Energy Technology, Policy, & Innovation

Portland – March 2010

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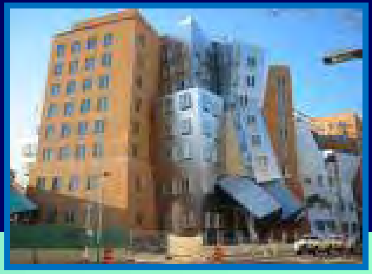
Director, MIT Energy Initiative

Launching MITEI

MIT President Susan Hockfield, in her May 2005 inaugural address, called for a renewed Institute commitment to energy-related research and education:

"[A] great opportunity, and a great obligation, is our institutional responsibility to address the challenges of energy and the environment. . . . it is our responsibility to lead in this mission."



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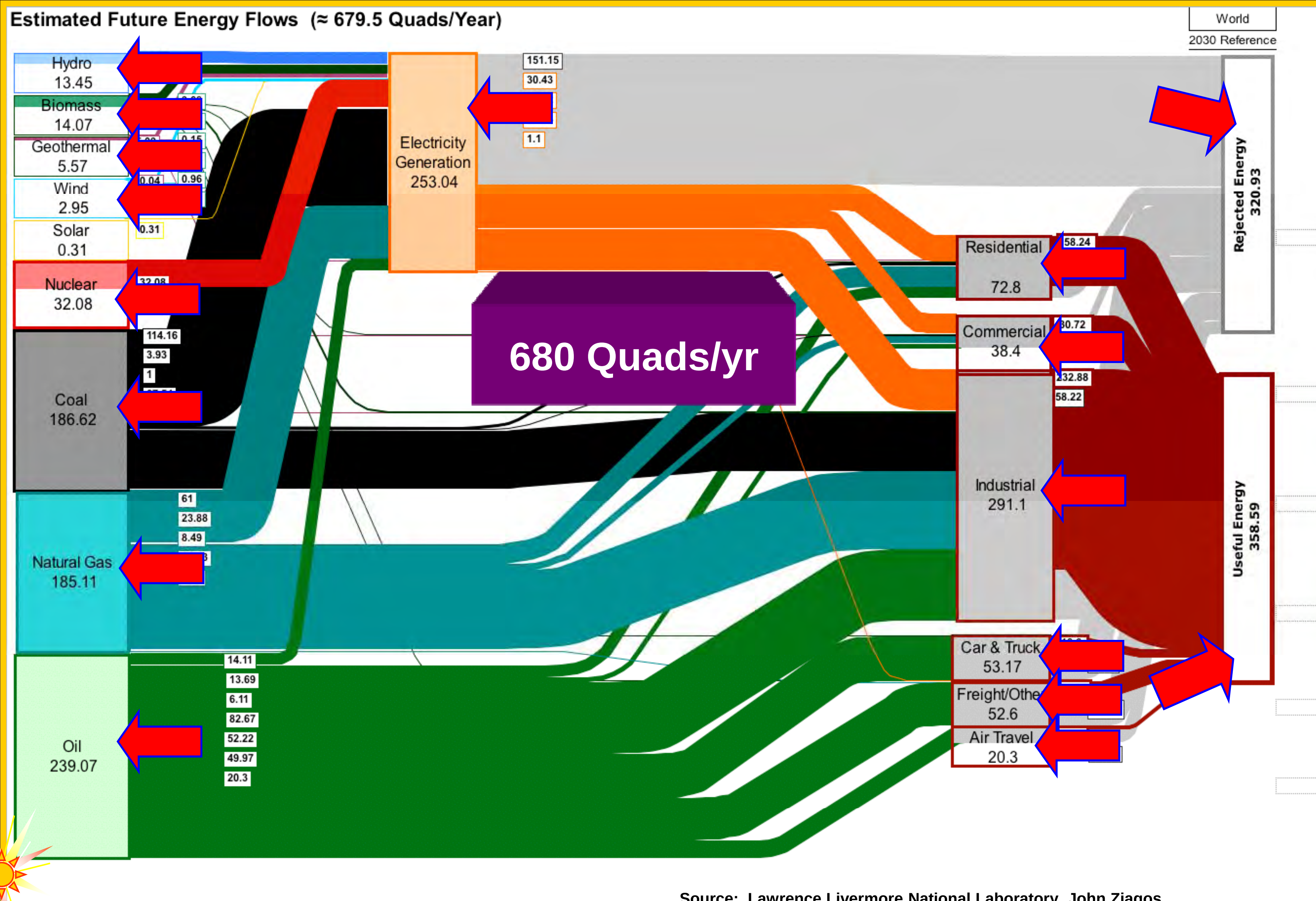
Global Energy Consumption 2030



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

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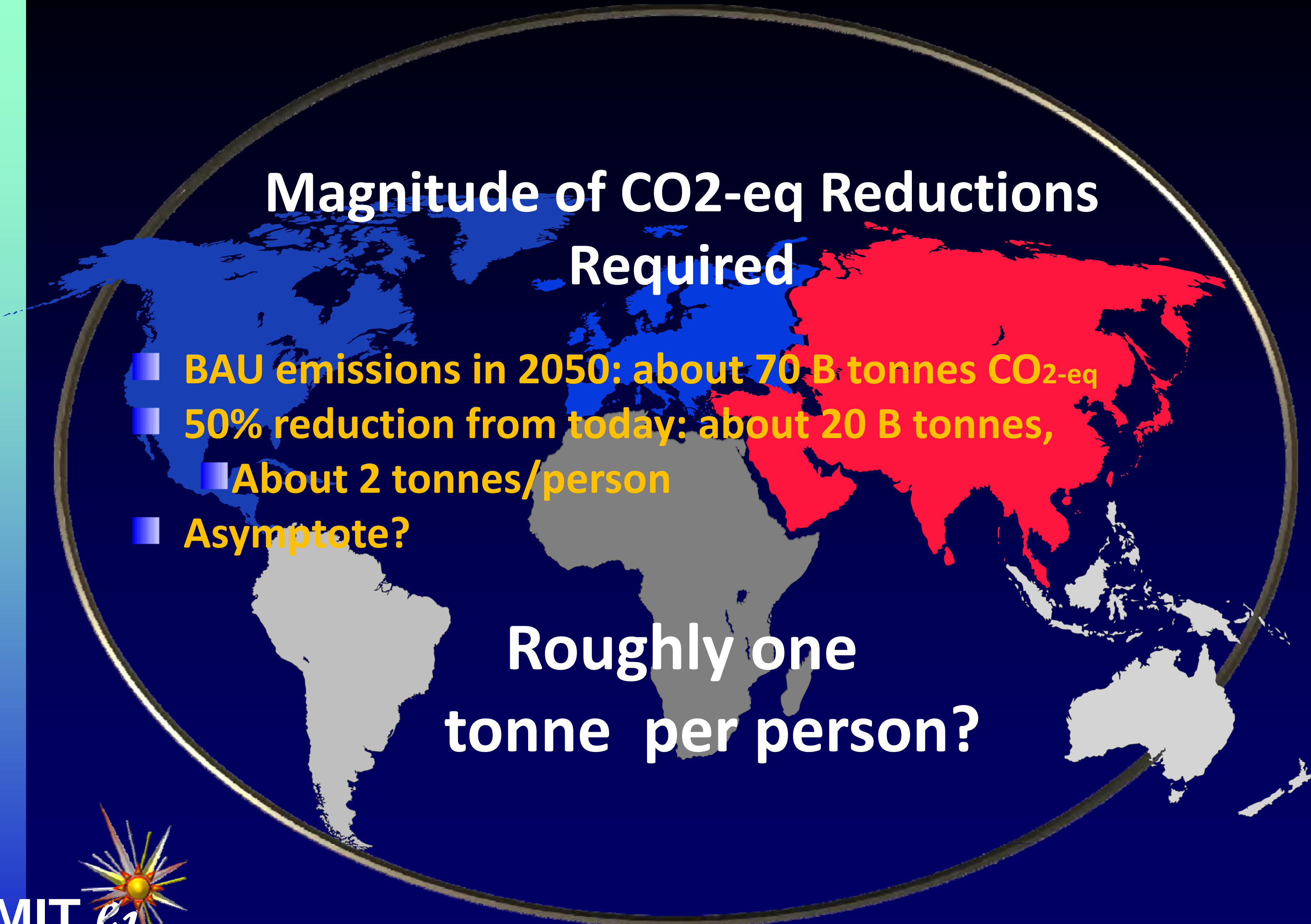
Magnitude of CO2-eq Reductions Required



- BAU emissions in 2050: about 70 B tonnes $CO_{2\text{-eq}}$
- 50% reduction from today: about 20 B tonnes,
  - About 2 tonnes/person
- Asymptote?

Roughly one tonne per person?

