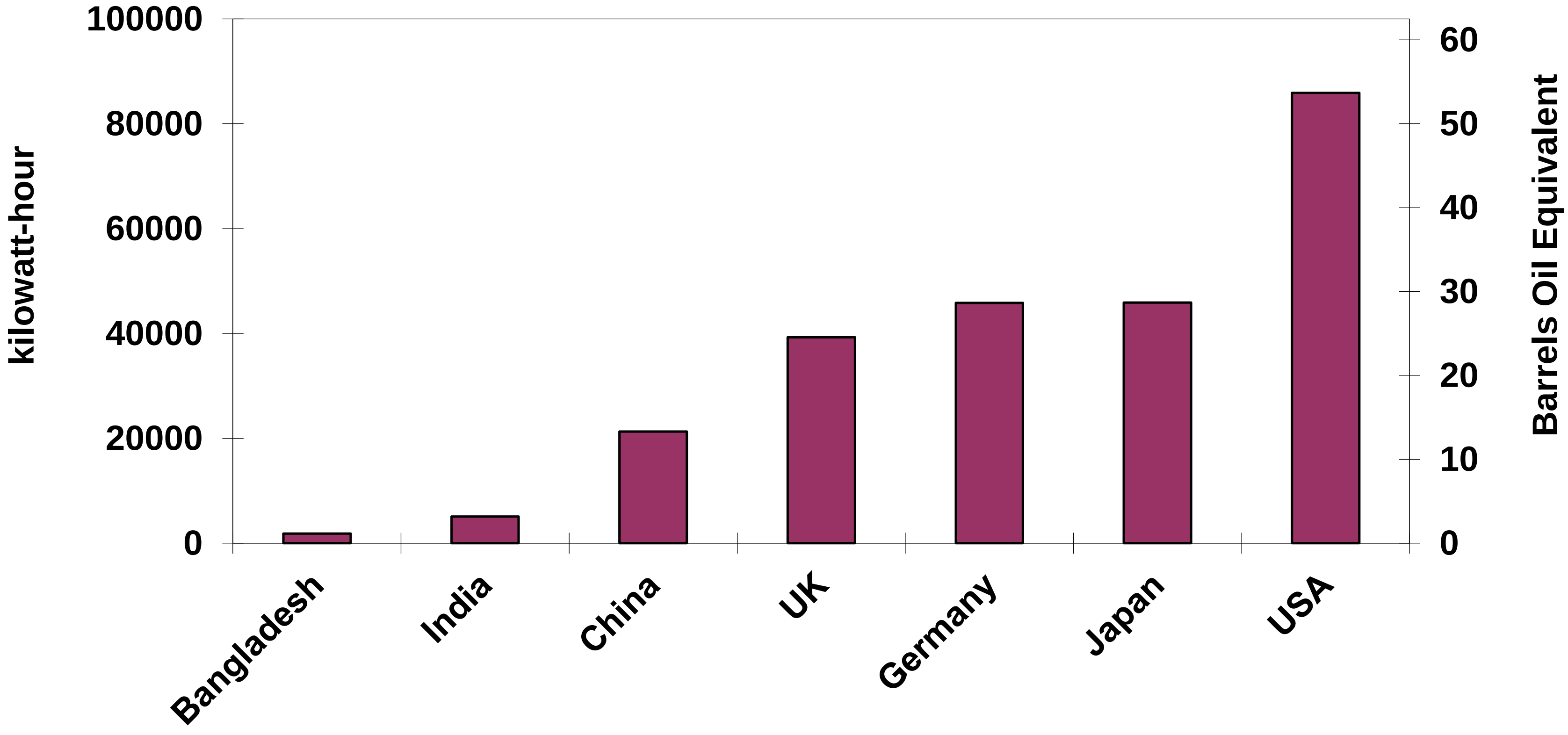
Data source: Wikipedia & UN

James Watt and his 1769 steam engine

Source: David J.C. Mackay 2009

Energy Consumption is Way of Life in Industrialized Countries

2010 Primary energy consumption per capita



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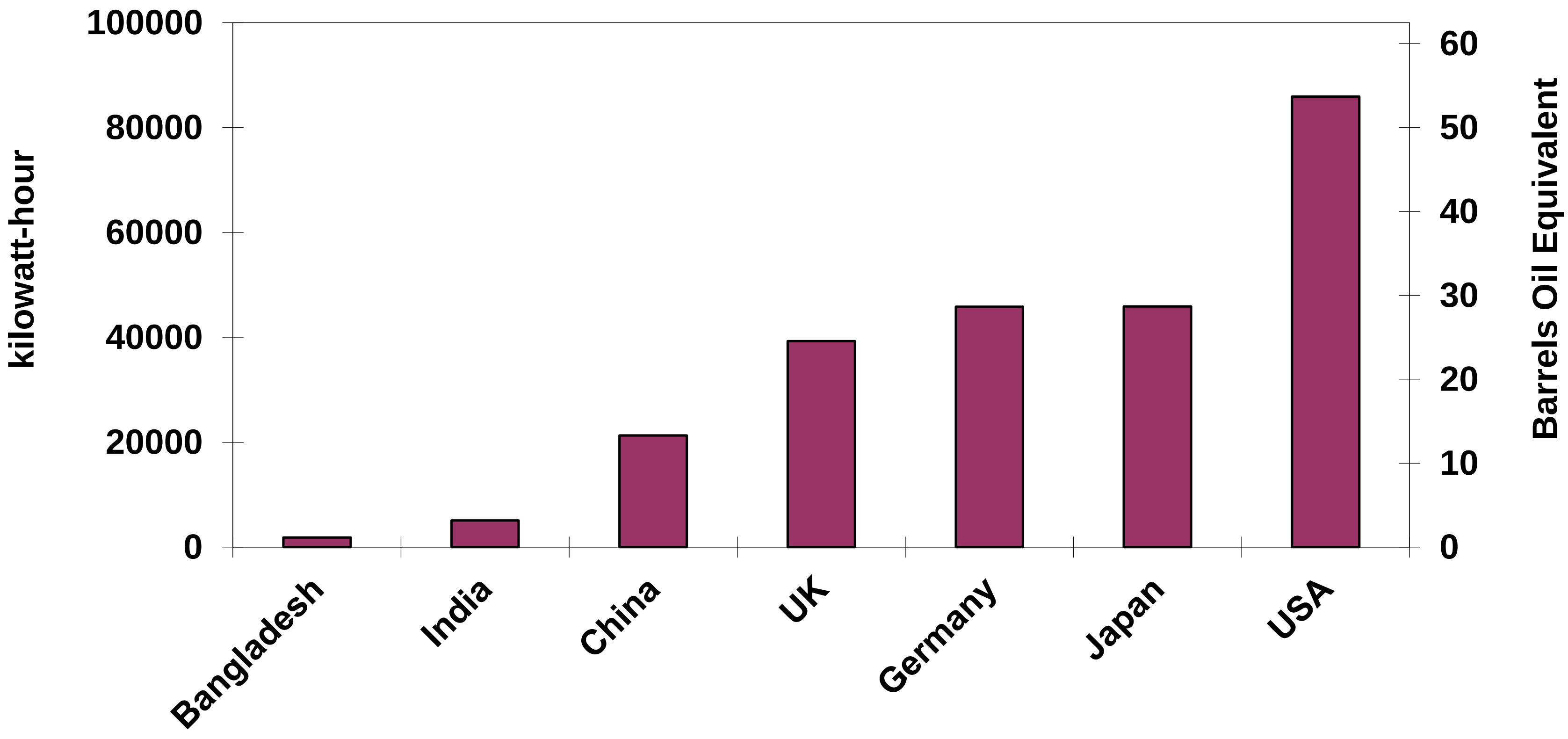

Fossil Fuel Provides 85% Energy!

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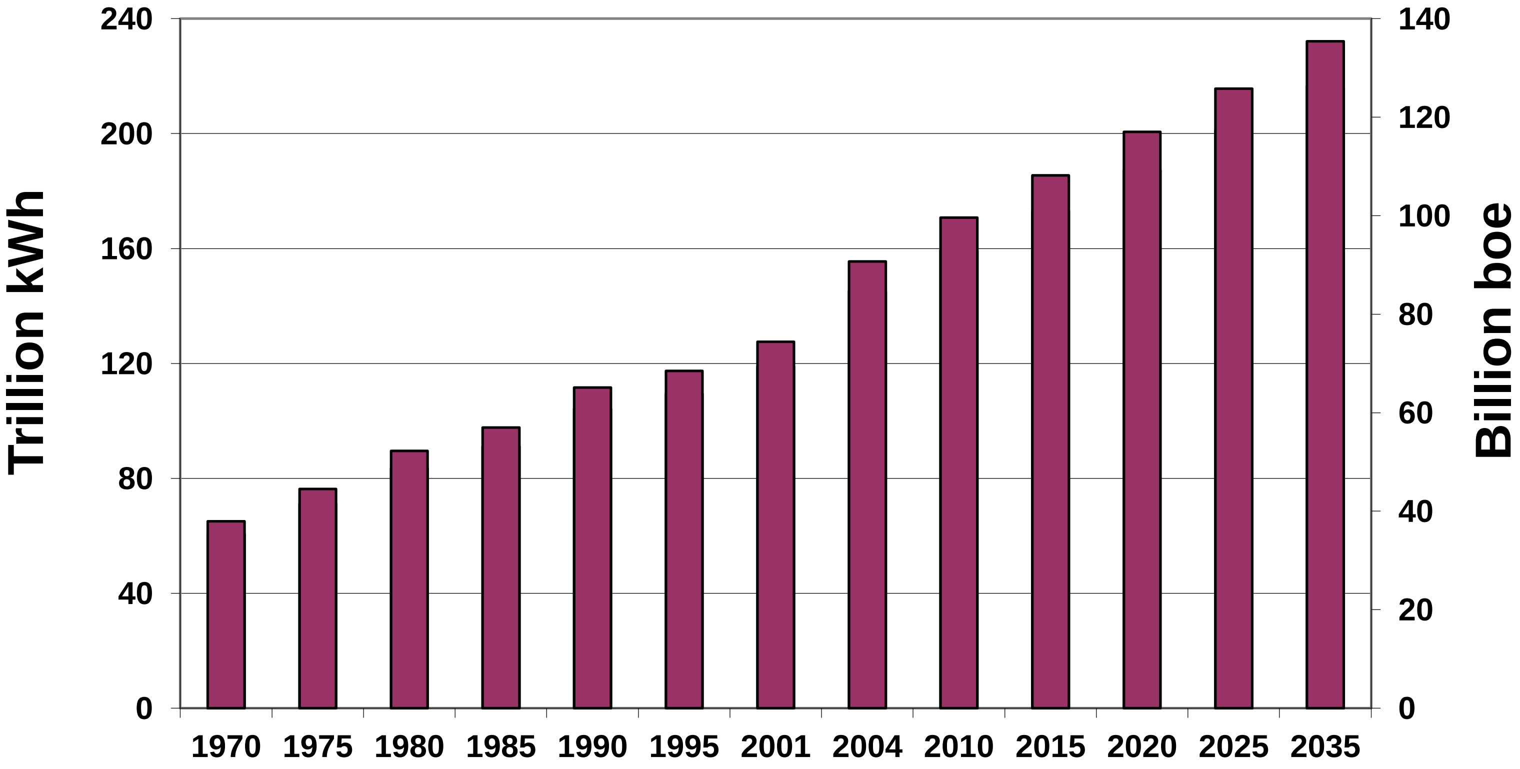
However…

- **The world population is expected to rise**

However…

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

World Market Energy Consumption



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

Consumption rate could double!

Adaptation : EIA

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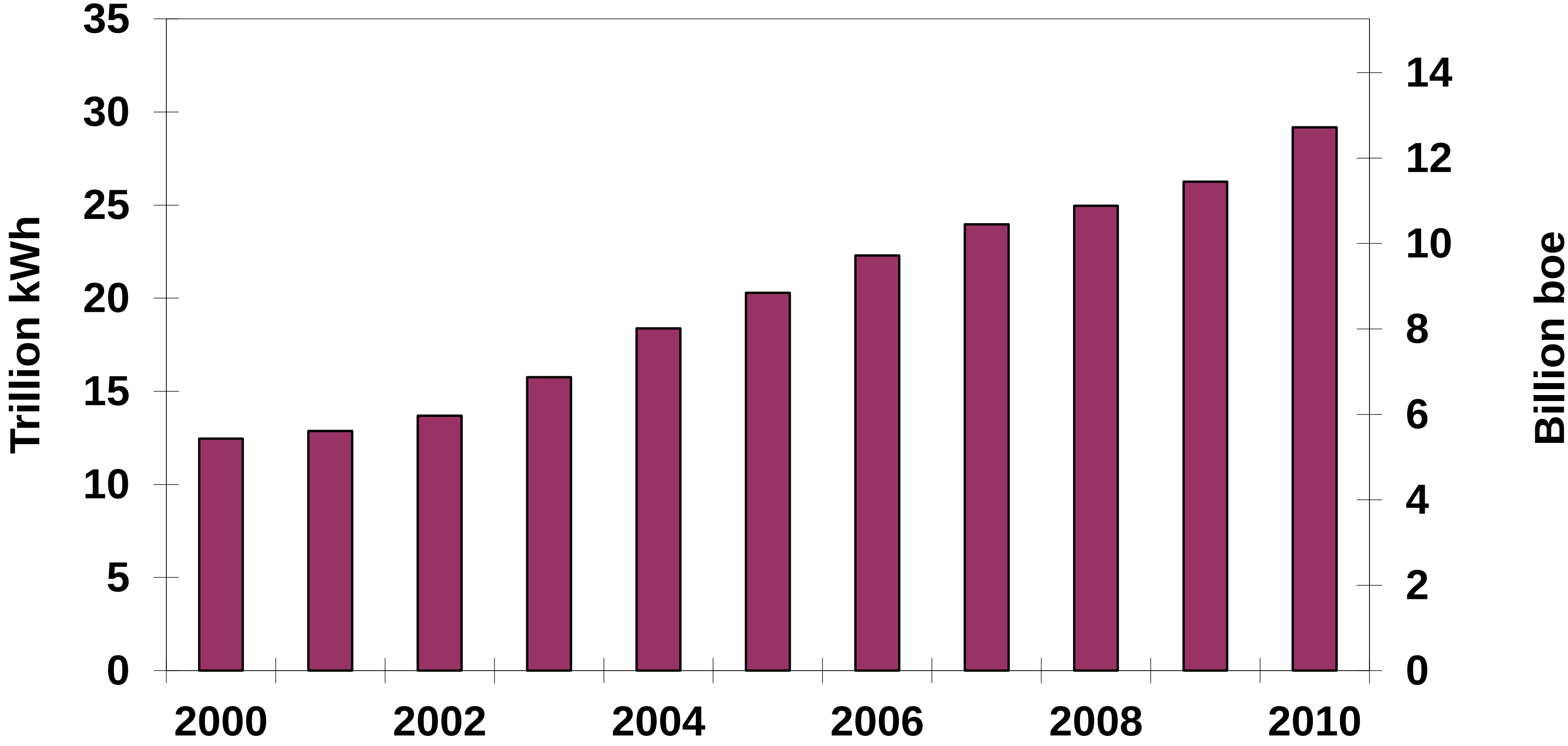
However…

- 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 = 17.8 billion boe**
- **Current USA's primary energy consumption = 16.7 billion boe**

Source : BP Statistical Review of world Energy 2011

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China's Recent Energy Consumption

- Average growth rate > 10%!
- 2007 China's primary energy consumption = 13.7 billion boe
- Current China's primary energy consumption = 17.8 billion boe
- Current USA's primary energy consumption = 16.7 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**

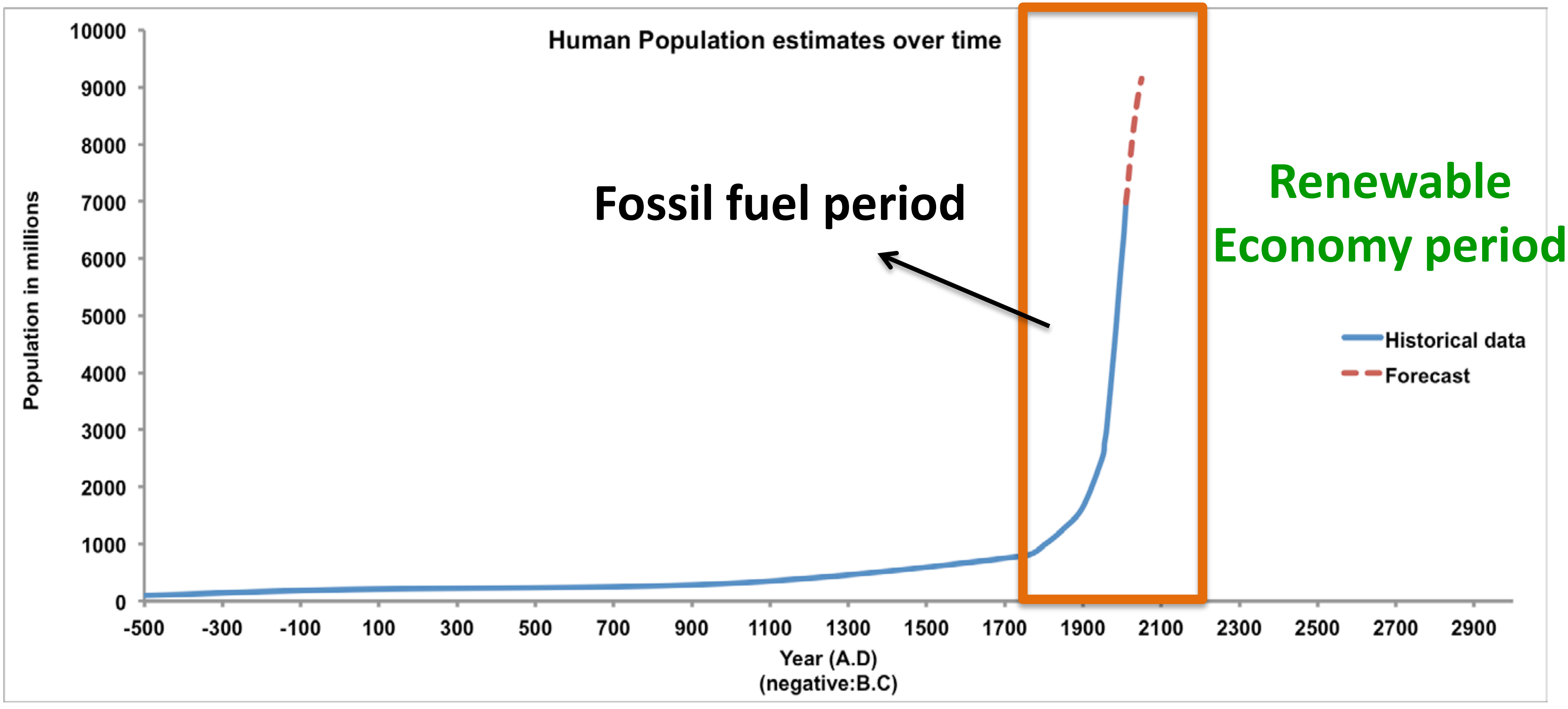
However…

- The world population is expected to rise
- 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**

However…

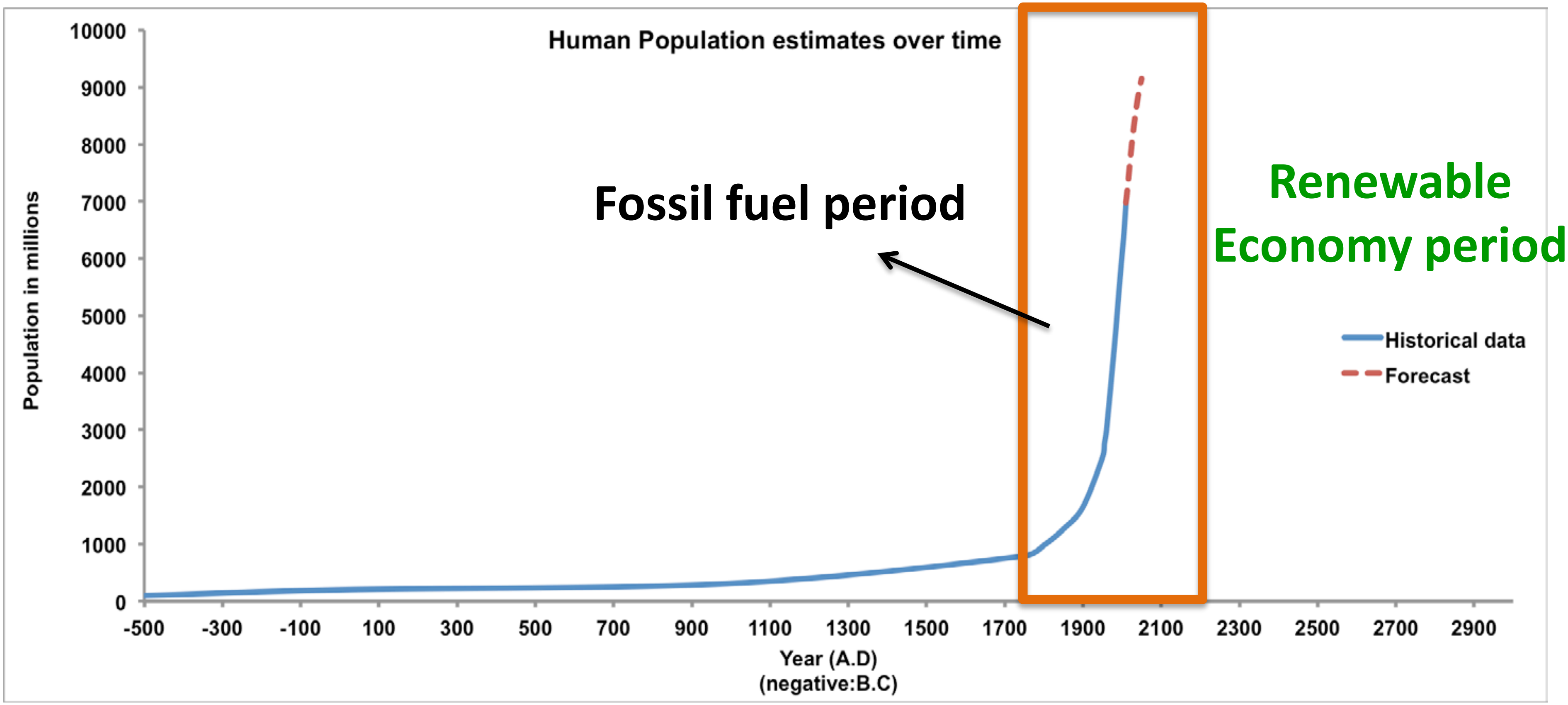
- The world population is expected to rise
- World energy consumption rate is expected to rise
- China's current economic growth is expected to accelerate energy consumption
- Oil production will peak during the lifetime of a child born today
- For most nations it is national energy independence and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

