Game Changers?

EIA Energy Conference
April 2011

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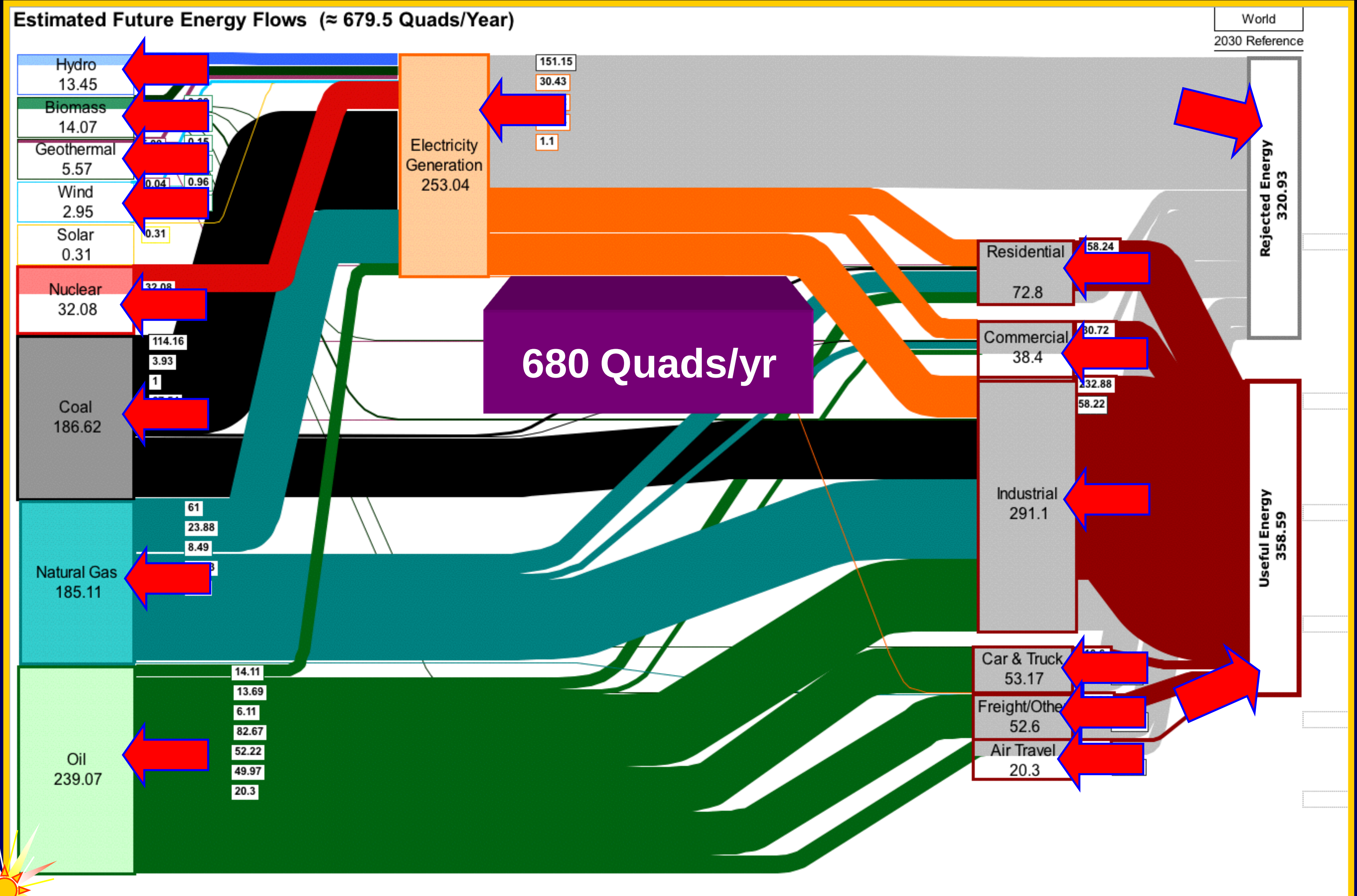
Cecil and Ida Green Professor of Physics and Engineering Systems
Director, MIT Energy Initiative

Global Energy Consumption 2030



Source: Lawrence Livermore National Laboratory, John Ziagos

Game Changers from 20th Century

100 years of innovation

- Artificial Fertilizers
- Green Revolution
- Polio Vaccination
- Antibiotics
- Airplanes
- Electrification
- Nuclear Energy
- Transistor
- Integrated Circuits
- Fiber Optic Communication
- Wireless Communication
- Internet

arpa·e

20 years

Imagine all of this happening in the next 20 years…

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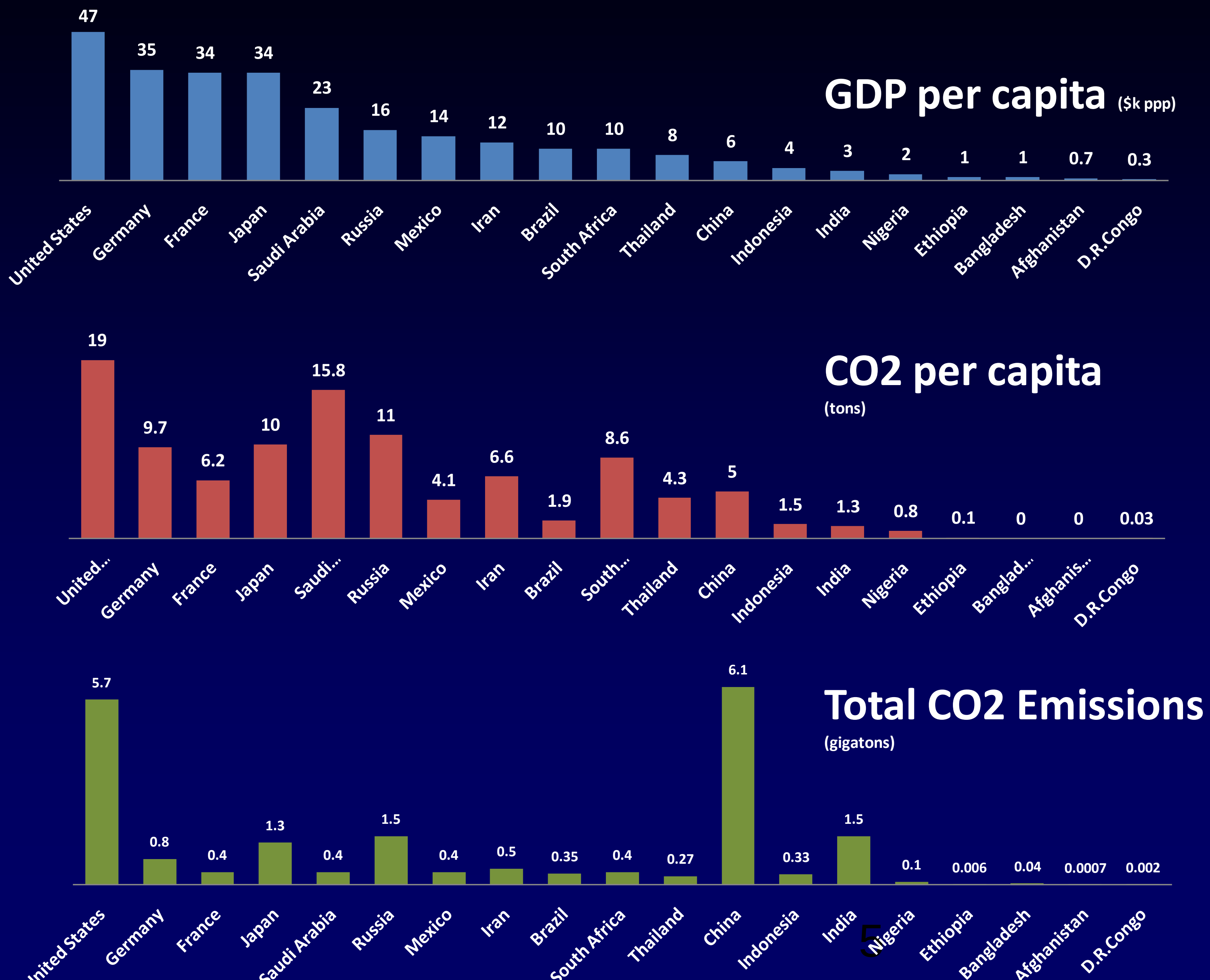
Energy System Characteristics

- Multi-trillion $/year revenues
- Very capital intensive
- Commodity business/ *cost sensitive*
- Established efficient supply chains, delivery infrastructure, and customer bases
- Provides essential services for all activities
- Reliability valued more than innovation
- Highly regulated
- Complex politics/policy driven by regional considerations


GDP per capita ($k ppp)
47
35
34
34
23
16
14
12
10
10
8
6
4
3
2
1
1
0.7
0.3
United States
Germany
France
Japan
Saudi Arabia
Russia
Mexico
Iran
Brazil
South Africa
Thailand
China
Indonesia
India
Nigeria
Ethiopia
Bangladesh
Afghanistan
D.R.Congo
CO2 per capita
(tons)
19
9.7
6.2
10
15.8
11
4.1
6.6
1.9
8.6
4.3
5
1.5
1.3
0.8
0.1
0
0
0.03
United...
Germany
France
Japan
Saudi...
Russia
Mexico
Iran
Brazil
South...
Thailand
China
Indonesia
India
Nigeria
Ethiopia
Banglad...
Afghanis...
D.R.Congo
Total CO2 Emissions
(gigatons)
5.7
0.8
0.4
1.3
0.4
1.5
0.4
0.5
0.35
0.4
0.27
6.1
0.33
1.5
0.1
0.006
0.04
0.0007
0.002
nited States
Germany
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Japan
Saudi Arabia
Russia
Mexico
Iran
Brazil
South Africa
Thailand
China
Indonesia
India
Nigeria
Ethiopia
Bangladesh
Afghanistan
D.R.Congo

“Perfect storm” of energy challenges

- Energy services for 10 billion people at mid-century?
- Environment/climate change: “de-carbonize” by mid-century?
- Energy security given geological and geopolitical realities: diversify transportation fuels?

Fundamental question: Can we significantly decrease energy and carbon intensity while accommodating needed economic growth? Is technology the solution?

Cost Reduction!

