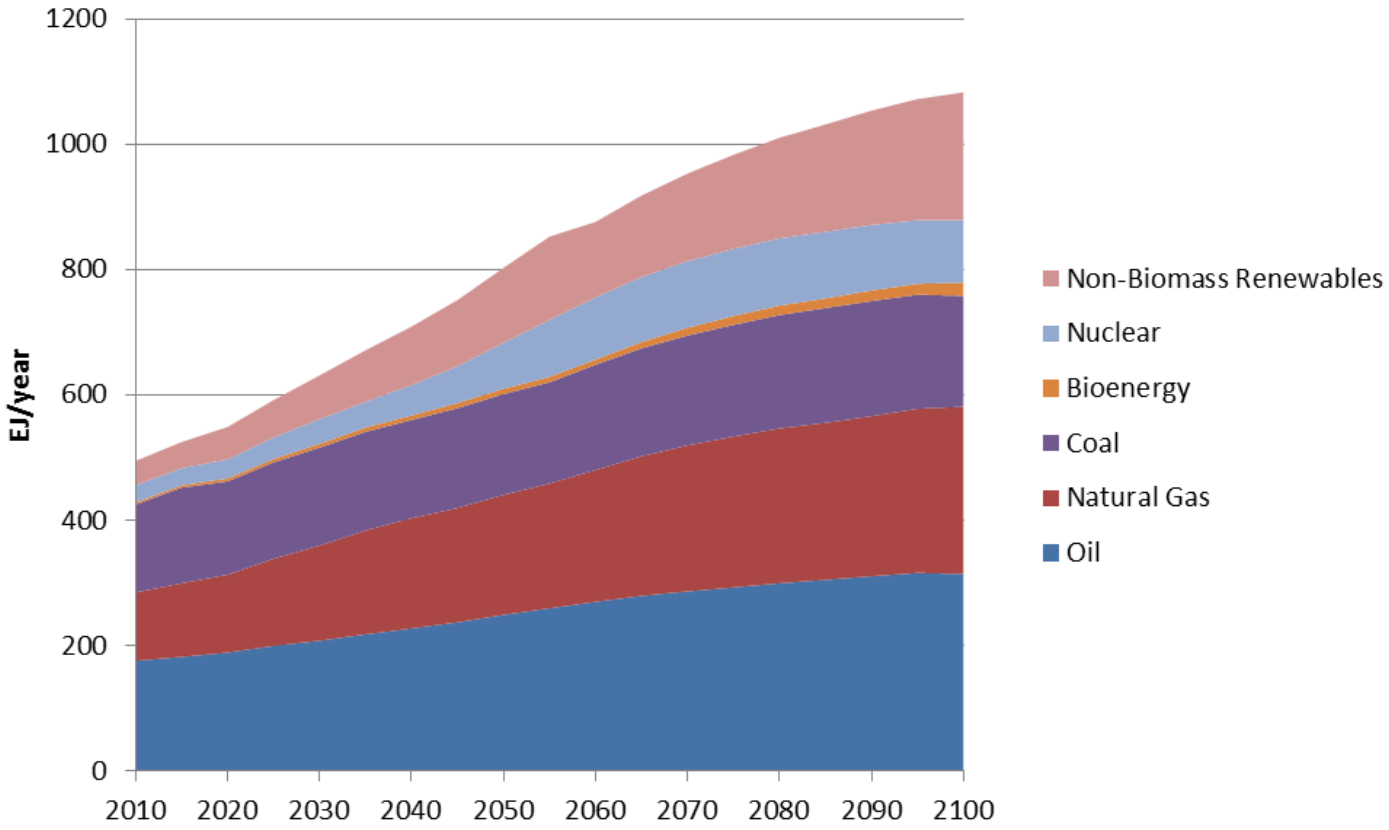
Technology Pathways for a Low-Carbon Future

Robert C. Armstrong
Director, MIT Energy Initiative
Chevron Professor of Chemical Engineering

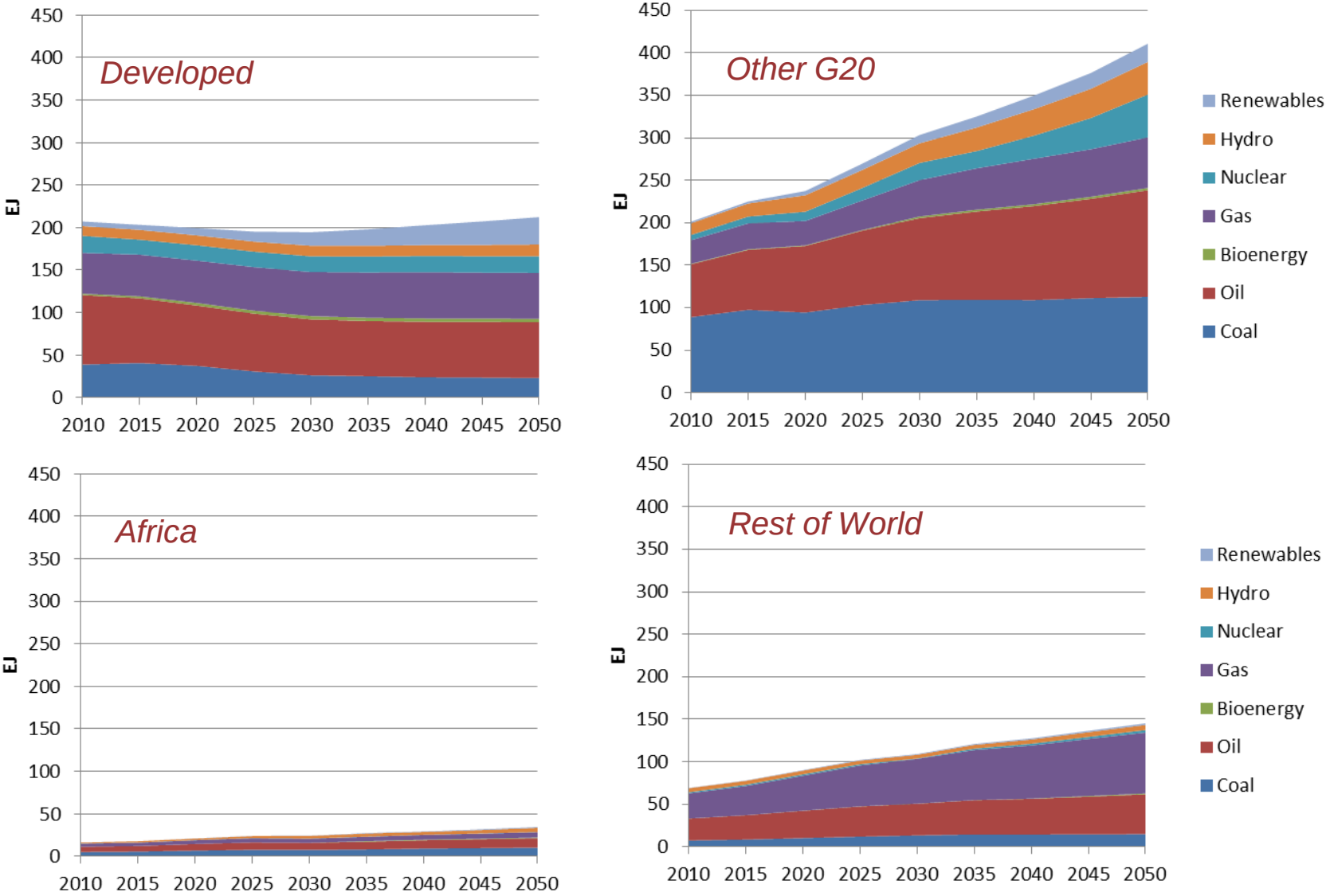

GRAND ENERGY CHALLENGE
Global energy demand is projected to double.
The world urgently needs to dramatically reduce greenhouse gas emissions while developing and deploying clean, affordable, reliable energy solutions.

MIT JP Outlook 2015 (No additional policy after COP-21 targets)



Global energy use: Most energy comes from the same sources currently utilized: oil, natural gas, coal.