Fossil Energy: in context of human civilization



Data source: Wikipedia & UN

Fossil Energy: in context of human civilization



Therefore, we must understand energy transformation and use issues to develop alternative energy strategies

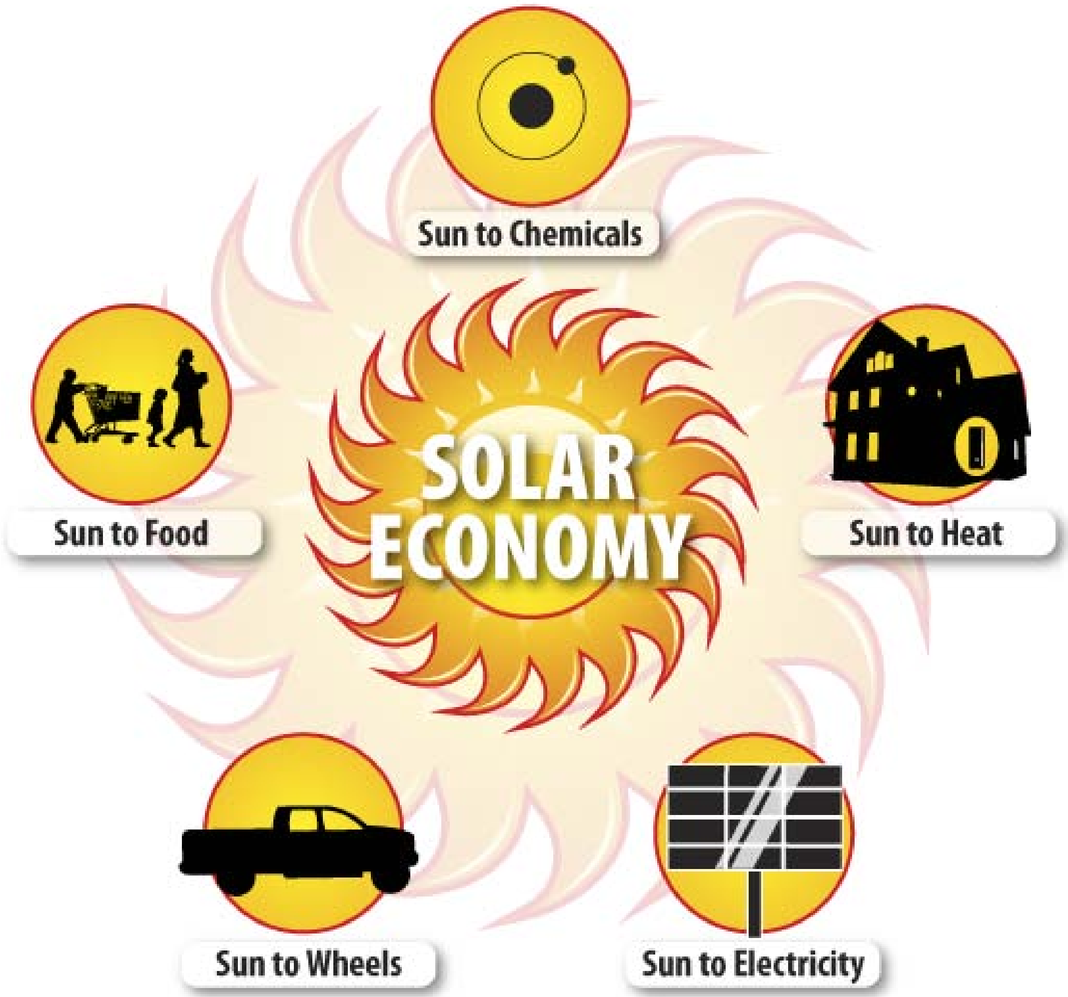
Data source: Wikipedia & UN

Some Alternate Resources

- Biomass
- Hydroelectricity
- Wind
- Geothermal
- Nuclear
- Solar

Solar is the only easily available energy source that can alone meet all the energy needs.

Solar economy vision



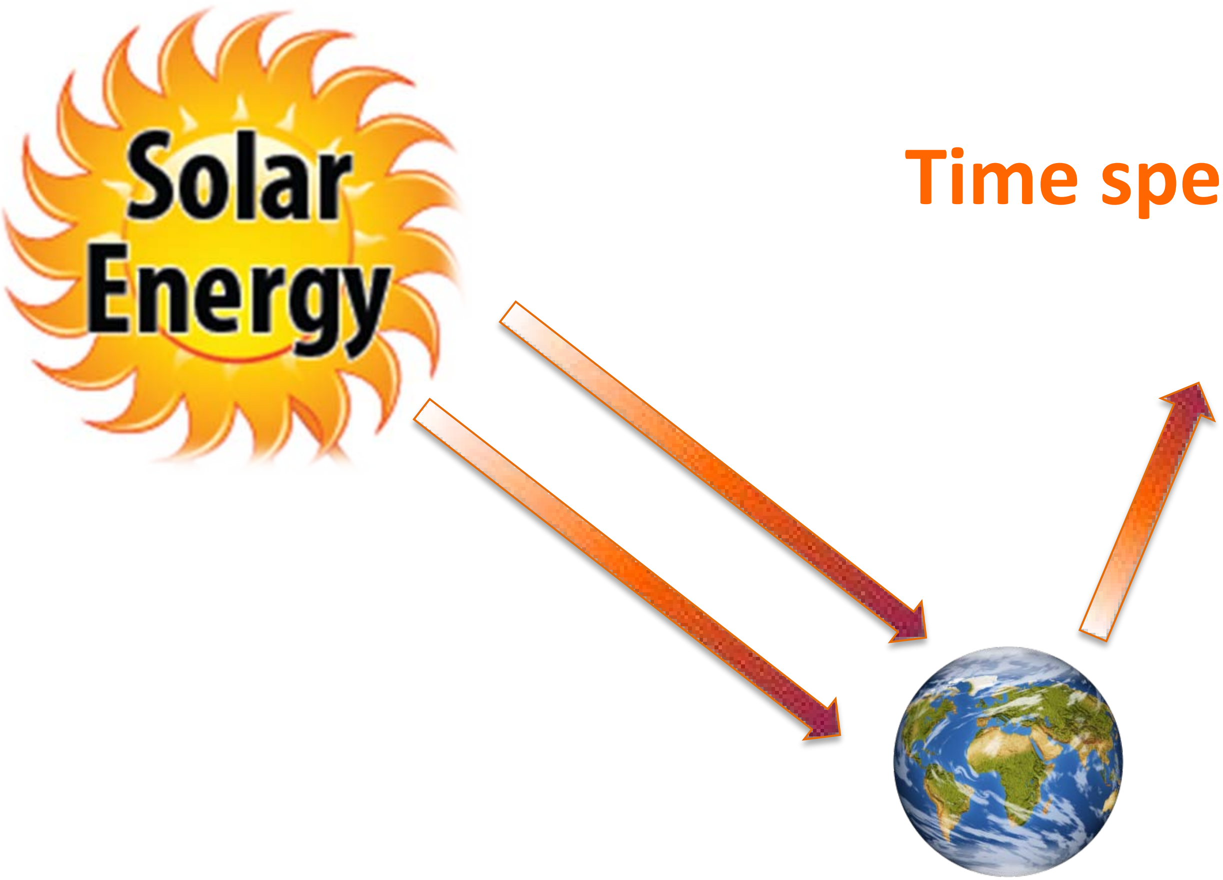
Agrawal and Singh, *Annual Rev. Chem. Bio. Eng.* , 2010

Development of a Solar Economy Provides Unprecedented opportunity for Innovations

The Journey of Solar Photons

Looking through the lens of time

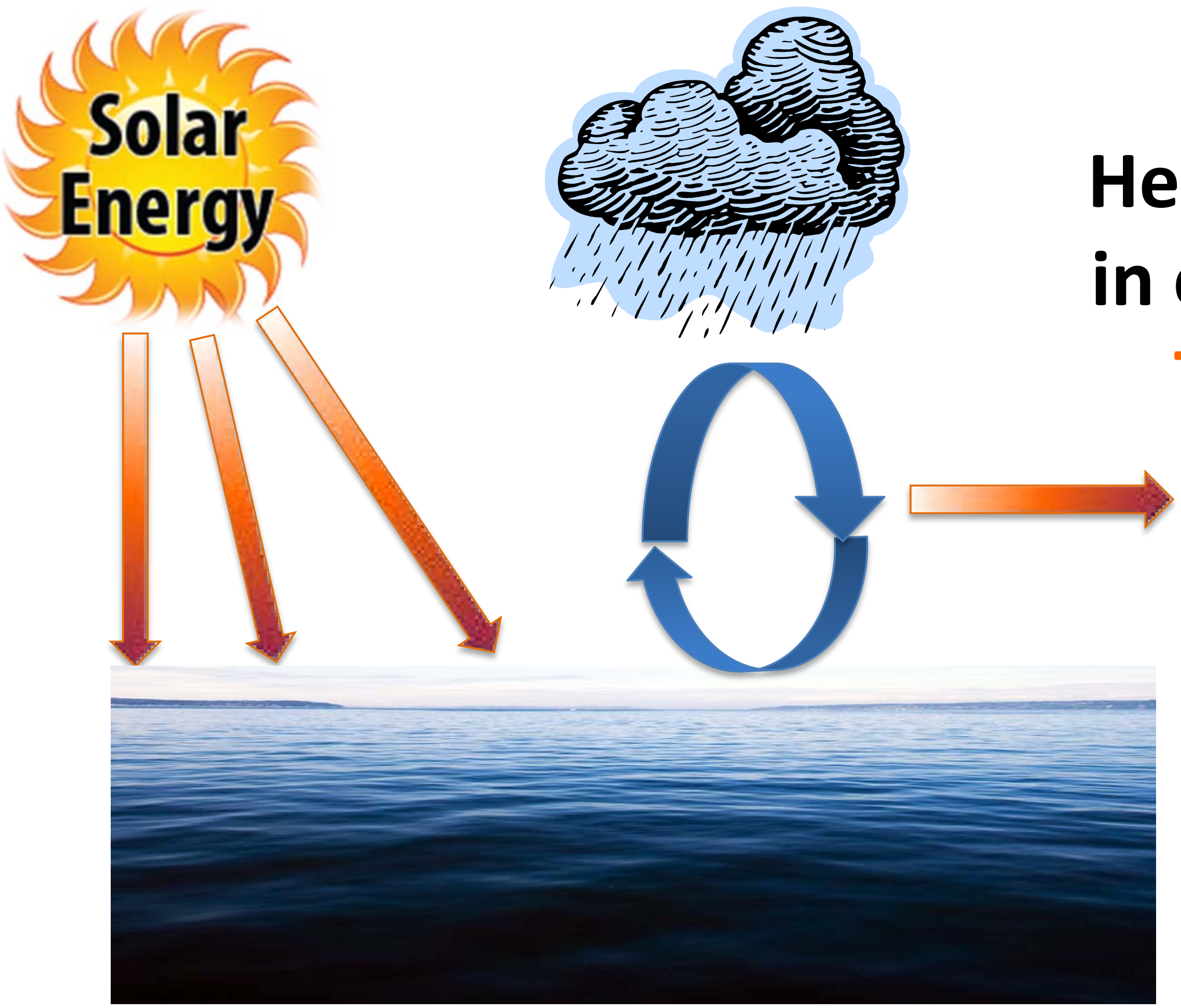
Absorption & Radiation from Earth's surface



Time spent ~ $O(10^0\ s)$

~ few seconds

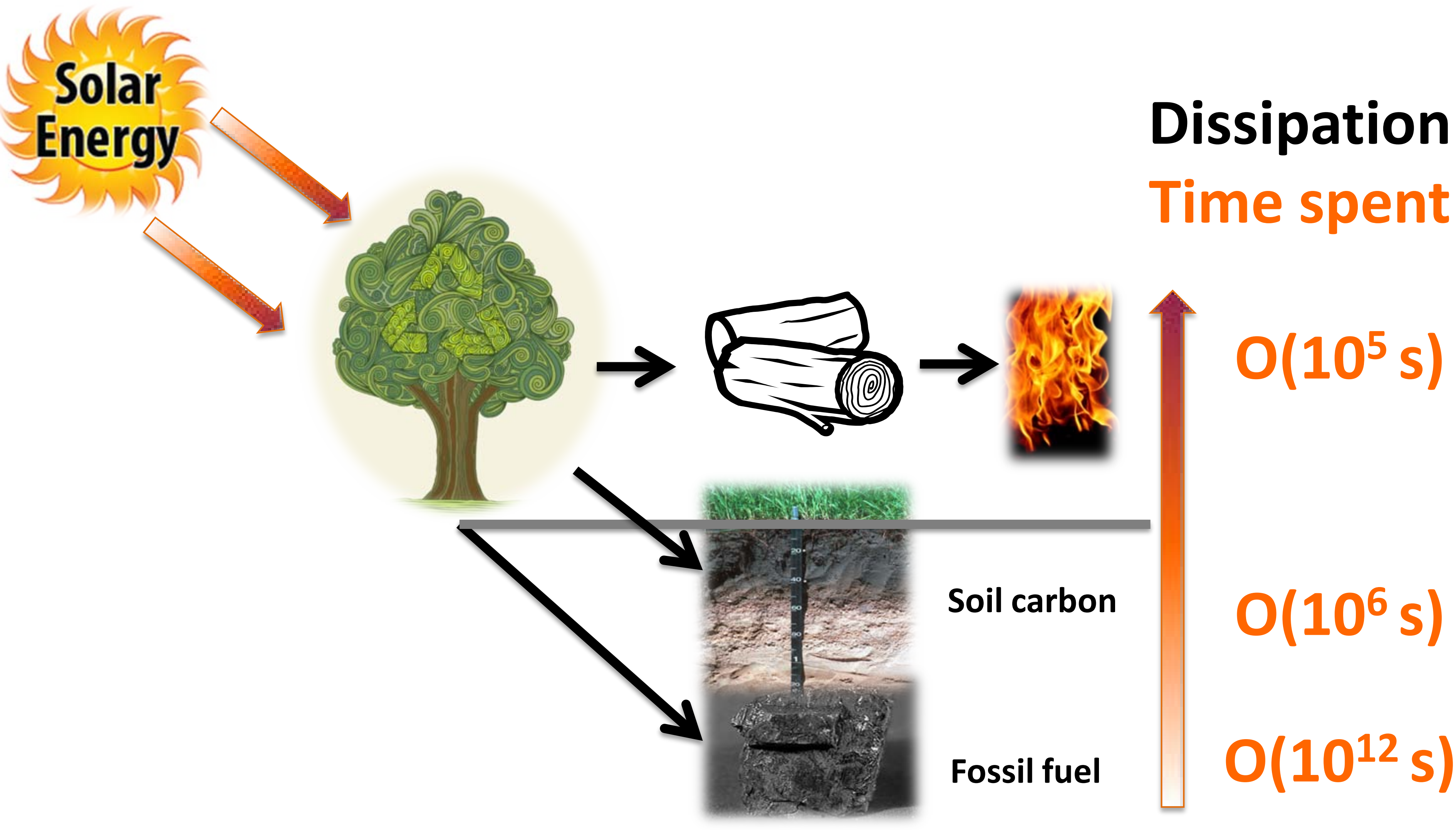
Dissipation during water cycle



Heat dissipation in condensation

Time spent ~ O(10^4 s)

Dissipation during carbon cycle



Harness solar energy

↓

Transform solar Energy

↓

Use it for human activities

↓

Dissipate to outer space

Challenge for solar economy

Harness, Transform, Store and Use solar photons on a time scale of human activities ~ O(10^3-10^5 s)!

A Three Part Presentation …..

1. Harnessing of Solar Energy -- Solar Cells from Nanocrystal Inks

2. Transformation of Solar Energy -- Energy System Analysis with Emphasis on Transportation Sector

3. Storage of Solar Energy -- A Chemical Storage Cycle

A Three Part Presentation …..

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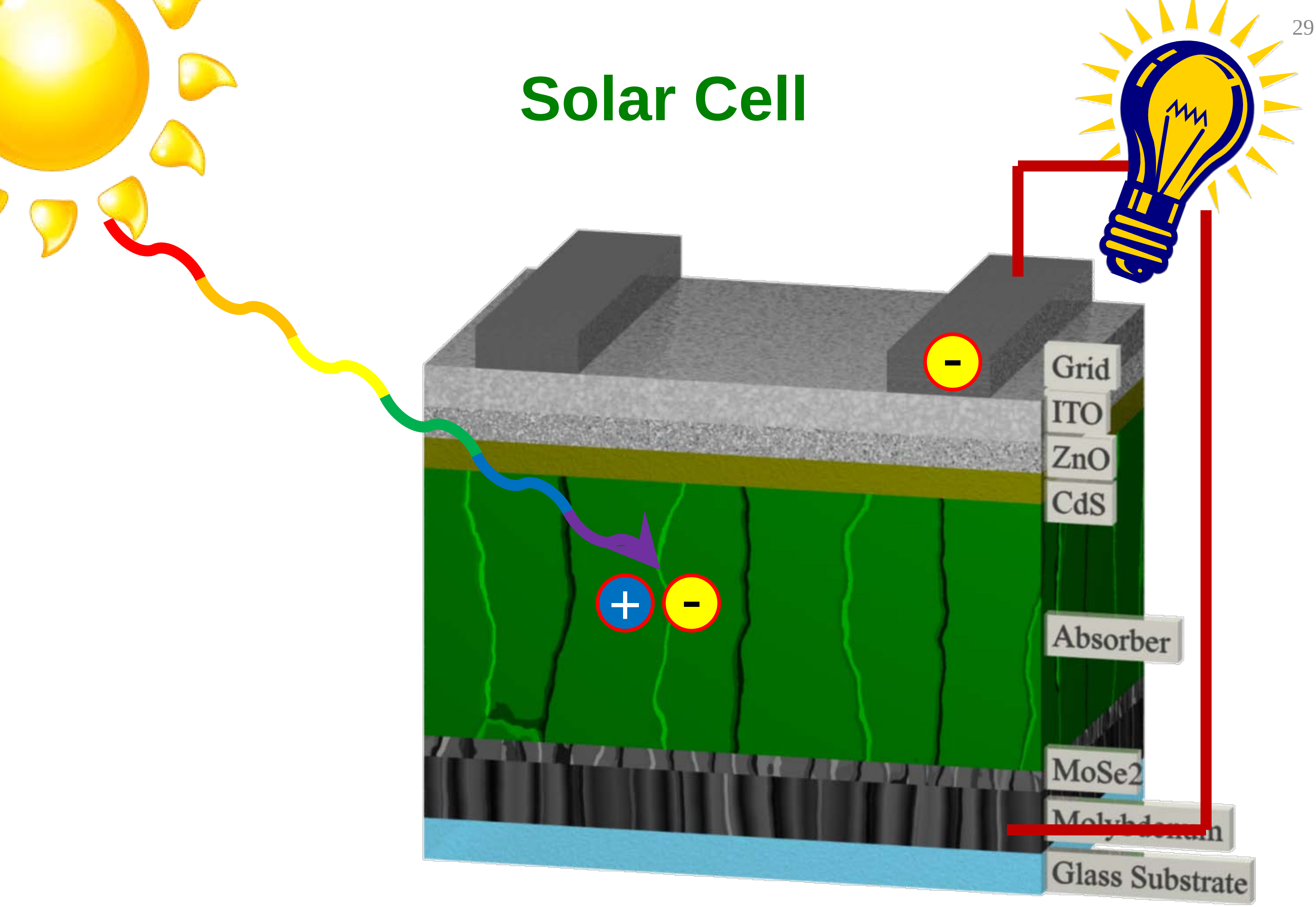
Solar Cell



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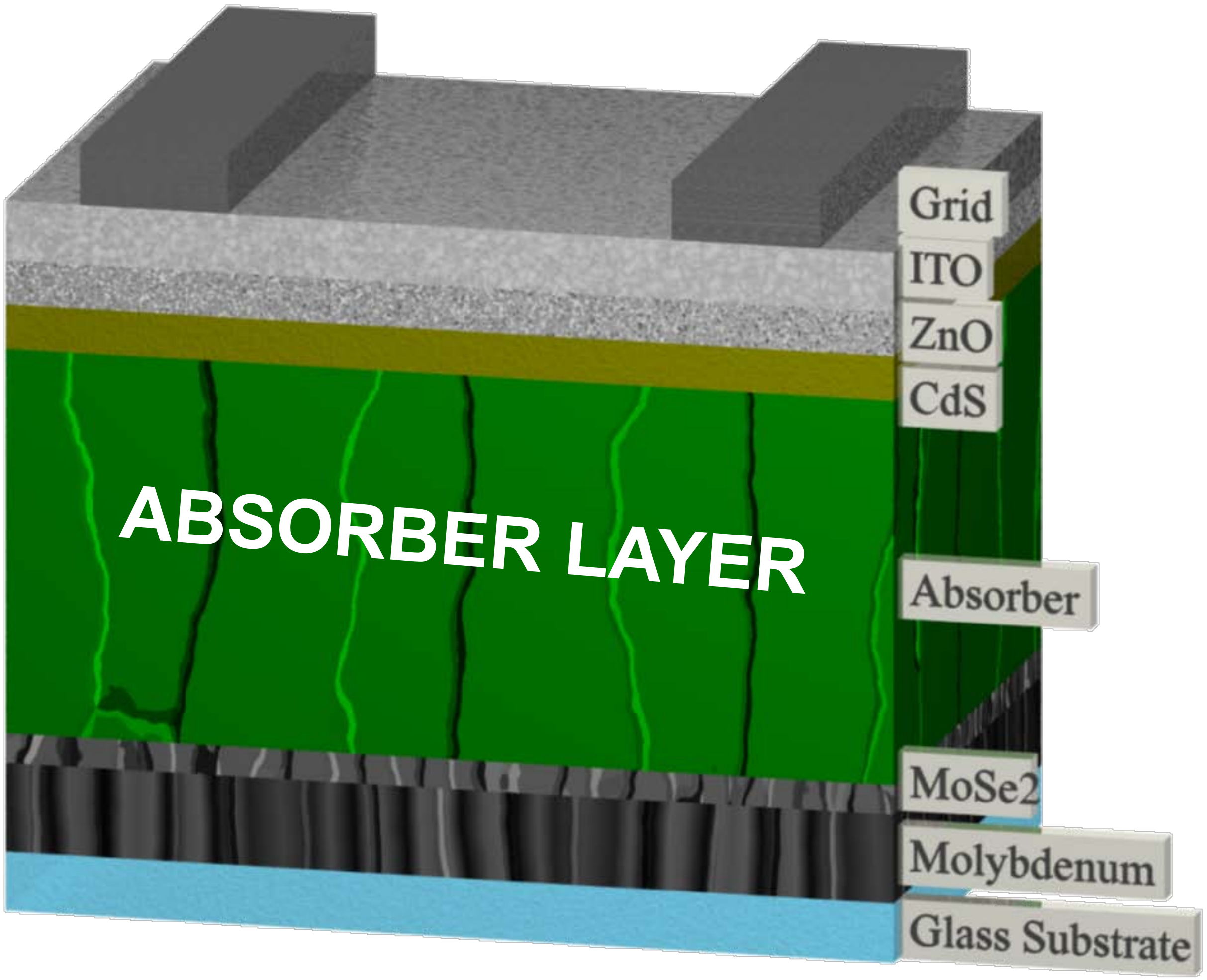
Solar Cell