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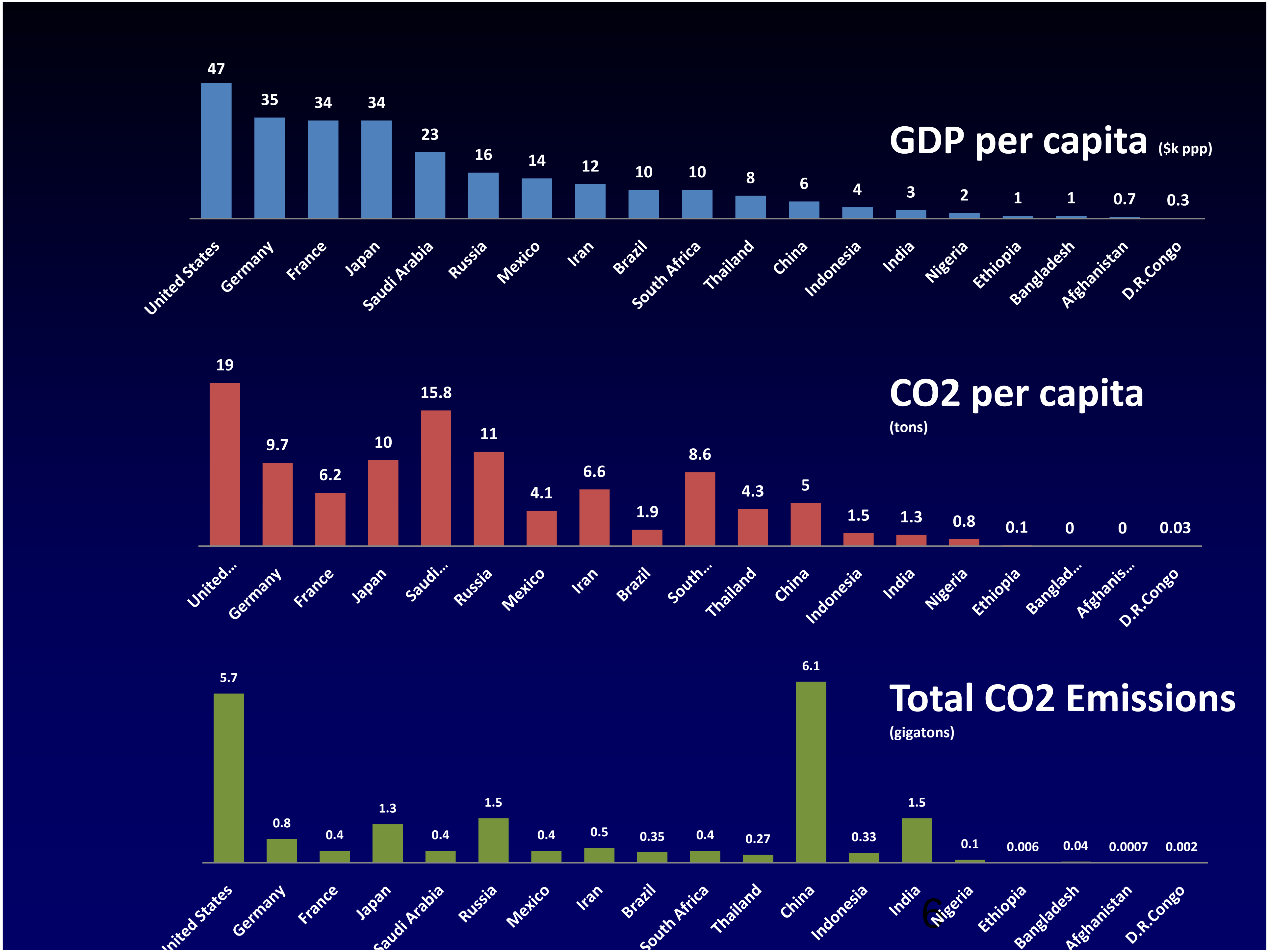
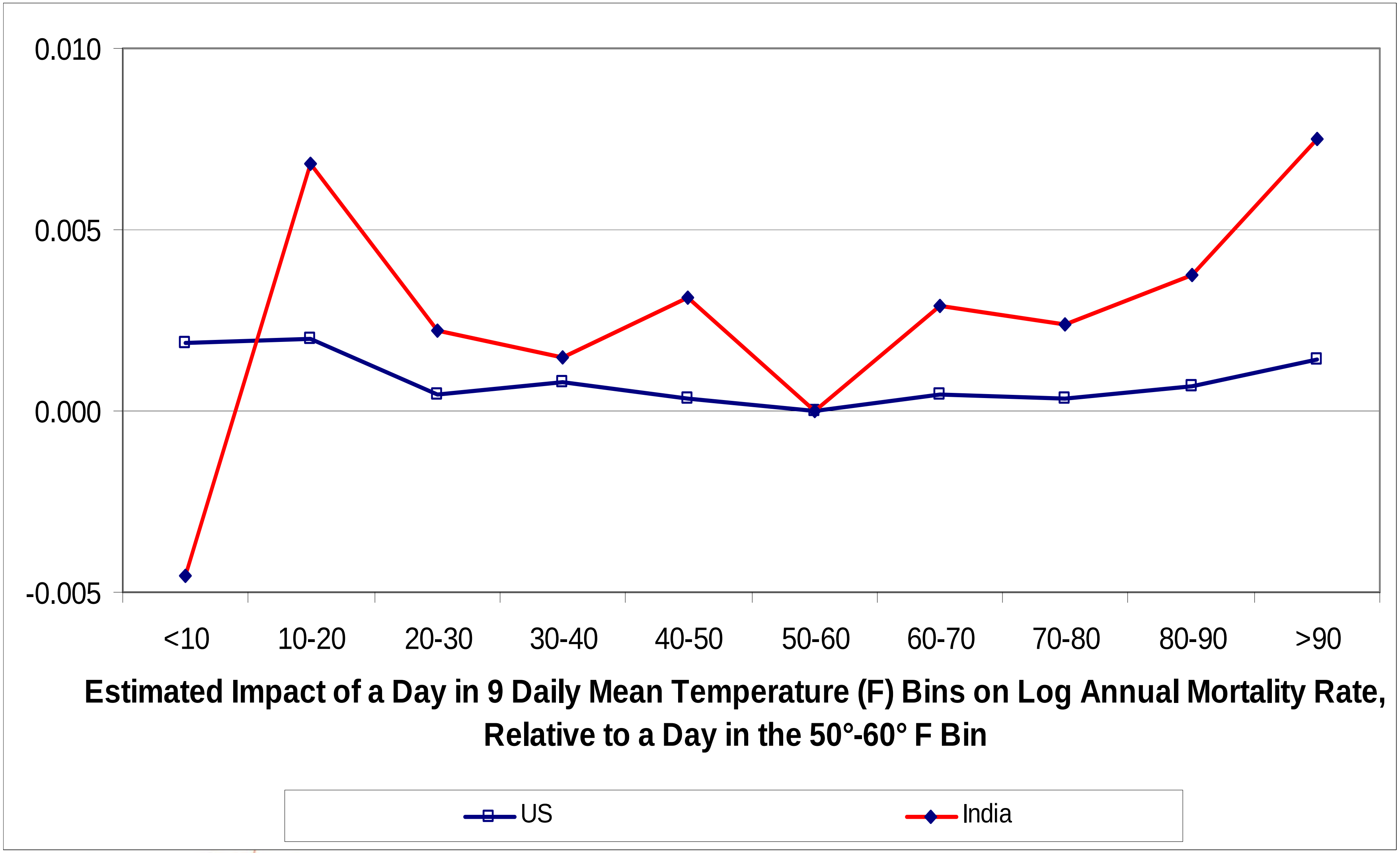
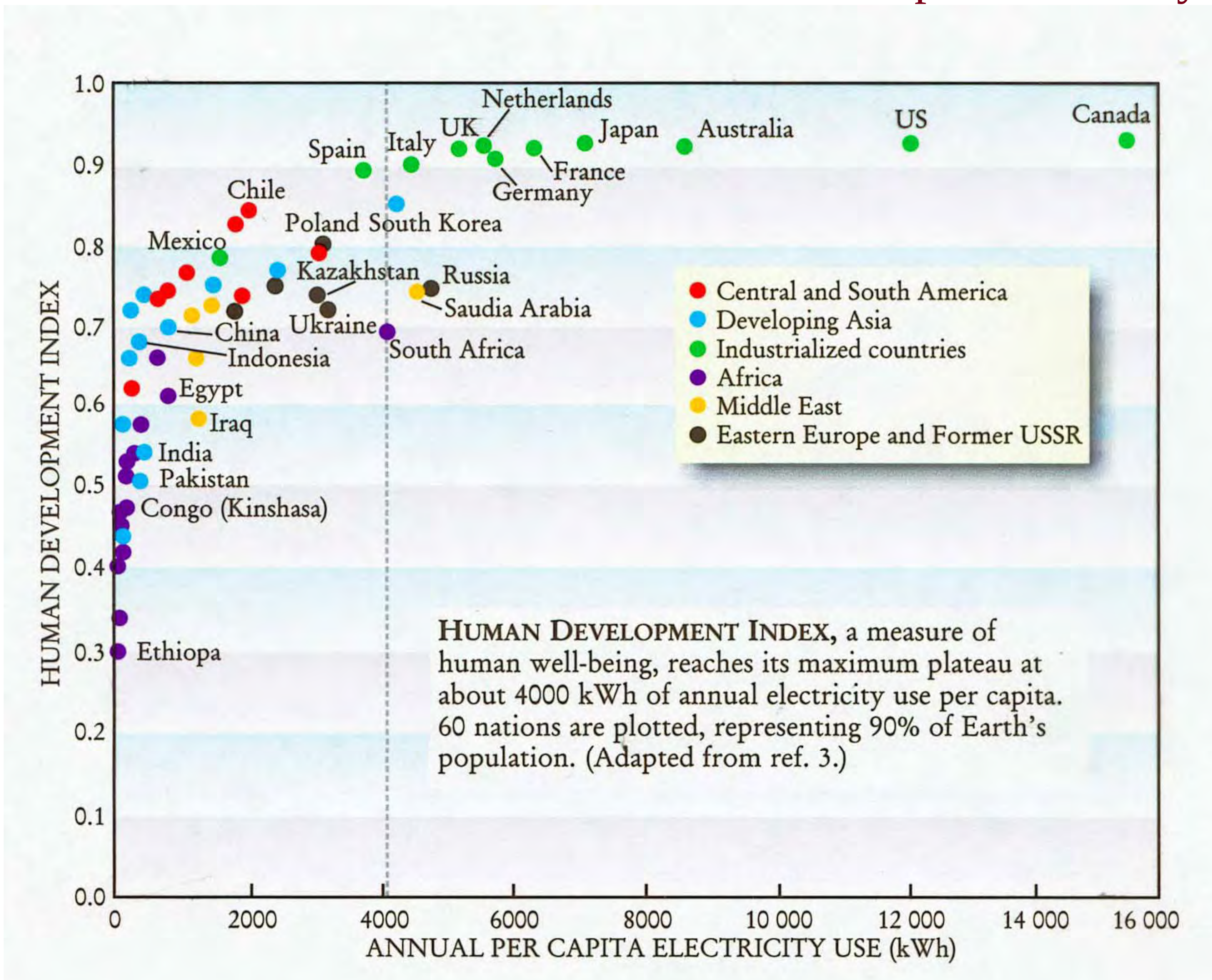


