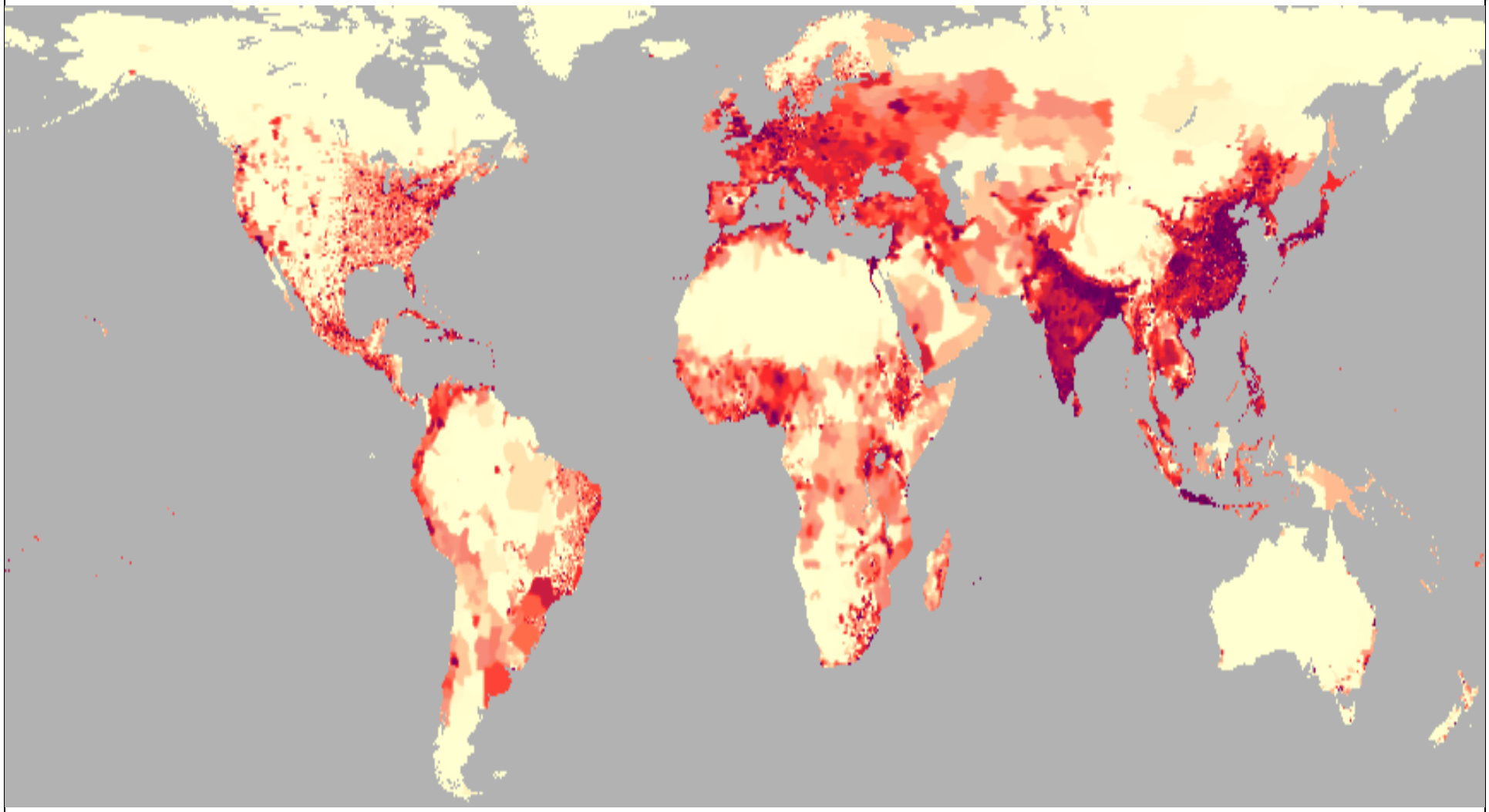
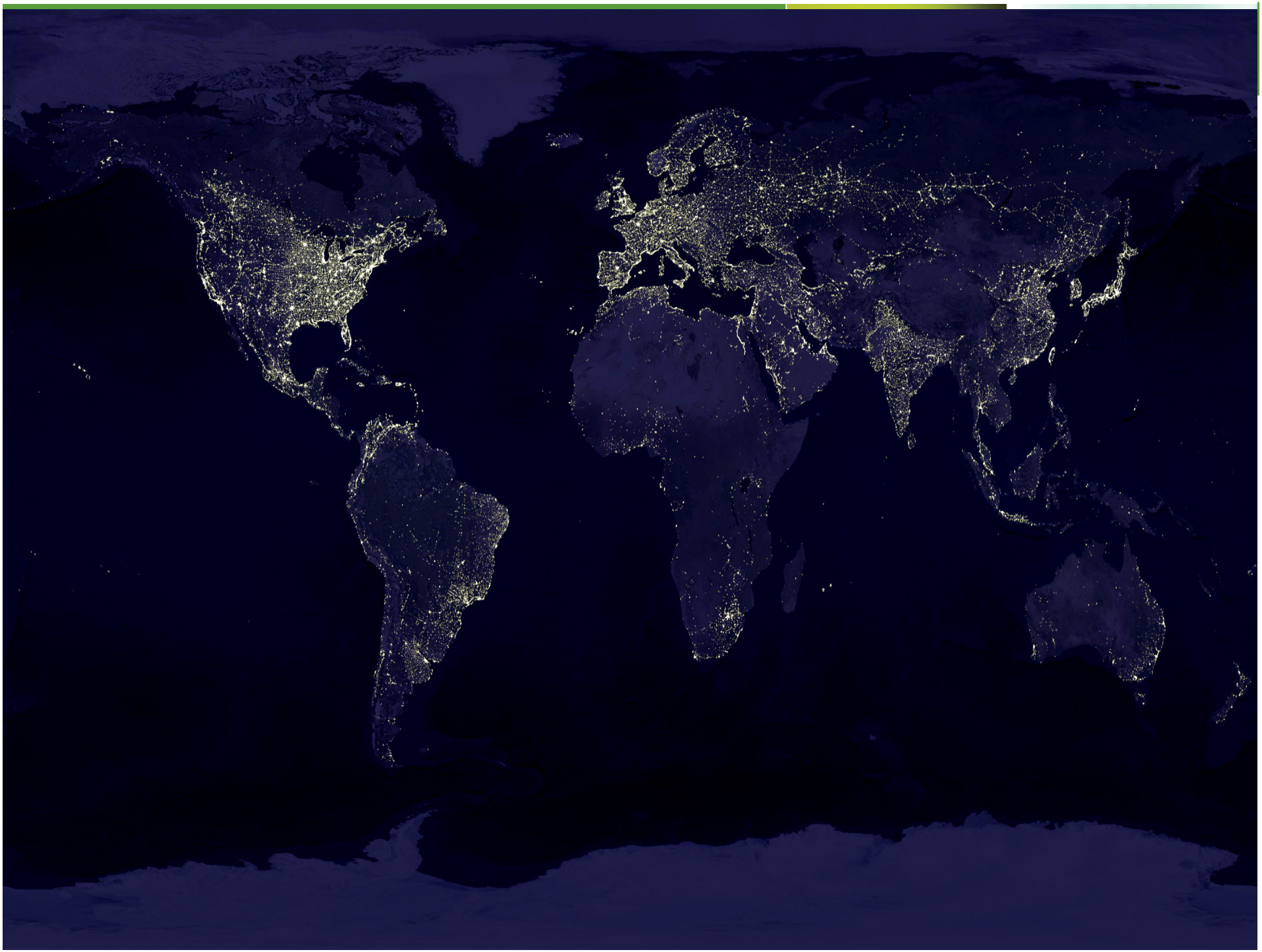