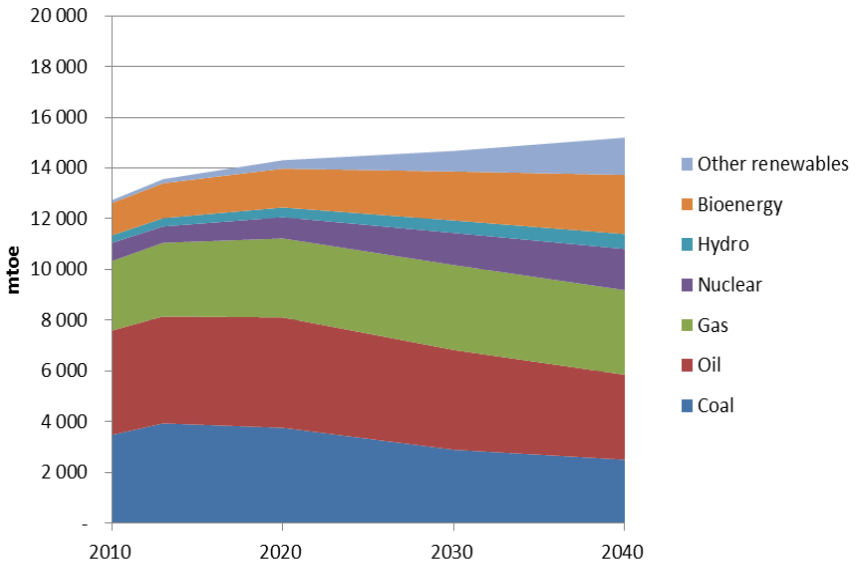
Energy Use by Region

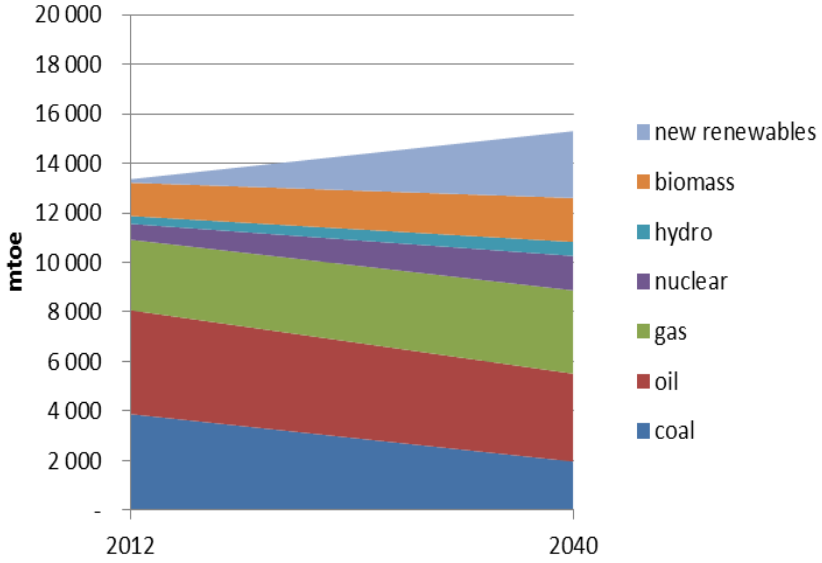


Slide from Sergey Paltsev, MIT Joint Program

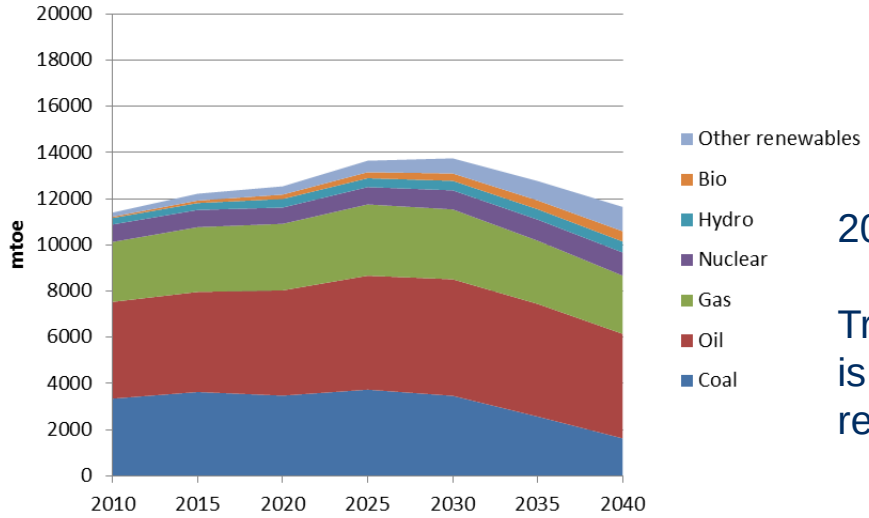
“450” – IEA, “2C” – MIT Joint Program, “Renewal” - Statoil

2015
IEA





2015 Statoil,
only 2012 and
2040 are reported



2015 MIT

Traditional biomass
is not explicitly
represented in the model

India – The Emerging Emissions Juggernaut

- Indians represent 18% of global population and use 6% of global primary energy.
- Approximately 250M lack electricity access and *many more* are undersupplied.
- Massive demand growth is likely with 4x electricity supply possible by 2040.
- High ash coal is by far the dominant domestic energy resource.

- Off-grid technologies will be important as grid expands slowly.
- Stated objective is to double coal consumption by 2020
- Commitment to 175GW renewables (100GW solar) by 2022 is a good start.
- Future growth with low greenhouse emissions will require engagement with the global research community and aggressive application of new technologies.

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Africa – Mid-Century Juggernaut

- Africans will comprise >25% of global population by mid-century.
- >75% lack electricity access and 80% use biomass for cooking.
- More Africans (mostly rural) will lack electricity by 2030 than do now and roughly half will lack access by mid century (>600M people).
- Africa overall has enormous and diverse fossil and renewable energy resources.

- Low incomes favor a least cost emphasis – further large cost reductions in renewables, and off-grid technologies (e.g., micro-grids) will be needed.
- Few countries individually have diverse energy resources; power pools, DERs and transmission will be important.

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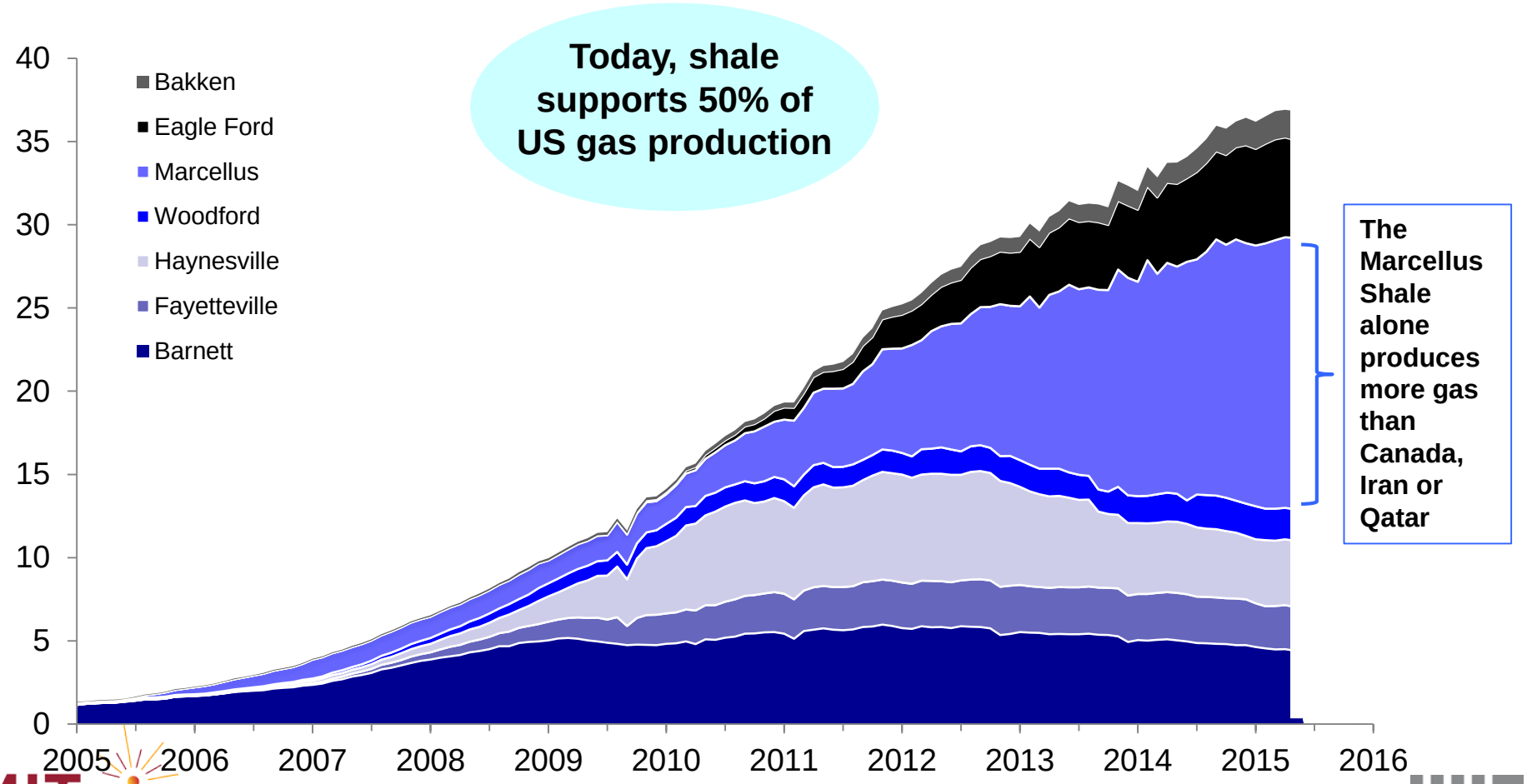
The global energy sector is currently bearing witness to a set of dramatic and unexpected dynamics – Global gas markets are being reshaped, oil prices have collapsed, and the level of renewables capacity is exploding

Illustration of gas production growth from the main U.S. shale plays since 2005

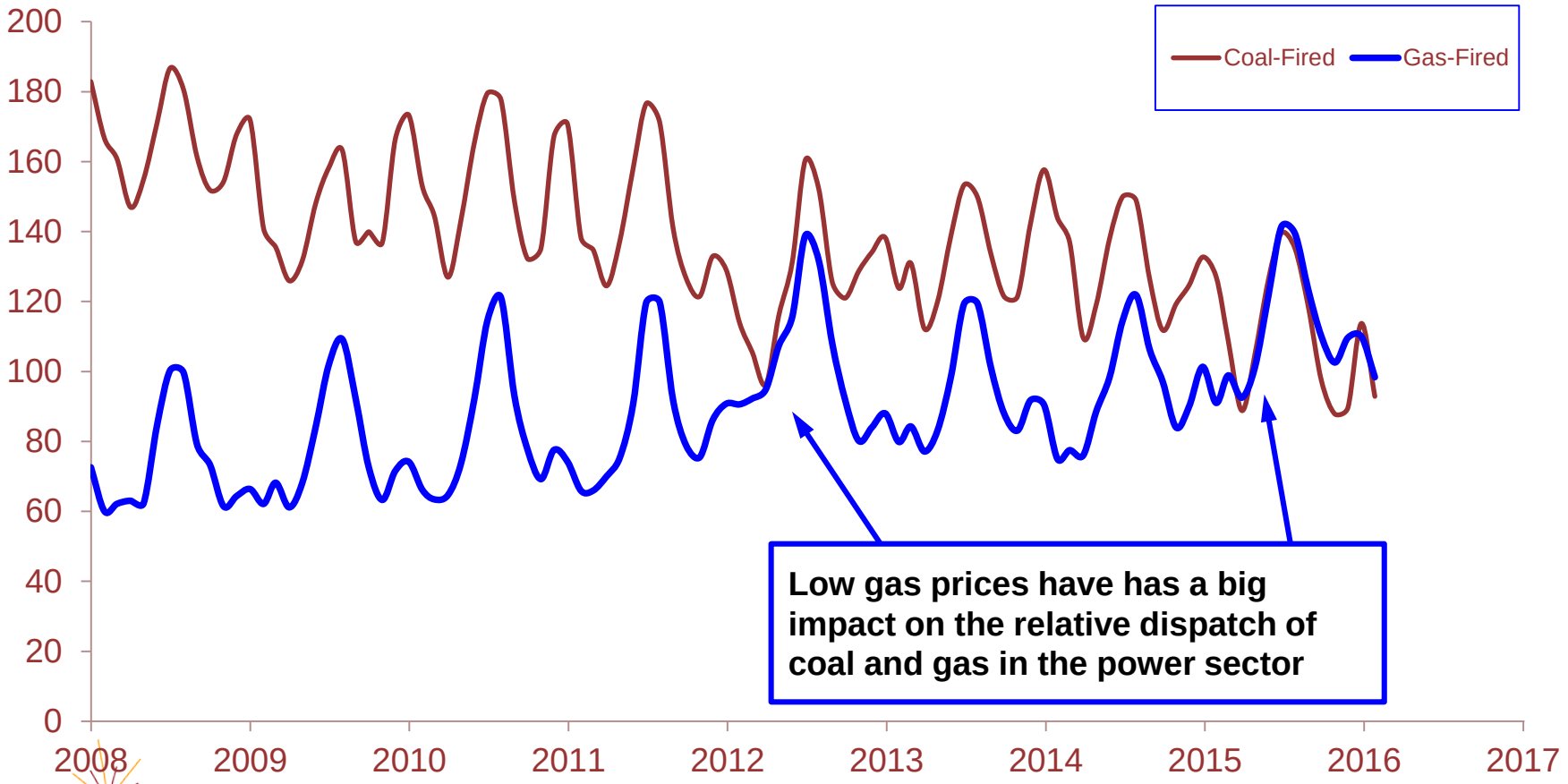
Bcf of gas per day



Source: F. O'Sullivan, United States Energy Information Administration, HPDI Production Database