GDP per capita ($k ppp)
47
35
34
34
23
16
14
12
10
10
8
6
4
3
2
1
1
0.7
0.3
United States
Germany
France
Japan
Saudi Arabia
Russia
Mexico
Iran
Brazil
South Africa
Thailand
China
Indonesia
India
Nigeria
Ethiopia
Bangladesh
Afghanistan
D.R.Congo
CO2 per capita
(tons)
19
9.7
6.2
10
15.8
11
4.1
6.6
1.9
8.6
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
Germany
France
Japan
Russia
Mexico
Iran
Brazil
South Africa
Thailand
China
Indonesia
India
Nigeria
Ethiopia
Bangladesh
Afghanistan
D.R.Congo

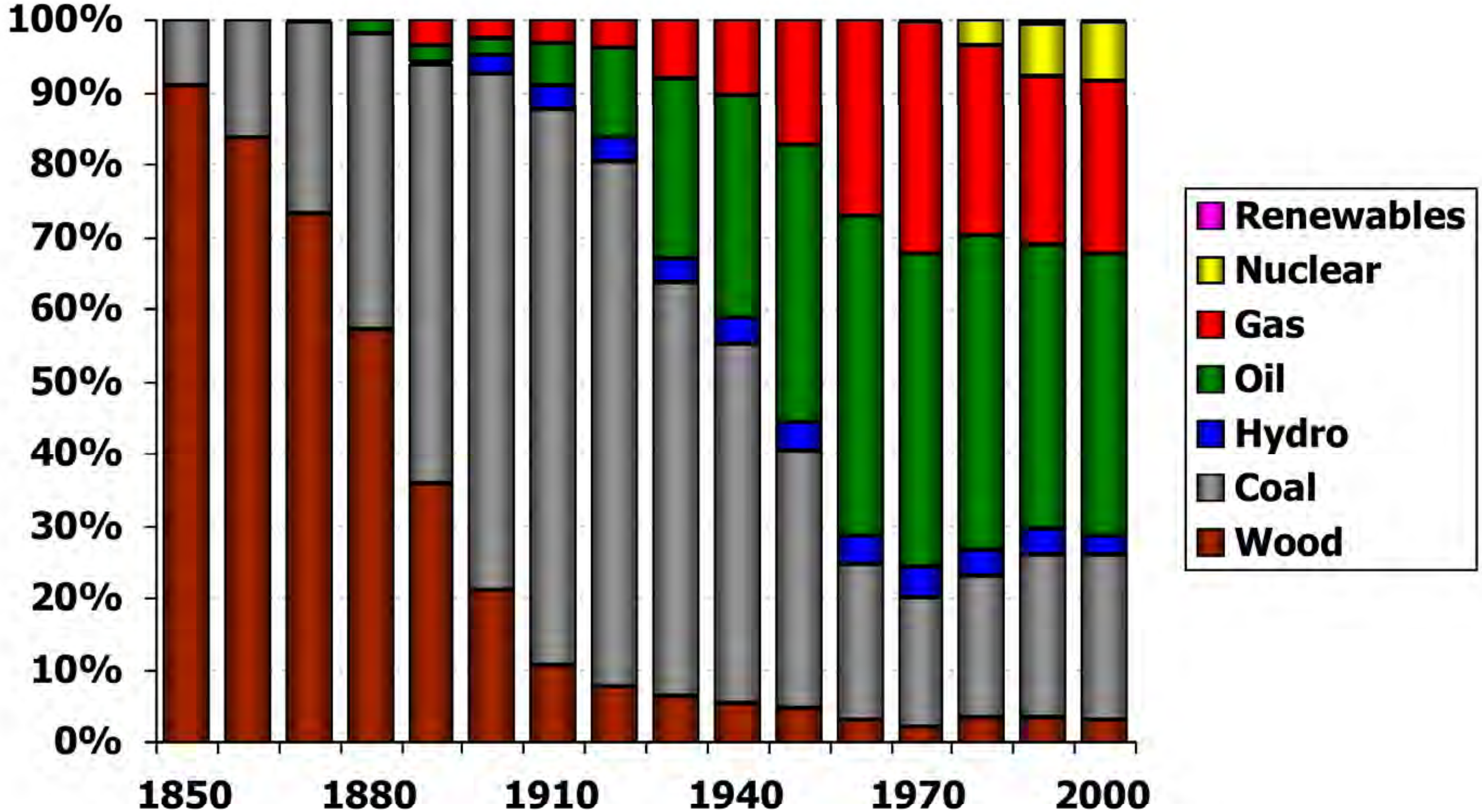
Developing Countries Focus on Income Growth



Annual Per Capita Electricity Use (kWh)



US Energy Supply Since 1850



Author: Koonin

Source: EIA

Innovation is key

- We must **accelerate** the transformation of the energy marketplace significantly if we are to meet prudent climate change risk mitigation goals, and meet demand and enhance security too
    - 2 deg/450 ppm? 550 ppm? CO_2 reductions by half at 2050?...
    - Need innovation and implementation at large scale, with **decadal** not century time scale

Innovation is key - in context

- Highly capitalized, multi-trillion $/year, commodity business, with efficient supply chains and established customer bases, providing essential services throughout society, thereby calling for extensive regulation and complex politics

    - Primary goal: in absence of new services/functionality enabled by new technology, **cost reduction** for a future where CO2 is priced
        - Solar, CCS, storage,…: “I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait until oil and coal run out before we tackle that.” – Thomas Edison
        - “developing economy test”
        - Rural applications? (“Hande principle”!)

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Multifaceted innovation is key

- Technology innovation
  - Cost reduction
- Business model innovation
  - Entrepreneurs and large scale energy incumbents
- Policy innovation
  - Road from Copenhagen?
- Need all three working in concert

Copenhagen Accord: Brazil, China, India, South Africa, USA

- Political vs treaty agreement
- Differentiated responsibilities acknowledged rationally
  - Different structure of national commitments, largely backed up by domestic legislative initiatives
  - Annex I/non-Annex I Kyoto construct largely superseded
  - Eliminate consensus straitjacket
  - Major emitters focus on **action**
- Start on transparency of monitoring and verification
- Critical role of adaptation acknowledged, with funds to least developed
- National responsibilities recorded for MANY countries

- Will UNFCCC process revive as central venue for negotiations? EU, Japan, Russia, Mexico, Indonesia,… position?
  - Major Economies Forum? G20? Other configurations of major emitters representing 80-90% of emissions?
- No real shot at 450 ppm CO2-eq?