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US Carbon Dioxide Emissions (EIA BAU)

Millions of Metric Tons

	Residential + Commercial		Industrial		Transportation		Total	
	2006	2030	2006	2030	2006	2030	2006	2030
Petroleum	153	137	421	436	1952	2145	2526	2718
Natural Gas	392	483	399	433	33	43	824	959
Coal	10	9	189	217	0	0	289	226
Electricity	1698	2295	642	647	4	5	2344	2947
TOTAL	2253	2924	1651	1733	1989	2193	5983	6822
		1.1%/yr		0.2%/yr		0.4%/yr		0.6%/yr

Meeting Administration's 2050 83% Emission Reduction Goal

Assume: - Constant per capita electricity use (13 MWhr/yr)
- 2050 Population grows from 300M to 400M
- Electricity Sector reduces emissions by 83%

Source	Electricity (TWhr)	CO^2 Emit (Gton)	Electricity (TWhr)	CO^2 Emit (Gton)
Coal	1800	1.85	0	0
Natural Gas	785	.4	800	0.4
Nuclear	800	0	1500-2500	0
Hydro	250	0	250	0
Renewables /CCS	130	0	2450-1450	0
Petroleum	40	.04	0	0
Total	**3800**	**2.3**	**5000**	**0.4**

2010 U.S Electricity Consumption and CO_2 Emissions. *EIA*

Assumed 2050 electricity production to meet -83% CO_2 emission goals.

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Oil and Energy Security

- Core Issue: inelasticity of transportation fuels market
  - need arbitrage at the consumer level/flex-"fuel" vehicles/open fuel standard

- Addressing sudden disruptions
  - Strategic reserves
  - Well-functioning markets

- Increasing and diversifying supplies
  - Enhanced production from existing fields
  - Arctic E&P
  - "Unconventional" oil (tar sands,…)

- Weakening the "addiction"
  - Very efficient vehicles/engines-fuels
  - Alternative fuels (coal, NG, biomass)
  - New transportation paradigm (electricity as "fuel"? H_2?)

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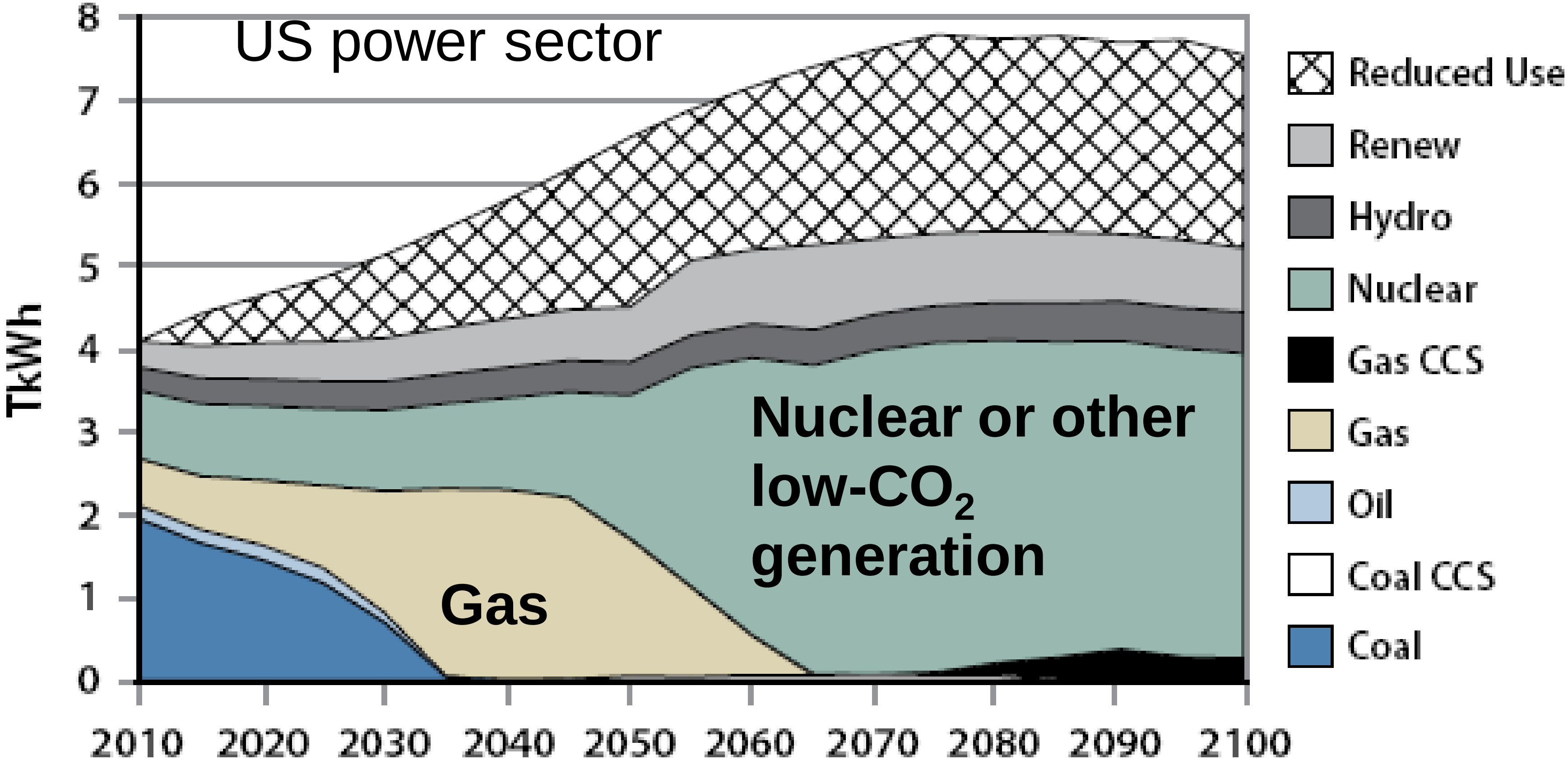
MIT Future of Natural Gas Study:
www.mit.edu/mitei/

Gas: A Bridge to ???



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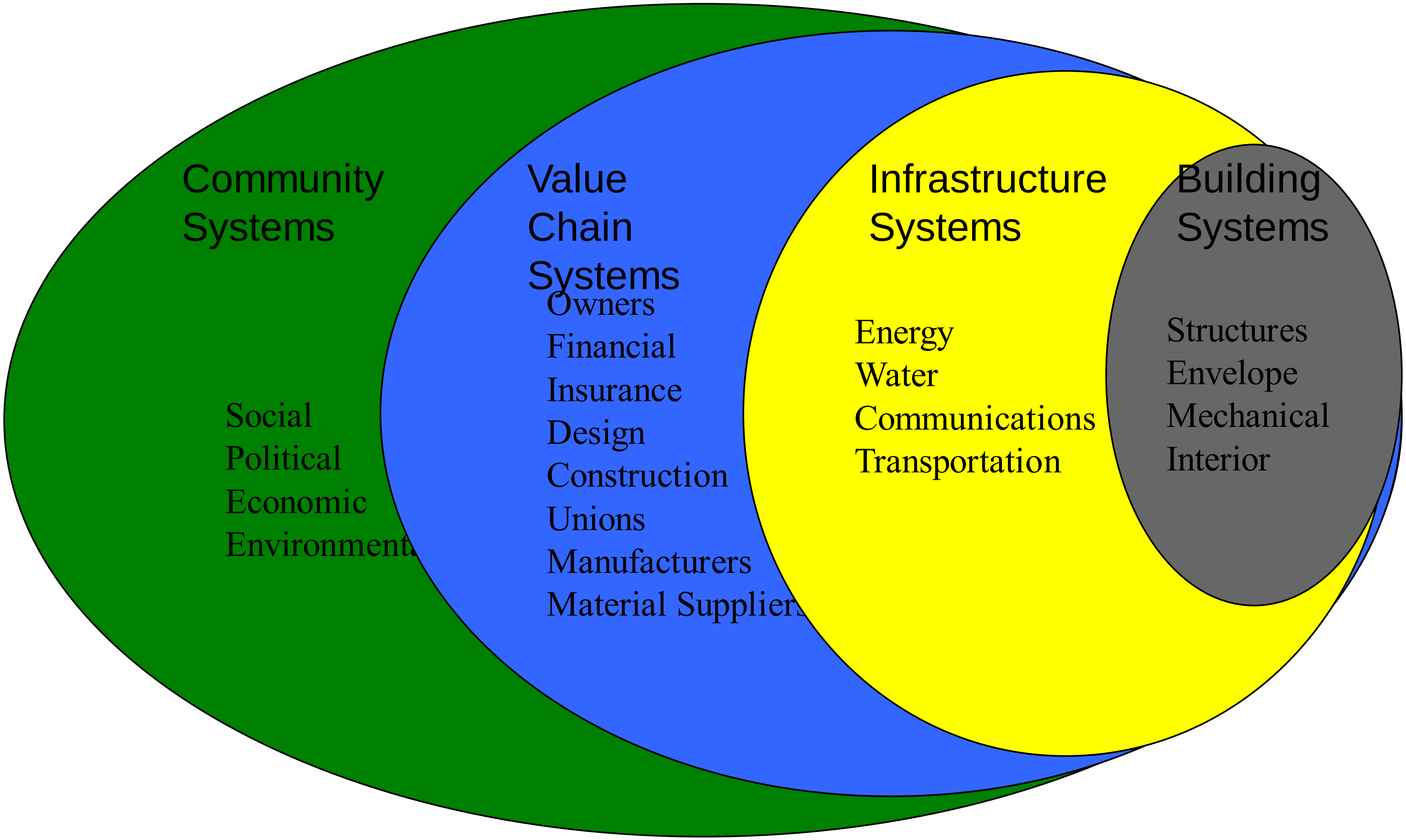
Technology Pathways

- **Efficiency** (buildings & cities, vehicles & transportation systems, supply chains, industrial processes, smart infrastructure)***
- **C-"free" electricity** (renewables/solar…, nuclear, coal/NG+CCS)***
- **Alternative transportation fuels** (biofuels, NG, electricity, H2)**
- **Energy delivery systems** (storage***, high quality power, distributed generation)**
- **Unconventional hydrocarbons** (EOR, heavy "oil", NG**)*
- **"Managing" global change** (adaptation*, atmospheric "re-engineering"/time scale, location) ?