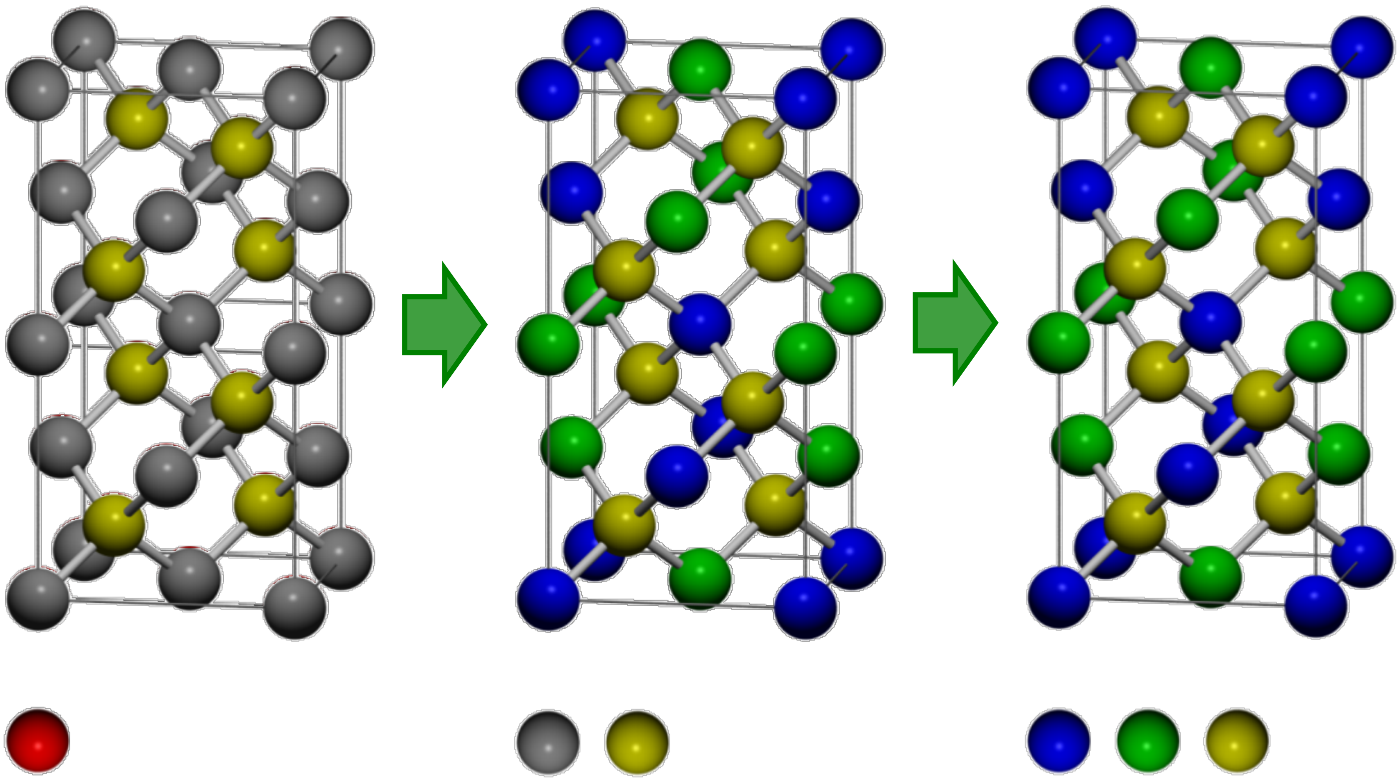

ABSORBER LAYER
Grid
ITO
ZnO
CdS
Absorber
MoSe2
Molybdenum
Glass Substrate

Solar Material Structure

Diamond Cubic
IV Silicon

Zincblende
II-VI CdTe
III-V GaAs

Chalcopyrite
I-III-VI_2 CIGSe



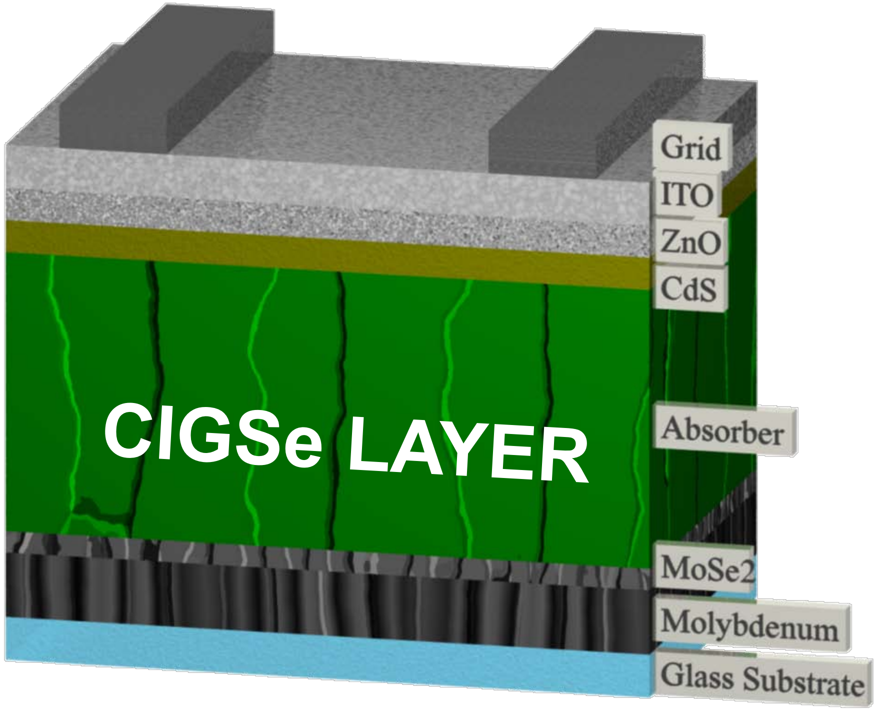
Si

Cd Te

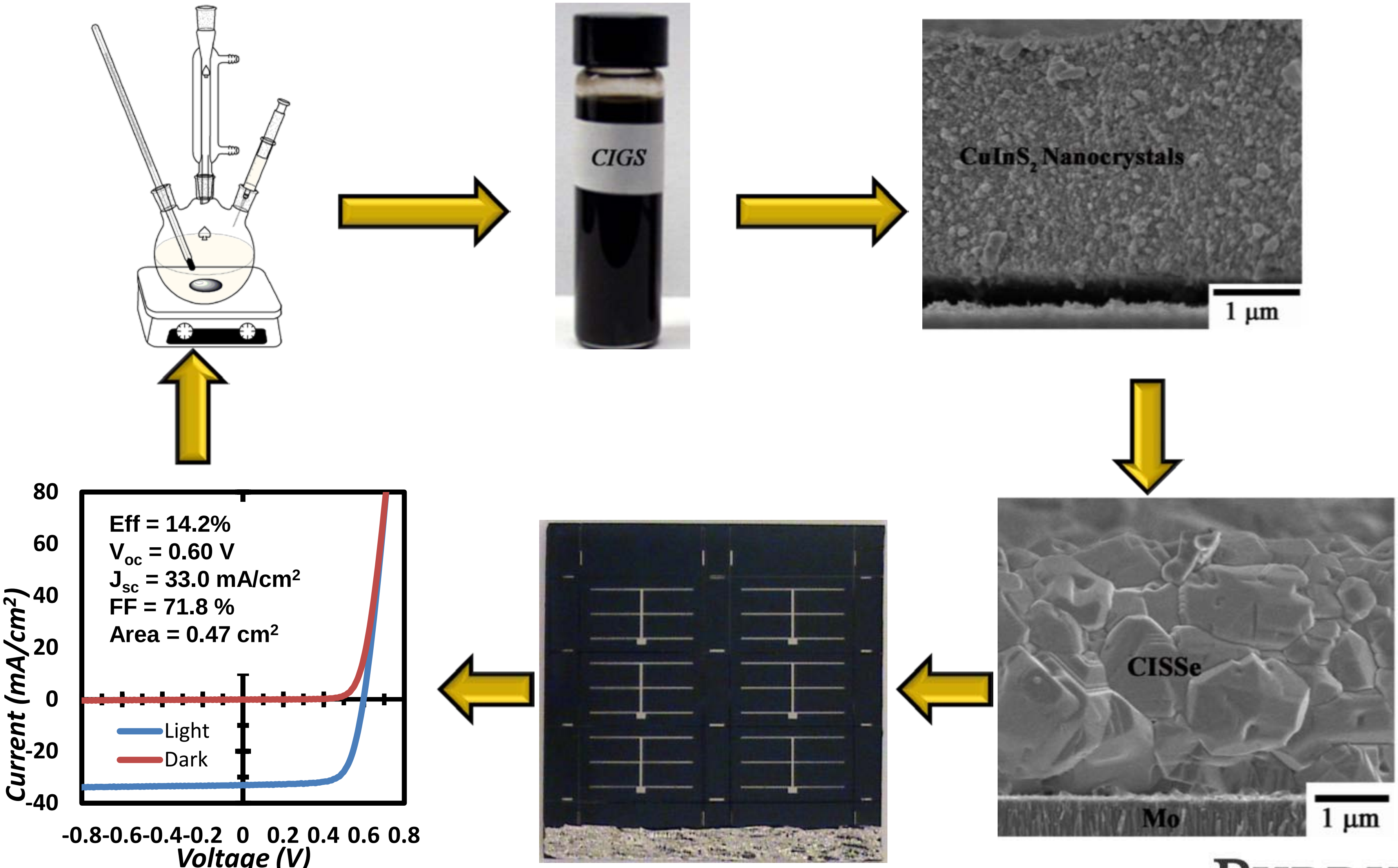
Cu In/Ga Se

$Cu(In,Ga)Se_2$ (CIGSe) Solar Cell

- **High photon absorption coefficient**
- **Low material consumption**
- **Optimal bandgap by adjusting In/Ga ratio – higher voltage achievable**
- **Most efficient (~20%) amongst thin-film solar cells at lab scale**



Our CIGSe Liquid Deposition Method



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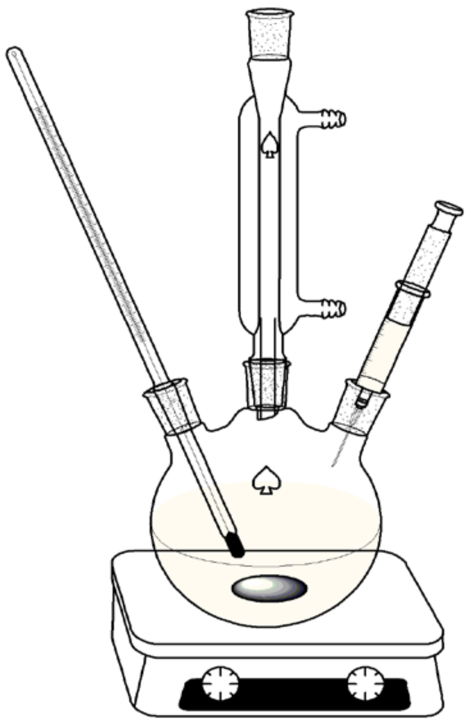
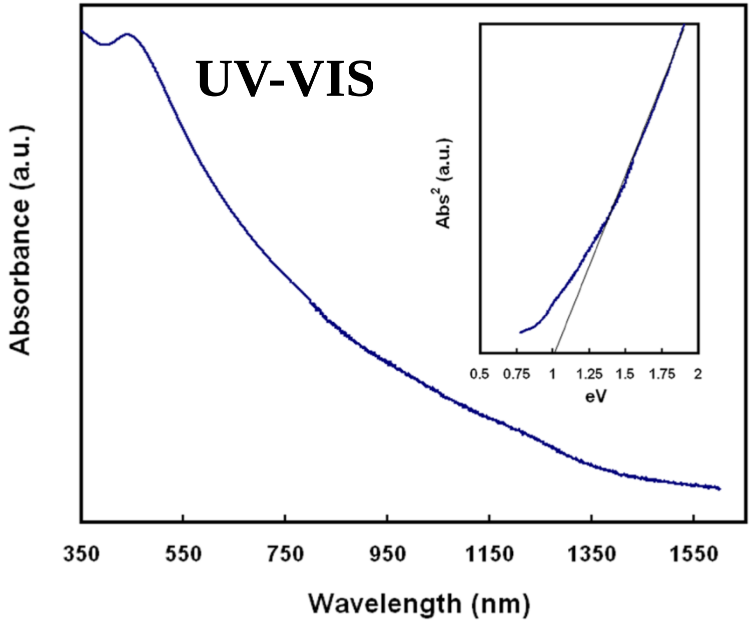
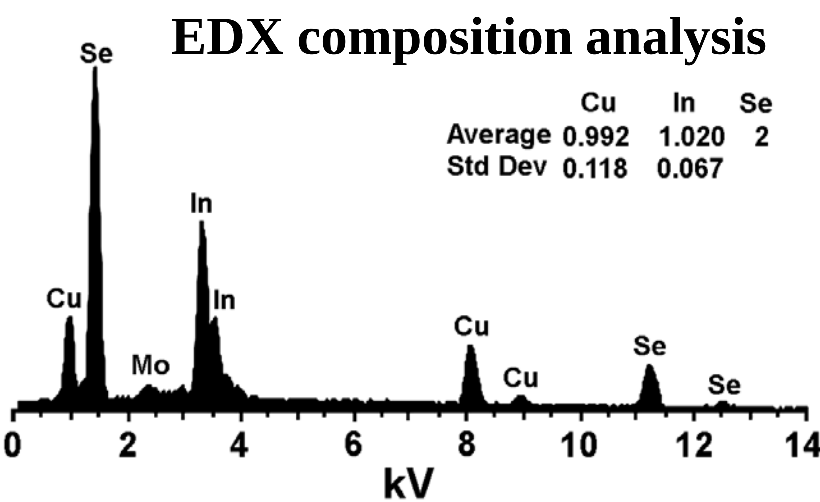
Synthesis of CISe Nanocrystal Ink

Solution Phase Batch Reaction



Observed band gap = 1.04ev

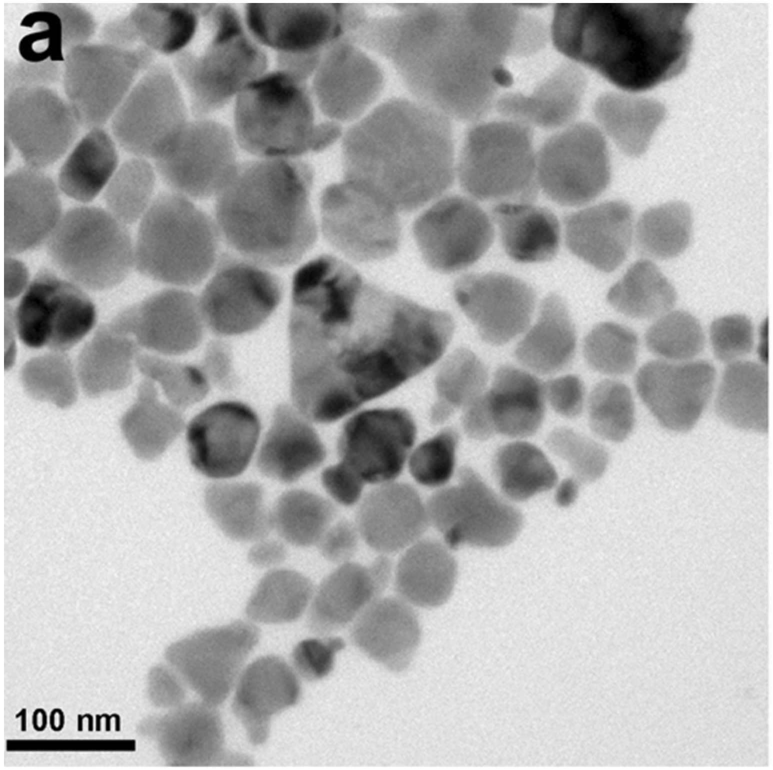




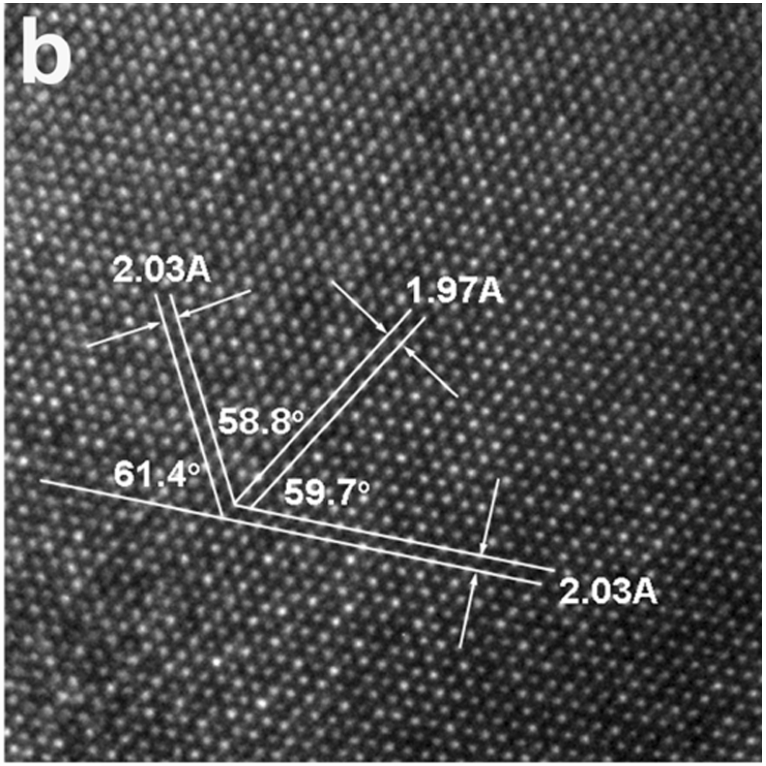
Precursors:	CuCl, $InCl_3$, Se
Solvent:	Oleylamine
Conditions:	P = 1 atm
	T = 225 – 285 C

HR-TEM of the Chalcopyrite Nanocrystals

[221] Zone Axis



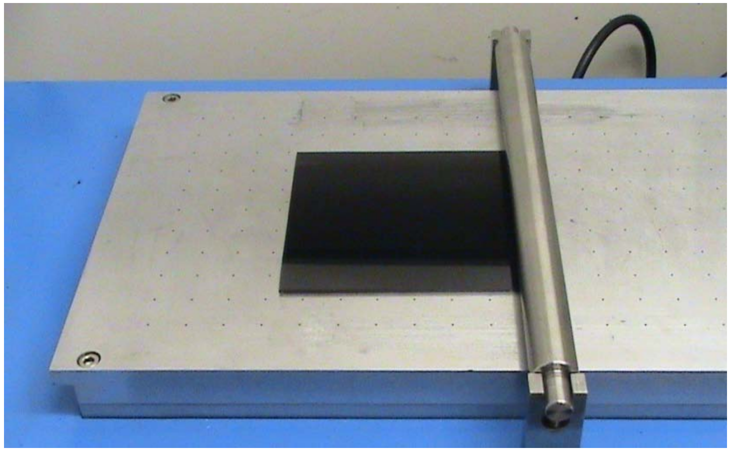
Large area TEM image

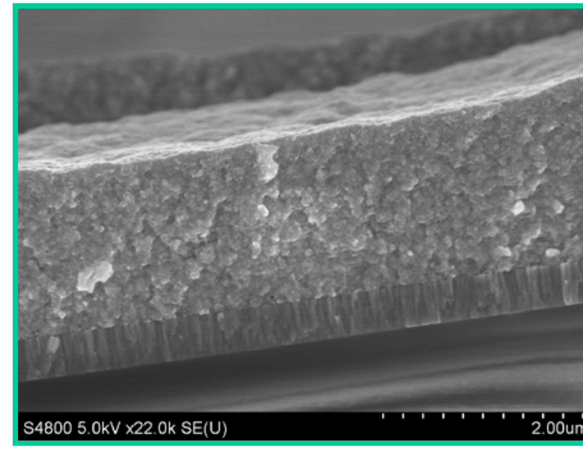


HR-TEM of a nanocrystal

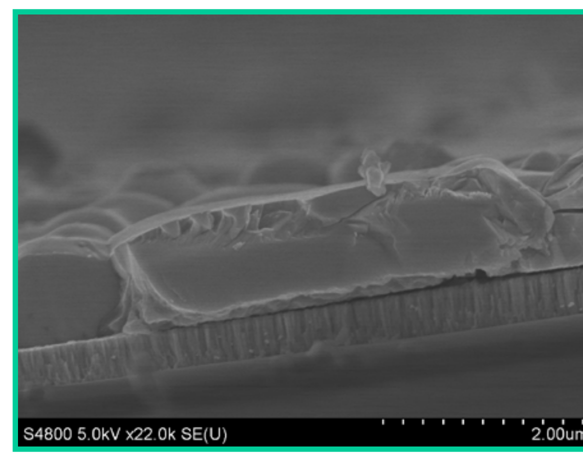
Scalable Coating Process and Dense Thin Film Formation

Slot, Knife, or Roll Coating





Rapid Thermal Processing (RTP) with Se at 500 ºC to form a dense highly crystalline layer