Copenhagen Accord Registrations: Brazil, China, India, USA

- USA
  - CO_2 emissions 17% below 2005 by 2020
  - 83% by 2050
  - Depends on Congressional action (above represent current discussions)
- China
  - 40-45% lower CO_2/GDP by 2020
  - 15% non-fossil by 2020
  - 40M additional hectares forest by 2020
- India
  - 20-25% lower CO_2/GDP by 2020
  - Near term implementation of standards on fuel efficiency and building energy use
  - 20% non-large-hydro renewables by 2020 (now 8%)
- Brazil
  - 36-39% less CO_2 than BAU in 2020 (roughly 1994 levels)
  - Reduce deforestation by 80% vs historical practice in 2020
- EU
  - CO_2 20% below 1990 levels by 2020
  - 30% if others play hard

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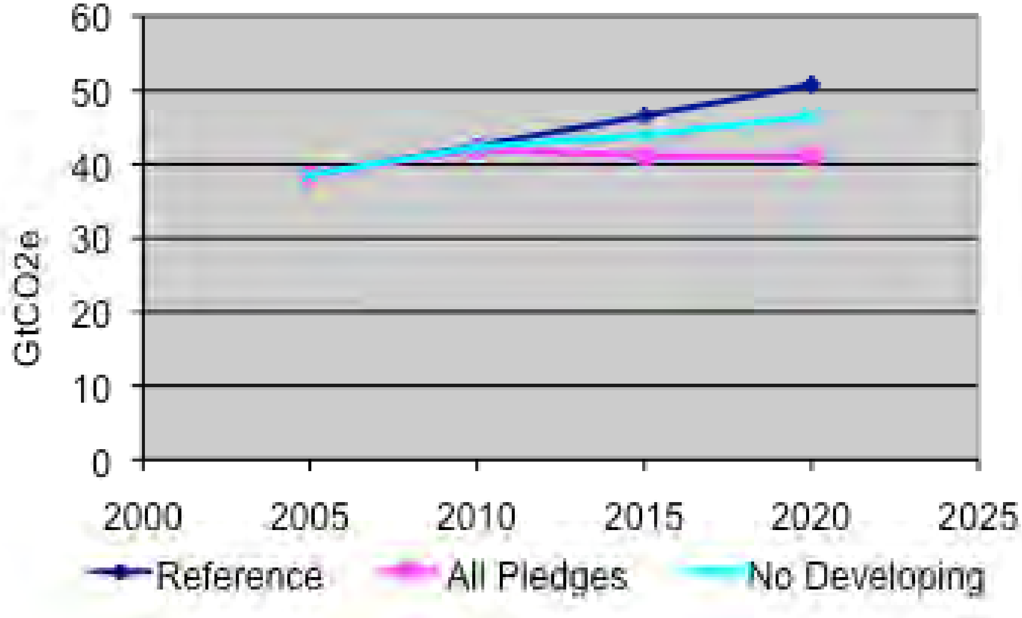
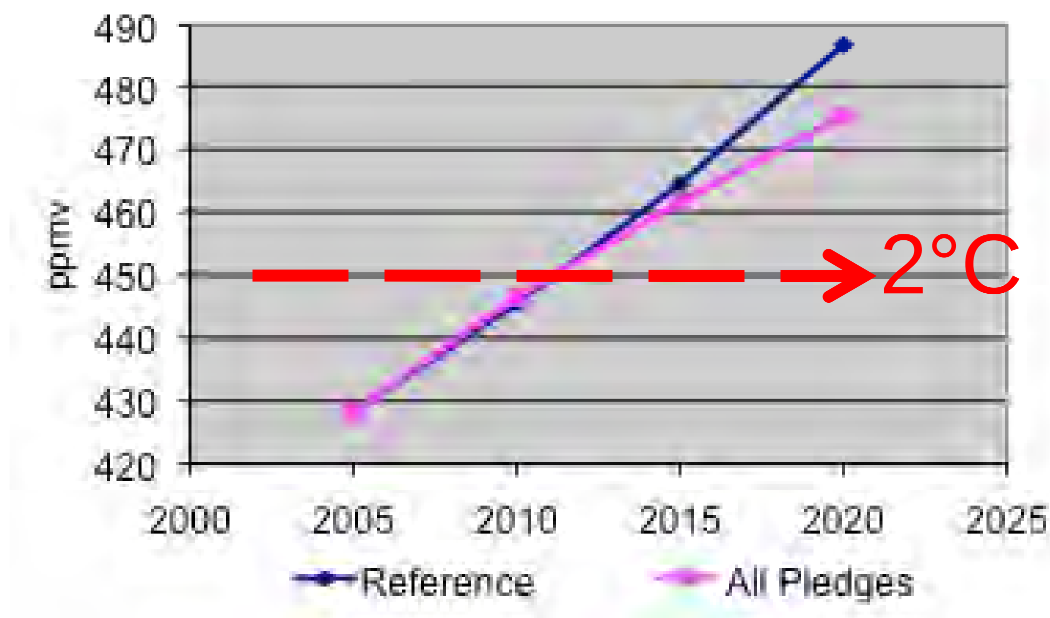
Copenhagen Mitigation "Pledges"



Emissions

Atmospheric Concentrations (All gas CO_2 equiv.)



Jacoby

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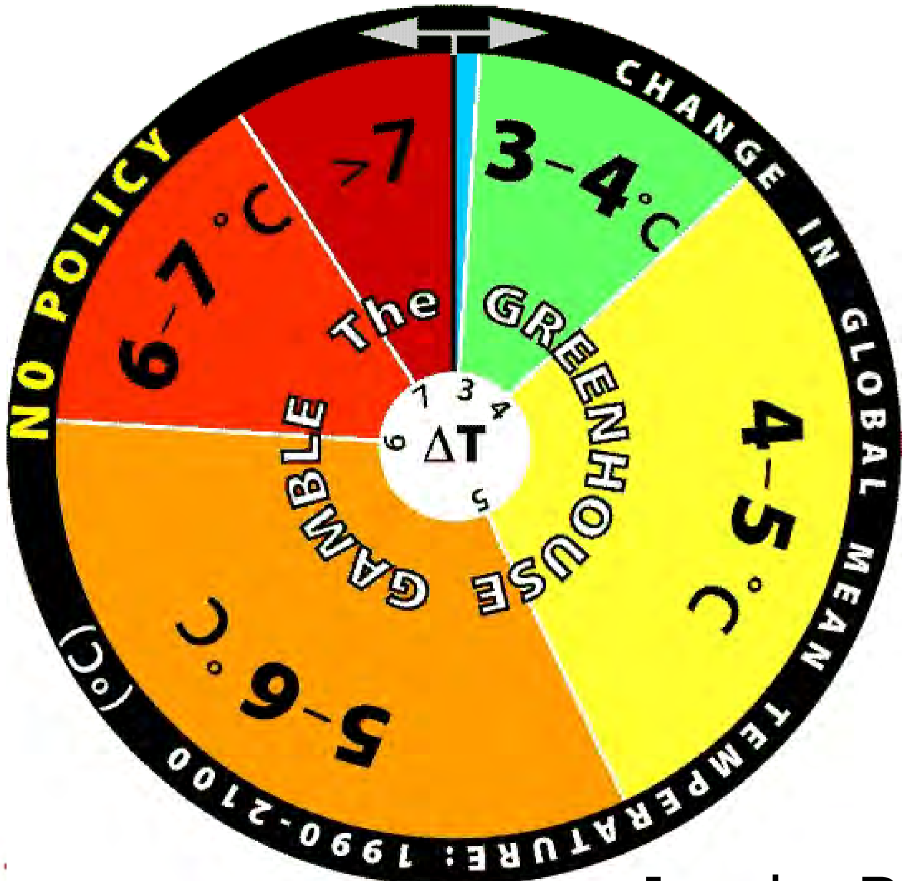
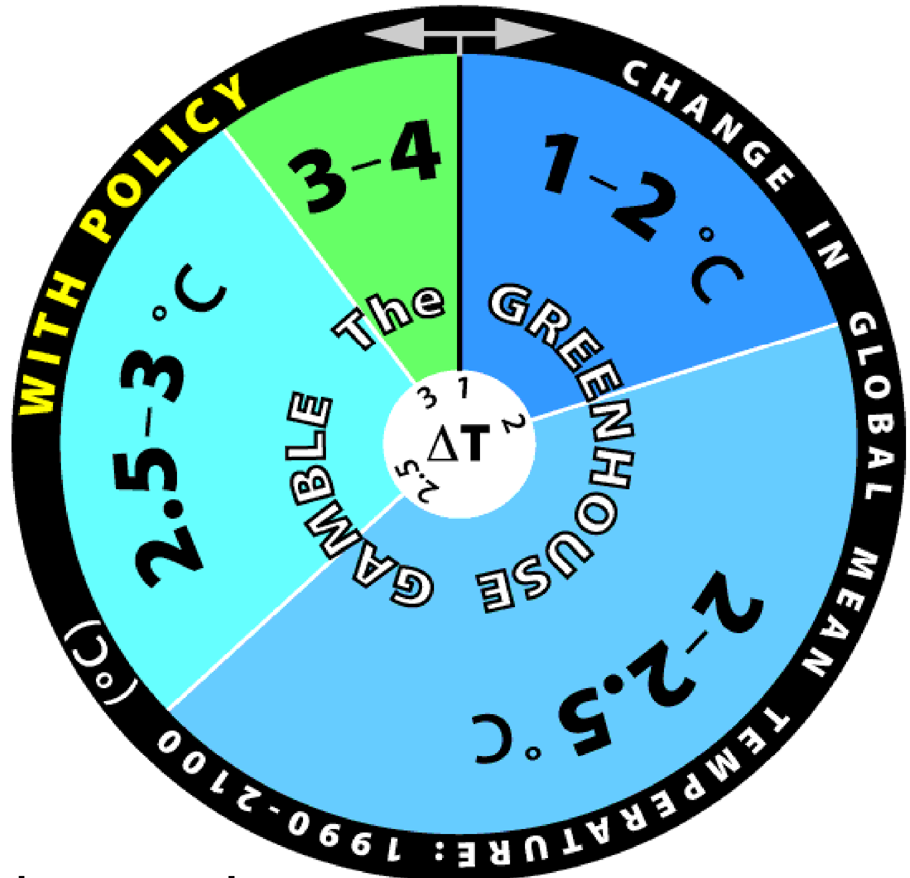
Biggest Policy Effect Is on the Tails

Thought experiment: NO POLICY



Even at 650 ppmv: lower odds of EXTREMES



Jacoby-Prinn et al

Technology-driven evolving business models for low-C world?