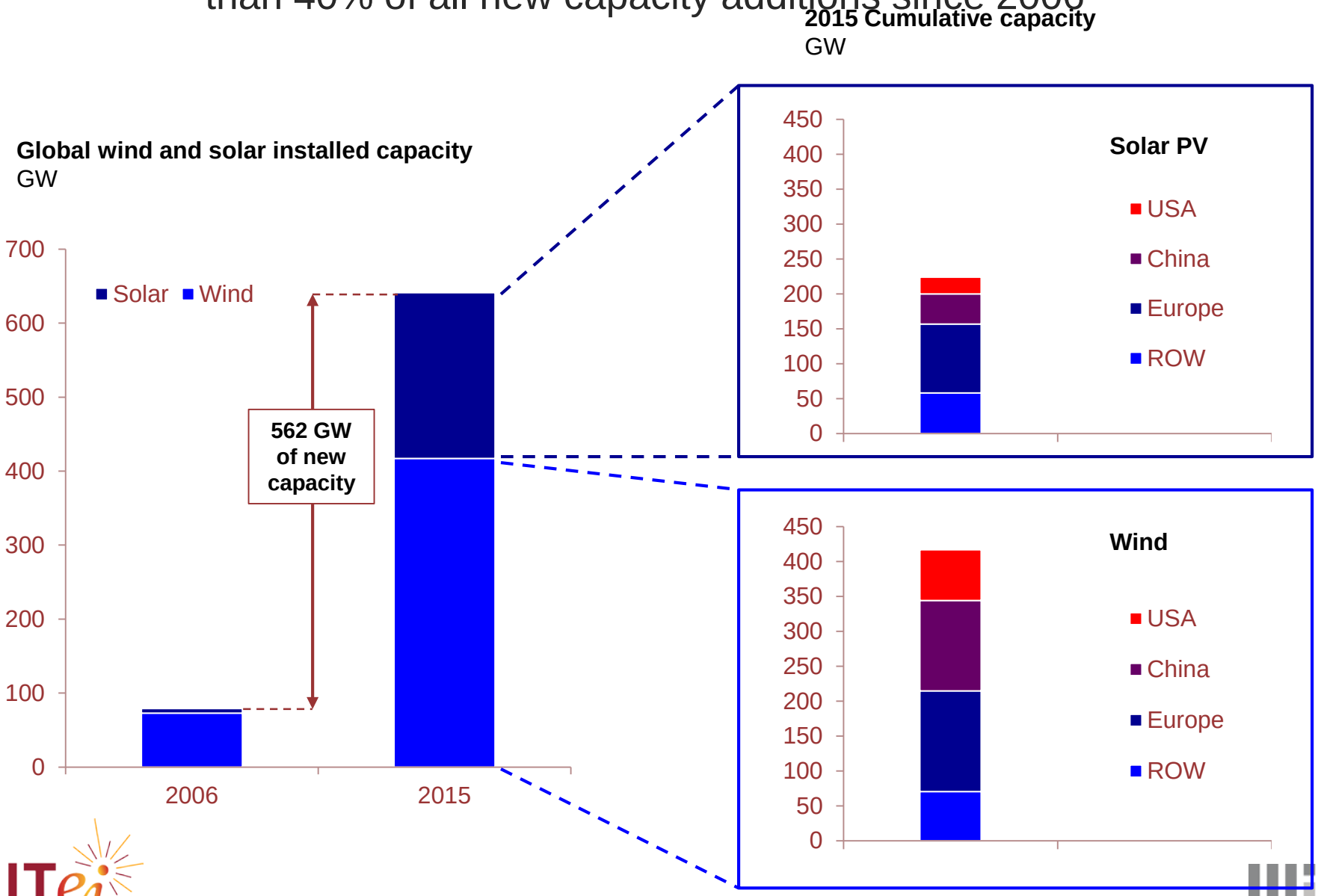
Over the past several years low gas prices have led to gas increasingly displacing coal-fired generation – More gas use in generation going forward looks likely

Comparison of coal and gas-fired power generation levels in the U.S. since January 2008
TWhrs



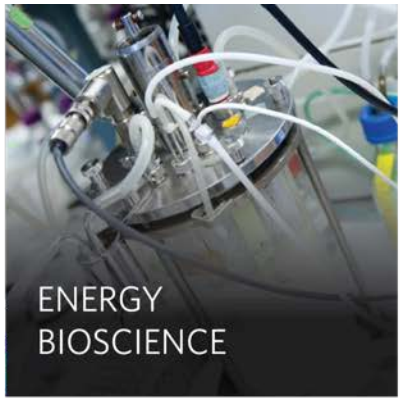
Source: F. O'Sullivan, United States Energy Information Administration

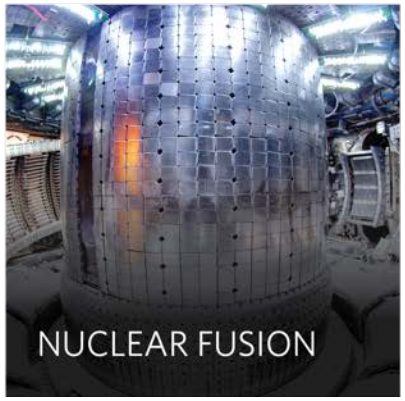
The past decade has borne witness to tremendous growth for both wind and solar globally – Together, wind and solar accounted for more than 40% of all new capacity additions since 2006



Source: National Renewable Energy Laboratory, Lawrence Berkeley National Laboratory, Solar Energy Industry Association

MITEI'S LOW-CARBON ENERGY CENTERS





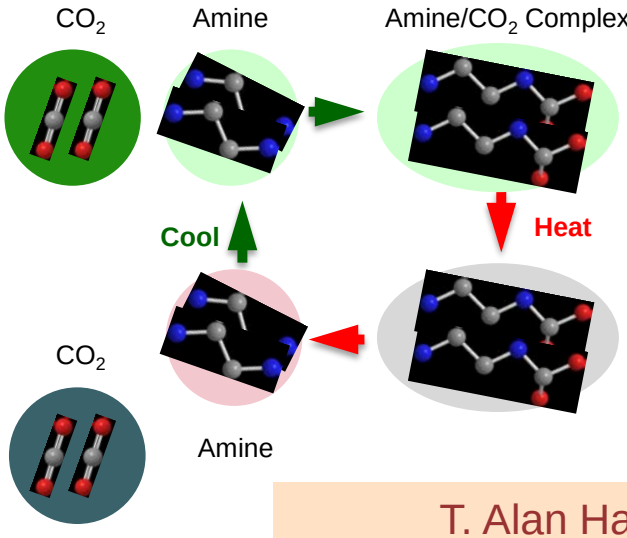
CCUS – WHAT PROBLEMS MUST WE SOLVE?

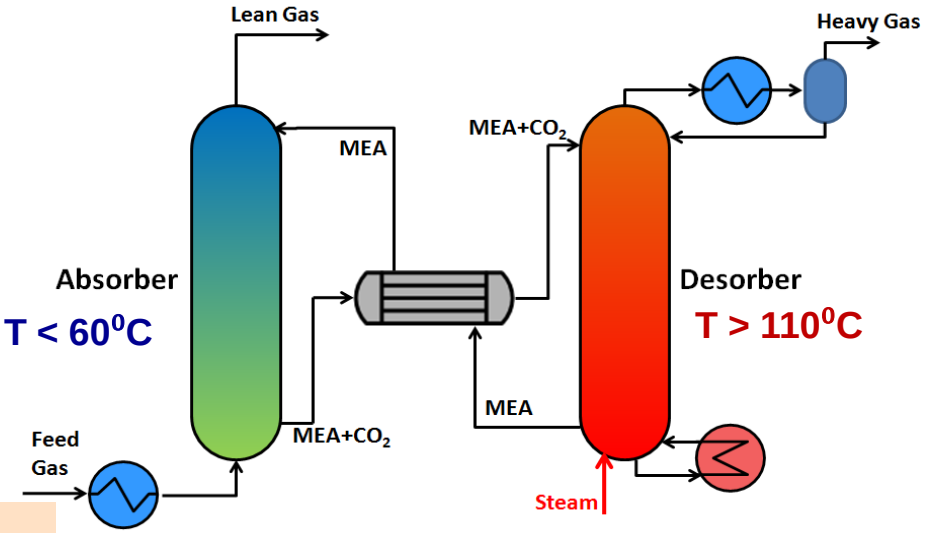
- Capture is expensive (30 - 60% additional energy penalty)
  - Improvements in capture technology are needed
  - Utilization provides incentive in the absence of regulations
  - Regulations required for capture at necessary scale to be implemented
- Meaningful quantities are huge – comparable to hydrocarbon use 5 Gt/yr equivalent to 40 Gbbl/yr