Systems Approach



S. Slaughter

Selected Example Projects

- Advanced Components and Materials
  - Nano-engineered surfaces for hydrophilic/phobic surfaces
  - Insulating wallpaper
  - Organic LED
  - Tuned Multi-Functional Envelopes
  - Sustainable Nano-engineered Structural Materials

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Innovative Building/Frugal Engineering

- Faculty and students conducted research in materials and construction to achieve 90% reductions in energy use, working closely with South African professionals
    - Non-toxic materials
    - Local labor
    - Innovative use of agricultural and industrial by-products

- Innovative Mapungubwe Museum won multiple international design awards, including "World Building of the Year" in 2009

- One faculty member (J. Ochsendorf) and three graduate students led this research

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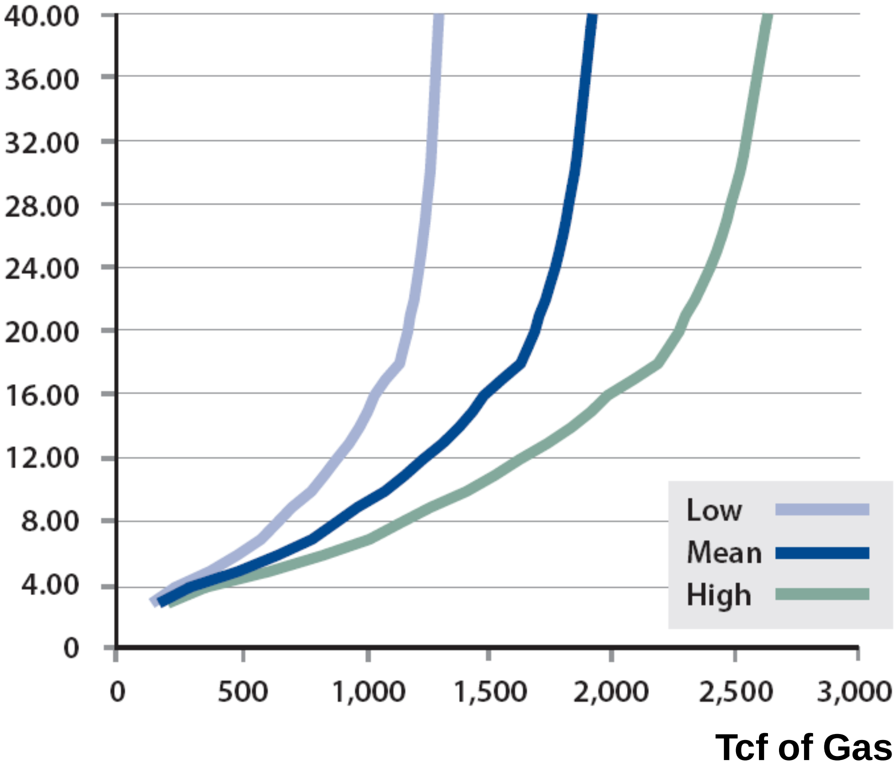
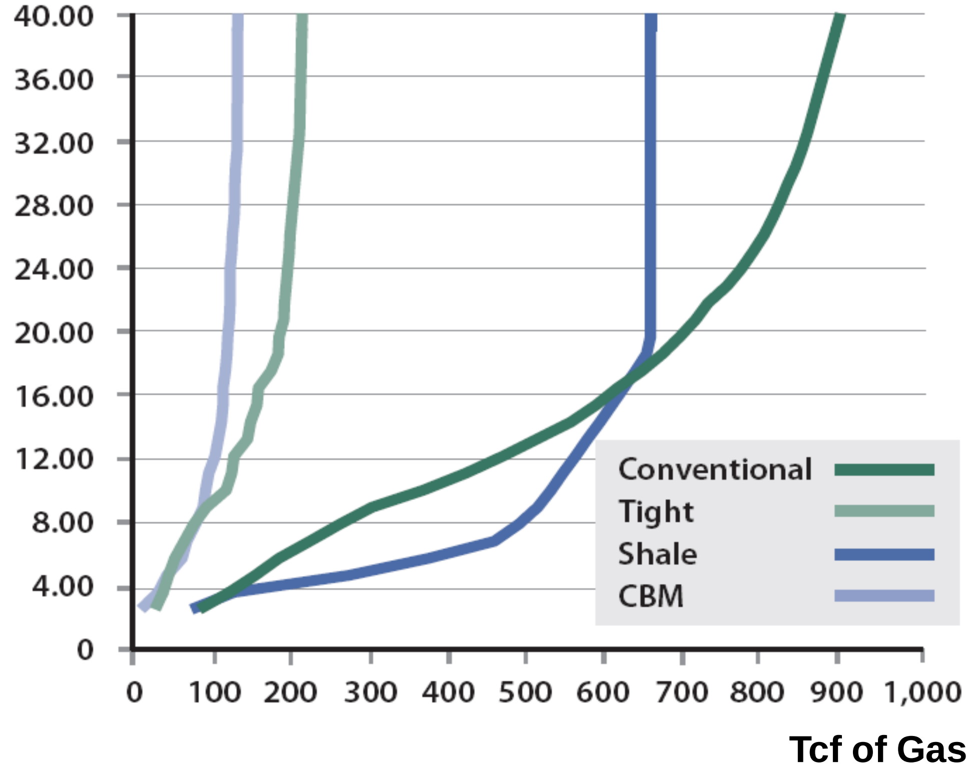
U.S. Gas Supply Cost Curve

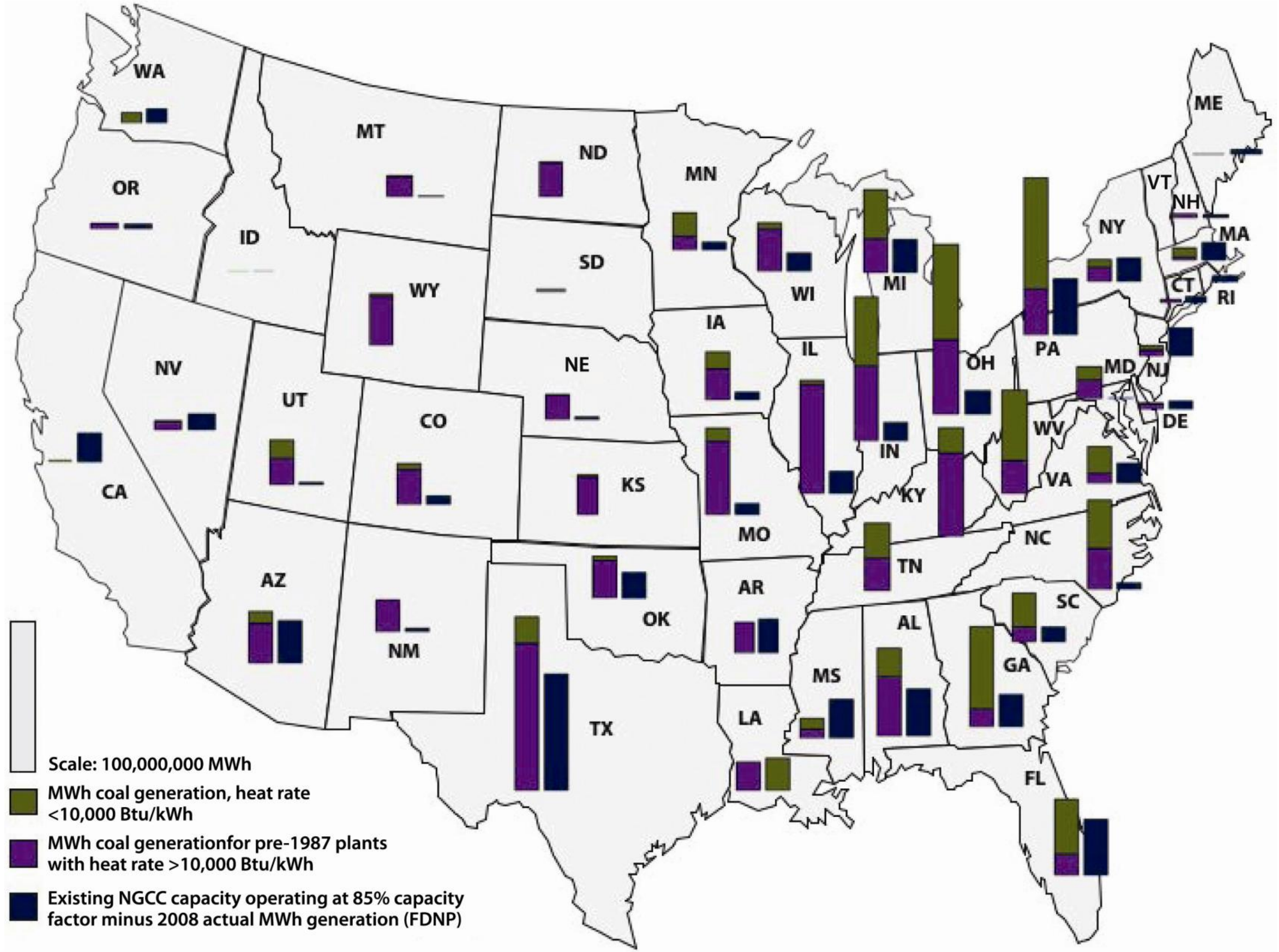
Breakeven Gas Price*
$/MMBtu



Breakdown of Mean U.S. Supply Curve by Gas Type
Breakeven Gas Price*
$/MMBtu



* Cost curves calculated using 2007 cost bases. U.S. costs represent wellhead breakeven costs. Cost curves calculated assuming 10% real discount rate, ICF Hydrocarbon Supply Model