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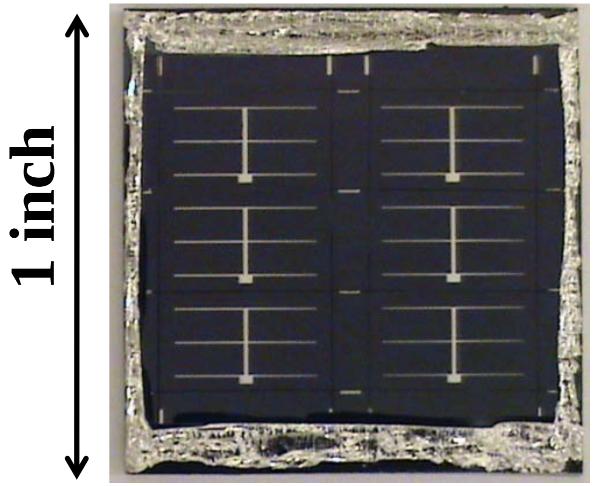
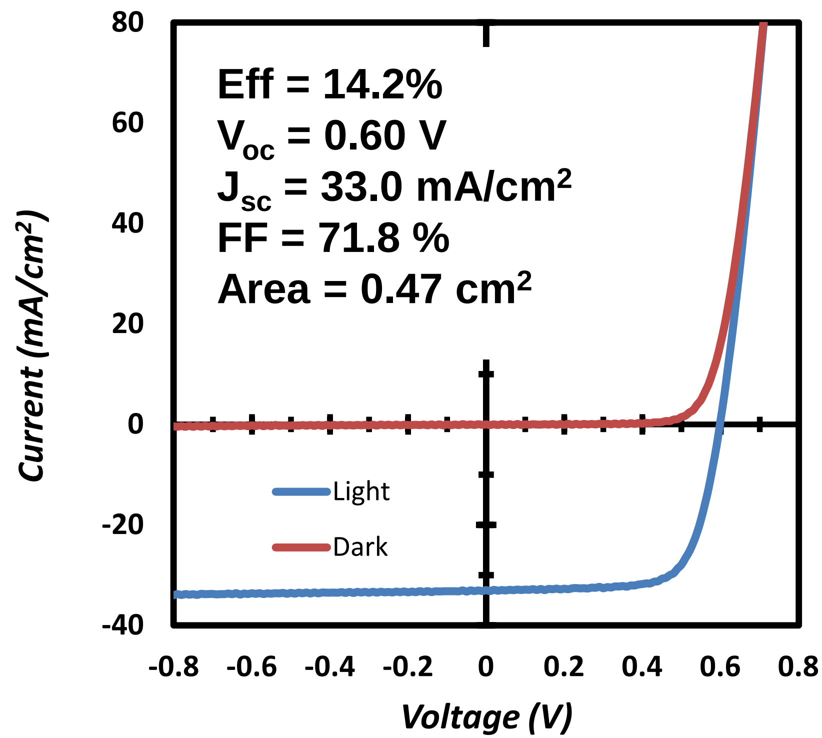
Photovoltaic Device Performance

$Cu(In,Ga)(S,Se)_2$ Solar Cell





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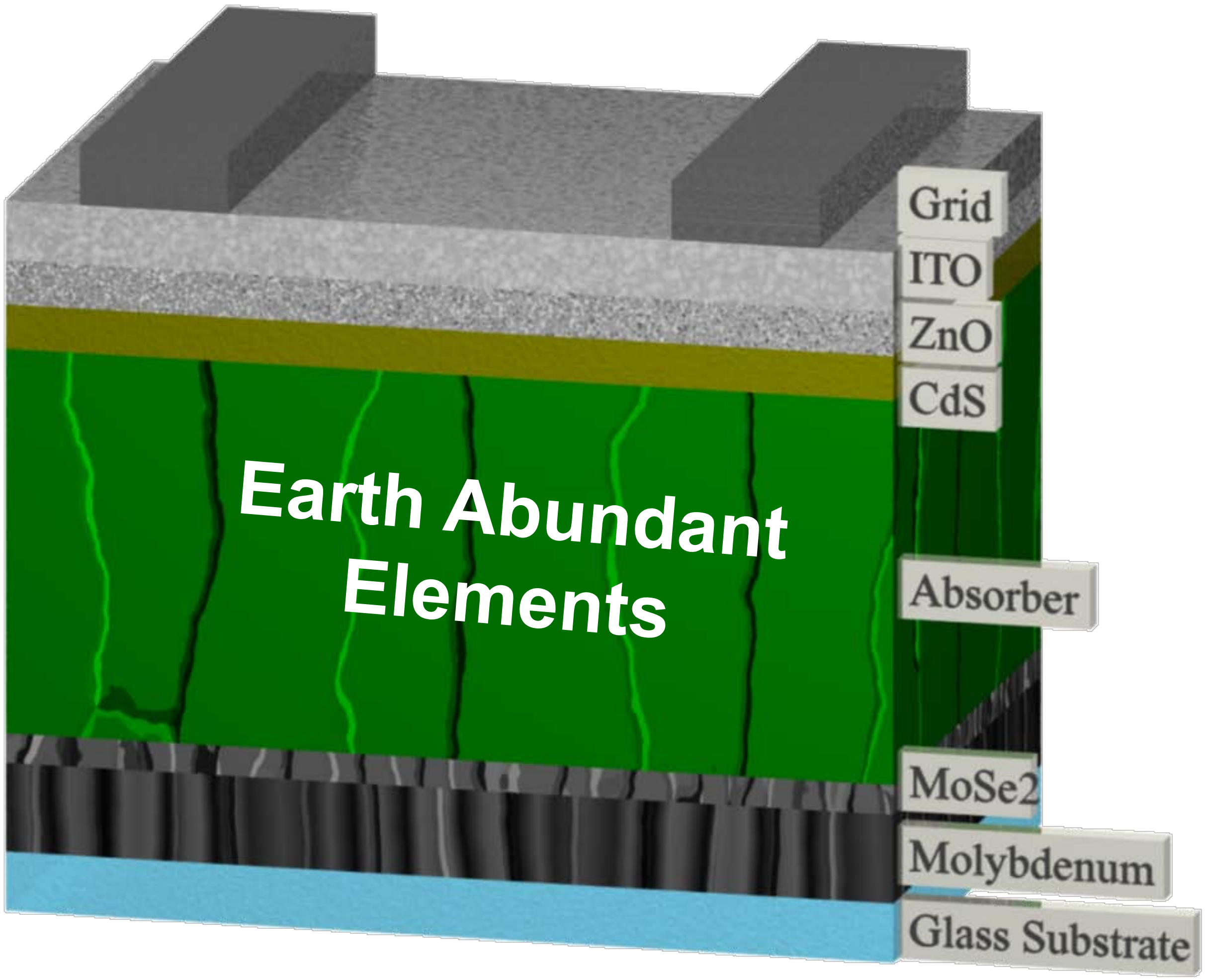
However, a need to make thin film solar cells from earth abundant elements….

Thin Film Solar Cells From Earth Abundant



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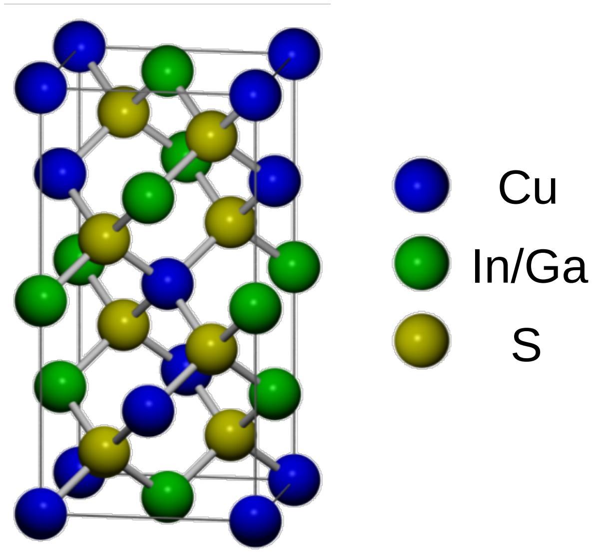
CIGS

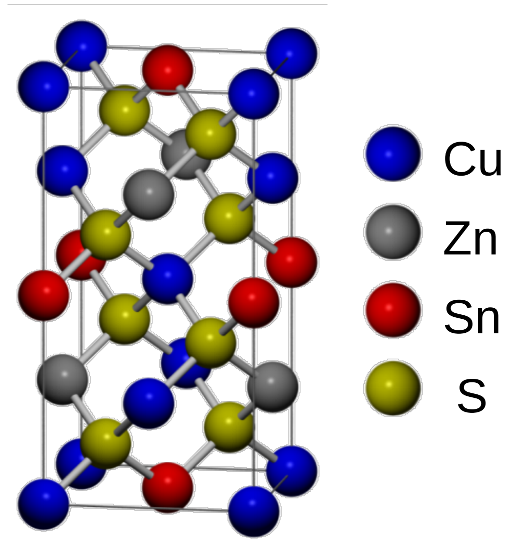
$Cu_2(In_yGa_{1-y})(S_xSe_{1-x})_4$



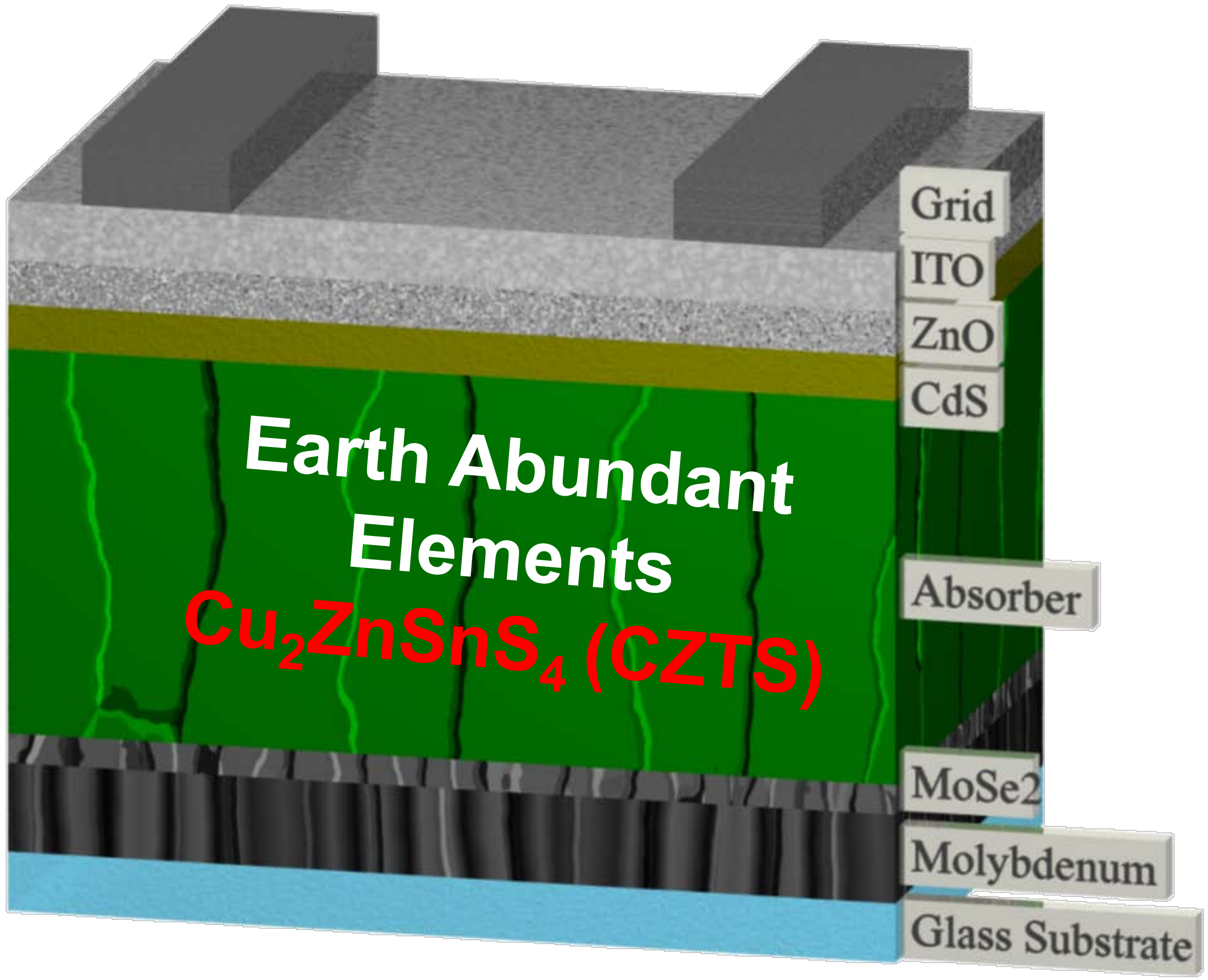
CZTS

$Cu_2ZnSn(S_xSe_{1-x})_4$

- **Earth-Abundant Materials**
- **Similar (Kesterite) Crystal System**



Thin Film Solar Cells From Earth Abundant



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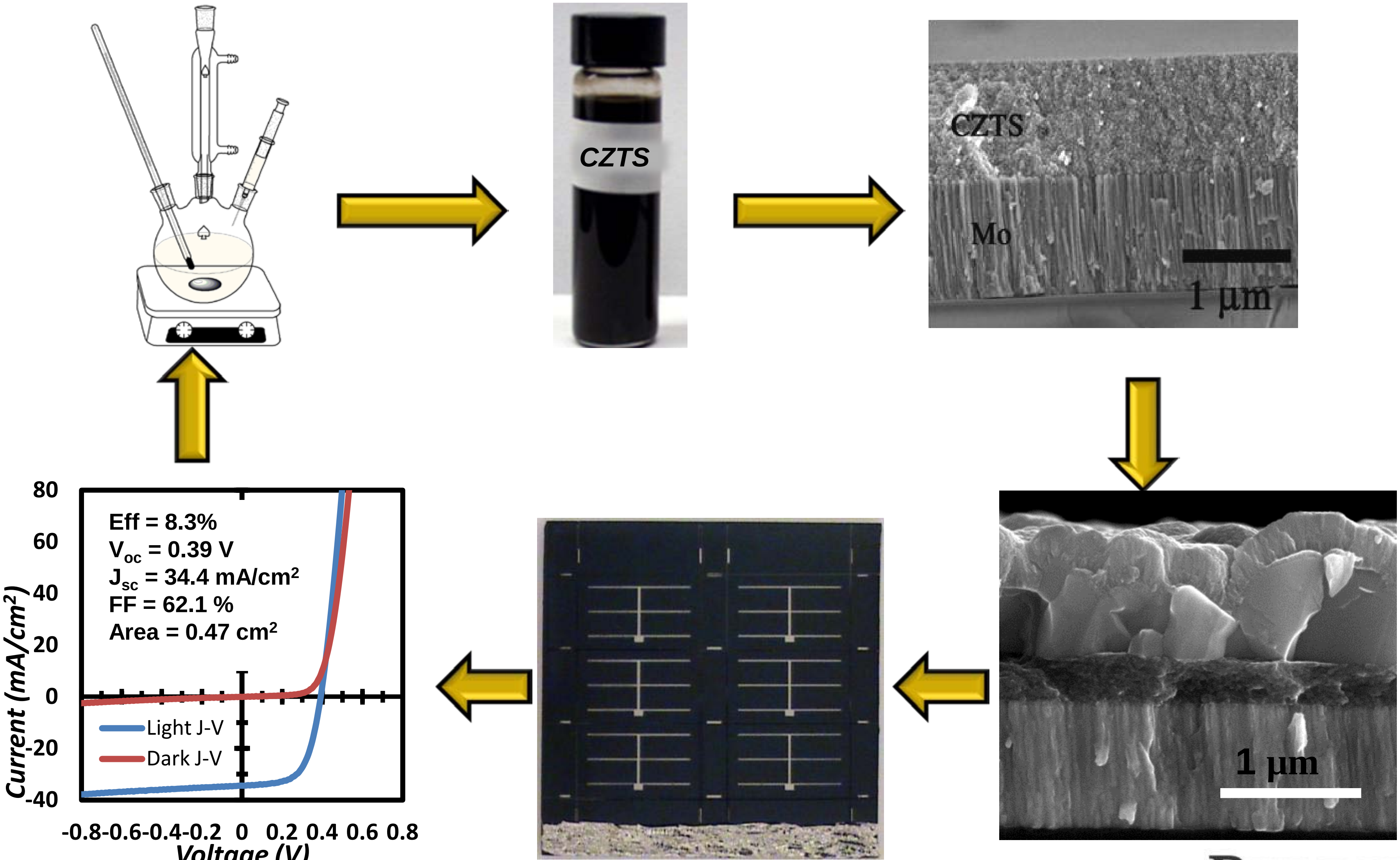
CZTSSe Liquid Deposition



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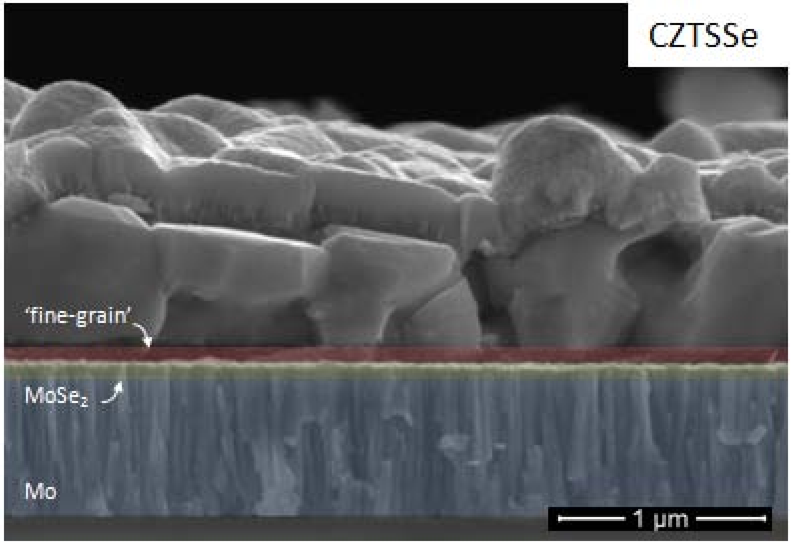
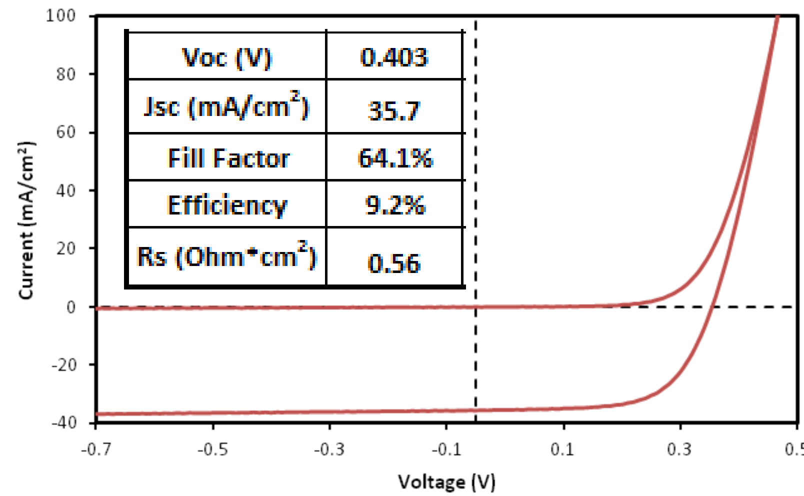
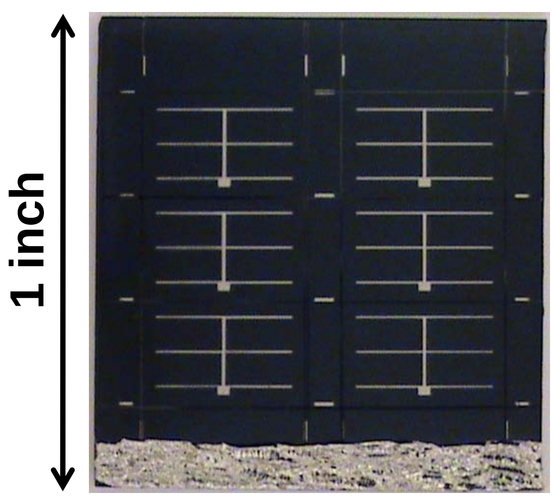
CZTSSe from Nanocrystal Ink

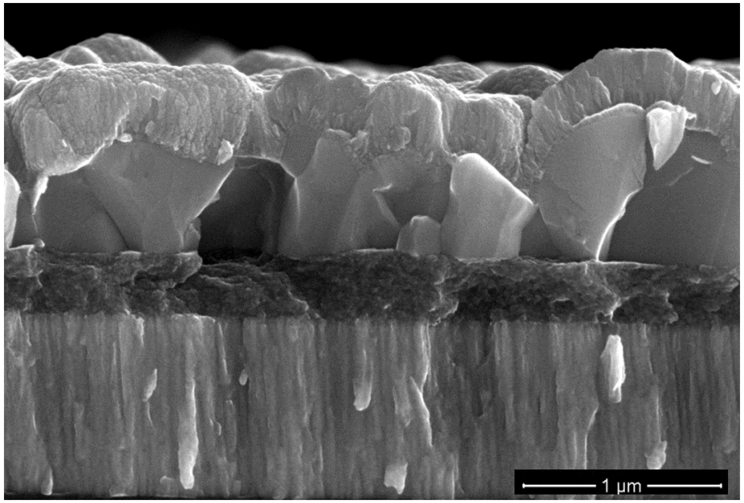


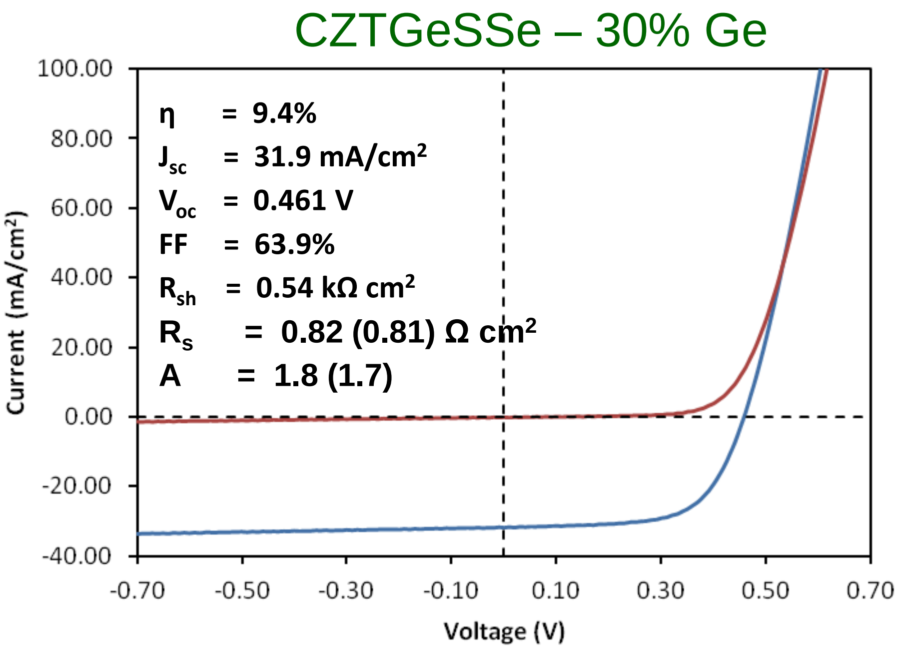




- **Nanoparticle Optimization**
- **Sintering Optimization**

Band Gap Tailoring with partial Ge substitution for Sn





Reproducible results > 9% efficiency with 30% Ge-alloying

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Summary – Harnessing of Solar Energy: Nanocrystal Based Solar Cells

- **Possible to make nanocrystal inks of the compound semiconductors.**
- **Proof-of-concept demonstrated for potentially low cost solar cells from nanocrystal inks.**
- **Kinetics of nanoparticle synthesis, insitu sintering of the absorber layer and optoelectronic characterization and modeling studies in progress to improve efficiency of these solar cells.**

A Three Part Presentation …..