  Global oil production: 34 Gbbl/yr

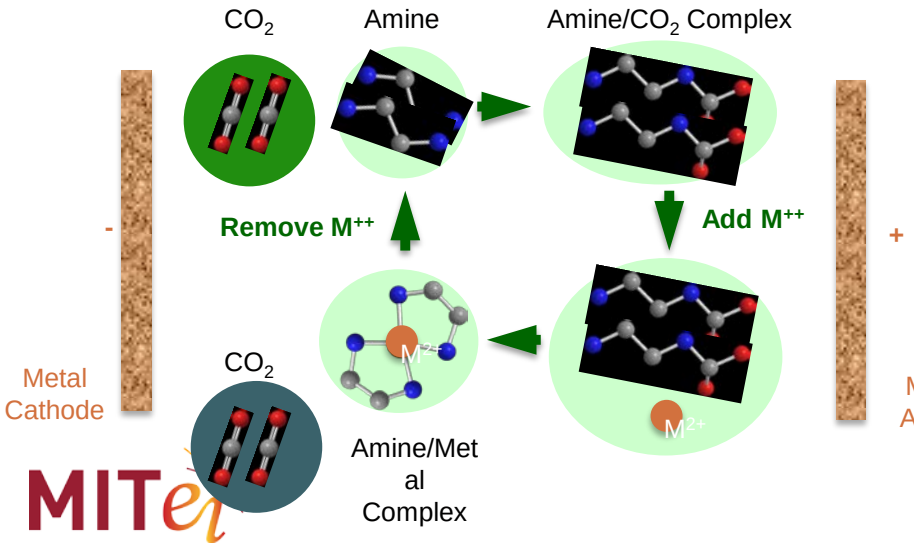
  Wastewater injection ~ 100 Gbbl/yr
- Transport is required if source is not adjacent to aquifer
- Storage is challenging, must be demonstrated at scale:
  - Large volumes of permanently isolated pore space required
  - Pressure management needed to limit earthquakes
  - Monitor for long time
- Solutions to these problems can be applied globally

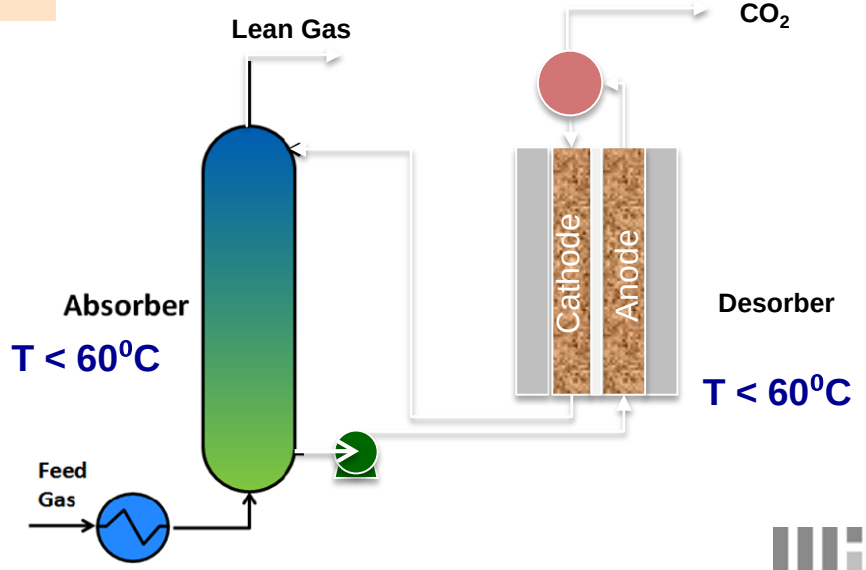
ELECTROCHEMICALLY-MEDIATED VS THERMAL AMINE REGENERATION





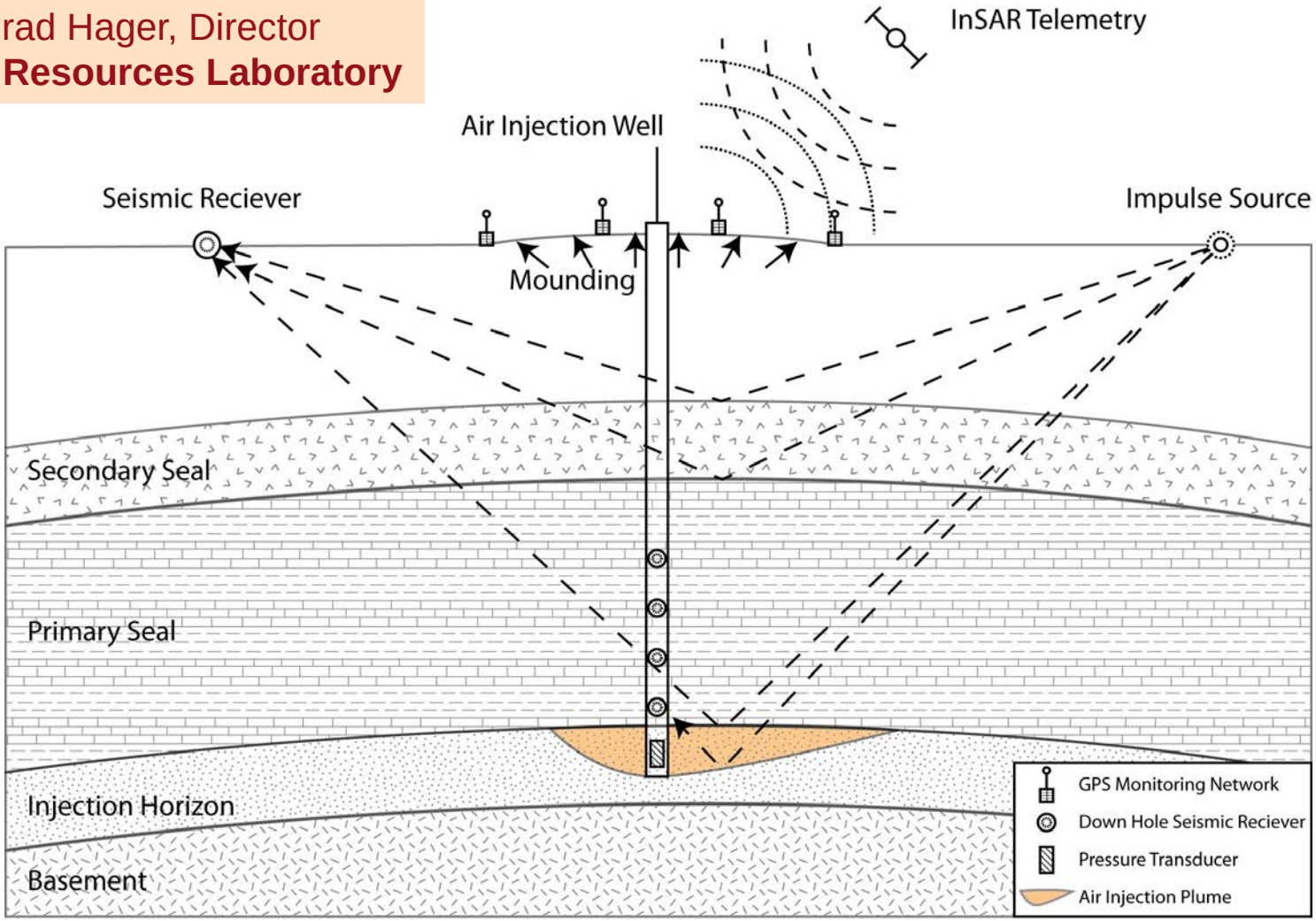
T. Alan Hatton
Chemical Engineering



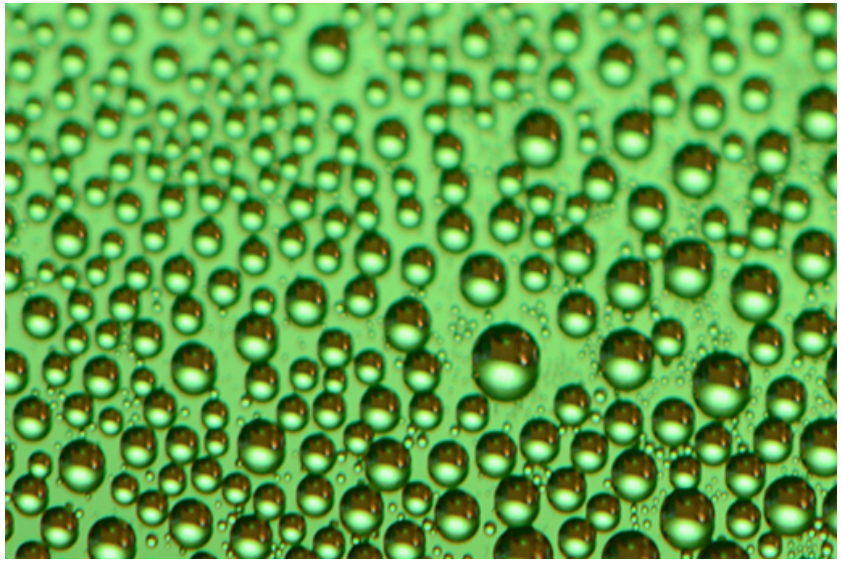


FORMATION TESTING, MONITORING, AND VERIFICATION

Brad Hager, Director
Earth Resources Laboratory



Materials for Energy and Extreme Environments



The new coating, seen here, maintains its ability to foster droplet formation over long periods.