WA
OR
ID
MT
ND
SD
WY
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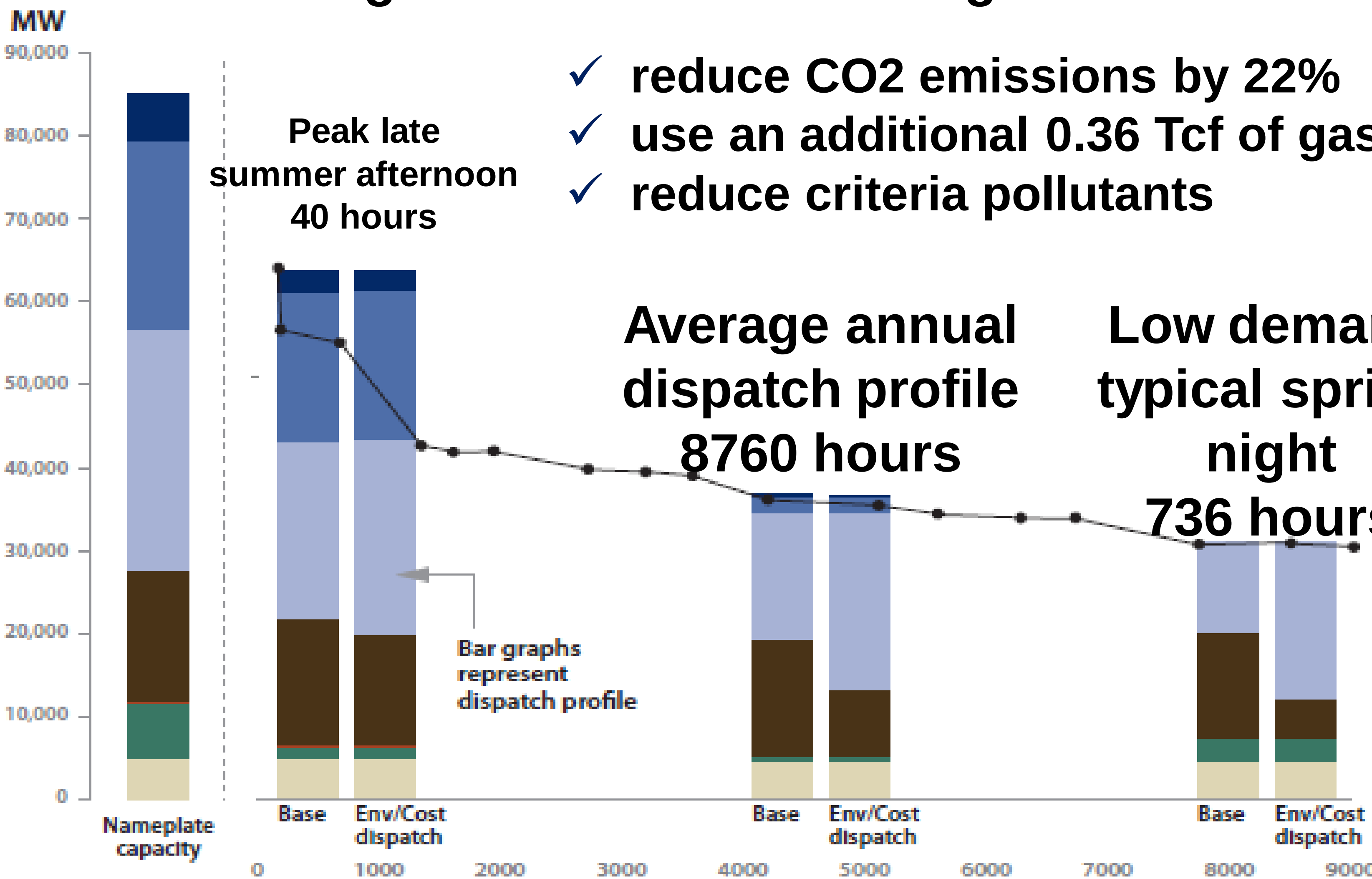
AR
LA
WI
IL
MI
IN
OH
KY
TN
MS
AL
GA
FL
SC
NC
VA
WV
PA
NY
MD
NJ
DE
ME
VT
NH
MA
CT
RI
Scale: 100,000,000 MWh
MWh coal generation, heat rate <10,000 Btu/kWh
MWh coal generationfor pre-1987 plants with heat rate >10,000 Btu/kWh
Existing NGCC capacity operating at 85% capacity factor minus 2008 actual MWh generation (FDNP)

Coal generation displacement with NGCC generation in ERCOT region would:

- ✓ reduce CO2 emissions by 22%
- ✓ use an additional 0.36 Tcf of gas/yr
- ✓ reduce criteria pollutants



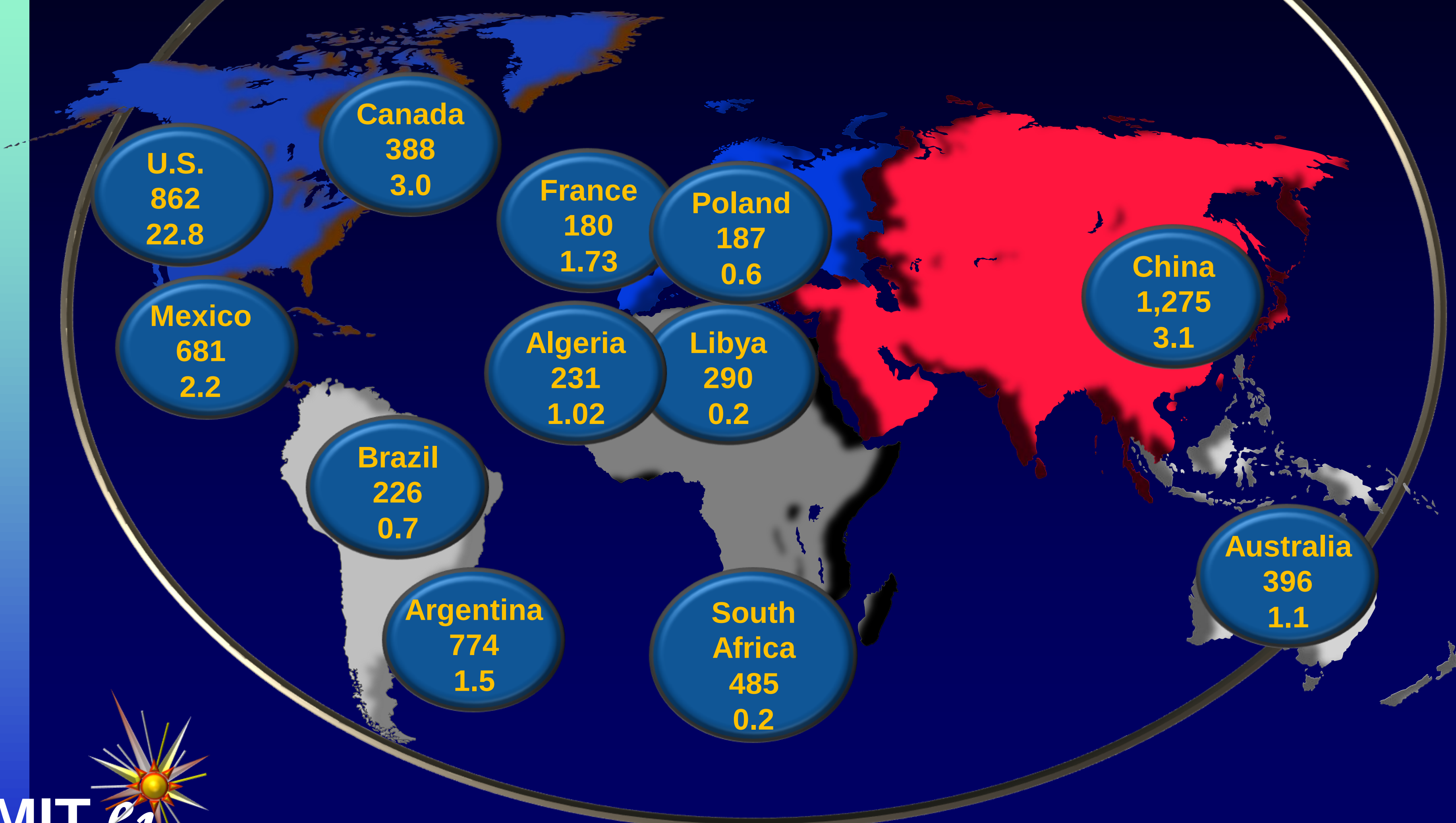
Peak late summer afternoon 40 hours

Average annual dispatch profile 8760 hours

Low demand typical spring night 736 hours

Global Shale Opportunities (EIA/ARI)

technically recoverable shale reserves and 2009 consumption (Tcf)



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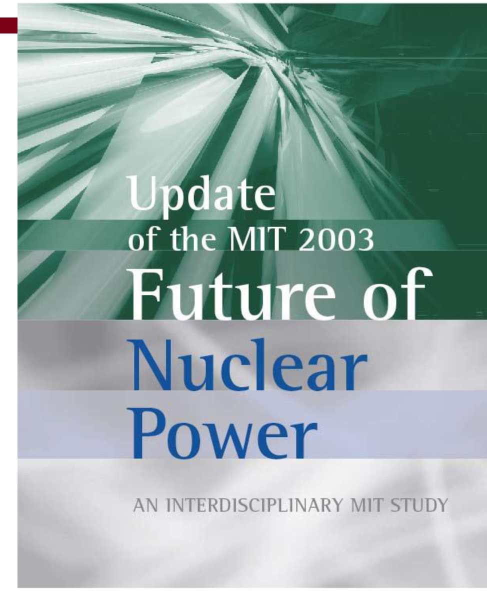
* Excludes Russia, includes Eurasia

Affordable Electricity

Large Plant Investment
$8-10B, >5yrs ???

"nuclear power can be economically competitive under appropriate market conditions."



Levelized Cost of Electricity

Cost of Carbon

	Overnight Cost	**Fuel Cost**	**Base Case**	**$25/Ton CO_2**	**= Cost of Capital**
$2007	$/KW	$/MBTU	¢ KWHR	¢ KWHR	¢ KWHR
Nuclear	4000	0.67	8.4		6.6
Coal	2300	2.6	6.2	8.3	
Gas	850	4/7/10	4.2/6.5/8.7	5.1/7.4/9.6	

Loan Guarantees for large plant "first movers"

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Post-Fukushima?

