A New Industrial Revolution for a Sustainable Energy Future

Opportunities and challenges for a sustainable energy future

Steven Chu and Arun Majumdar

Industrial Revolution: Horse Power to Horsepower

304 Horsepower

10,000 Horsepower

100,000 Horsepower
Global per Capita GDP

Global Primary Energy Consumption 1830 - 2010

www.theoildrum.com
World Population

Haber-Bosch process for making artificial fertilizer

Source: United Nations
Oil & Gas Reserves & Production

Global Oil Reserves

Global Gas Reserves w/o US Shale


Global Oil Production Capacity

US Gas Production Capacity


Edward Morse, “Energy: 2020 – North America, the New Middle East?” Citi Global Perspectives & Solutions (Citi GPS).
Weather Extremes

Shifting Distribution of Summer Temperature Anomalies

Hansen, Sato, Ruedy, “Perception of climate change,” PNAS, Aug. 6 (2012)
Cumulative CO₂ emissions since Industrial Revolution

1,100 Billion Tons

How much more CO₂ can we emit based on known fossil fuel reserves?

About 3,000 Billion Tons

75-100 years

Worth $10s of Trillion
The Stone Age did not end because we ran out stones

Sheikh Ahmed Yamani, former Oil Minister of Saudi Arabia

We transitioned to better solutions

New York, 5th Avenue, ~1890s

Detroit, circa 1920

The ~160,000 horses in New York and Brooklyn in 1880 were producing 3 - 4 millions pounds of horse manure a day.
Energy Systems

Current Learning Curve (Assured Path)

Scale in Size or Volume

Low-Cost Long-Term Capital (>20 years)

Project Size & Time
- <$10M (2-5 yrs)
- $10-100M (5-10 yrs)
- $100M-1B (>10 yrs)
- >$1-10B

Cost ($)/Performance

Technology Innovations

R&D from DOE

Applied Energy Programs

Manufacturing/Scaling Innovations

Deployment

R&D for Breakthrough Technologies to Create New Learning Curves

US Markets

Businesses

Consumers

US Gov't

Global Markets

Current Learning Curve (Assured Path)
Stationary Energy Systems
LEVELISED COST OF ENERGY Q3 2012 ($/MWH)

SunShot 2020 Target

LCOE=$400/MWhr

$8.00/W

$3.80/W

$190/MWhr

$1/W Target

Power Electronics
Balance of Systems (BOS)
PV Module

2004 Systems Prices
2010 Systems Prices
Power Electronics Cost Reductions
BOS Improvements
BOS Soft Costs Reductions
Module Efficiency Improvements
Manufacturing Cost Reductions

$0.22
$1.88
$1.70
$0.12
$0.72
$0.76
$0.80
$0.40
$0.10
$0.40
$0.50

$1/W

$0.00
$1.00
$2.00
$3.00
$4.00
$5.00
$6.00
$7.00
$8.00

Installed Systems Price ($/W)
\[
\frac{\text{Manufacturing Cost}}{\text{Watt}} \propto \frac{\eta}{\text{Efficiency}}
\]

\[
\eta \propto J_{SC} \cdot V_{OC} \cdot FF
\]

III-V Based 28% efficient solar cells on plastic substrate
Grid-Scale Storage (GWhr Scale)

MIT-24M
Target: $60/kWh
Electricity Grid
Power Electronics

8000 lbs, 60 Hz Distribution Transformer

Average Age: 42 years, 2 years beyond projected lifespan

Silicon Carbide IGBT; 15 kV, 100 A; 50 kHz from Cree Inc.

Potentially 100 lbs transformer
Transportation

- Light Duty Vehicles: 58.8%
- Trucks: 22.2%
- Buses: 7.8%
- Air: 5.8%
- Rail: 5.0%
- Water: 0.5%
- Pipeline: 0.5%
Reducing Vehicle Fuel Consumption


**10% WEIGHT REDUCTION = 6-8% HIGHER FUEL EFFICIENCY**

Carbon-Fiber Composite Cost Reduction
Vehicle Electrification

Electric Vehicles Comparable in Range and Cost w/o subsidies by 2022

<table>
<thead>
<tr>
<th></th>
<th>Current Status</th>
<th>PHEV40</th>
<th>AEV100</th>
<th>AEV300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Cost</td>
<td>$/kWh (usable)</td>
<td>650</td>
<td>190</td>
<td>300</td>
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<tr>
<td>Pack Specific Energy</td>
<td>Wh/kg</td>
<td>80-100</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Pack Energy Density</td>
<td>Wh/L</td>
<td>200</td>
<td>250</td>
<td>300</td>
</tr>
<tr>
<td>State-of-Charge Window</td>
<td>%</td>
<td>50</td>
<td>80</td>
<td>90</td>
</tr>
</tbody>
</table>