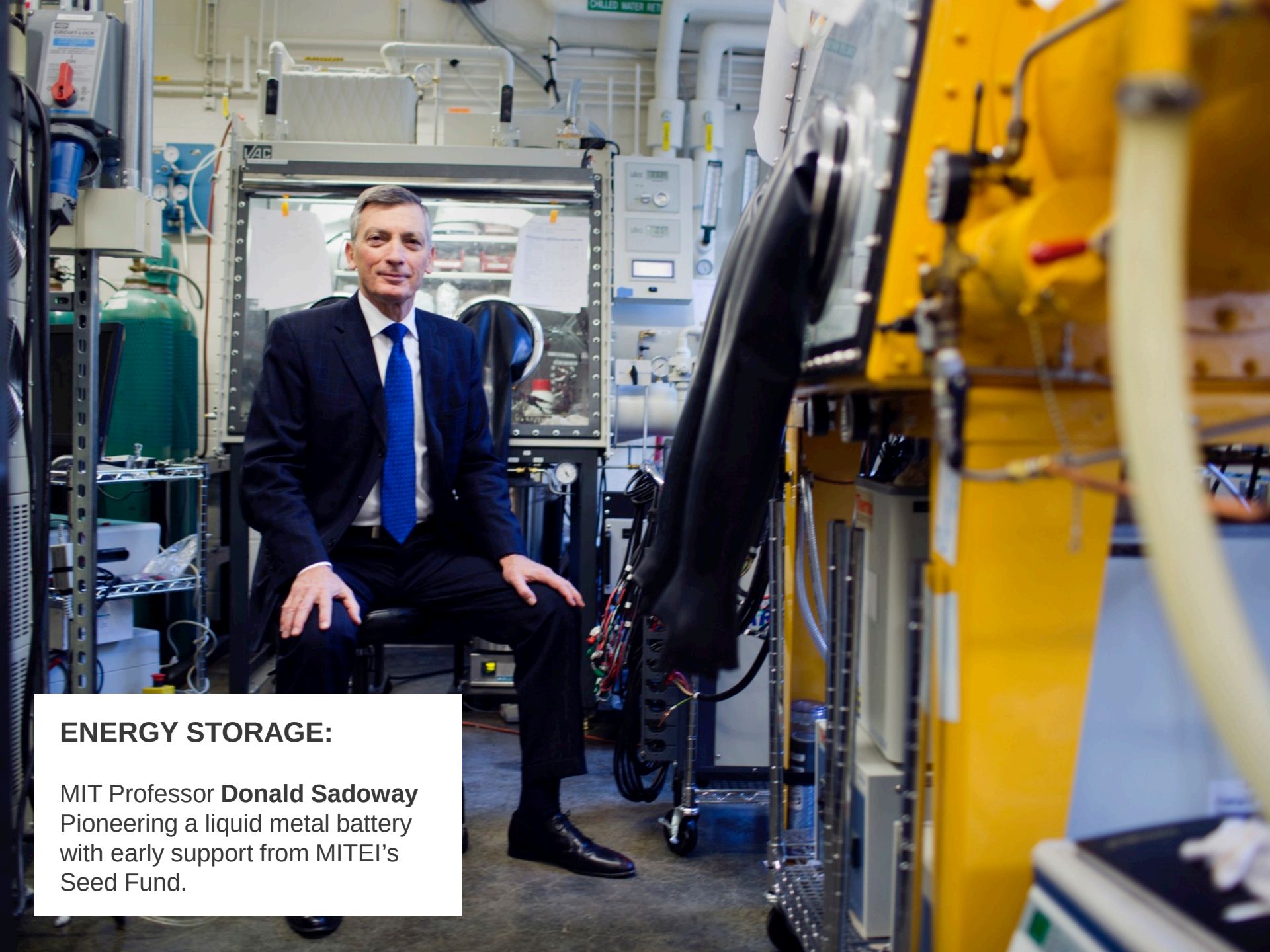
Karen Gleason and Kripa Varanasi

- Steam condensation drives 85% of all electricity-generating plants globally
- Improve efficiency of steam condensation with new coating that repels water, causing water droplets to quickly form
- The new coating can easily be applied to conventional condenser materials in existing facilities, using initiated chemical vapor deposition (iCVD)
- One-thousandth the thickness of conventional hydrophobic coatings – electrical or thermal conductivity are hardly affected

SOLAR ENERGY:

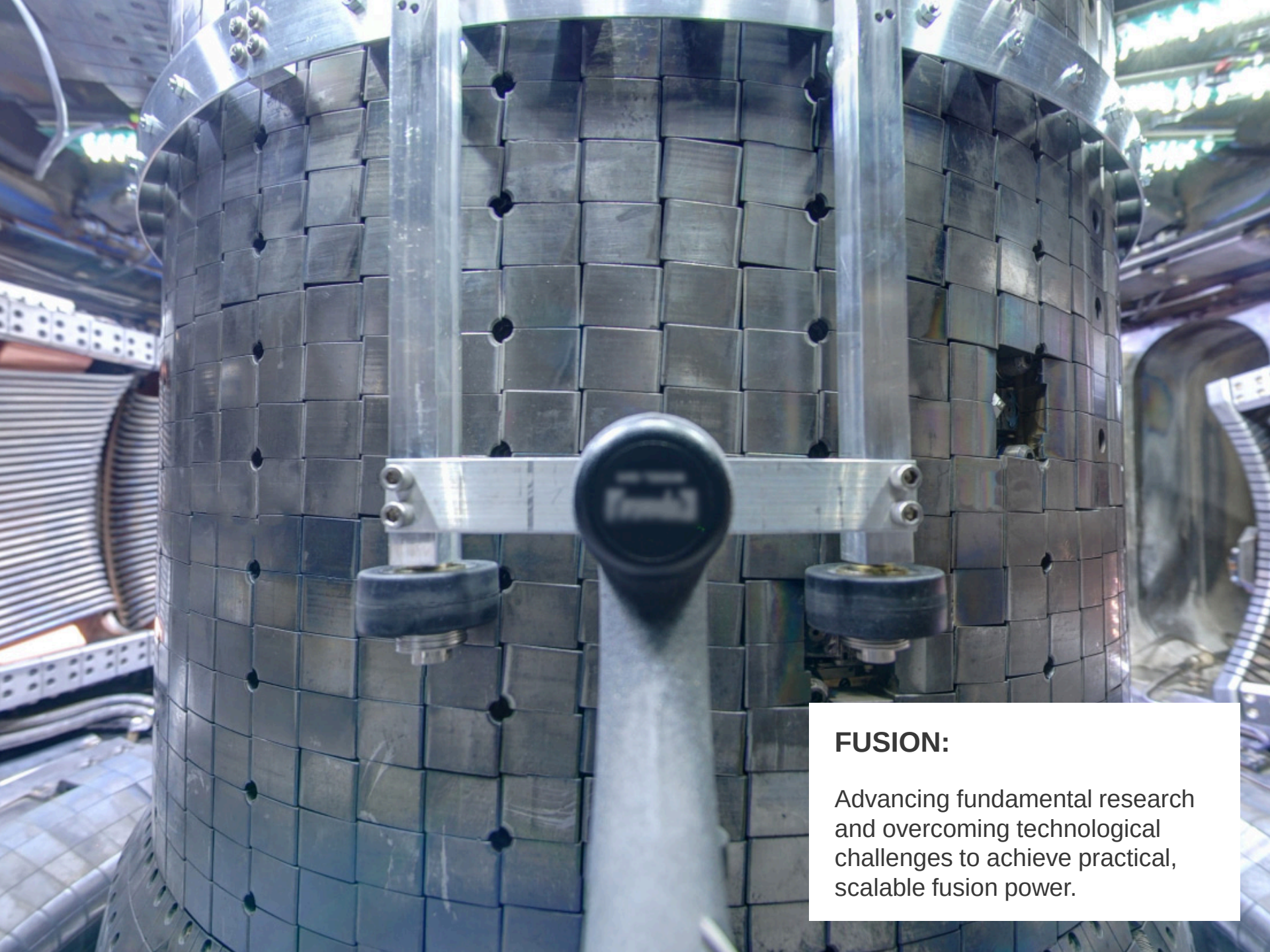
MIT Professor **Vladimir Bulovic**
Developing ultrathin, flexible solar cells that could fit on almost any surface, with potential applications in developed and developing countries.

Supported by Eni through the Eni-MIT Solar Frontiers Center, and through the National Science Foundation.



ENERGY STORAGE:

MIT Professor **Donald Sadoway** Pioneering a liquid metal battery with early support from MITEI's Seed Fund.

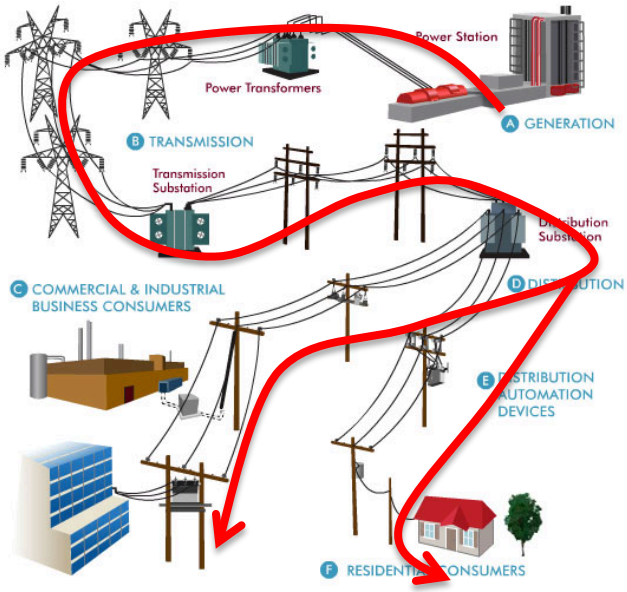


FUSION:

Advancing fundamental research and overcoming technological challenges to achieve practical, scalable fusion power.

UTILITY OF THE FUTURE

"Analysis of the future of the provision of electricity services, either in a *centralized or decentralized* manner, via alternative business models, with transformative technologies, and under diverse regulatory and market contexts, within the global framework of an increasingly *decarbonized power sector*."



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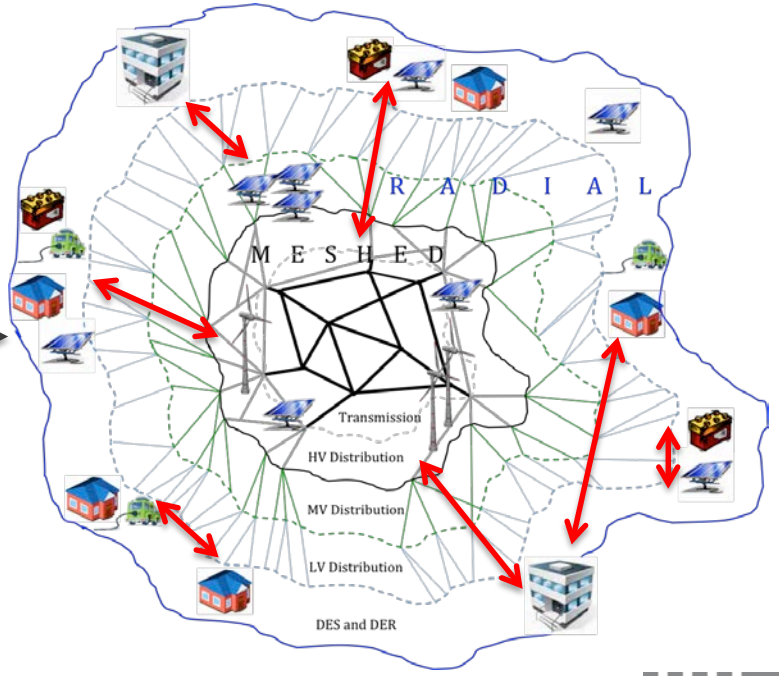


MOBILITY OF THE FUTURE

Consortium of industry leaders in fuels, vehicles & technology supporting a multidisciplinary MIT team addressing tough questions:

- What combination of fuels, vehicles, and technologies will be selected by consumers over the coming decades?
- What are the critical factors/sensitivities that drive uncertainty in future mobility?
- Which combination of future mobility options offer the best insurance against key uncertainties?