- Will not know for some time how events unfolded, extent of health and environmental problems, and lessons learned
- Nevertheless there are some good bets

- Costs will go up – spent fuel management, design accidents,…?
  - Increased focus on small modular reactors?
- Life extension of existing plants (active safety systems) from 40 years to 60 years will get more scrutiny – replacement? New nuclear?
- Spent nuclear fuel will be managed differently – consolidate dry storage?
- The R&D focus will shift from advanced fuel cycles more towards next generation reactors and waste management

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CASL vision: Create a virtual reactor (VR) for predictive simulation of LWRs

Leverage

- Current state-of-the-art neutronics, thermal-fluid, structural, and fuel performance applications
- Existing systems and safety analysis simulation tools

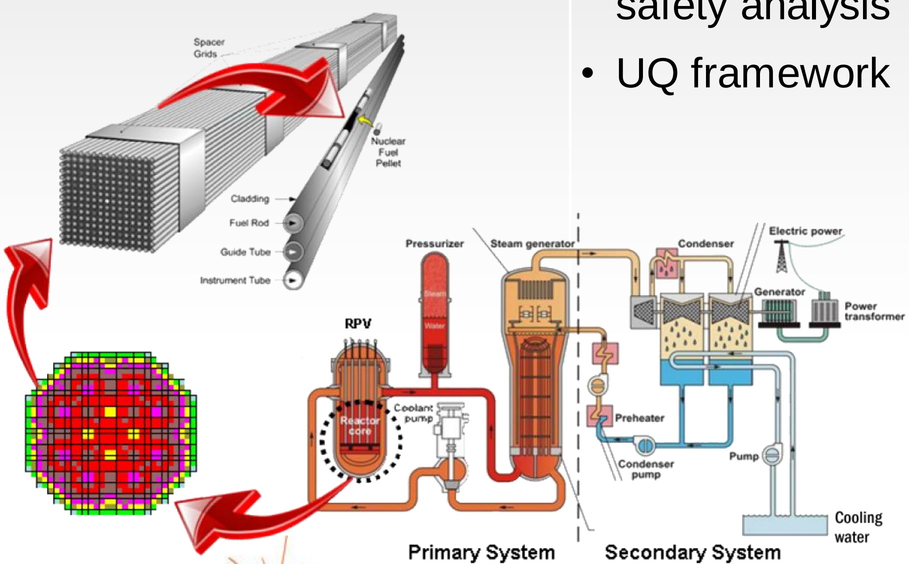
Develop

- New requirements-driven physical models
- Efficient, tightly-coupled multi-scale/multi-physics algorithms and software with quantifiable accuracy
- Improved systems and safety analysis tools
- UQ framework

Deliver

- An unprecedented predictive simulation tool for simulation of physical reactors
- Architected for platform portability ranging from desktops to DOE's leadership-class and advanced architecture systems (large user base)
- Validation basis against 60% of existing U.S. reactor fleet (PWRs), using data from TVA reactors

M&S LWR capability



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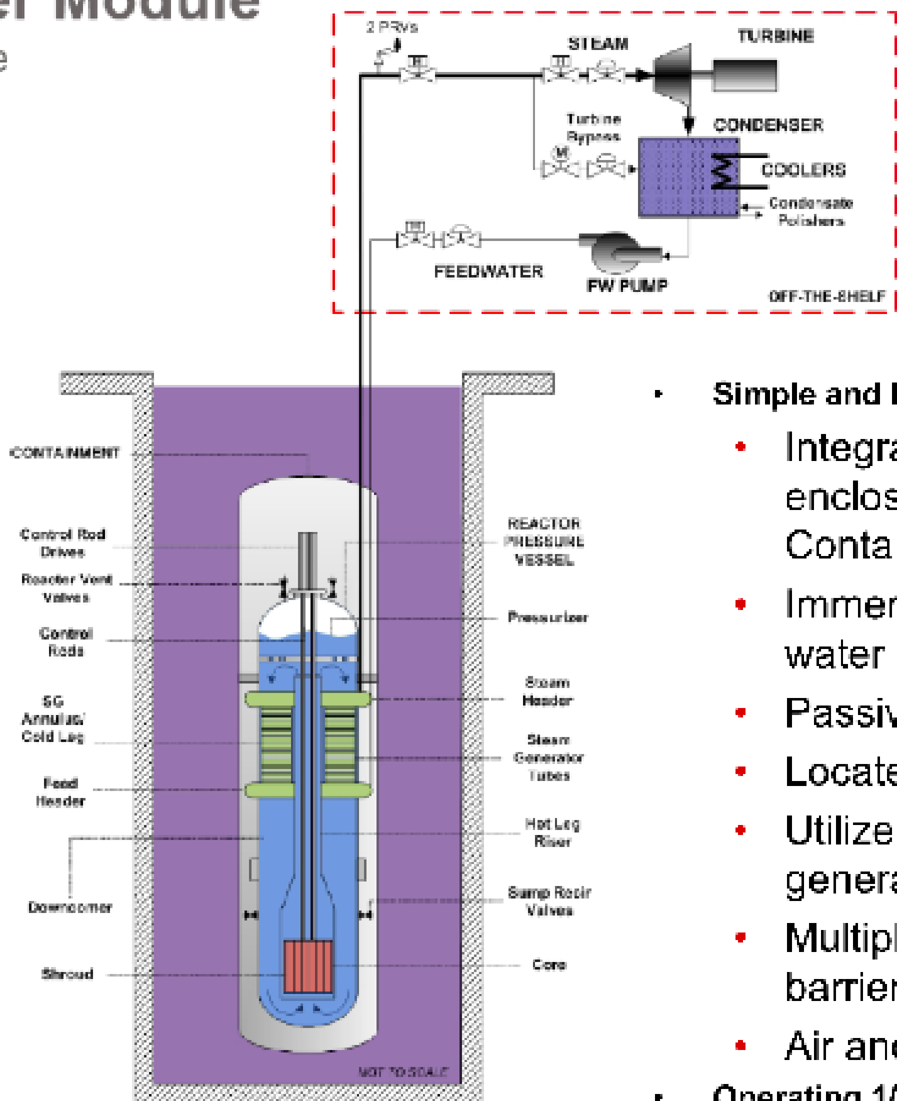
Small Modular Reactors: Economies of manufacturing vs scale???

NuScale Power

Power Module

45 MWe



- **Simple and Robust Design**
  - Integrated Reactor Vessel enclosed in an air evacuated Containment Vessel
  - Immersed in a large pool of water
  - Passively safe
  - Located below grade
  - Utilizes off-the-shelf turbine-generator set
  - Multiple fission produce barriers
  - Air and water cooled options
- **Operating 1/3-scale test system**

CO2 capture and geologic sequestration

- Extensive technical program needed to resolve scientific issues for storage of Gigatonne quantities annually
- Immense infrastructure requirements need study
- Broad range of regulatory issues to be resolved (permitting, liability, monitoring,…)
- Urgently need to put 10-15 year research and demonstration program in place; it must operate at large scale to resolve issues
  - Initial approach involving coal conversion with minimal CO2 capture marginal cost, combined with enhanced hydrocarbon recovery in select circumstances
  - Game changer: CO2 EOR strategy? MITEI-BEG symposium
- CO2 capture proven, but basic research needed to improve cost/performance dramatically ($70/t – 6 cents/kWh)

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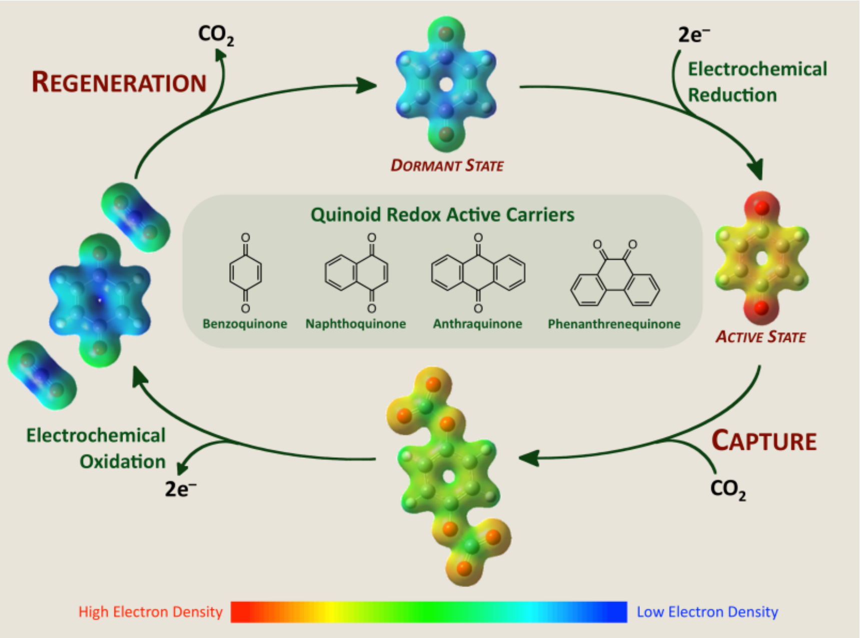
Fossil Energy

- Game-Changer: Energy efficient carbon capture

  - Advanced Amines
  - Phase Change Absorbents
  - Stimuli-Response Capture
  - Electrochemical Mediation
  - Membranes



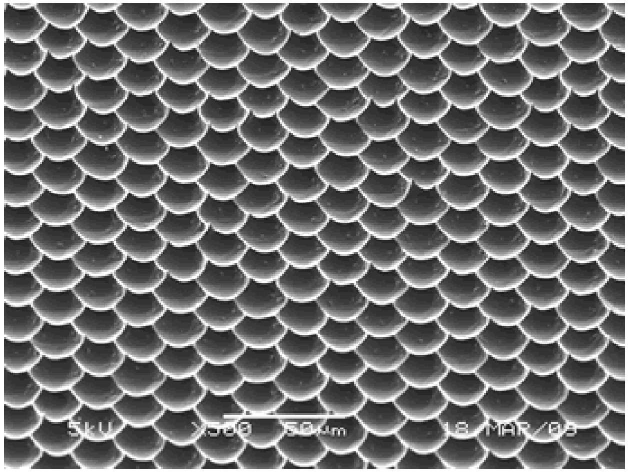
Hatton Group, MIT

Electrochemistry of CO_2 Sorbents

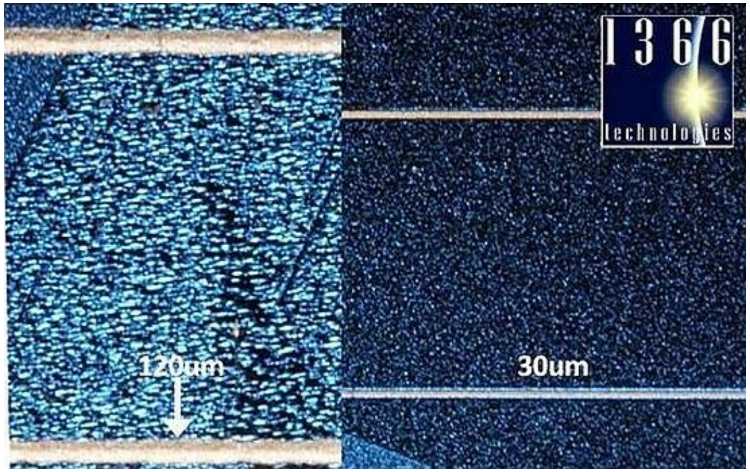
Si PV Wafer and Device Innovation

Approach: Innovate on huge Si manufacturing base
Who: Prof. Ely Sachs, MIT Mechanical Engineering