- Electricity as transportation "fuel"?
- Coal "refineries" as power plants and fuel sources?
- Sequestration? Petroleum companies in "waste" business?
- Biofuels? Agri-energy business?
- Smart grids/distribution systems? Information-energy companies?
- ….

- Overarching challenge: integration of entrepreneurial and incumbent energy company "cultures" ?

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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** (bio/syn-fuels, 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) ?

MITEI Scope

Research

- Innovations
- Transformations
- Global systems
- New tools

- Sponsored research and seed funds across all Schools
- Multi-faculty, multi-disciplinary, sustained commitment

Education

- New curricula/e.g. undergraduate minor in energy
- Graduate fellows

Campus Energy Management

- Significant efficiency advances/e.g. hood design and operation

Policy outreach

- Multidisciplinary technology/policy analyses for low-C world

- *About 20% of MIT faculty engaged!*

MITEI Sponsored Research Projects

Innovations

- Solids conversion: coal, biomass,…
- Ultradeep/robotics: oil/NG E&P
- CO2 capture and sequestration
- Nuclear fuel cycles
- Electricity networks
- Subsurface imaging, EOR,…

Transformations

- Solar power: advanced PV, photosynthesis/catalysis, thermal/storage
- Biofuels
- Wind/deep water
- Geothermal/sub-surface science & engineering

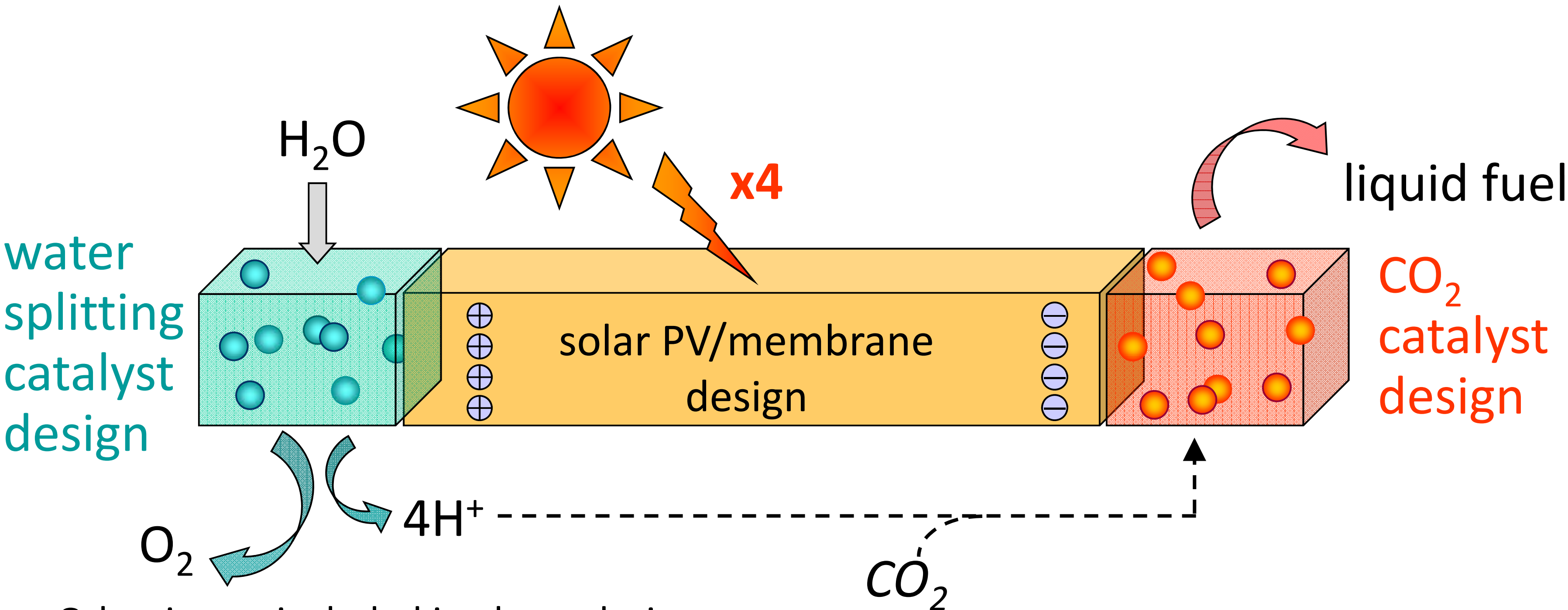
Global Systems

- Science and policy of global change
- Efficient buildings/smart infrastructure
- Transportation systems/supply chains,…
- Developing country infrastructure

Tools

- Novel materials: nanoscale, biological self-organized,…
- Social science/management: innovation, public attitudes,…

Direct (Decentralized) Solar Fuels Models at MIT



Other issues included in above design:

- Process engineering (fuel targets, water splitting followed by CO_2 redn vs H_2O and CO_2 to fuels)
- Engineering cost analysis of direct vs indirect
- Transport in PV, in catalyst, at interface
- Interfacial chemistry: catalysts to charge separating network
- Photon management

Sunlight to Fuels is a Science, Engineering, and Integration Challenge with Transformational Potential

- Catalysis
- Bandgap engineering
- Membranes
- Simulations
- Photonics
- Materials under Extreme Conditions
- Systems and process engineering
- Solar thermochemical cycles

- About 30 faculty from multiple departments in the conversation!

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Indian Solar Lantern Business in Karnataka

Developing a business model for solar lighting using school-based charging stations and high efficiency LED lanterns.

MIT – Technology Policy & Planning student Shreeja Nag (Jan. 2010)
(Collaboration with Indian social entrepreneur Harish Hande of Selco)

Low Cost Concentrated Solar Power

MIT D-Lab student Matt Orosz

Reengineered large scale concept for rural *use* and *manufacture*.

Half the cost of PV, or diesel.

Photo: STG International

Prototype 1kWe Solar ORC (Organic Rankine Cycle)

Ha Teboho, Lesotho 2008

Research Into Reality: Innovative Building

- 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 soil, thin brick, minimal cement
    - Local labor
    - Innovative use of agricultural and industrial by-products
    - Specialized software/compression only vaults

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

- One faculty member and three graduate students led this research

MITEI Seed Fund Projects

Many early career faculty, and many faculty bringing world-class capabilities to bear on energy problems for the first time

Example: just bio and bio-inspired seed grants

2008

- Advancing our understanding of Prochlorococcus, the Earth's smallest and most abundant photosynthetic machine – Penny Chisolm (CEE)
- Ensymatic control of pollutants and greenhouse gases – Cathy Drennan (Chemistry)
- Microbial biosynthesis of pentanol as a biofuel – Kris Prather (ChemE)
- Renewable biofuels production in the oleaginous bacterium Rhodococcus – Tony Sinskey and Jason Holder (Biology), Alex van Oudernarden (Physics)
- Investigation of subsurface microbial processes during and after geological carbon sequestration – Janelle Thompson and Roman Stocker (CEE)
- Bioinspired hierarchical thermal materials – Markus Buehler (CEE)
- Engineering tolerance in yeast for improved biofuel production – Greg Stephanopoulos (ChemE)

MITEI Seed Fund Projects

Example: just bio and bio-inspired seed grants

2009

- **Design of novel biofuels: biosynthesis and predicted fuel performance – Bill Green and Kris Prather (ChemE)**
- **Bio-inspired underwater adhesion system for deep-sea oil mining – Sangbae Kim (MechE)**
- **Optimization of coherent energy transfer in photosynthetic systems – Bob Silbey and Jianhu Cao (Chemistry)**
- **Genetic identification and expression of efficient cellulose degrading complexes from fungi – Chris Kaiser (Biology)**
- **Learning from nature: design principles for resilient bioenergy systems – Martin Polz (CEE)**

- **12/55 projects**
- **6 academic departments**
- **Projects and a faculty network to match with industry sponsor interests**

US DOE and Innovation

- New approaches to innovation, with elevated risk-taking
  - Mostly outside applied energy offices

- Recovery Act (“cliff event”?)
  - Loan guarantees

- Energy Frontier Research Centers (46): Science “grand challenges”
  - E.g., MIT: excitons/PV; thermoelectrics

- ARPA-E (Advanced Research Projects Agency): 3-5 year technology investment horizon
  - $400M stimulus; e.g. MIT:Sadoway+4 spinouts (+1)

- Innovation Hubs (3 in 2010): large groups pursuing “radical” technologies and working across innovation chain
  - @ $25M/year center

New Program:
Energy Frontier Research Centers (EFRCs)

Big Picture:

Purpose: Address "grand challenges" in energy and science. (Grand challenges defined through series of workshops held by the Office of Science Basic Energy Science Program.)