1. Harnessing of Solar Energy -- Solar Cells from Nanocrystal Inks

2. Transformation of Solar Energy -- Energy System Analysis with Emphasis on Transportation Sector

3. Storage of Solar Energy -- A Chemical Storage Cycle

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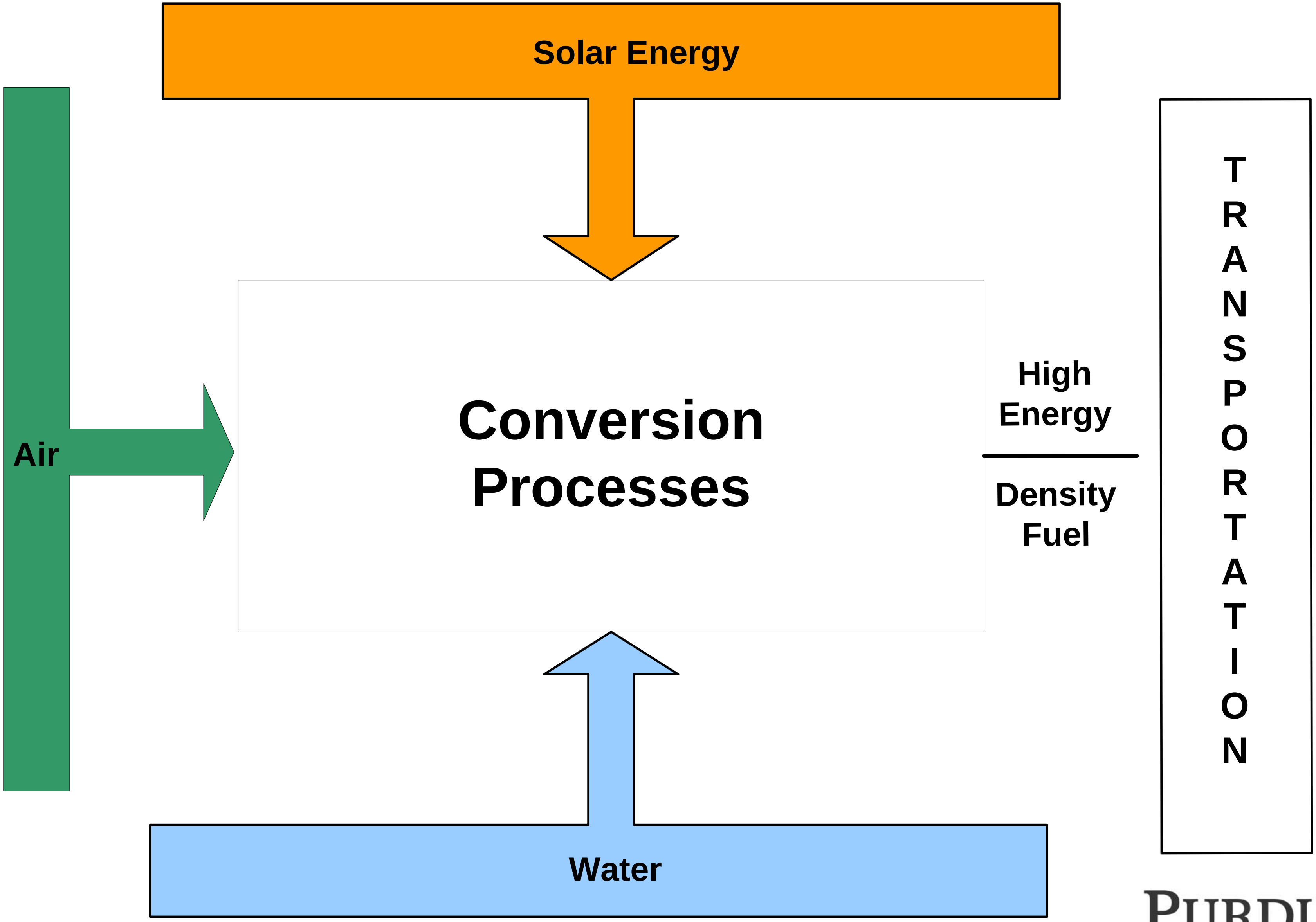
… Of all the end uses most challenging is transportation



High Energy Density Fuel from Renewable Resources

An Obvious Choice is Use of Biomass for Liquid Hydrocarbon Fuel ….

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Liquid fuels from biomass

Biomass Resource Classification

SAW biomass

- **Sustainably available waste**
- **Crop, forest residues**
- **Manure, municipal waste etc.**

Dedicated fuel crops

- **Grown on spare land**
- **Minimal additional energy input**

→ **Sustainably Available (SA) Biomass**

Regulated fuel crops

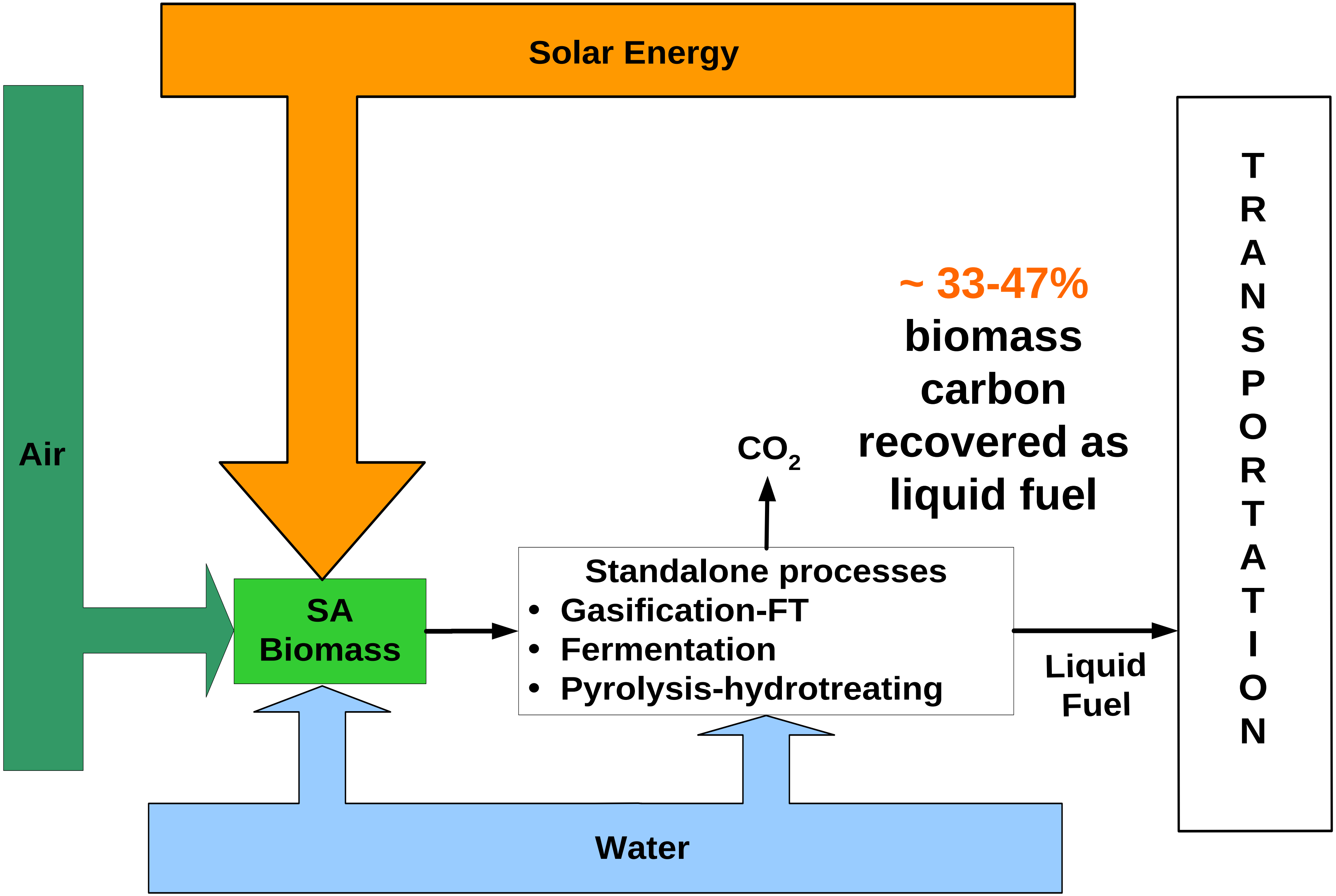
- **Grown on land managed for energy use**
- **Compete with other forms of energy for land use**

→ **RF crops**

Agrawal and Singh, *Annual Rev. Chem. Bio. Eng.* , 2010

What are the process options of converting biomass to liquid fuel?

Biomass -to-liquid fuel: carbon recovery



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1. Singh, Delgass, Ribeiro and Agrawal, *Environ. Sci. Tech.*, 2010
2. Agrawal and Singh, *Annual Rev. Chem. Bio. Eng.* , 2010

Self-contained processes + SA biomass for US transportation

- **SA biomass availability potential= 498 Million metric tons/yr[1]**

- **Transportation fuels use in the USA, 2007 =13.28 Mbbl/day[2]**

21% (2.8 Mbbl/day) of current US transportation demand produced using SA biomass with best self-contained process

1. **Liquid transportation fuels NRC report, 2010**
2. **Davis *et al.*, Transportation energy data book, 2009**

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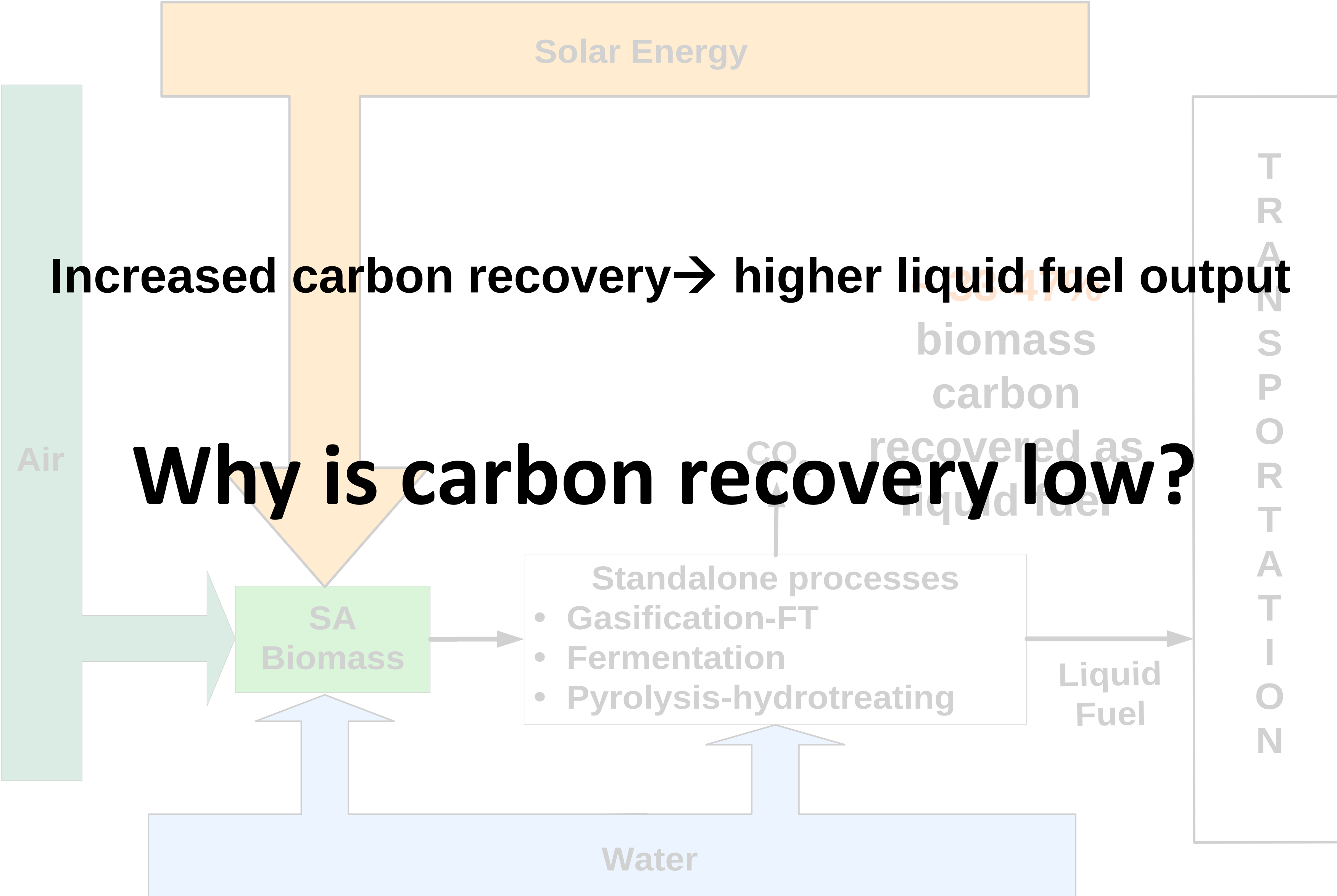
How do we increase liquid fuel from SA biomass?

Biomass -to-liquid fuel: carbon recovery

Increased carbon recovery→ higher liquid fuel output

Why is carbon recovery low?



1. Singh, Delgass, Ribeiro and Agrawal, *Environ. Sci. Tech.*, 2010
2. Agrawal and Singh, *Annual Rev. Chem. Bio. Eng.* , 2010

High oxygen content in biomass

↓

Energy per carbon atom in biomass is lower than the corresponding energy per carbon atom in high energy density fuels such as gasoline

Biomass	Gasoline
~450 kJ/mol C	605 kJ/mol C

↓

Lower carbon recovery during conversion to high energy density liquid Fuel

Let us examine efficiencies at which supplemental forms of energy are recovered from Sunlight

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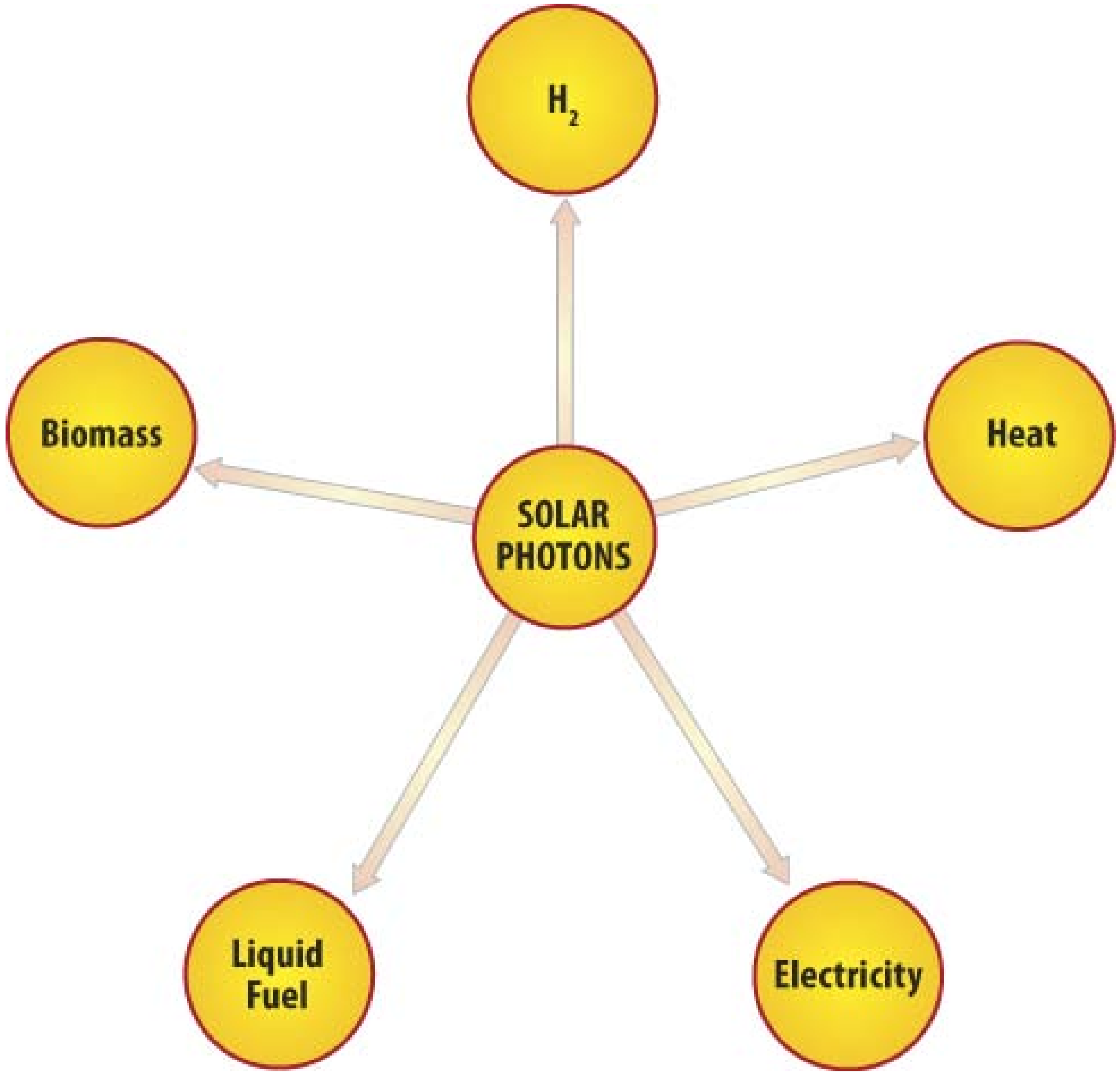
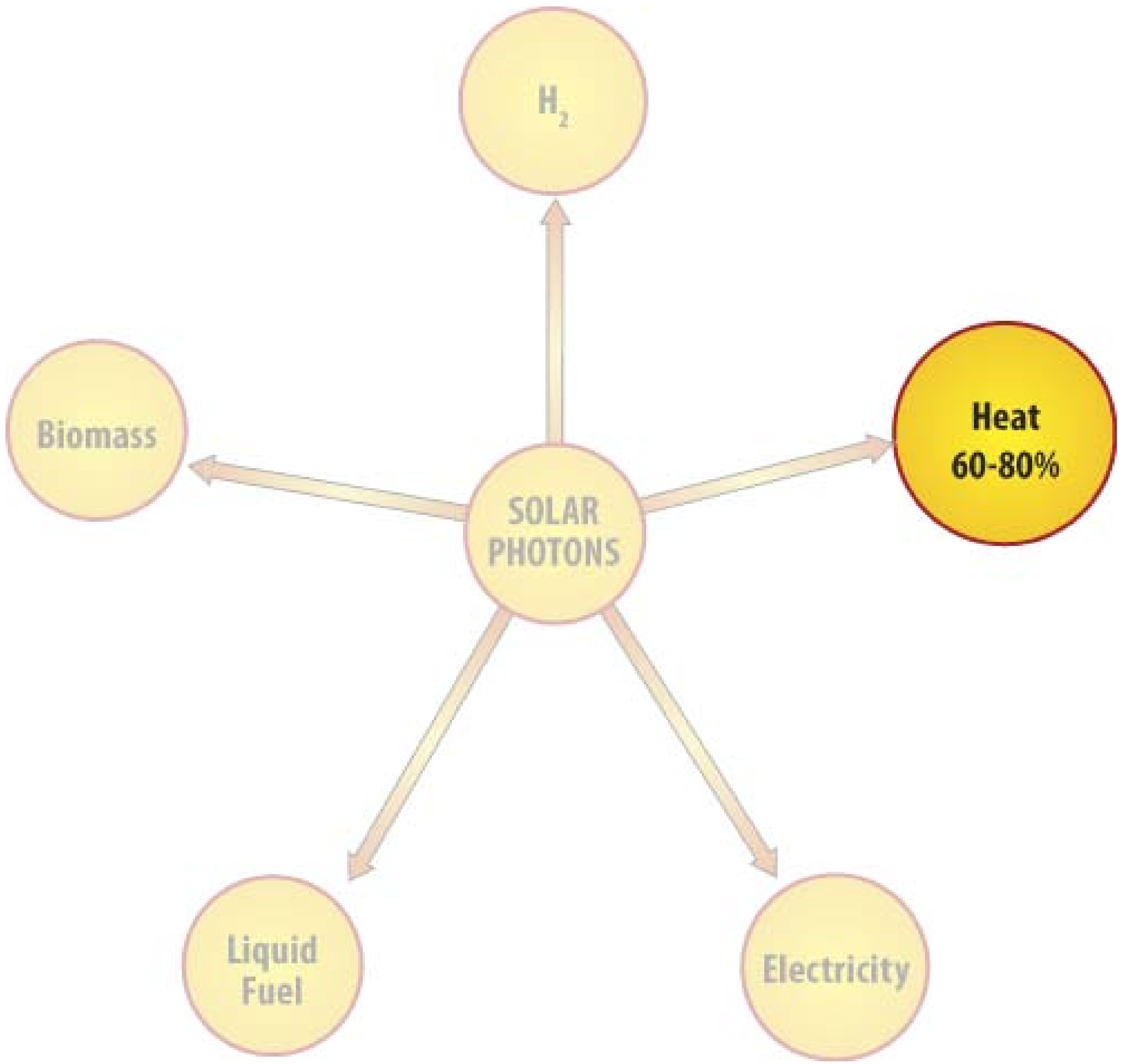
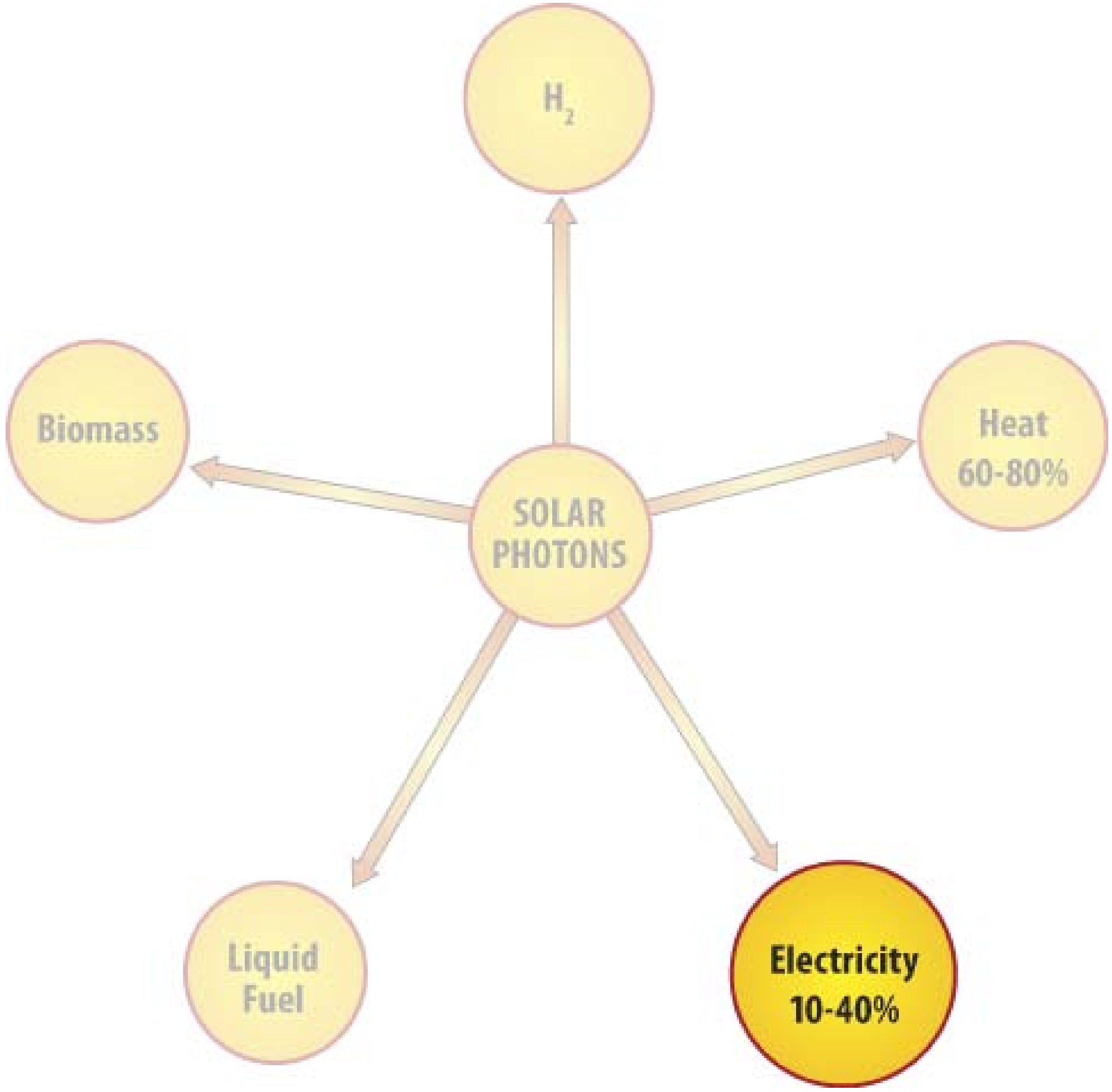
Efficiencies of Solar Energy Recovery