(1) Wafer texture to improve light trapping



(2) Improved metallization



Now:
- Technology licensed to 1366, new equipment provider
- 2 significant U.S. DOE grants, including new ARPA-E programs
- Working on two additional technologies, including direct wafer manufacturing

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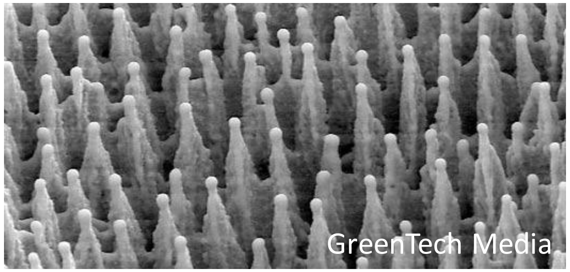
Solar Beyond Crystalline Silicon

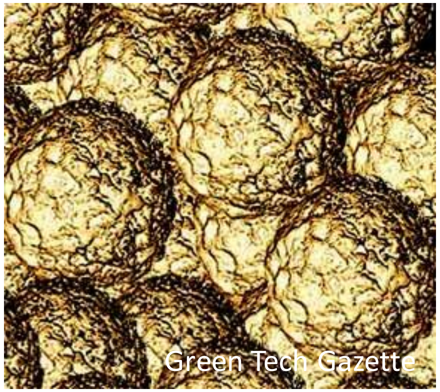
- Beyond Thin-Film:
  Potential game-changers in "Third Generation" photovoltaics



Nanostructured Photovoltaics:
Increase Light Trapping and Absorption

Organic Photovoltaics:
Ultra-Inexpensive Material

Quantum Dot
Photovoltaics:
Efficiency Boost



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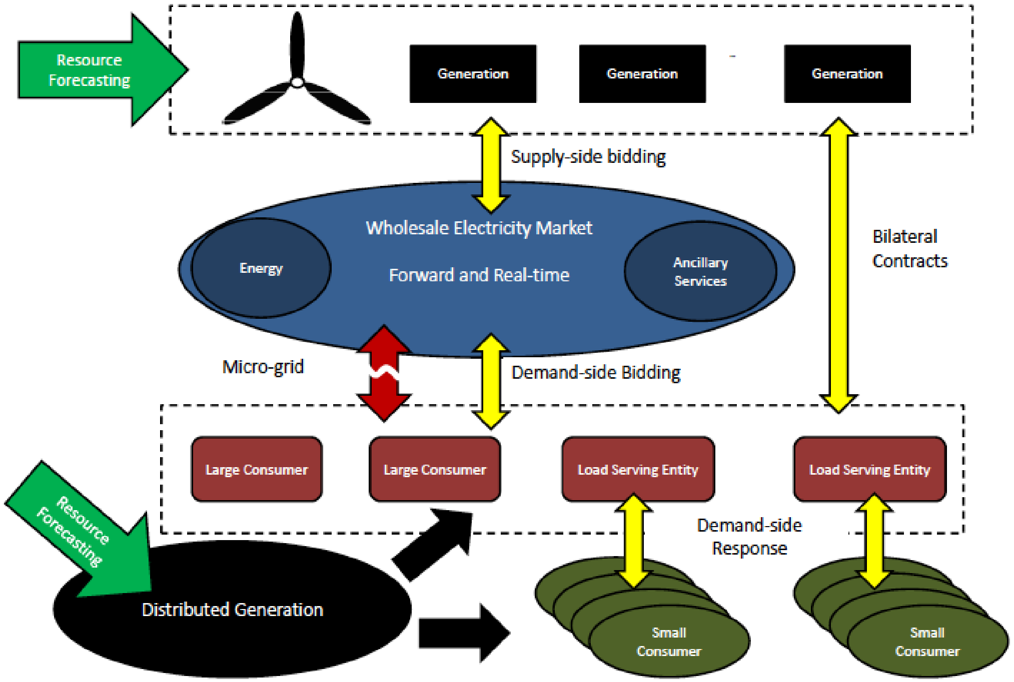
Not Just Devices – Grid Integration Research

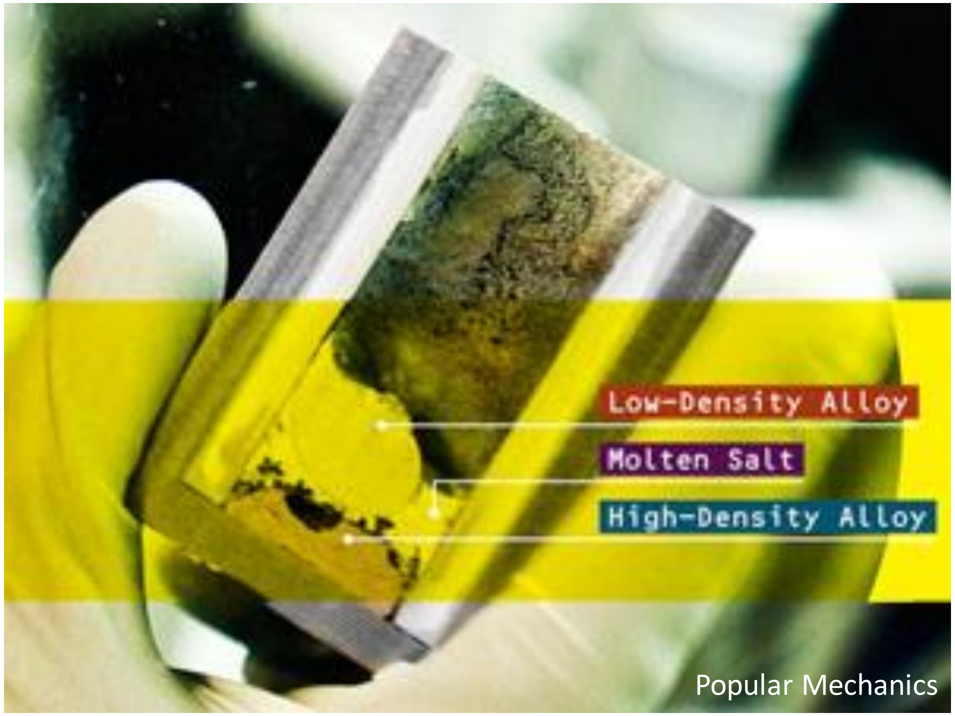
Approach: Design systems of power systems and markets for high penetration of DG
Who: Prof. Jim Kirtley, MIT EE & Profs. Scott Kennedy, Hatem Zeineldin, Masdar Institute

- Coupled simulations between power system operation and sequentially clearing power markets.
- Optimal power flow and unit commitment problems are solved for testing different distributed generation technologies under a range of grid topologies and transmission capacity limitations.
- Game changer: transparent high fidelity dynamic simulation tools (including grid/NG infrastructures)
- Game changer: strengthened capacity markets for firming intermittency/variability?



Advanced Storage for the Grid

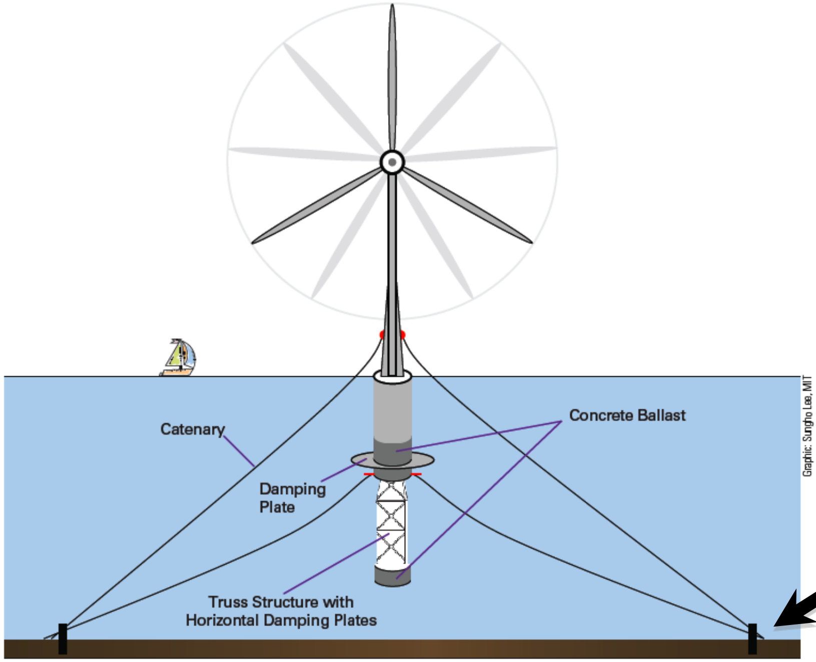
- Flow Batteries
- Liquid Metal Batteries
- Metal-Air Batteries
- Compressed Air
- Flywheels
  (frequency regulation)



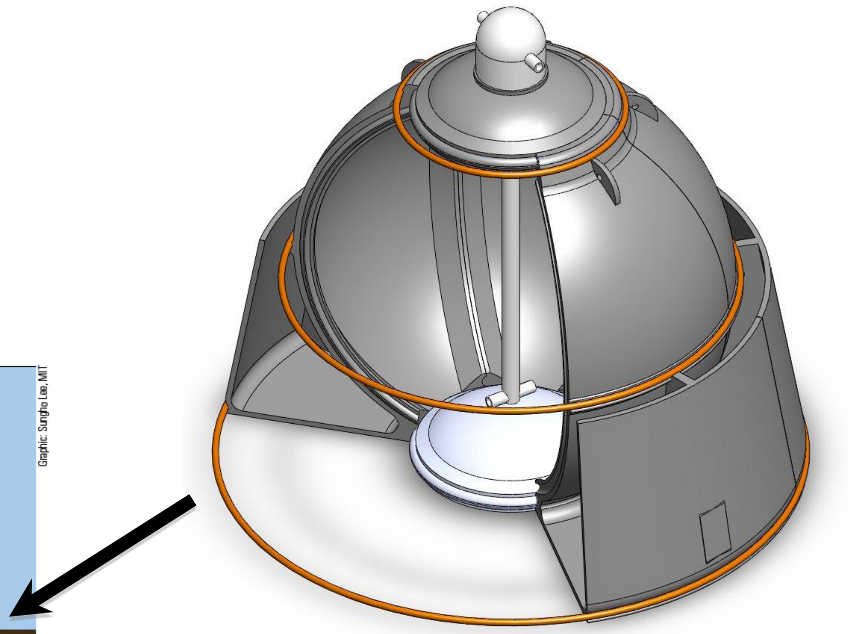
Liquid Metal Battery
Donald Sadoway, MIT