Important Notes:

- Awards announced in April 2009
- 46 EFRCs awarded, 16 through ARRA
- $2MM-$5MM per year per center

MIT is only university to lead 2 EFRCs!

+ a partner on 4 other EFRCs!

Covers of 10 BES Workshop Reports

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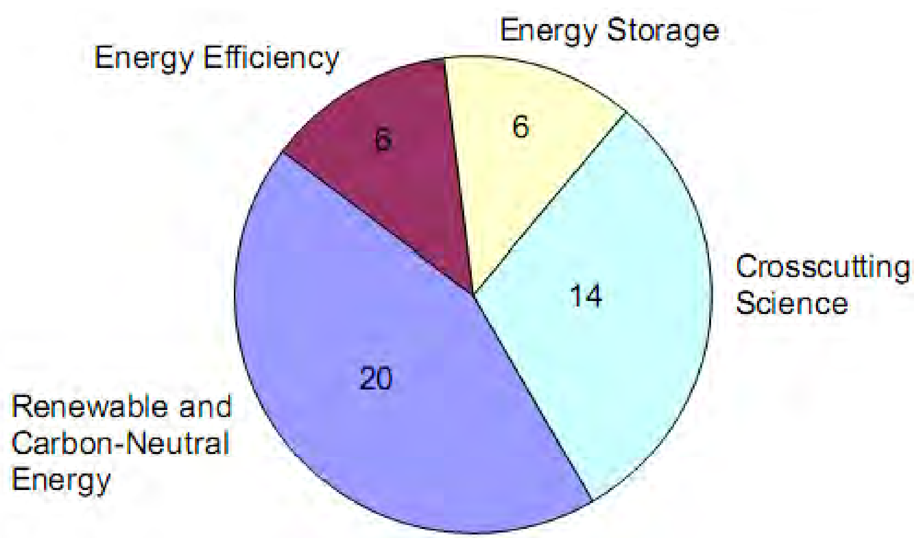
DOE Programs: EFRC

- 30 centers funded through FY2009 Federal Budget ($100 Million)
- 16 centers forward-funded for 5 years through the Recovery Act ($277 Million)
- Total DOE commitment of $777 Million over 5 years
  - $400 Million left for the 30 centers subject to future appropriations



DOE (2009). EFRC Fact Sheet. Obtained at: http://www.er.doe.gov/bes/EFRC_fact_sheet.pdf

EFRC Solar Awards

- Sunlight to electricity
  - U Arizona: hybrid inorganic-organic
  - UCalSB: nanoscale for improved conversion
  - UCLA: nanoscale material architectures
  - USC: hybrid inorganic-organic
  - NREL: inverse design
  - Northwestern: molecular design and synthesis
  - Northwestern: far-from-equilibrium materials
  - MIT: charge carrier transport (Baldo)
  - Umass: self-assembled polymers
  - U Michigan: nanoscale materials
  - LANL: nanoparticles
  - Columbia: nanometer sized thin films
  - Cornell: surface reactions
  - U Texas Austin: charge transfer processes

EFRC Solar Awards

- Sunlight to fuels
  - Arizona State: bioinspired solar fuel production
  - Washington U: photosynthetic antenna system
  - UNC: nanoscale architectures and new molecular catalysts
  - ORNL: fluid interfaces

- Sunlight to heat
  - CalTech: light-material interactions
  - MIT: solid-state solar-thermal conversion (Chen)

  - 20/46 awards/$341M over 5 years

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New Program:
Advanced Research Projects Agency - Energy

Big Picture:

•*Purpose: Develop breakthrough energy technologies to (a) reduce need for foreign oil, (b) reduce energy-related emissions, and/or (c) improve energy efficiency of economy; and ensure U.S. maintains technological lead in developing and deploying advanced energy technologies.*

•Modeled after Defense Advanced Research Projects Agency

Notes:

•Authorized in America COMPETES Act, August 2007

•Initial funding of $400M though stimulus package

•First awards of $151M in October 2009

- •MIT: Sadoway liquid metal battery + 4 recent spinouts + 2008 MIT Clean Energy Prize winner

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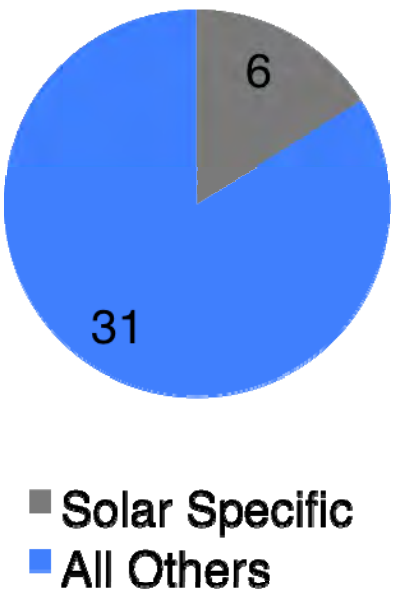
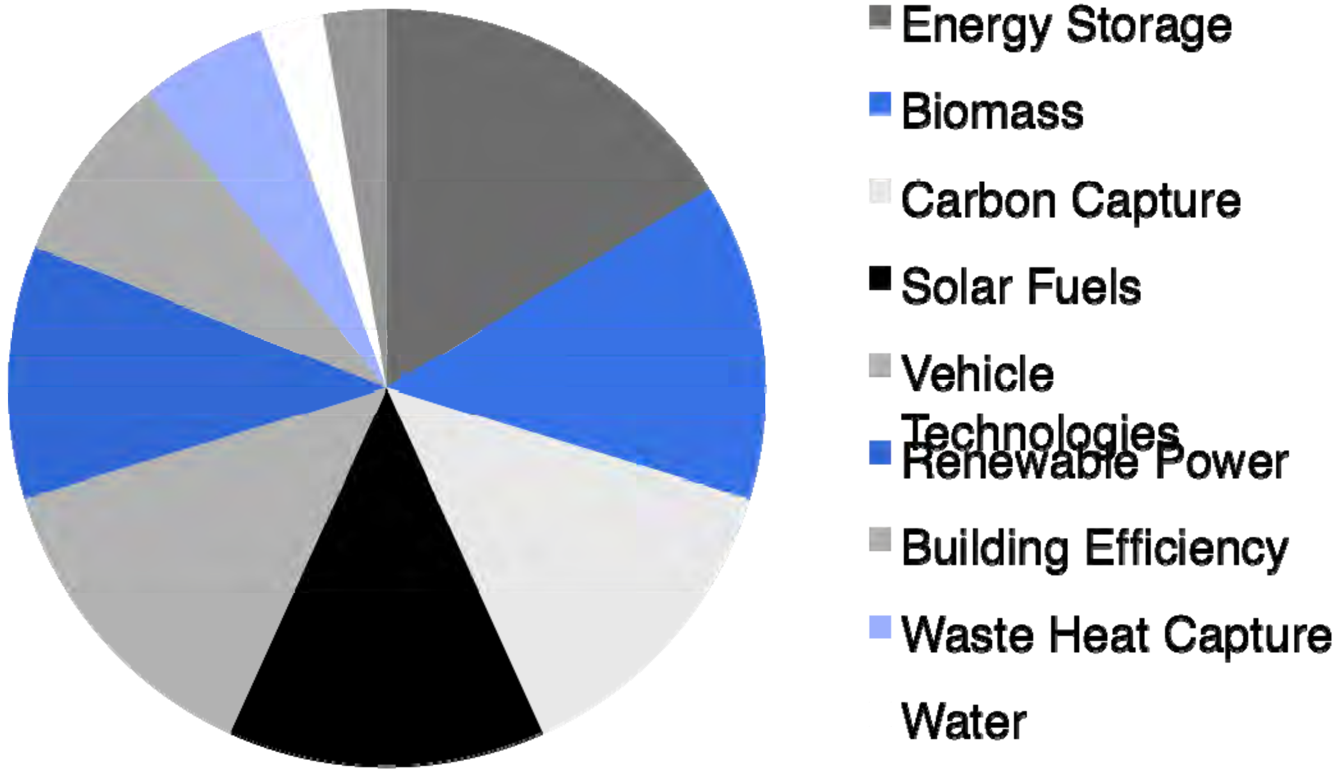
DOE Programs: ARPA-E

Division of 37 Program Awardees





http://arpa-e.energy.gov/index.html

ARPA-E Solar Awards

- Sunlight to electricity
  - 1366 Technologies (Sachs): “monocrystalline equivalent” silicon wafers directly from molten silicon

- Sunlight to Fuels
  - Arizona State U: cyanobacteria to biofuels
  - Iowa State: metabolic engineering of algae
  - Penn State: nanotube membranes for solar to fuels
  - Sun Catalytix (Nocera): novel catalyst for water splitting
  - U Minnesota: bacteria for producing direct solar hydrocarbon biofuels

- 6/37 awards/$21.8M out of $151M
  - Note: 4 universities + 2 MIT spinouts

The Changing DOE Innovation Ecosystem

Anticipated New Program:
DOE Energy Innovation Hubs

Big Picture:

Purpose: Mutli-disciplinary, multi-investigator, multi-institutional research centers focused at overcoming technological barriers to U.S. achieving leadership in emerging green economy and reducing dependence on imported oil and GHG emissions.