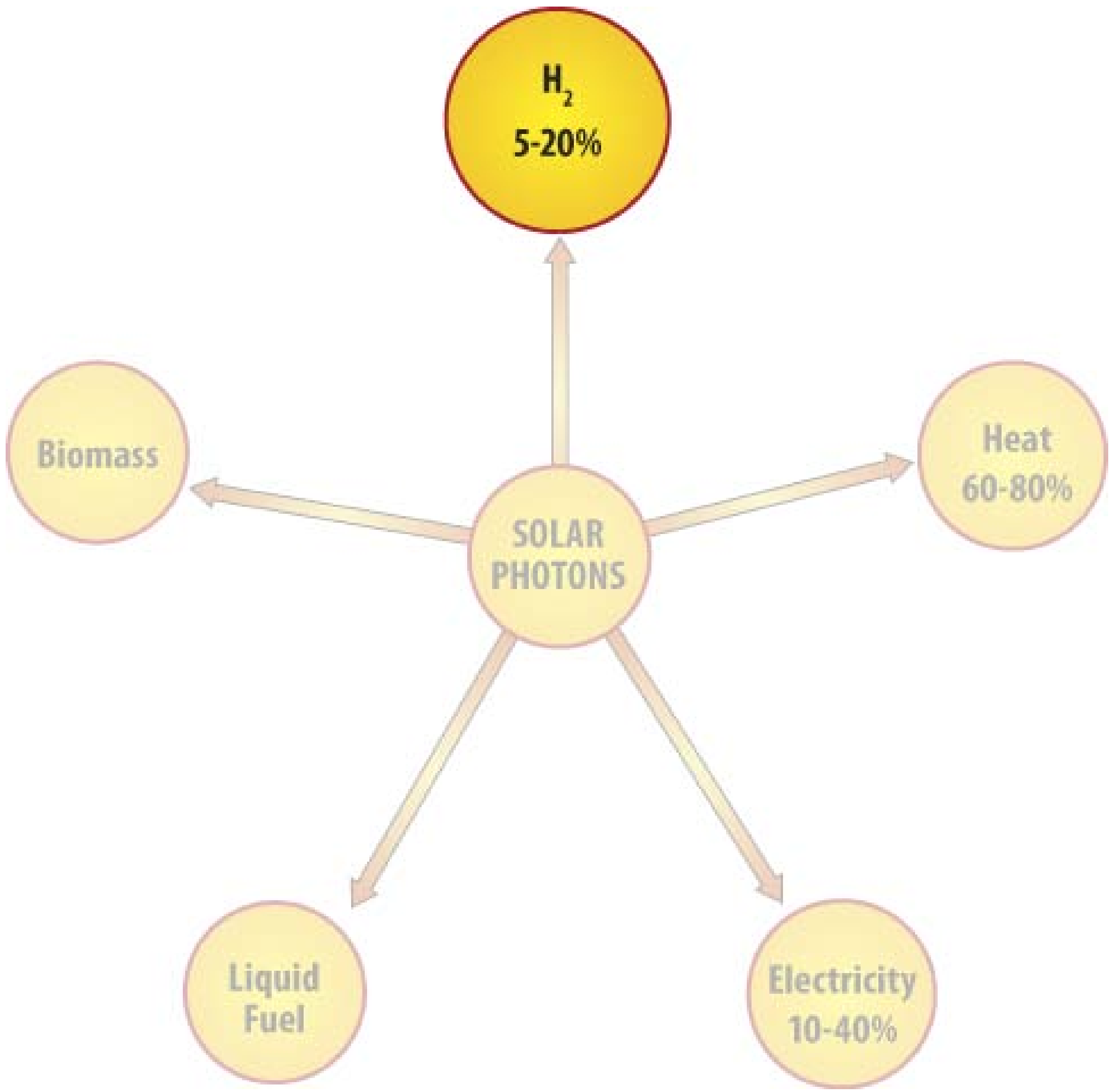
Efficiencies of Solar Energy Recovery



Efficiencies of Solar Energy Recovery



Efficiencies of Solar Energy Recovery



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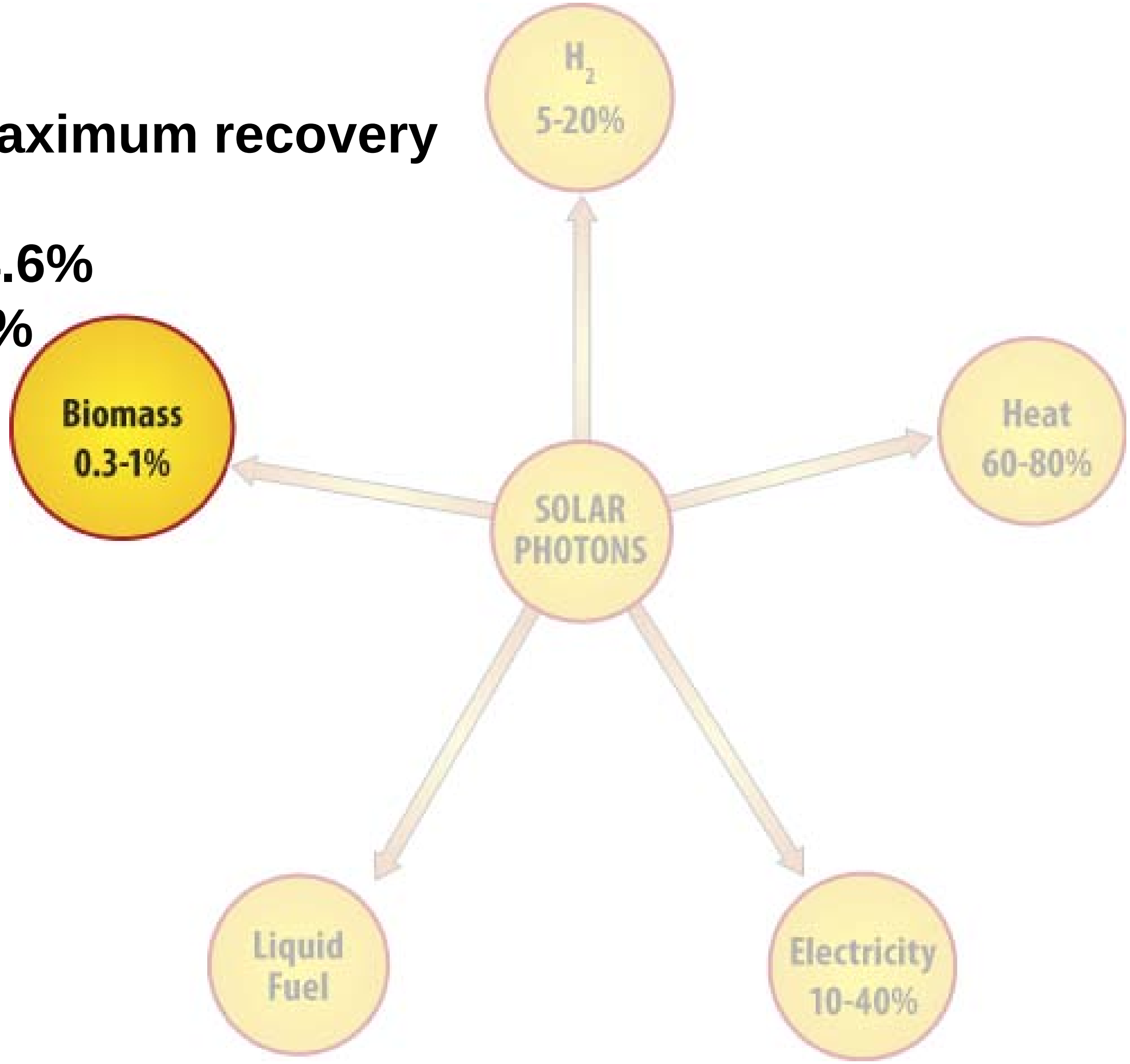
Efficiencies of Solar Energy Recovery

Estimated maximum recovery efficiency [1]
- **C3 crops= 4.6%**
- **C4 crops=6%**



1. Zhu *et al*. *Curr. Opin. Biotechnol.* , 2008

Efficiencies of Solar Energy Recovery

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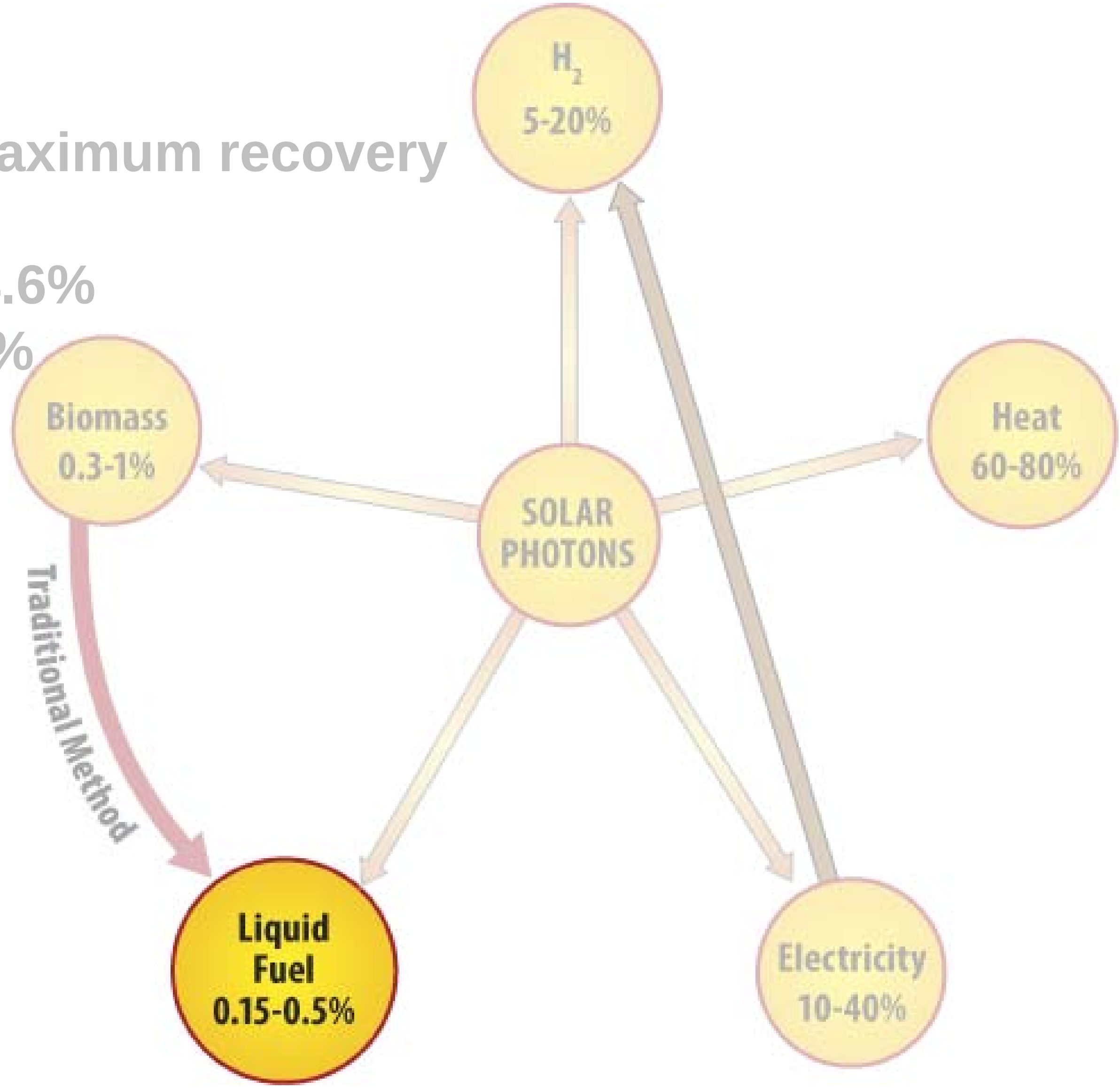

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An Observation

Biomass Should be Viewed as a Source of Carbon
and
NOT as a Primary Source of Energy

An Observation

Biomass Should be Viewed as a Source of Carbon
and
NOT as a Primary Source of Energy

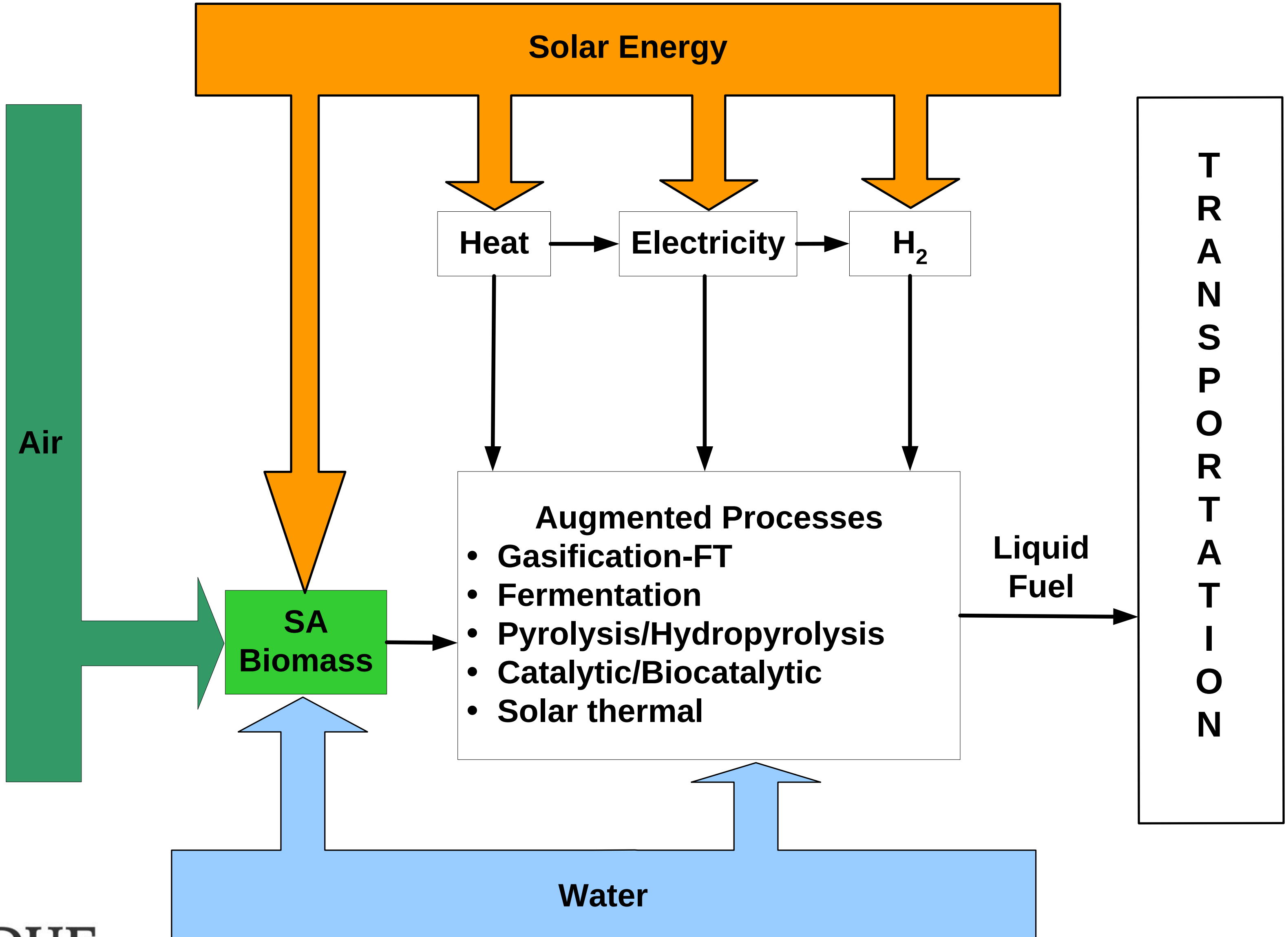
Challenge & Opportunity:

Design New Processes to increase biomass carbon recovery

Available forms of supplementary energy to increase biofuel yield

- Heat
- Electricity
- H_2

Augmented Processes : up to 100% biomass carbon recoverable as liquid fuel



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Augmented processes using H_2

100% SA biomass carbon recovery for US transportation

• SA biomass availability potential= 498 Million metric tons/yr[1]

•Transportation fuels use in the US, 2007 =13.28 Mbbl/day[2]

47% (6.2 Mbbl/day) of current US transportation demand produced using SA biomass with H_2CAR process

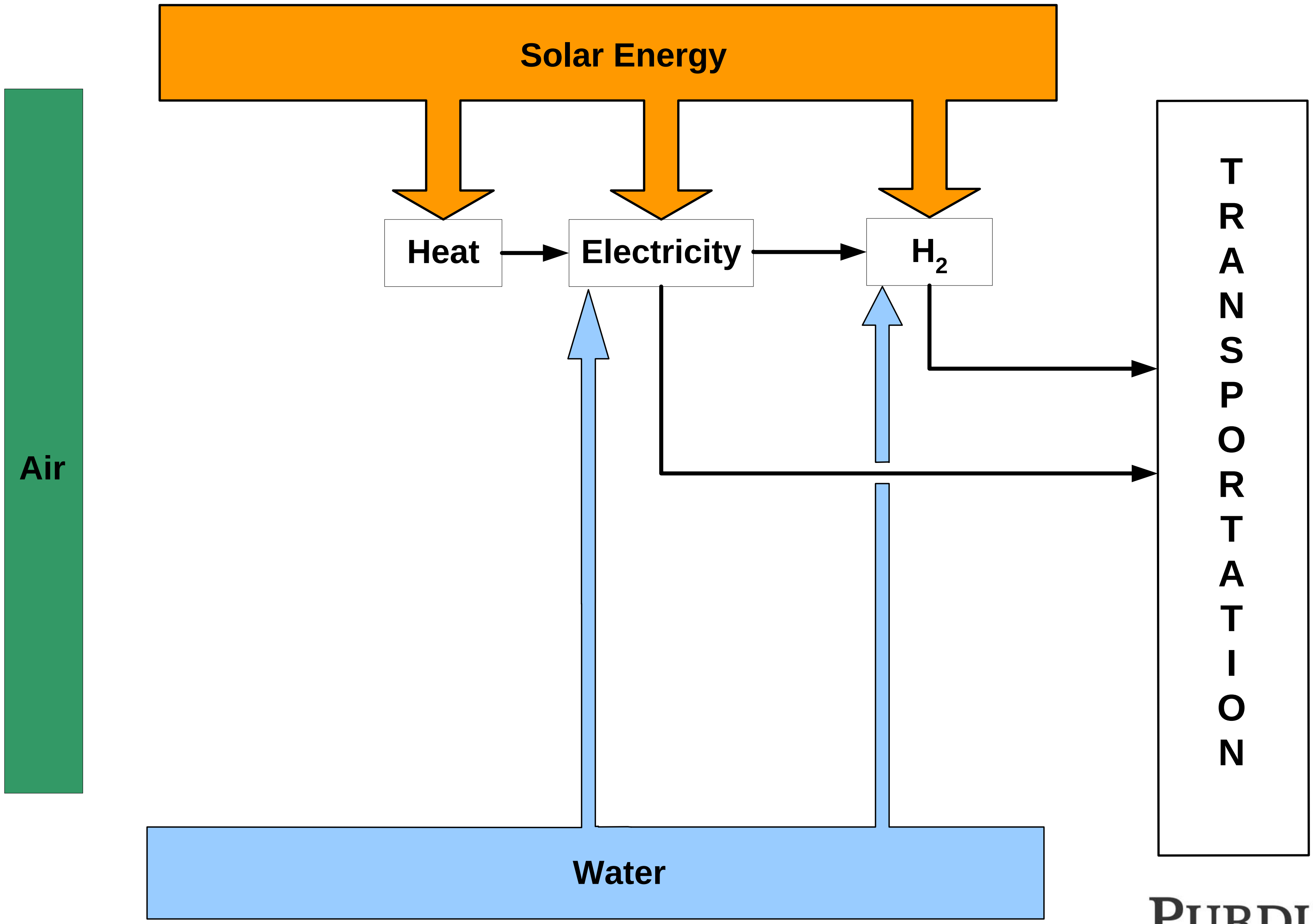
1. Liquid transportation fuels NRC report, 2010
2. Davis *et al.*, Transportation energy data book, 2009

H_2CAR estimated yield: 329 ethanol-gallon-equivalent/ton

Still >50% of deficit liquid fuel demand exists

How can we harness incident solar energy efficiently to meet the demand?