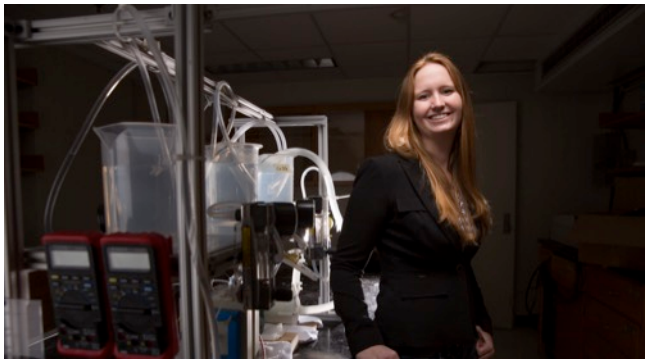
MULTI-DISCIPLINARY STUDIES: POLICY IMPACT

- Future of Solar Energy (2015)
- Future of Natural Gas (2011)
- Future of the Electric Grid (2011)
- Future of the Nuclear Fuel Cycle (2010)
- Future of Geothermal (2008)
- Future of Nuclear Power (2003, 2009)
- Future of Coal (2007)

Study participants have briefed trade associations, NGOs, elected officials and their staffs, administration officials; have testified on study results at Congressional hearings; and have spoken in scores of venues in the US and around the world, including Norway, Cyprus, Abu Dhabi, Hungary, Japan, Peru, Australia, Turkey, Monaco, Spain, Brazil, Colombia, Ecuador, and other countries

TATA CENTER FOR TECHNOLOGY AND DESIGN

- Training engineers and entrepreneurs to tackle challenges of resource-constrained communities in India and the developing world
- Some recent highlights:
  - Won numerous international research prizes including USAID Desal Prize
  - Two spinout companies, Khethworks and Ulink and policy partnerships at state and national levels
  - Annual International Symposia at MIT and in India
  - Hosted Ministers of the Environment, and Energy at MIT
  - Establishing major program with India on low carbon energy technology and policy
- 60 active projects and students (Master's and Ph.D.)
- Postdocs, faculty, and researchers: all 5 schools



Natasha Wright won USAID's prestigious Desal Prize for a solar electrodialysis system that creates clean drinking water at village scale.

Katie Taylor, Tata Fellow and CEO of Khethworks, with Indian Prime Minister Narendra Modi

CHALLENGES AHEAD

- Small penetration dynamics is not necessarily a guide to large scale deployment for renewables
  - Economics
    - Cost
    - Subsidies do not scale
    - Value to asset owner collapses (without storage)
  - System issues with large penetration
    - Operational challenges
    - Capacity challenges
    - Zero-carbon baseload
- Developing countries present special challenges/opportunities
- Technology opportunities
- Policy

Thank You!

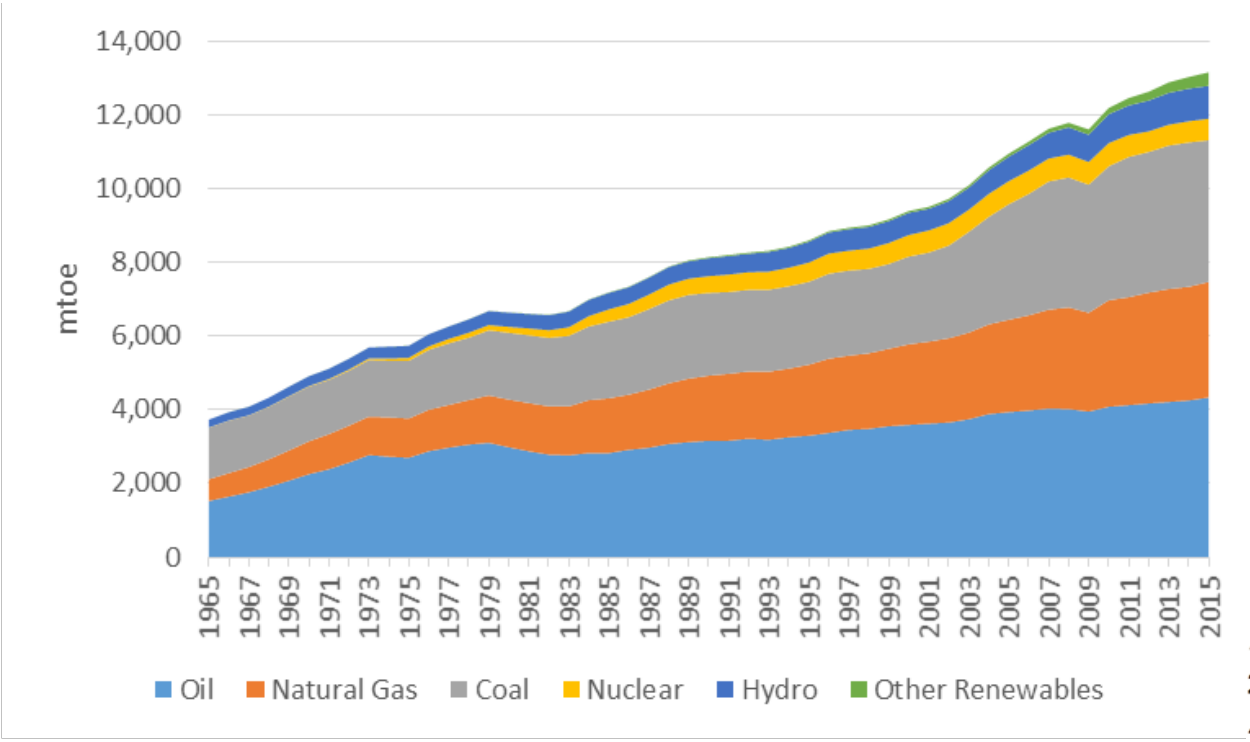
OUTLINE

- Introduction and framing
- MIT Plan for Climate Action
- Low-carbon energy centers
- System studies
- Developing countries
- Challenges ahead

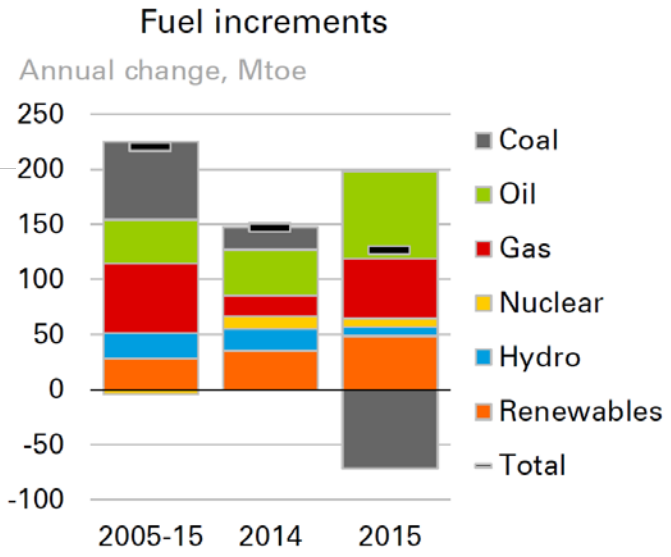
MIT PLAN FOR CLIMATE ACTION?

- Climate science and mitigation and adaptation solutions
- Low-carbon centers
- Energy system transitions/studies
- Education
- Global sharing
- Campus

Energy Trajectory - Global Primary Energy Use



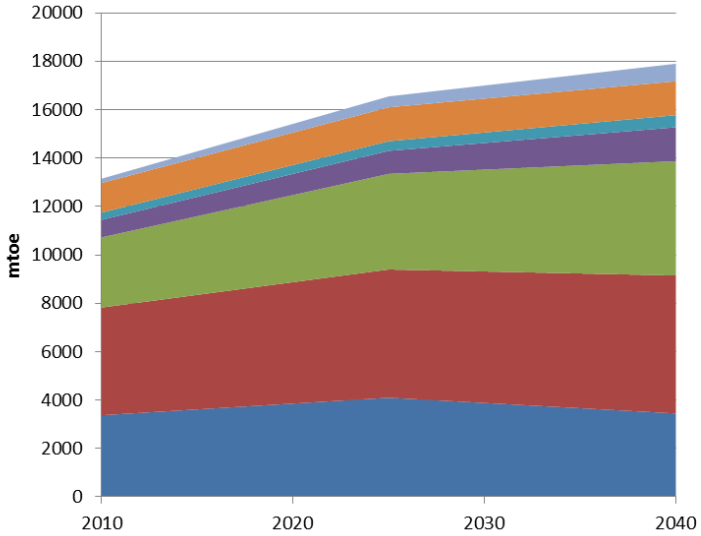
Data source: BP (2016).
Slide from Sergey Paltsev, MIT Joint Program

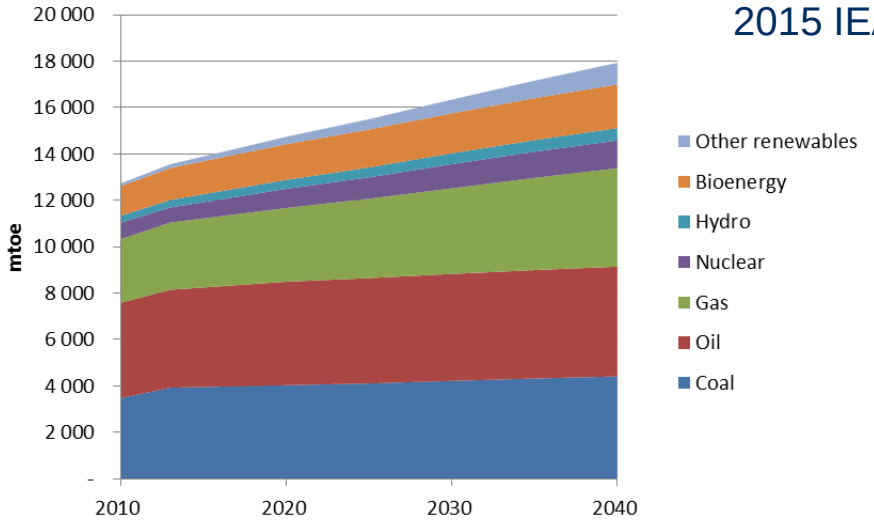


Data source: BP (2016).