(Conditional) Funding Approved For:

- Nuclear Modeling and Simulation
- Fuels from Sunlight
- Energy Efficient Building Systems
- $22MM per hub per year; 5 years

DOE Secretary Chu's May visit to MIT involved discussions on the DOE Energy Innovation Hubs.

Loan guarantees - 2009

- $13B in “clean tech” loan guarantees in 2009
  - Go to $40B?

- VCs: $2.7B

- Anecdotal:
  - VCs: which companies attract public funds?
  - Government: which companies attract VC funding?
  - Role of recession?

    - Note: need to check all numbers

ENERGY STUDIES MINOR at MIT

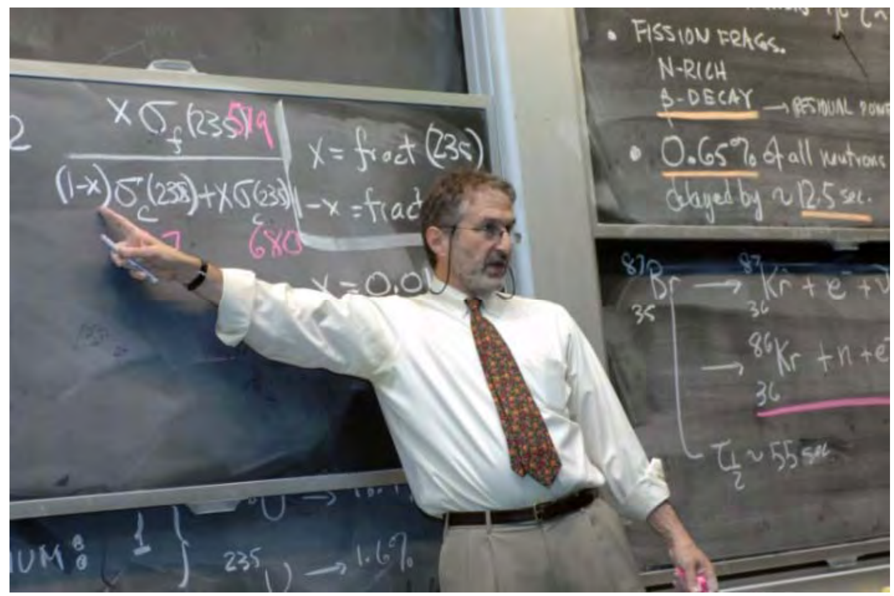
Core Curriculum

- one class in each domain
  - energy science foundations
  - social science foundations in energy
  - energy engineering/technology in context

PLUS

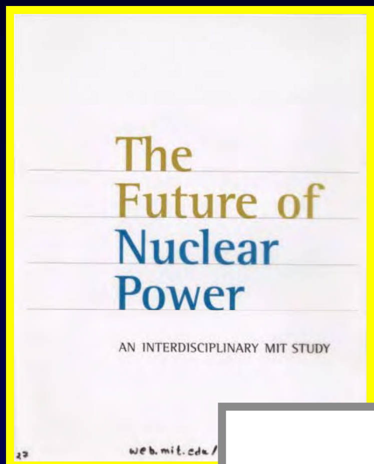
Energy Electives

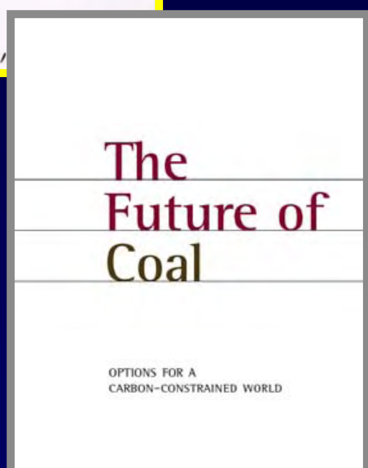
- 24 units, typically two classes



- first Institute-wide minor
- three-year experiment

MITEI Outreach Activities





Integrative multi-disciplinary studies: MITEI as an "honest broker –

- **Existing Studies on the *Future of Nuclear Power, Future of Coal***
- **New Studies on *Future of Solar Energy, Future of Natural Gas, Future of Advanced Nuclear Fuel Cycles, Future of the Grid,…***

Public outreach through –

- **Timely policy-relevant symposia**
- **Seminars, colloquia, lectures, testimony, speeches**
- **Newsletters, websites, research spotlights**
- **CleanSkiesTV broadcasts of energy activities at MIT (presidential campaign debate on energy, Sen Bingaman, President Obama,…)**

Nuclear power future?

- Economics ?
  - “first mover” financial incentives using public funds (PTC, loan guarantees,…)
- Nuclear spent fuel management?
- Proliferation risks/enrichment and reprocessing?

Reference frame

- GHG emissions and nuclear “renaissance”?
  - TW scale is a tripling
  - Inevitably a spread to new regions, some of proliferation risk
- Long term geological isolation of SNF/HLW appears to be scientifically sound in well chosen sites with good project execution
  - Once through fuel cycle is a viable economically-favored option for some time
- Storage of SNF for a century or so should be implemented

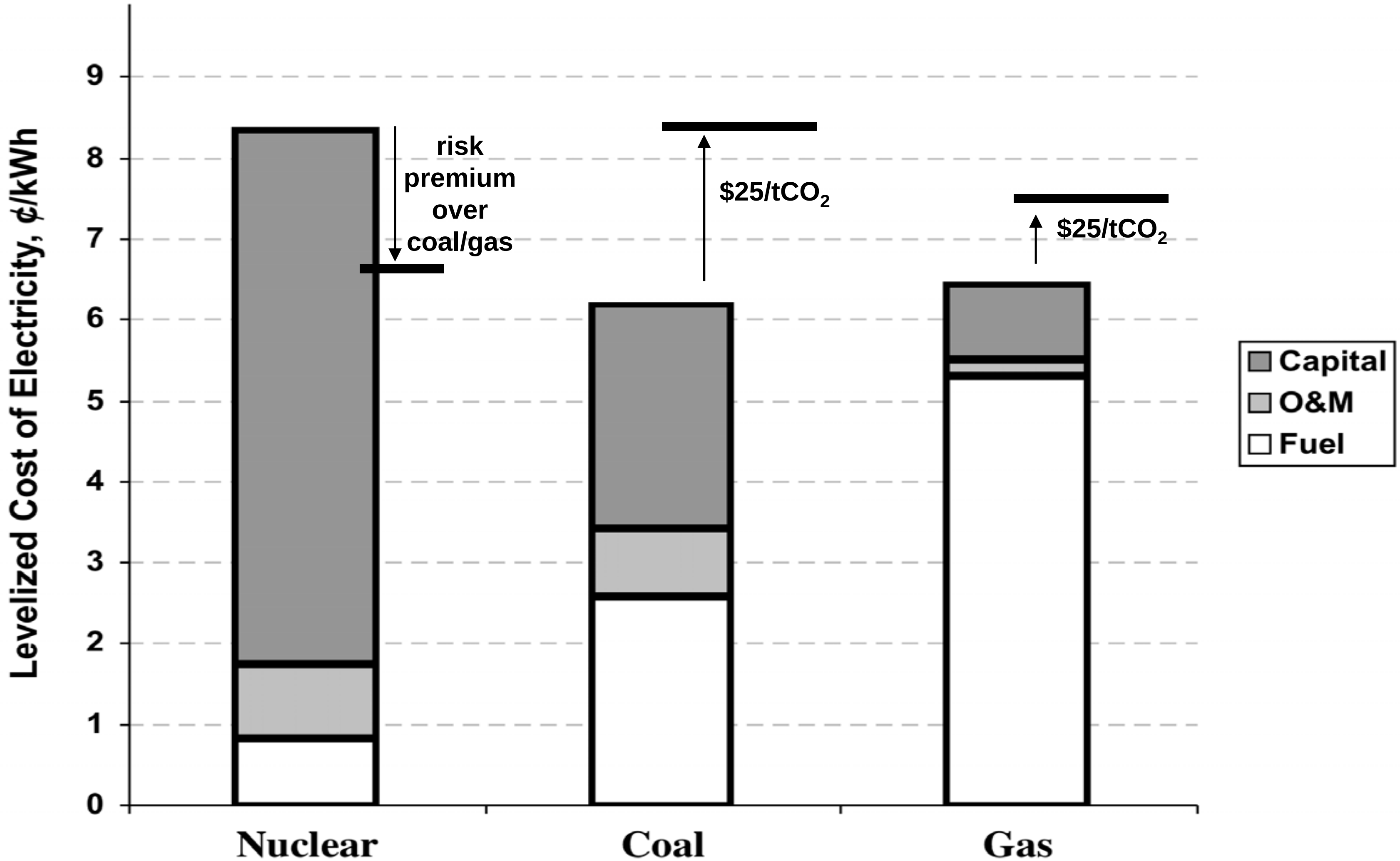
Reference frame cont'd

- APS POPA: "There is no urgent need for the US to initiate reprocessing or to develop additional national repositories…there is time to determine the best path for the next phase of the expansion of nuclear power…It Is important, however, to use that time effectively to explore the options more thoroughly than has been done to date."