Use other efficient secondary energy forms from Sun



Use other efficient secondary energy forms from Sun

- Electricity via PHEVs for light duty vehicles (LDV)
- H_2 for Fuel Cell Vehicles

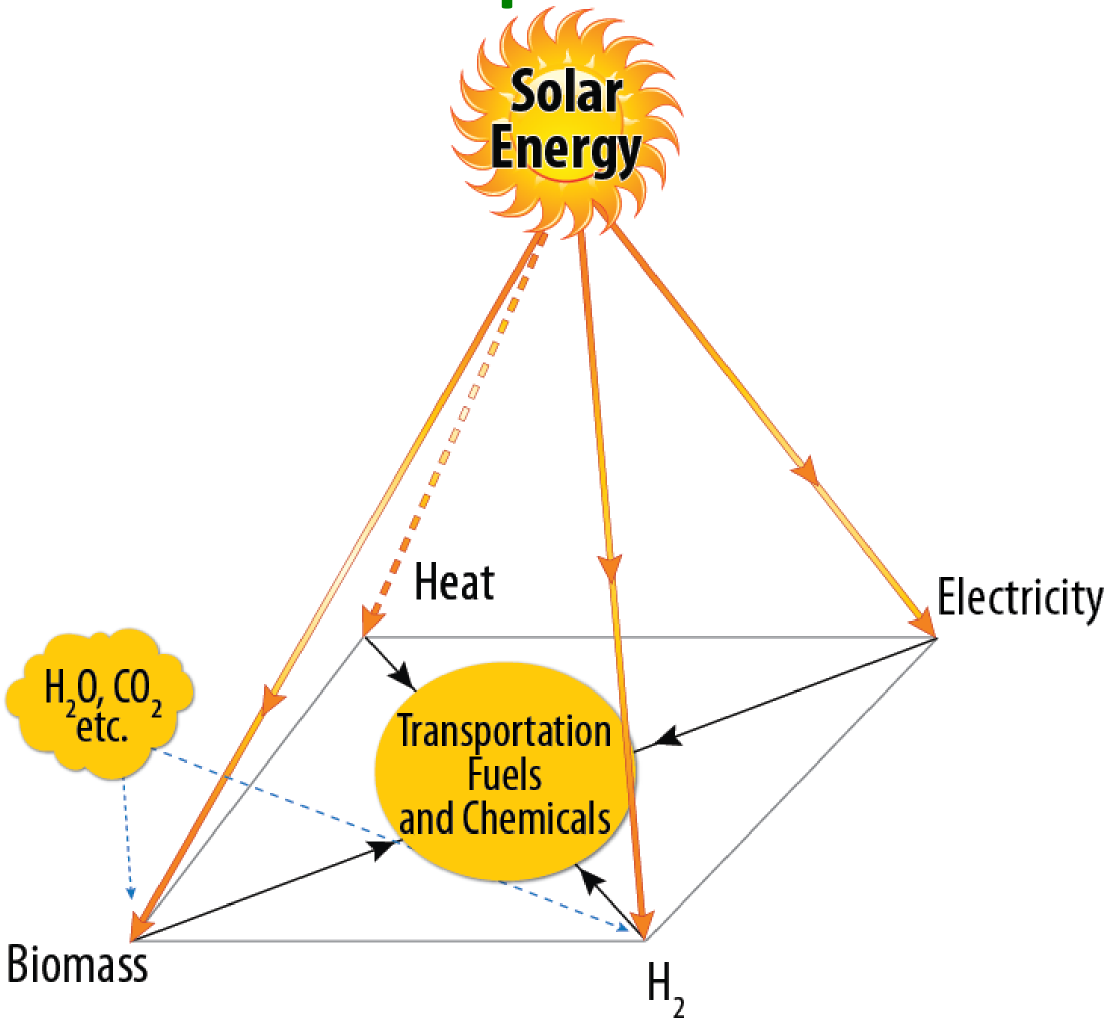
Use of PHEVs + Augmented processes (H_2CAR)

- SA biomass availability potential= 498 Million metric tons/yr[1]
- Transportation fuels use in the US, 2007 =13.28 Mbbl/day[2]
- Liquid fuel produced from SA biomass = 6.2 Mbbl/day
- Oil potentially displaced by PHEV40 = 5.5 Mbbl/day[3]

88.1% (11.7 Mbbl/day equivalent) of current US transportation demand could now be met

1. Liquid transportation fuels NRC report, 2010
2. Davis *et al.*, Transportation energy data book, 2009
3. Parks, Denholm and Markel, *NREL/TP-640-41410*, 2007

Systems analysis of the transportation sector and chemicals production



Synergistic integration at various levels needed!

Agrawal and Mallapragada, *AIChE J.* , 2010

Summary – Transformation of solar Energy: Analysis of Energy System

- Energy Systems Analysis is important – it provides valuable insights.

- Must develop efficient and cost effective solutions for a world driven by renewable energy.

- Must provide solutions for transition from fossil to renewable energy

- Energy Systems Analysis is Fun!

A Three Part Presentation …..

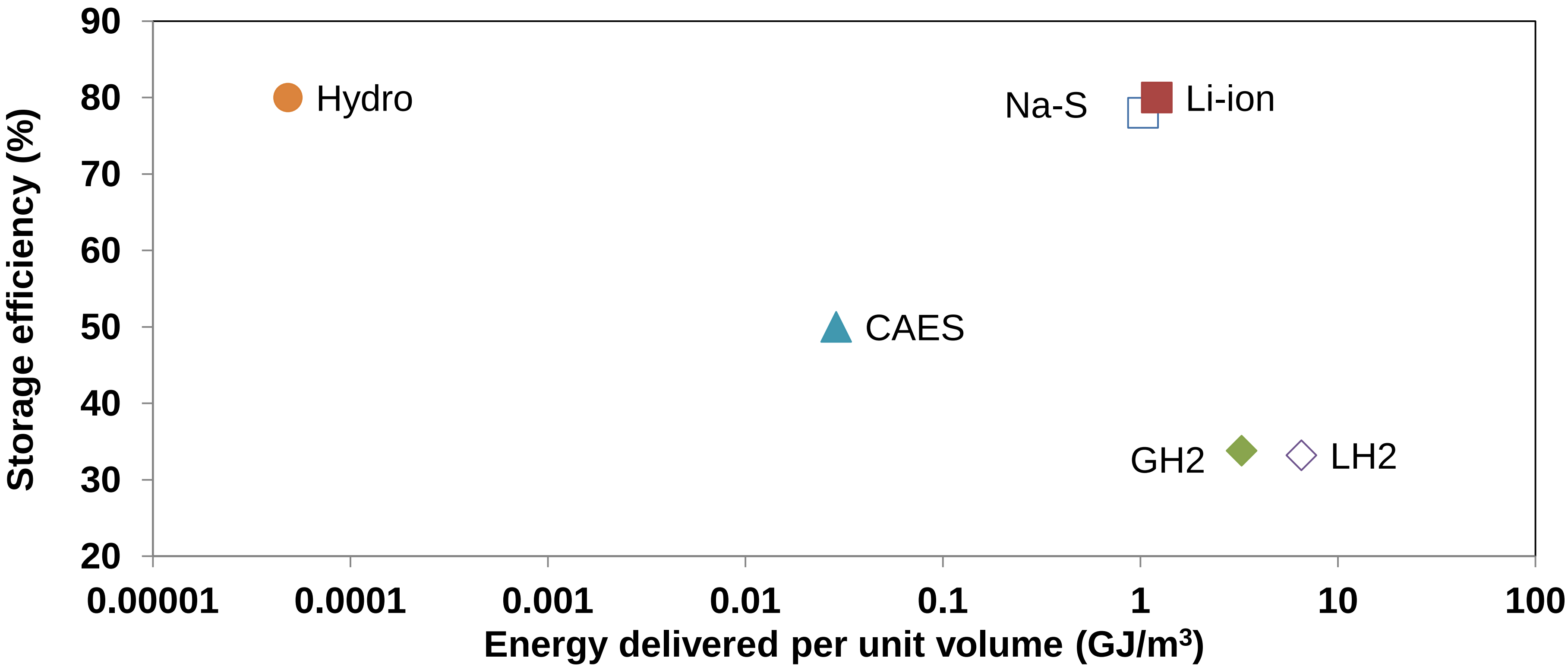
1. Harnessing of Solar Energy -- Solar Cells from Nanocrystal Inks

2. Transformation of Solar Energy -- Energy System Analysis with Emphasis on Transportation Sector

3. Storage of Solar Energy -- A Chemical Storage Cycle

GWh level Electrical Energy Storage

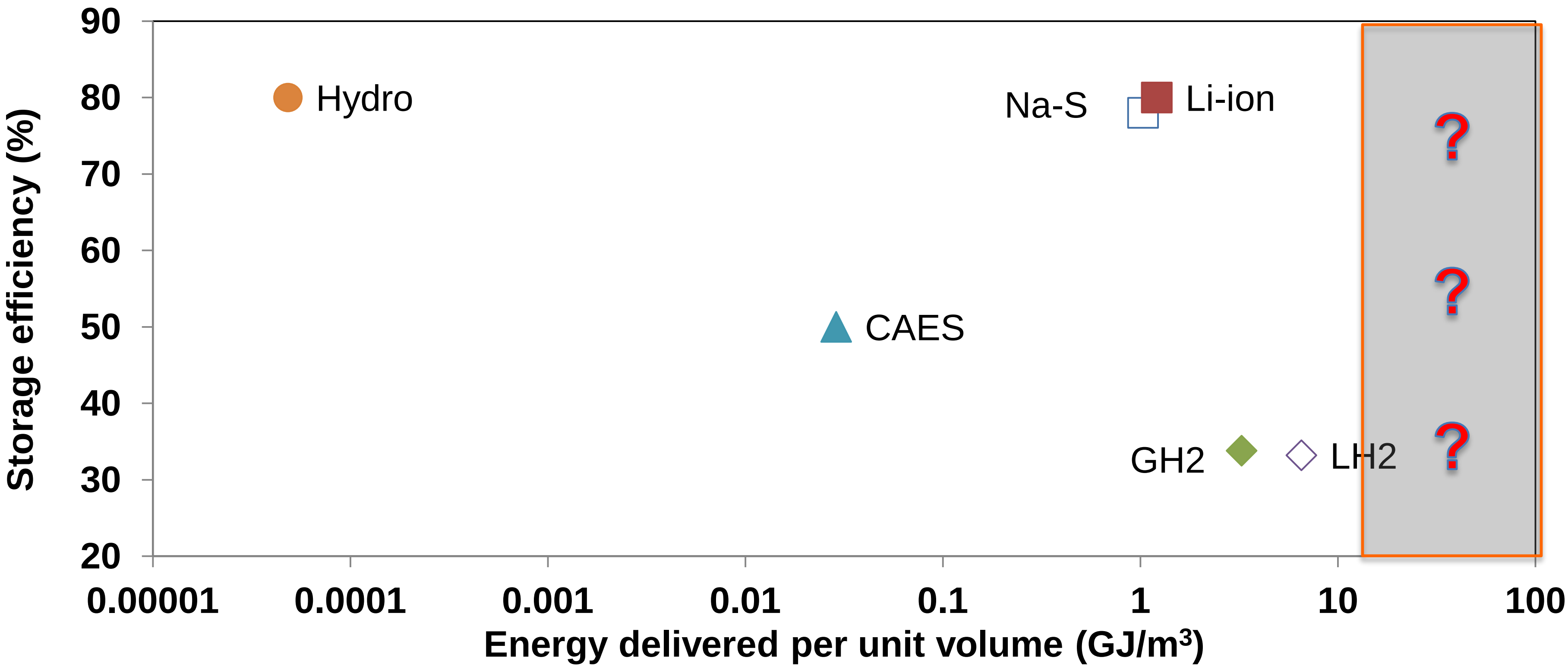
Some energy storage options



Need- high energy density and storage efficient solutions!

Reference: EPRI report on Storage Technologies, 2010
Hydro= pumped hydroelectric power, CAES= compressed air energy storage

Carbon fuels for energy storage



- **Store as liquid to minimize volumes**
- **Avoid handling large volume of pressurized gas**

Reference: EPRI report on Storage Technologies, 2010
Hydro= pumped hydroelectric power, CAES= compressed air energy storage

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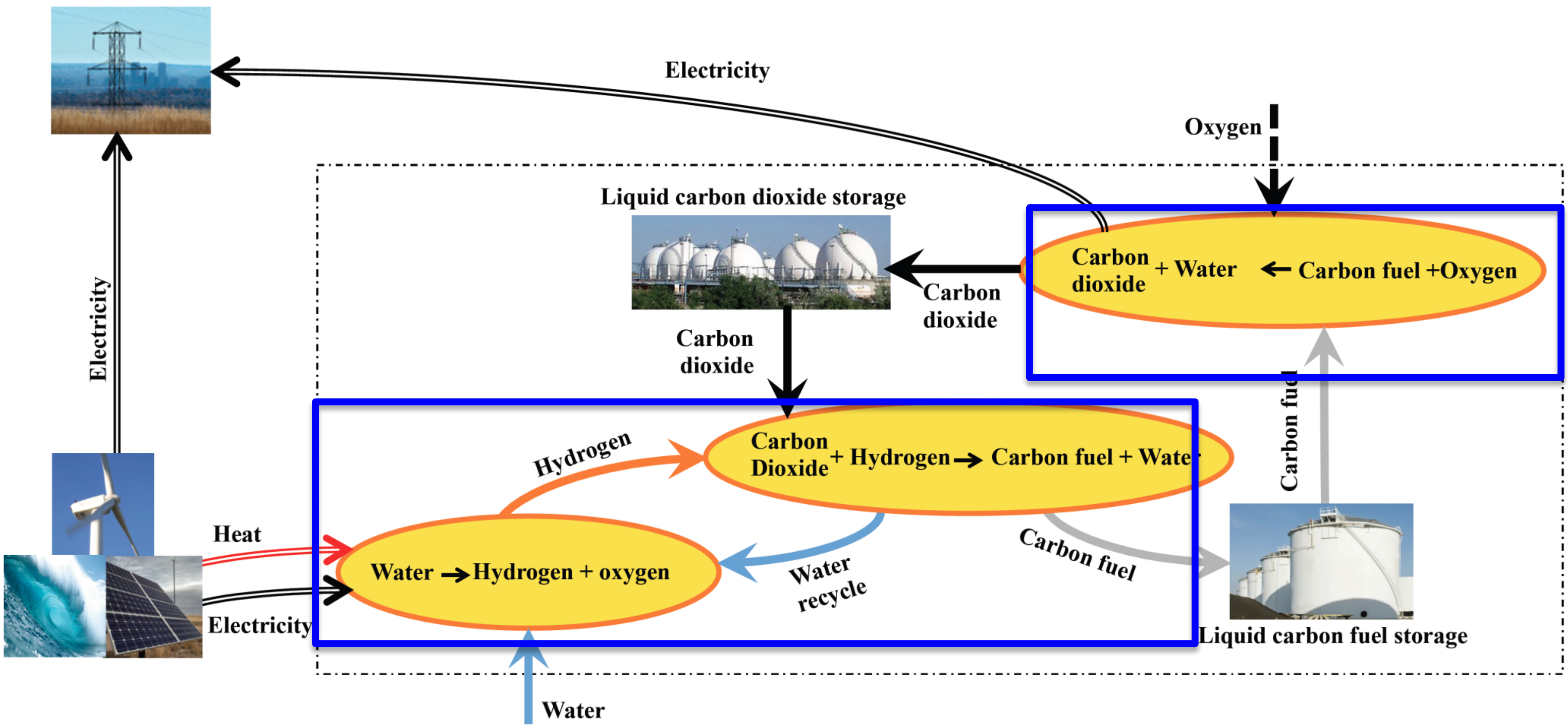
Closed carbon cycle for energy storage liquid CO_2 ←→ liquid fuel



Very little external carbon required as make up!

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Among carbon fuels..
… consider the use of methane

Fuel	Exergy per carbon (kJ/mol C)
Methane	**806**
Ethane	723
Propane	692
Iso-octane	652
Cetane	640
Methanol	693
Ethanol	654
Dimethyl Ether (DME)	684

- **CH_4 → highest energy content per carbon**
- **Liquefaction energy penalty (-162 ^{o}C)**

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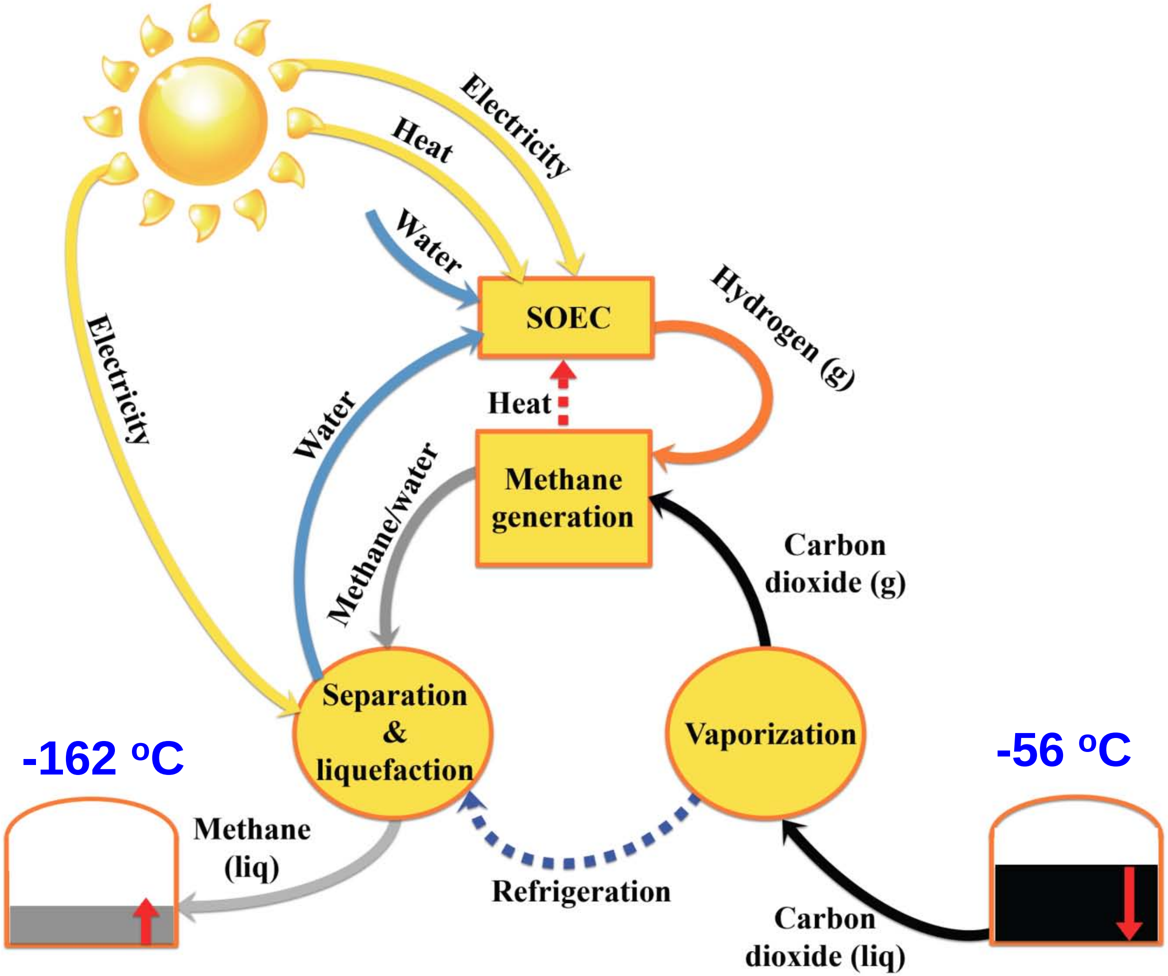
Methane-cycle (Storage mode)

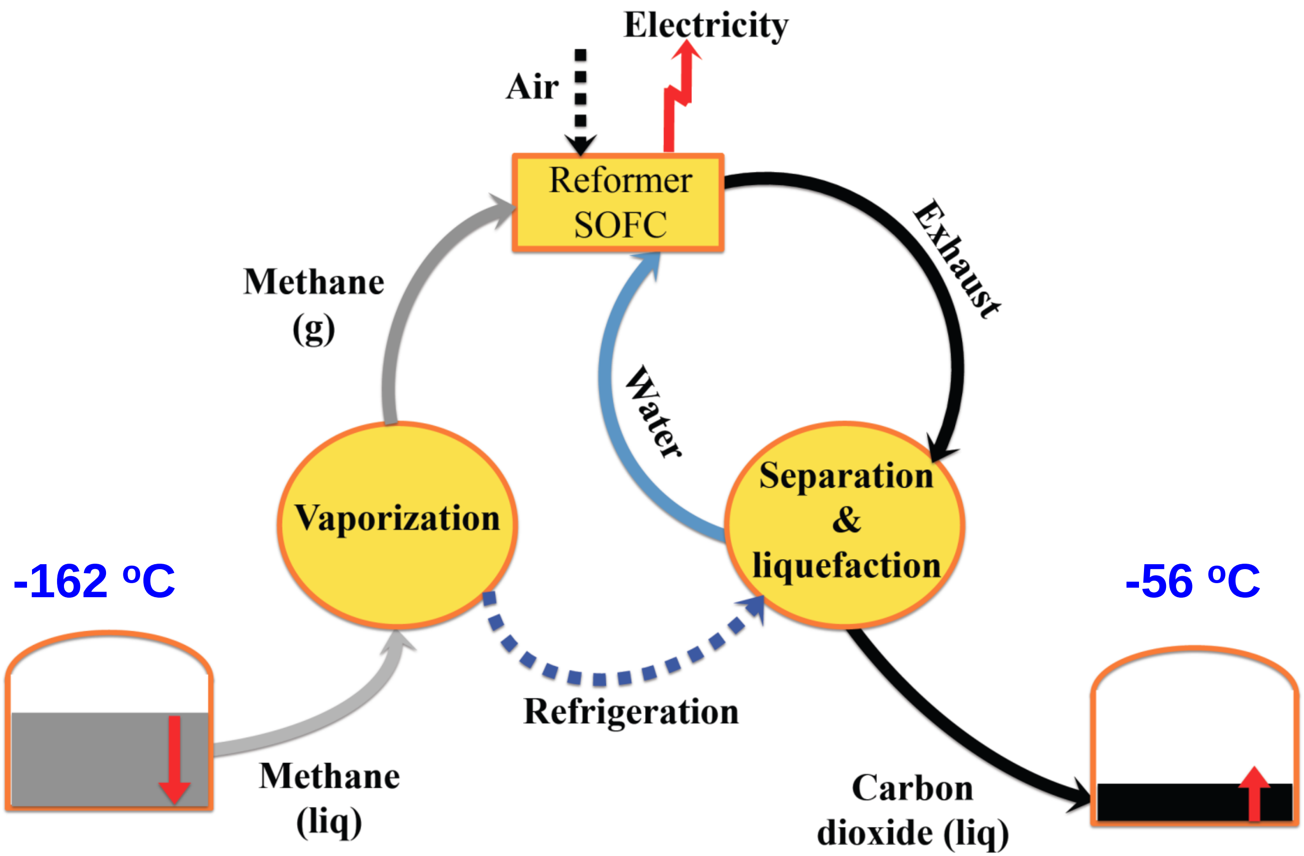


Minimize solar energy penalty of CH_4 liquefaction

SOEC=Solid Oxide Electrolysis

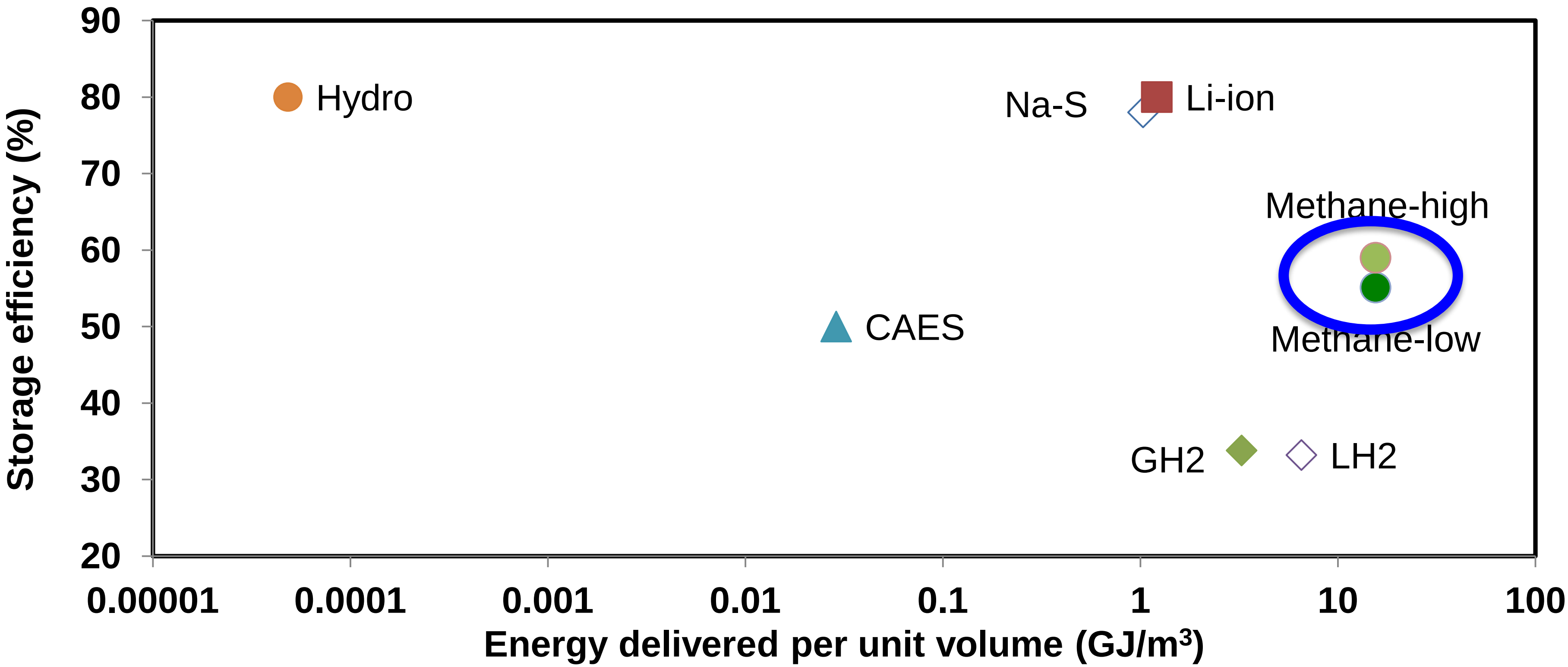
Methane-cycle (Delivery mode)