"Best guesses" – ExxonMobil, BP, "New Policies" – IEA, "Outlook" – MIT Joint Program

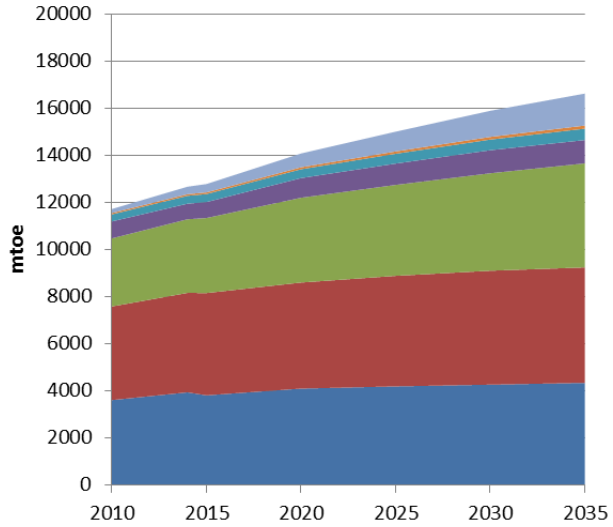
2015 Exxon

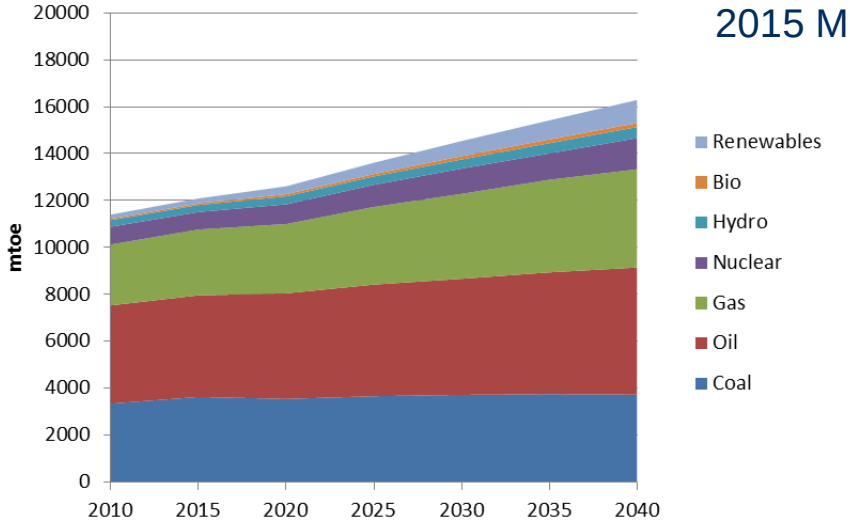




2015 IEA

2016 BP

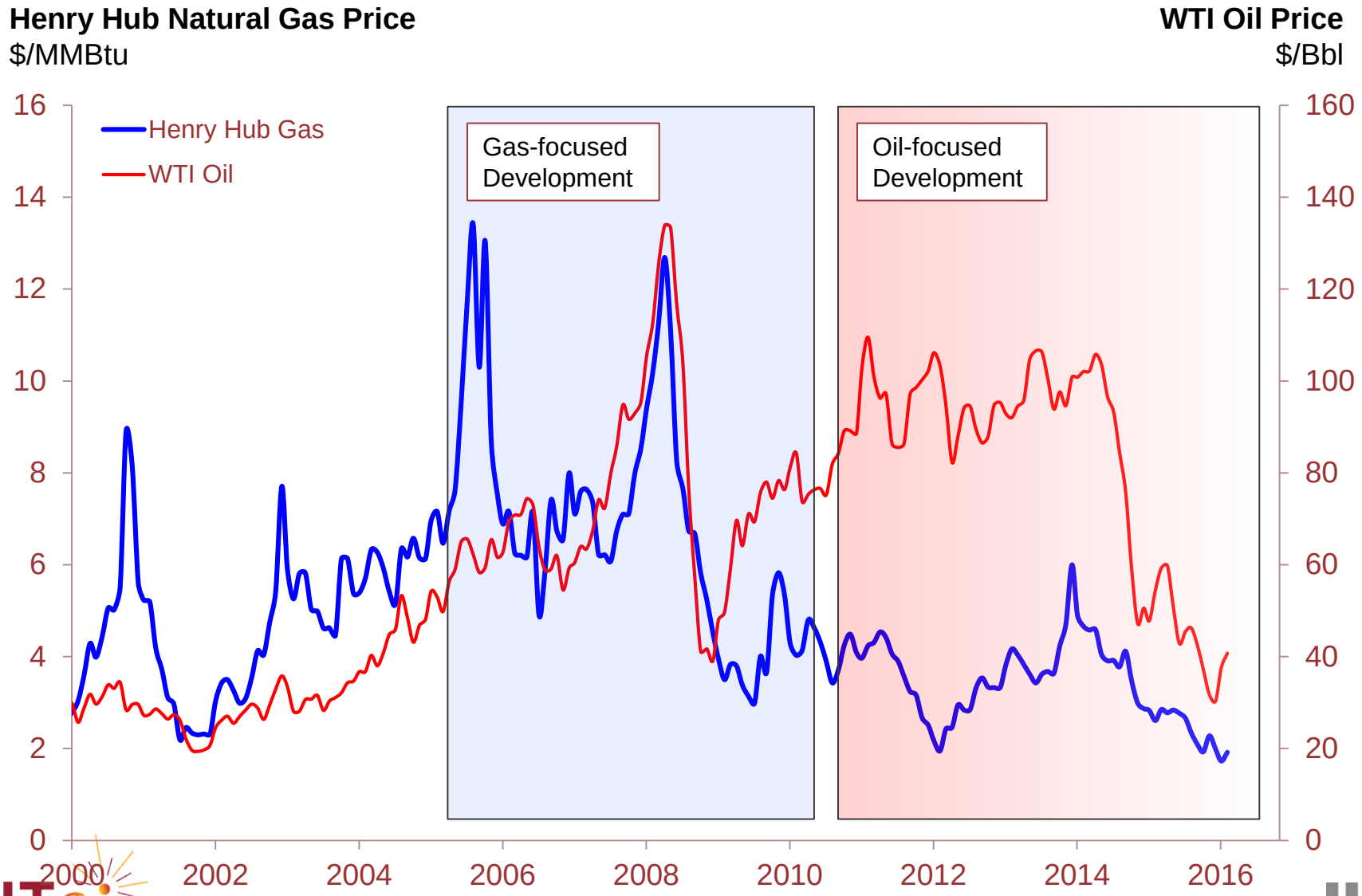




2015 MIT

Slide from Sergey Paltsev, MIT Joint Program

Lower commodity prices are certainly a challenge for producers, but they are proving a boon for other segments of the sector – In the US they are impacting the power sector and helping push coal out of dispatch



Source: F. O'Sullivan, EIA, Thompson Reuters

CAMPUS

- Reduce GHG emissions by 32% by 2030
- Phase out fuel oil by 2019
- Pursue carbon-cutting strategies across campus
- Shadow price on carbon
- Open data platform for campus energy use
- Campus as living lab

WHAT CAME FROM COP 21?

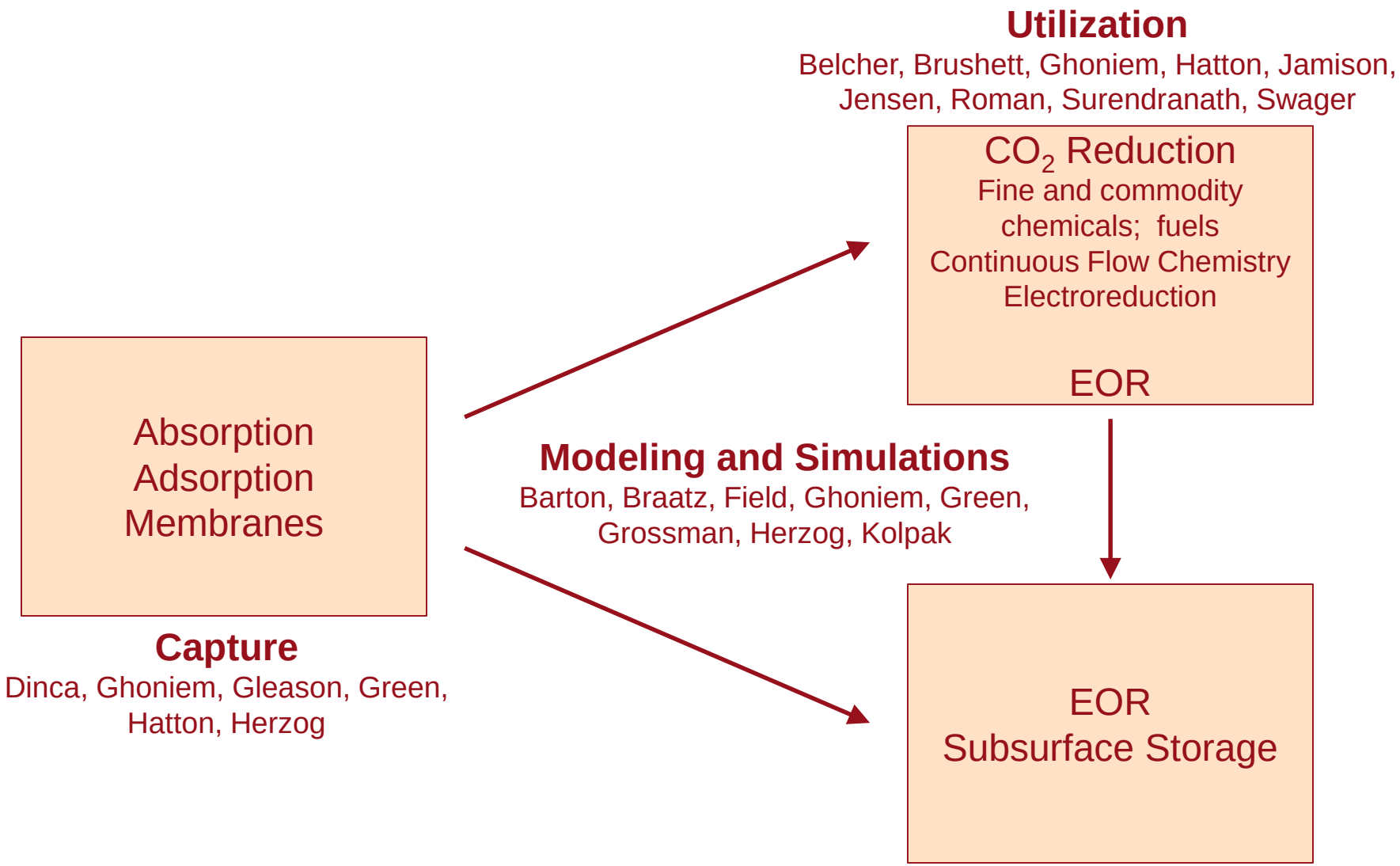
- Sharper focus on lowering costs of zero/low carbon energy technologies
  - Mission innovation
  - Breakthrough energy coalition
    - Breakthrough Energy Ventures (BEV) announced in December
- Agreement
  - Essentially all of the countries in the world agreed
  - “Ratified” last fall – sooner than expected
  - Target temperature rise of 2 °C (or preferably 1.5 °C) above preindustrial levels

WHAT CAME FROM COP 22, MARRAKECH?