Update of MIT 2003 Future of Nuclear Power Study

- Compared to 2003, motivation to make more use of nuclear power is greater
- Public acceptance of nuclear power is greater
- Performance of nuclear plants has been excellent
- New nuclear plants are still more expensive (cost/kwh) than new coal or natural gas plants but removal of risk premium and/or CO2 price can make nuclear power competitive
- Government first mover incentives have not been effective to date to make firm nuclear power commitments; no new plants under construction
- Clear need for a robust long term waste management policy
  - Interim/managed storage
  - Fuel cycle alternatives including reactor technologies
  - Disposal options (post Yucca?)

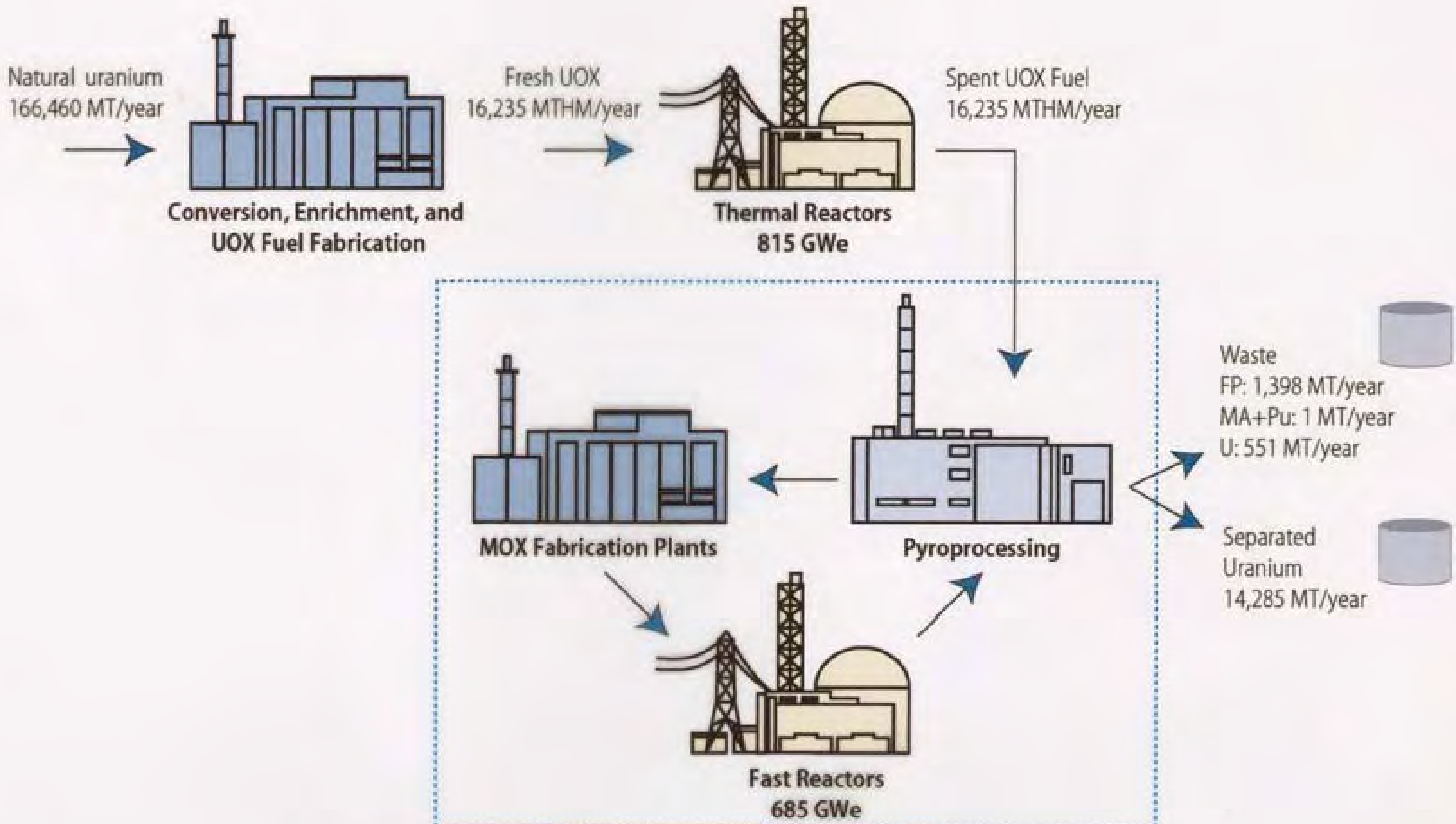
Update of the economics to reflect climbing costs



Spent fuel reprocessing

- Links waste and nonproliferation considerations
  - Long term heating from actinides and weapons usability
  - Risk primarily with enrichment and reprocessing
  - Today about 250 tons of separated plutonium globally
  - Exaggerated claims for waste management benefits of PUREX/MOX fuel cycle
  - New technologies may address these concerns and provide significant waste management benefits

Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



Nuclear fuel leasing

- Fresh fuel supply, used fuel return
- “supplier” states and “user” states
  - Marketplace reality today
  - “stay-put” period of 10 to 15 years
  - R&D participation
  - Fresh fuel incentives
    - E.g., CO_2 emissions credits
    - Candidate user states in Mideast?

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MIT Future of the Nuclear Fuel Cycle Study

- **Two Overarching Questions:**

  1. What are the long-term nuclear fuel cycle choices that have desirable features?

  2. What are the implications for near-term policy choices?

Ground Rules and Assumptions

Range of Cases Analyzed to Understand Sensitivity of Results to Input Assumptions

- **Alternative nuclear growth rates considered**
- **Several fuel cycles analyzed/baseline cases and alternatives**
  - Once through
  - Recycle for fissile fuel recovery
  - Recycle for waste management
  - Evaluate in "modern" context of U resources and LWR staying power
- **Emphasize fuel cycle dynamics and value of options for different growth scenarios and technology development**

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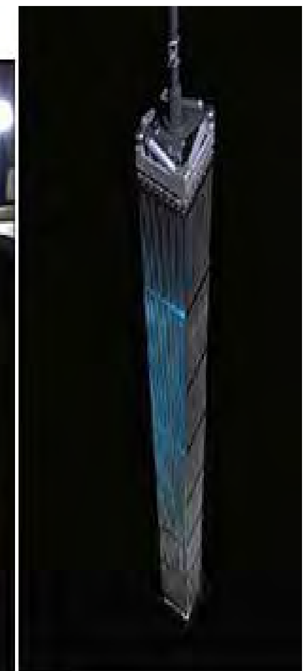
What Should Be Our Used Nuclear Fuel Storage Strategy?

- Storage can provide time to determine what is more important within the duality of Used Nuclear Fuel
  - Resource
  - Waste
- Storage is a nuclear-chemical process: heat and radioactivity decrease with time
  - Lowers reprocessing costs and risks
  - Lowers transport costs and risks
  - Increases repository capacity
- Approach to storage should be integral to fuel cycle choices/ choice of storage time has major fuel-cycle impacts
- Three classes of storage option
  - At reactor (U.S.)
  - Centralized monitored retrievable storage
  - Combined Storage/Repository

What Are the Preferred Fuel Cycles for a Sustainable Future?

Compare/Contrast Multiple Cycles To Understand Range of Implications

- What are the implications to the repository and other waste management facilities of alternative fuel cycles?
- What are the uranium resource implications?
- What are the nonproliferation implications to the world of our choices for fuel cycles?
- What are the technical challenges of the alternative fuel cycle options?

What Are the Technical Challenges and Viability of Alternative Fuel Cycle options?

- Must consider the complete fuel cycle
  - Reprocessing
  - Fuel Fabrication
  - Reactors
  - Waste Disposal/Multiple streams from different fuel cycles
    - Separations small part of cost of reprocessing
- Commercial reprocessing is a relatively new enterprise
  - Value for long term waste management?

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R&D Recommendations

- Align with reality of next decades
  - Global Uranium Resource Assessment
  - Enhancement and life extension of LWRs
  - New build LWRs/new materials, fuels,…
  - Long term dry storage assessment/engineered barriers
- Alternative disposal options
  - E.g. MA's and deep boreholes

R&D Recommendations

- Explore long term options
  - Closed fuel cycles and fast reactors
  - Safety and operations analysis of fuel cycle facilities
  - Advanced simulation tool development/reactors and waste management systems
- Nuclear materials security
- Demonstrations?

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Summary & Conclusions

- Changes since 2003 indicate the need to rethink fuel-cycle strategies
- There is time to assess alternatives before selecting a path forward/focus on optionality.
- There are major questions that need to be addressed to provide *a durable widely-supported long-term fuel-cycle strategy*
- The goals of the MIT study are to aid in the process to develop such a strategy
- Identification of research, development and demonstration needs aligned with important fuel cycle options.

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