Advanced Storage for Offshore Wind

- Game-Changer: Floating Turbines Moored with Storage Systems
  - Floating turbines located beyond coastal visual horizon
  - Using the ocean as a pumped hydro storage systems



Spar Buoy Floating Turbine Design; Sclavounos Lab, MIT



Mooring / Pumped Hydro Storage; Slocum Lab, MIT

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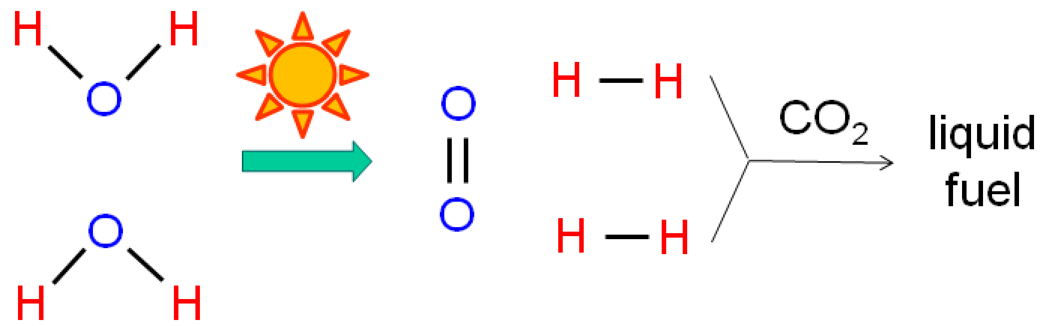
Direct Solar Fuels

- Game-Changer: Sunlight + CO_2 ➔ Renewable Liquid Fuels

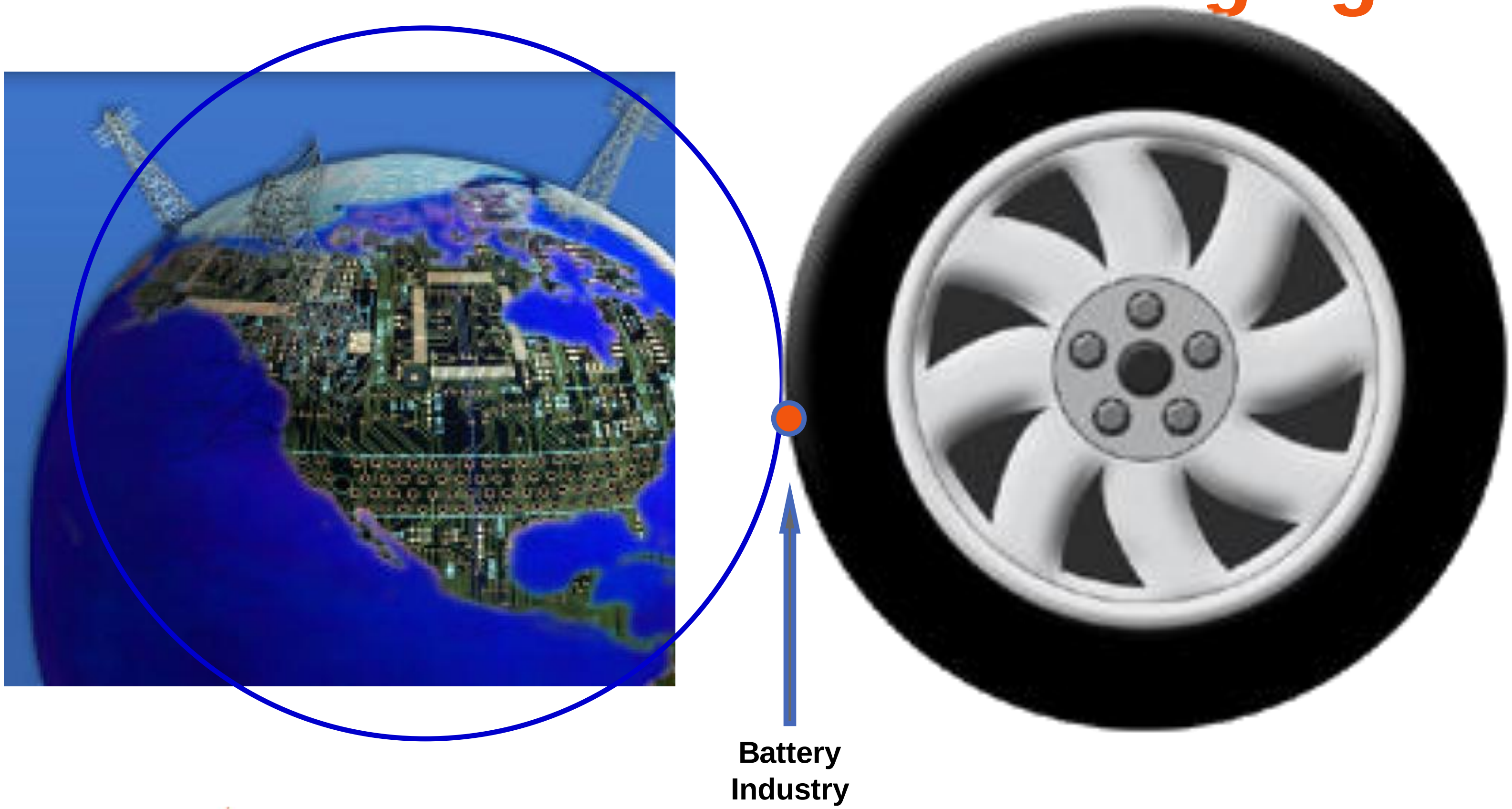


Solar input rearranges the low energy bonds of water (H_2O) to make high energy ones of hydrogen (H_2) and oxygen (O_2). Hydrogen can then be combined with carbon dioxide (CO_2) to make a liquid fuel

- Phase 1: Hydrogen from water splitting can be used for direct combustion, biomass and other fuels upgrading, fuels cells, etc
  Phase 2: If CO_2 can be effectively reduced, liquid fuels can be directly produced

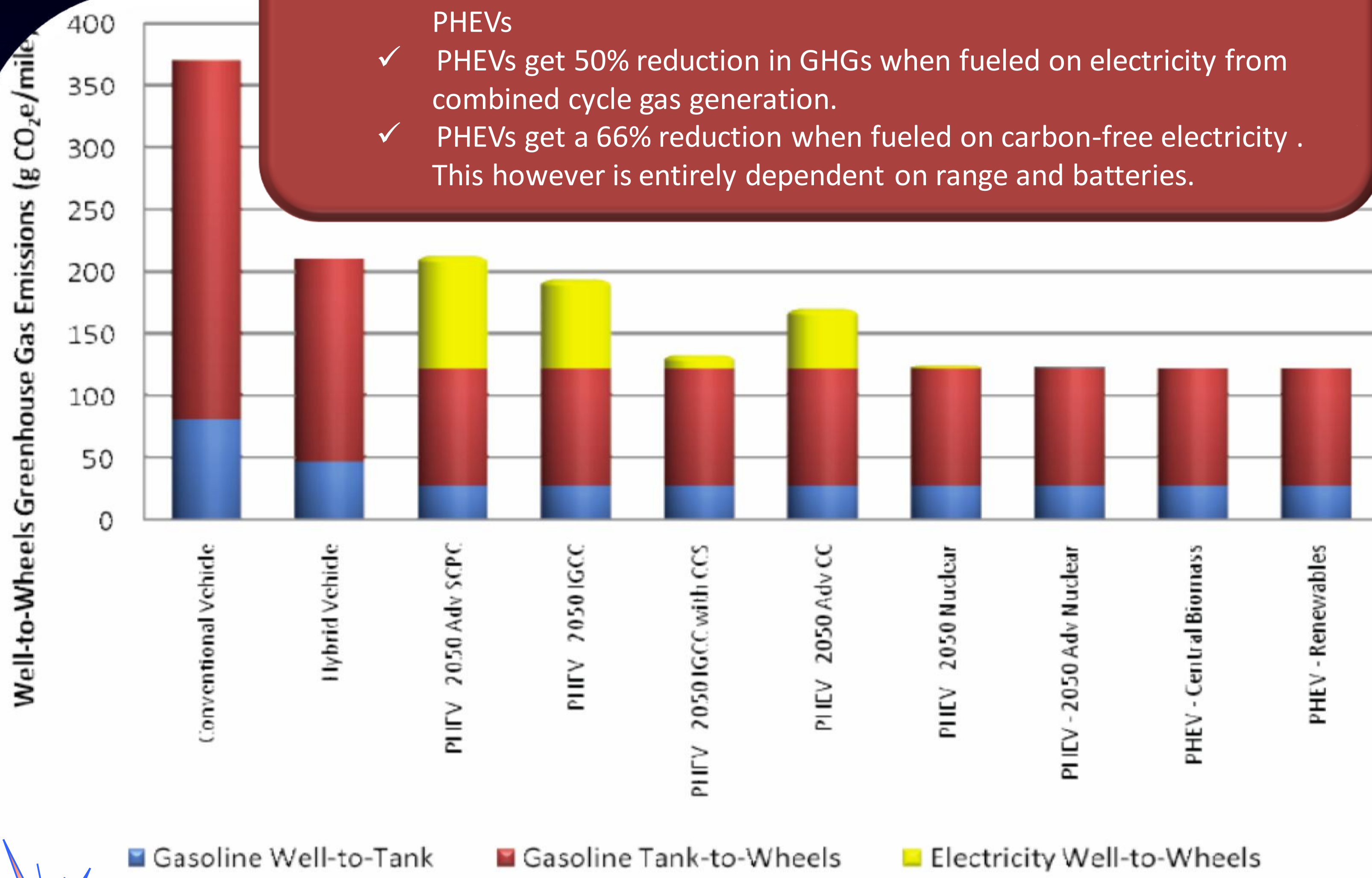
Two huge industries are transforming

and a new one is emerging...