- ~26,000 delegates
  - 18,000 from national governments
  - 1,500 from UN and intergovernmental agencies
  - 5,000 from non-governmental organizations
  - 1,500 from media
- This was also CMA 1 (conference of the parties to the Paris Agreement)
  - COP 22 welcomed this, but really wasn't ready
  - Many issues kicked down the road
    - Differentiation between developed and developing countries
    - Common framework for form and content of (I)NDCs
    - Transparency and "rulebook"
    - Global stocktakes and assessments of collective progress
      - Framing dialogue in 2018
      - Begin 5-year interval stocktakes in 2023
    - …
  - CMA 1 will continue in COP 23 and 24

Source: Brian Flannery, RFF

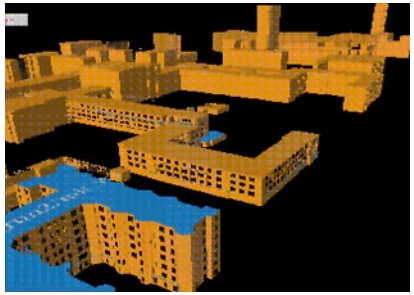
MIT ACTIVITY IN CCUS

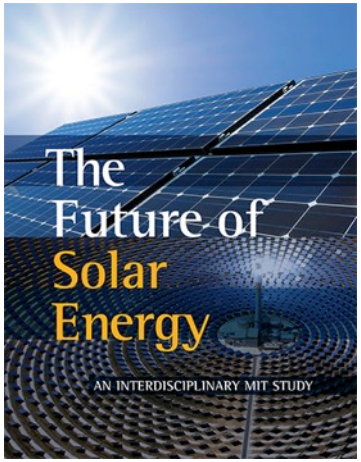


ABOUT MITEI

Linking science, innovation, and policy to transform the world's energy systems

- Launched in late 2006
- Campus-wide initiative
- Focused on energy and associated environmental challenges
  - Energy production, delivery, use, and associated environmental and climate linkages
- Main Objectives
  - Research
    - Innovate
    - Transform
    - Integrate
  - Education
  - Outreach





RESEARCH PROGRAM

- 800+ energy research, analysis projects supported by MITEI members
  - Includes 151 member-funded Seed Fund projects
  - $19.9M in seed fund awards to MIT faculty/senior researchers
  - 300+ faculty, ~500 PIs and co-PIs since 09/07, 29 departments, labs, and centers have received funding for energy research, analysis, education
- 2 US DOE Energy Frontiers Research Centers
  - Both renewed June 2014
- 7 DOE Advanced Manufacturing Institutes
- Core University Partner in DOE Innovation Hub
  - Renewed January 2015
- Multiple DOE ARPA-E Awards
- International Partnerships:
  - Abu Dhabi, China, Cyprus, France, India, Norway, Portugal, Russia, Rwanda, Spain, Switzerland, UN, World Bank ...
- DOE, NREL, Argonne ...

SEED FUND INNOVATION PATHWAYS

- Route to Member funding

  Kripa Varanasi - nanotextured surfaces

  – seed project lead to follow-on projects with Chevron, Shell, and Masdar

  Peter Fisher - Enel picked up the project and funded it as sponsored research

- Route to government funding

  Paul Woskov / Dan Cohn - millimeter wave drilling research

  – received DOE funding and a MITEI seed grant (2008-2010)

  Jeffrey Grossman, et al. - solar thermal fuels research

  – received ARPA-E funding and a MITEI seed grant (2009-2011)

- Route to start-up

  FastCAP Systems – an MIT spinoff commercializing a nanotube-enhanced ultracapacitor for use in vehicles and grid-scale energy storage

  – Technology developed in the MIT lab of Joel Schindall

  – Received funding from an ARPA-E award and a MITEI seed grant (2008-2010)

MIT has spun out

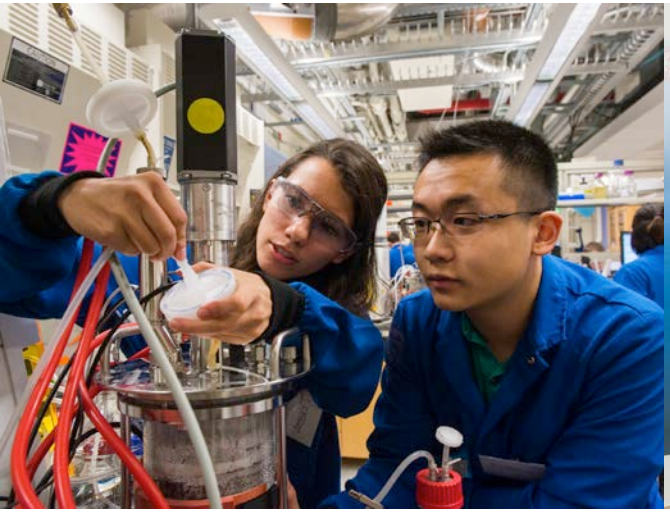
60

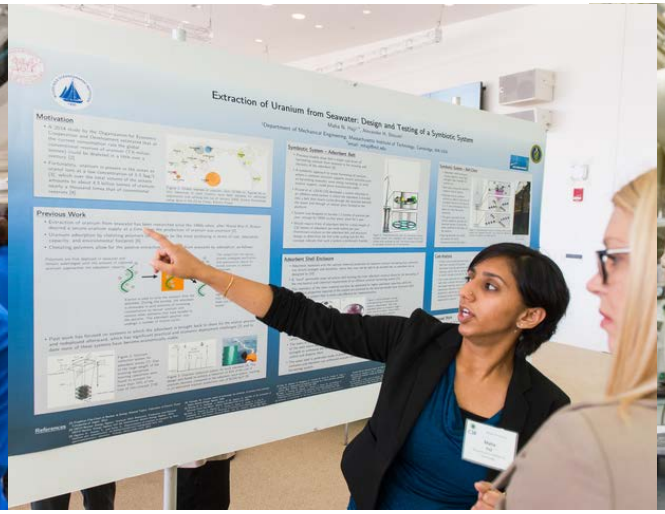
energy start-ups

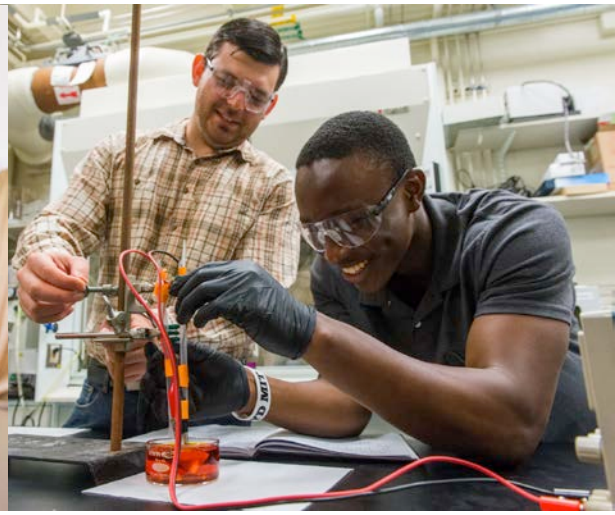
since MITEI's inception

EDUCATION

- Student and Faculty Fellowships
- Research and Teaching Assistantships
- Energy Undergraduate Research Opportunities Program (UROP)
- Energy Studies Minor
- MISTI internships







OUTREACH

- Multi-disciplinary Studies
- Technology & Policy Symposia
- Engagement with policymakers

MITEI: ENERGY HUB OF MIT

- Engaging academia broadly with industry and government on energy
- Leveraging multifaculty, multidisciplinary teams to drive innovative solutions to energy challenges
- Facilitating federal funding opportunities
- Supporting student-led MIT Energy Club
- Convening faculty and students, industry, and government for in-depth, fact-based discussions on the future of energy

TECHNOLOGY AND POLICY SYMPOSIA

- Designing Markets for a Decarbonizing Power System (May 2016)
- Storage, Renewables, and the Evolution of the Grid (May 2015)
- Large Opportunities, Complex Challenges: Seizing the Energy Efficiency Opportunity in the Commercial Built Environment (May 2014)
- Integrated Natural Gas – Electricity Infrastructures (April 2013)
- Bi-fuel / Flex-fuel Vehicles (April 2012)
- Managing Large Scale Penetration of Intermittent Renewables (April 2011)
- The Role of Enhanced Oil Recovery in Accelerating the Deployment of Carbon Capture and Storage (July 2010)
- Critical Elements for New Energy Technologies (April 2010)
- The Electrification of the Transportation System: Issues and Opportunities Symposium (April 2010)
- Retro-Fitting of Coal-Fired Power Plants for CO2 Emissions Reductions (March 2009)

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MITEI'S IMPACT

- Deploying **over $600 million** to date
- **90** industry and public partners
- Support for more than **800** *sponsor*-originated research/analysis projects + **hundreds more**.
- More than **350** named fellows and **thousands of other graduate and undergraduate students** supported by MITEI
- Institute-wide Energy Studies Minor has graduated **100+ students** from all five schools and is one of the most popular undergraduate minors
- MIT has spun out **more than 60 energy startups** since MITEI inception.

MEMBERSHIP

Founding Members

bp

eni

ExxonMobil

ارامكو السعودية
Saudi Aramco

Sustaining Members

BOSCH
Invented for life

Chevron

LOCKHEED MARTIN

Schlumberger

Statoil

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