400 Wh/kg; C/10
80% depth of discharge

Roughly $250/kWh
Liquefied Natural Gas in Long-Haul Trucking

LNG Trucks
Extra Cost = $100,000
Fuel Savings = $40,000/year

Fueling Stations
Cost = $1.6M
Payback Period = 2-3 years

Source: Clean Energy Fuels
Natural Gas Light-Duty Vehicles

Infrastructure Challenge

160,000 gasoline stations
CNG Infrastructure Cost > $100B

60M Homes have NG

Storage Challenge

System = Compressor + Tank < $2000

High Pressure
Multistage Compressor
Carbon-fiber composite tank

Low Pressure
Sorbent material

REDUCE STORAGE SYSTEM COST TO REDUCE PAYBACK PERIOD FROM 10-15 YEARS TO 5 YEARS
Photosynthetic Biofuels

Sugarcane

Corn

Algae

Cellulose

Less than 1% efficient
Alternative Fuels Cost (10-15 years)

$50/tCO₂

CO₂ cost (ignoring indirect CO₂ consequences)
Carbon storage cost
Additional transportation
Non-feedstock operating cost
Capital cost
Feedstock cost
Total cost (without carbon price)

Electrofuels

Non-photosynthetic Microbes

Electricity

Sour Crude

H₂S

H₂

>10X more efficient than photosynthesis

OPX Biotechnology & North Carolina State University
Typical Time and Money Needed for Energy Projects

- $1-10M: 2-5 yrs
- $10M-1B: 5-10 yrs
- $1B & more: >10 yrs

Demand Pull

R&D to translate science into innovative technologies

Manufacturing: Innovations in cost reduction and scale up

Commercial Deployment

Markets

Government RD&D Investment

Equity and Debt Investments from Public & Private Capital Markets

Financial and Regulatory Policy Options

- 48C
- Energy Efficient Appliance Manufacturing Tax Credit
- Loan Guarantees

- 1603 Grants
- ITC & PTC
- Clean Energy Bonds
- Master Limited Partnership (MLPs)
- Loan Guarantees
- Energy Efficient New Homes Tax Credit

- CAFE standards
- Renewable Fuel Standards
- Renewable Energy Standards
- Appliance Standards
- Clean Energy Standards
- Government Procurement
## How are we doing?

<table>
<thead>
<tr>
<th>Stationary Energy Systems</th>
<th>Capacity for Technological Innovation</th>
<th>Markets</th>
<th>Access to Long-Term Low-Cost Capital</th>
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<tr>
<td></td>
<td>Need sustained increasing funding for Energy RD&amp;D: ARPA-E; Office of Science; Applied Energy Programs;</td>
<td>Carbon price; Clean energy standards; Appliance standards; Building/Industrial codes &amp; standards</td>
<td>Master Limited Partnerships; Real Estate Investment Trusts; Time-limited predictable financial incentives</td>
</tr>
<tr>
<td>Transportation</td>
<td></td>
<td>CAFE; Low-Carbon Fuel Standards</td>
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</table>
If we don’t change direction soon, we will end up where we are heading!

IEA World Energy Outlook
Green Electricity Network Integration (GENI)

Telephone ➔ Fiber Optics, Wireless, Internet
Today’s Grid ➔ ?

• Electric Power Routers
• Grid Operating System

Interruption Storage
Baseload
Buildings
Fast Start/Stop
Plants Engineered to Replace Oil (PETRO)

Today
80 GJ/ha-yr

Future
160 GJ/ha-yr @ $50/BOE

Algae
LBL & UC Berkeley

Tobacco

Loblolly Pine

Tapping pine trees

U. Florida
Matching Generation and Load Instantaneously

New England Independent System Operator (NE-ISO)

Energy Dispatch (Day Ahead): 12,985 MW
Energy Dispatch (Real-Time [includes Day Ahead]): 14,937 MW

Thirty Minute Operating Reserve: 5785 MW

Ten Minute Spinning Reserve: 725 MW
Ten Minute Non-Spinning Reserve: 1519 MW

Frequency Regulation: 100-200 MW
Control Infrastructure

**Improved Sensing**

A PMU measures
- Current (Hall sensor)
- Frequency (LC Circuit)
- Time (GPS)
- Voltage
- Relative Phase
- **Sample 30 msec**
- Petabyte-scale data

**Improved Communications**

Grid Connected Router
- Low-latency
- MPLS
- Cyber security
- 100-600 μs for crypto

**Improved Computation**

Distributed computing
- Fast
- Secure
- Resilient