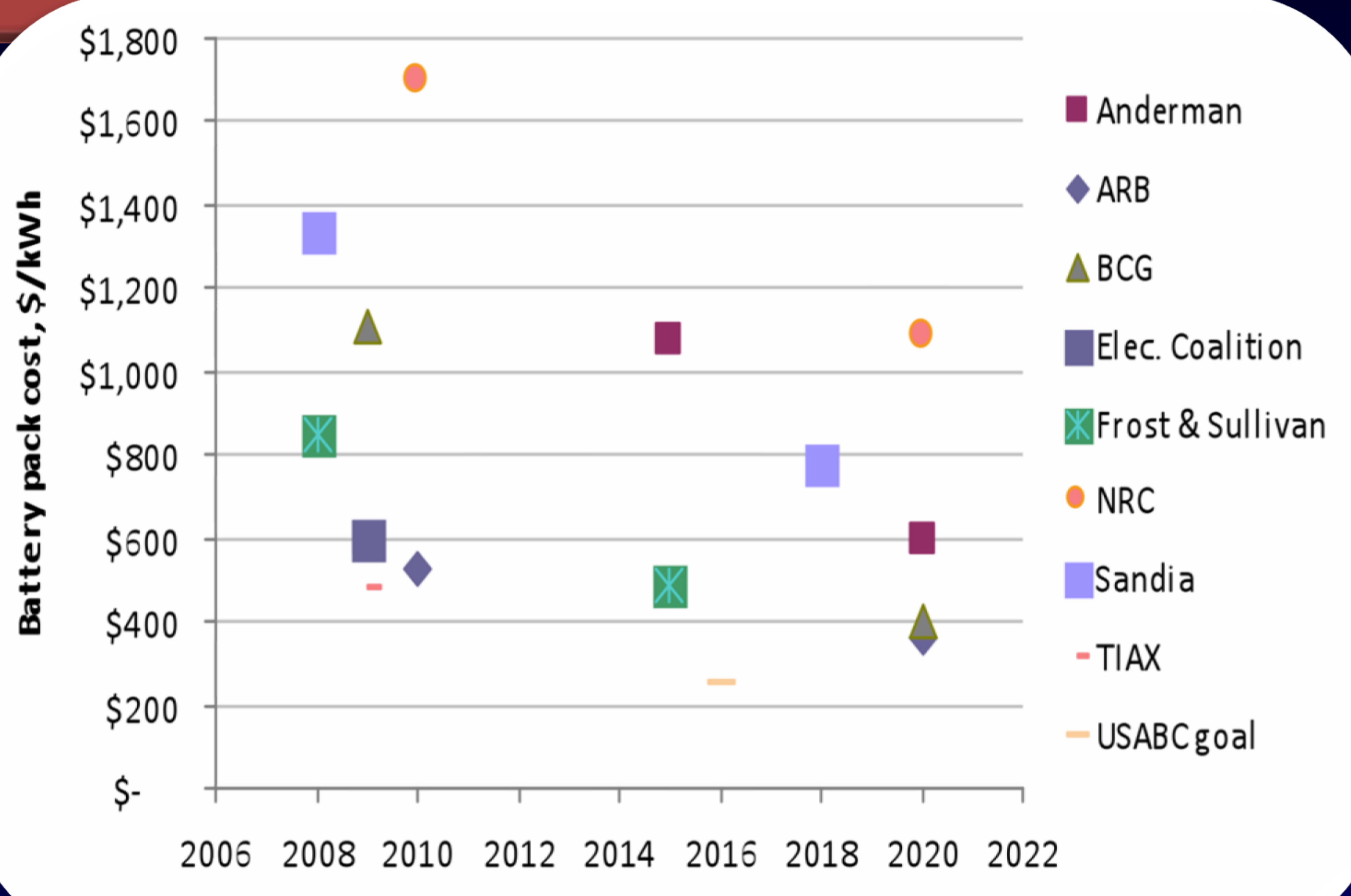
Chiang

- PHEVs can reduce carbon emissions relative to cars operating on ICEs, but generation portfolio is the key
  - ✓ If our generation mix remains coal-centric, conventional hybrids beat PHEVs
  - ✓ PHEVs get 50% reduction in GHGs when fueled on electricity from combined cycle gas generation.
  - ✓ PHEVs get a 66% reduction when fueled on carbon-free electricity . This however is entirely dependent on range and batteries.



Year 2050 comparison of PHEV 20 GHG emissions charged entirely with electricity from specific power plant technologies (12,000 miles driven per year)

- Academics, national labs, battery manufacturers and analysts disagree about the cost of batteries, creating uncertainty
- This lack of certainty is reflected in the decisions on the development of a charging infrastructure
- EV charging may have an impact on the grid, and utilities may need to work proactively to manage these impacts
- Few state PUCs have established a regulatory framework for public electric vehicle charging.



MIT Energy Initiative

Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy

President's Council of Advisors on Science and Technology (PCAST)

November 29, 2010

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PCAST Energy Technology Innovation System Working Group

- **Co-Chairs**

Ernest Moniz*
Maxine Savitz*

- **Members**

Dennis Assanis
Rosina Bierbaum*
Nick Donofrio
Robert Fri
Kelly Sims Gallagher
Charles Goodman
John Holdren*
Shirley Ann Jackson*
Raymond Orbach
Lynn Orr
William Powers
Arati Prabhakar
Barbara Schaal*
Daniel Schrag*

*PCAST member

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Recommendation: The President should establish a Quadrennial Energy Review (QER).

* Short and long term objectives in context of economic, environmental, and security priorities;

* Outlines legislative proposals and resource requirements (RD&D, incentives,…) and anticipated Executive actions (programmatic, regulatory,…) across multiple agencies;

* Provides strong analytical base.

QER led in the EOP, but with the Department of Energy providing the Executive Secretariat.

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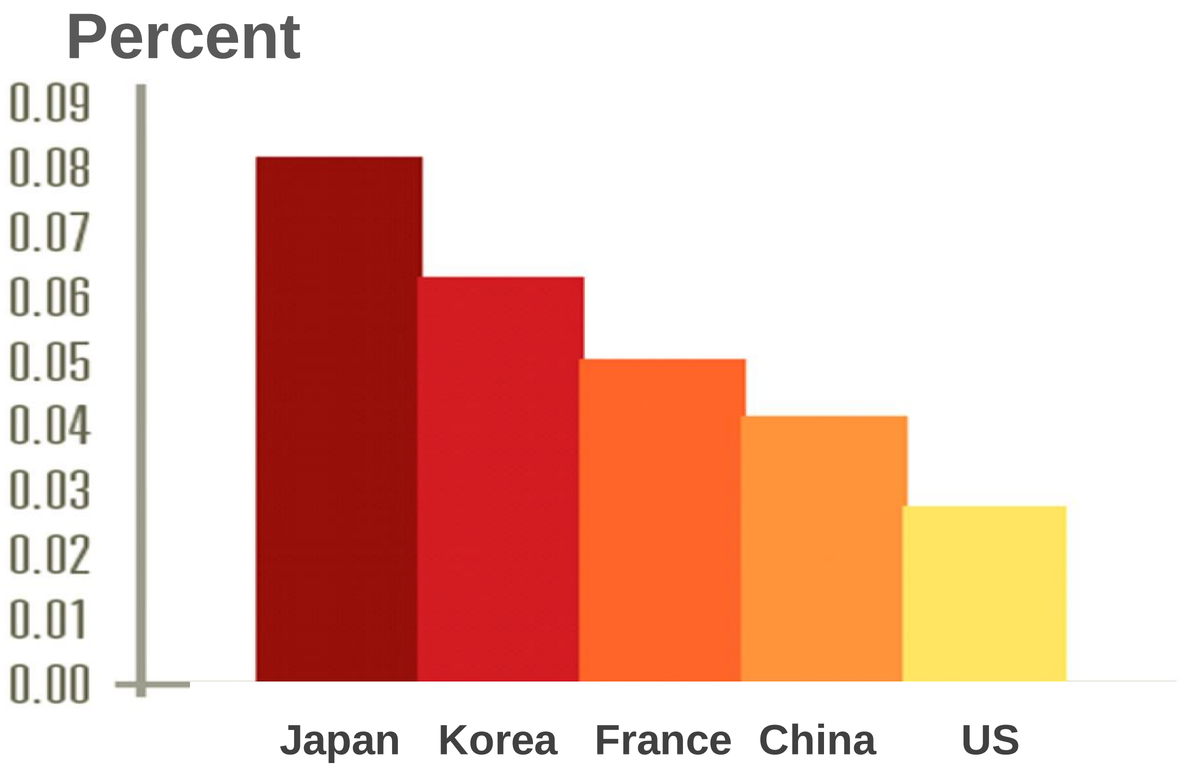
PCAST recommends that the President support annual energy RDD&D expenditures of about $16B – an increase of about $10B.

- PCAST concludes, along with many others, that we are substantially underinvesting relative to leapfrog opportunities;
- Scale appropriate to role of energy in GDP and commensurate with investments of leaders;
- Actual funding will be bottom-up, incorporating results of QER, but it is important to set a scale for R&D portfolio construction;
- Experience with the initial solicitations in the new competitive peer-reviewed energy technology innovation programs suggests that there is ample research capacity to utilize such a funding increase effectively;
- Additional DOE R&D funding should emphasize these competitive programs driving energy technology innovation.

Public Energy RD&D Spending as a Share of GDP, 2007



Source: American Energy Innovation Council (2010). *A Business Plan for America's Energy Future.*

PCAST recommends that the President engage the private sector and Congress to generate the additional funding through "new" revenue streams. This can be accomplished through legislation or through regulatory mechanisms put in place with the collaboration of industry and consumers.

- Where can we find $10B/year? Neither annual appropriations nor a CO2 emissions charge look promising for the near term.
- E.g., 1mill/kWh and 2 cents/gal would yield about $8B/year.
- Prospect is for innovation that lowers consumer costs, protects the environment, and enhances security.
- Precedent exists.

Coalbed Methane RD&D Spending and Supporting Policy Mechanism