Solid Oxide Fuel Cell for electricity



No additional power consumed for CO_2 capture and liquefaction!

Methane storage simulation results



- **Efficiency:** **Methane superior to H_2**
- **Volume**: **Methane superior to other options**

Simulations carried out using Aspen Plus

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Summary – Storage of solar Energy: A Chemical Storage Cycle

- High storage efficiency cycles using methane and carbon dioxide storage.

- Other chemicals should also be explored.

In Conclusion…

- **Solar Economy is a must for long term existence of human civilization.**

- **We will have to learn to harness, transform and store solar energy on a time scale of use.**

- **Need for a careful systems analysis to identify synergies and create efficient conversion and use technologies.**

Overall Summary

" Great time to be a Scientist & an Engineer"

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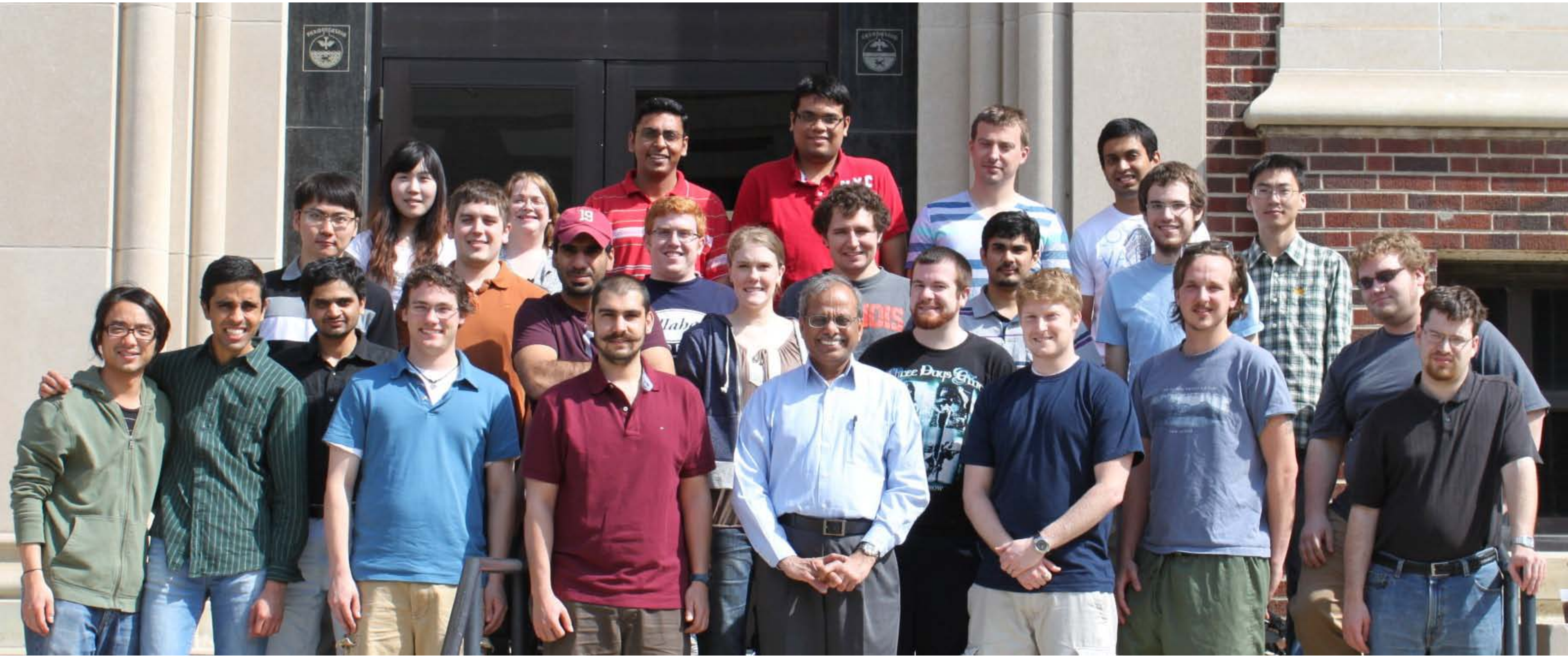
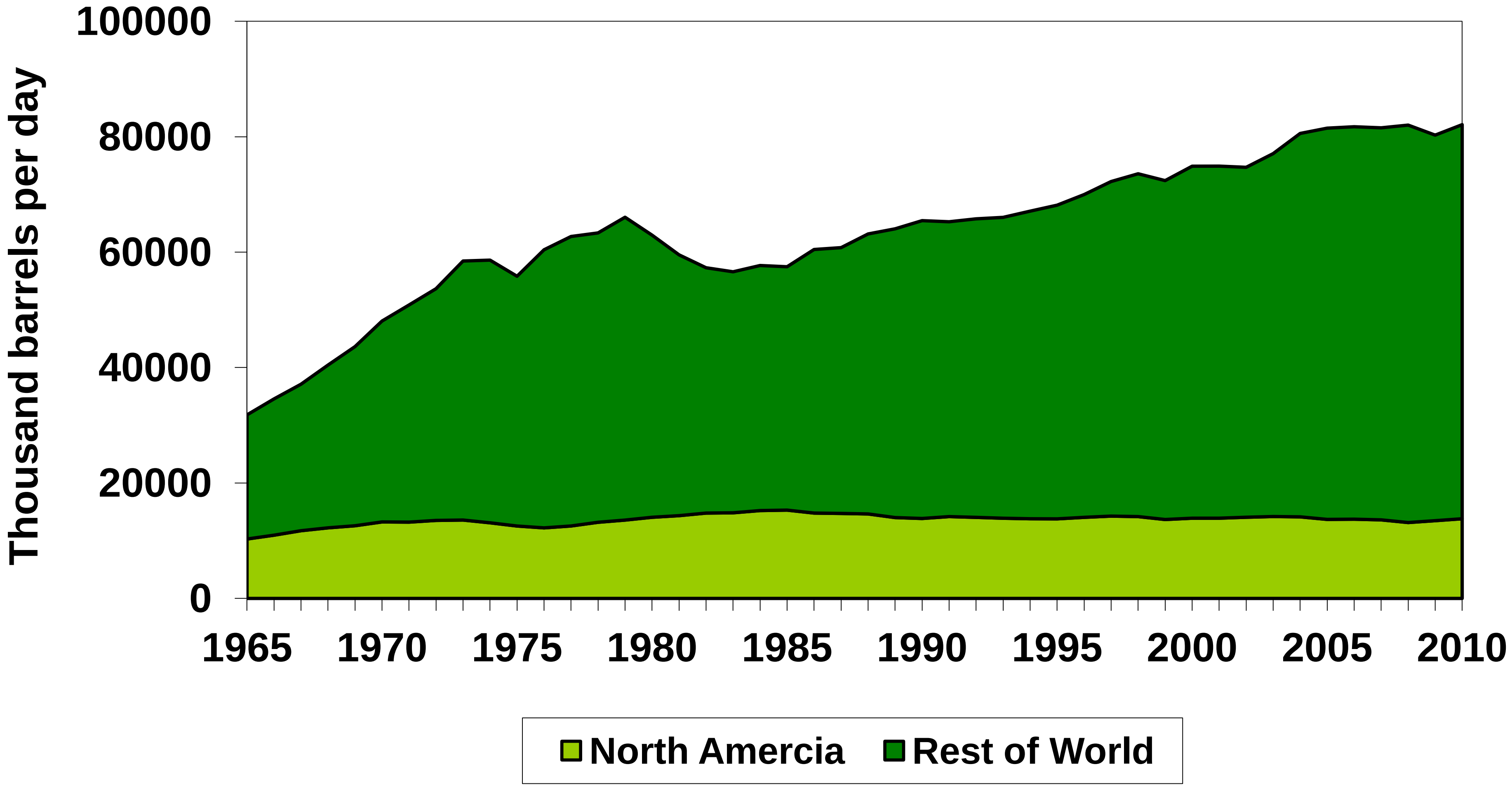
The Research Team




….Thank you

Availability of Primary Energy Sources

World Oil Production



Total proven conventional oil reserve = 1383 billion bbl

Source : BP Statistical Review of world Energy 2011

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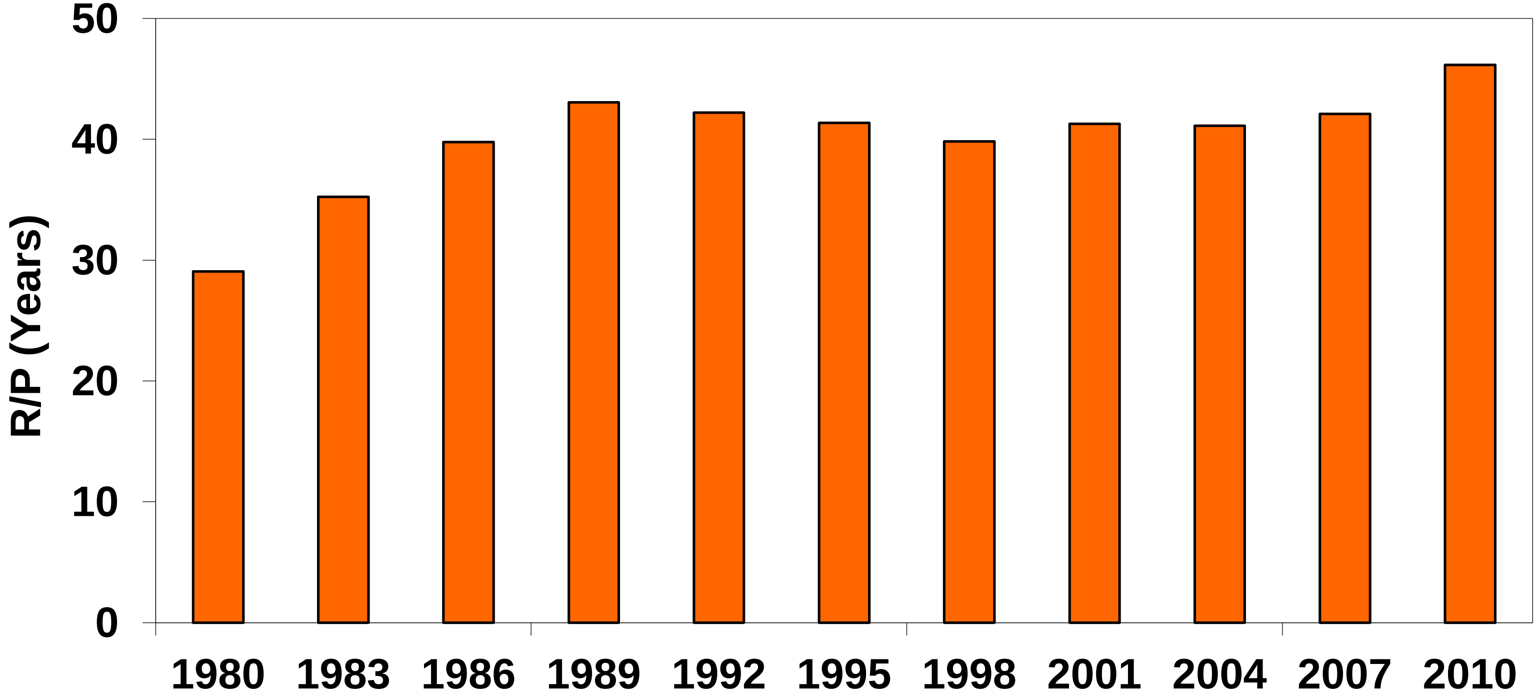
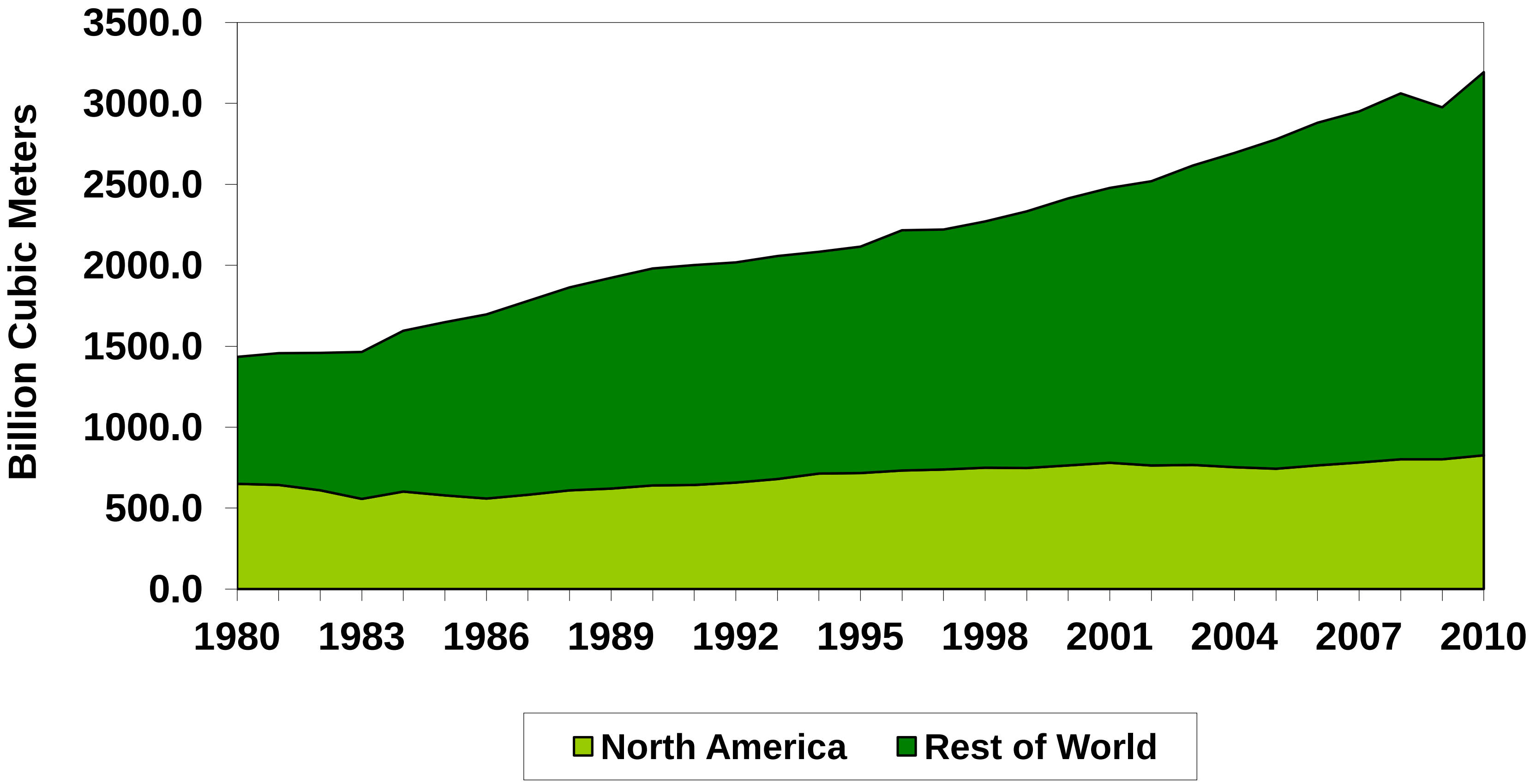
World Oil Reserves-to-Production (R/P) Ratios



- Reserves are 29% above 1997 level
- Production is 14% higher than 1997 level
- USA R/P = 11.3 years
- USA R/Consumption = 4.4 years

Source : BP Statistical Review of world Energy 2011

Natural Gas Production



- **Total proven gas reserve = 187.1 trillion m^3**
- **Natural gas demand continues to rise**

Source : BP Statistical Review of world Energy 2011

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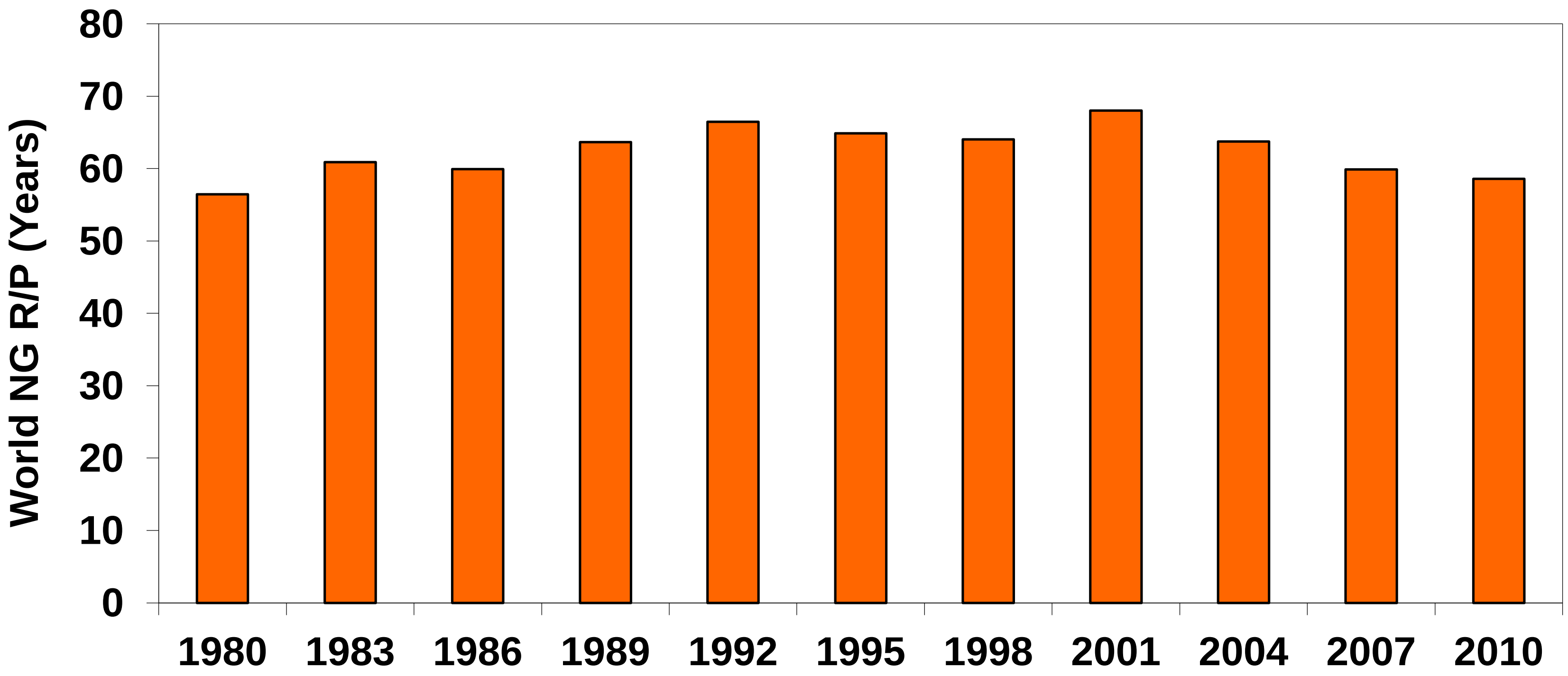
Natural Gas Reserves-to-Production Ratios



- **Reserves are 64% above 1997 level**
- **Production is 14% higher than 1997 level**
- **USA R/P = 118 years***
- **In USA, natural gas production has remained flat over the last decade, but sudden spike since 2007**

Source : BP Statistical Review of world Energy 2011
*** US Energy Information Administration**

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Coal

- Proven World Reserve = 860 billion tons
- World Reserve-to-Production Ratio = 118 years
- USA Reserve-to-Production Ratio = 241 years

Source : BP Statistical Review of world Energy 2011

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…..