Hawkins Memorial Lecture

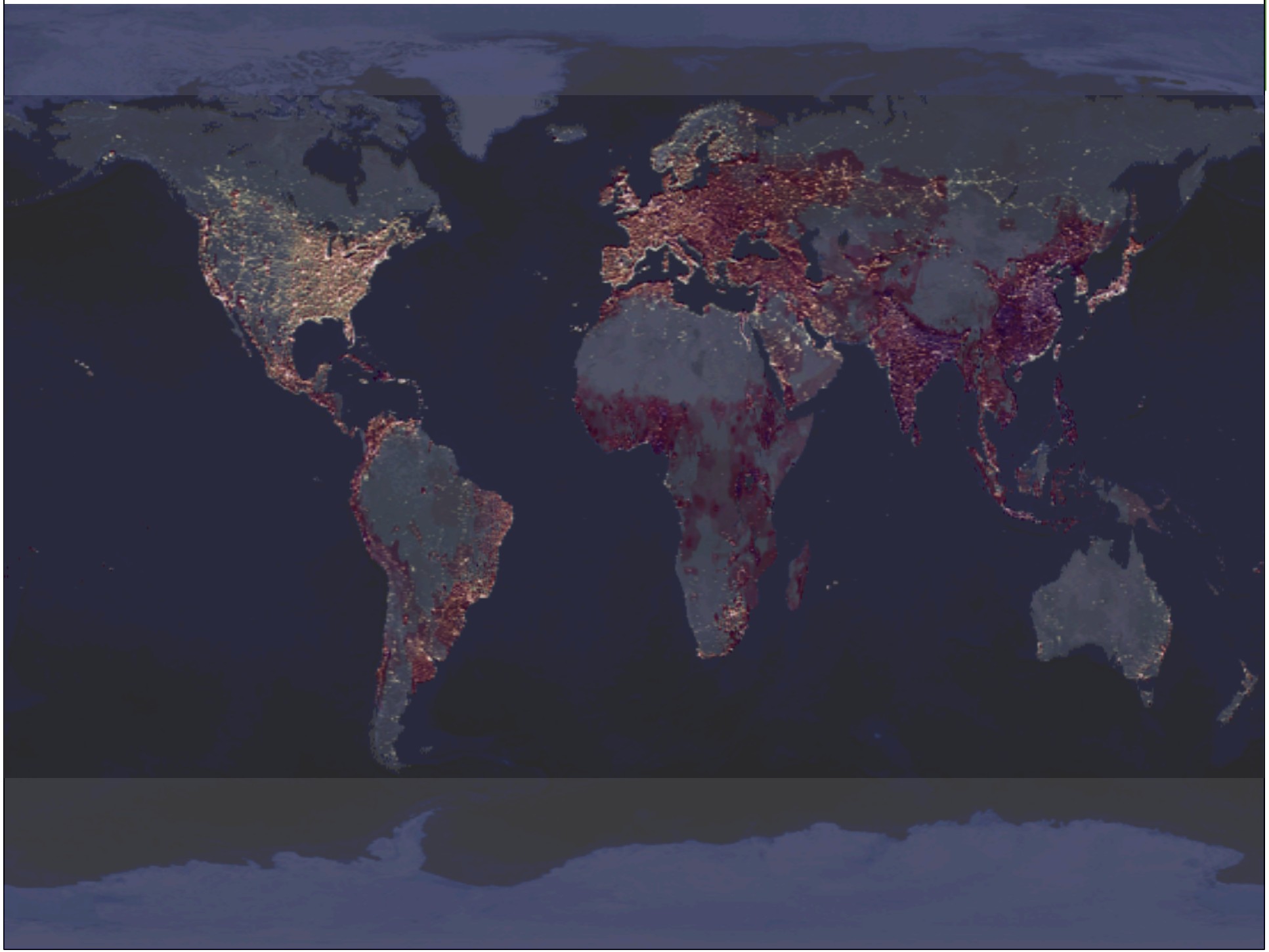
Energy Innovations in 21st Century: Role of ARPA-E

Arun Majumdar
Director, ARPA-E
U.S. Department of Energy

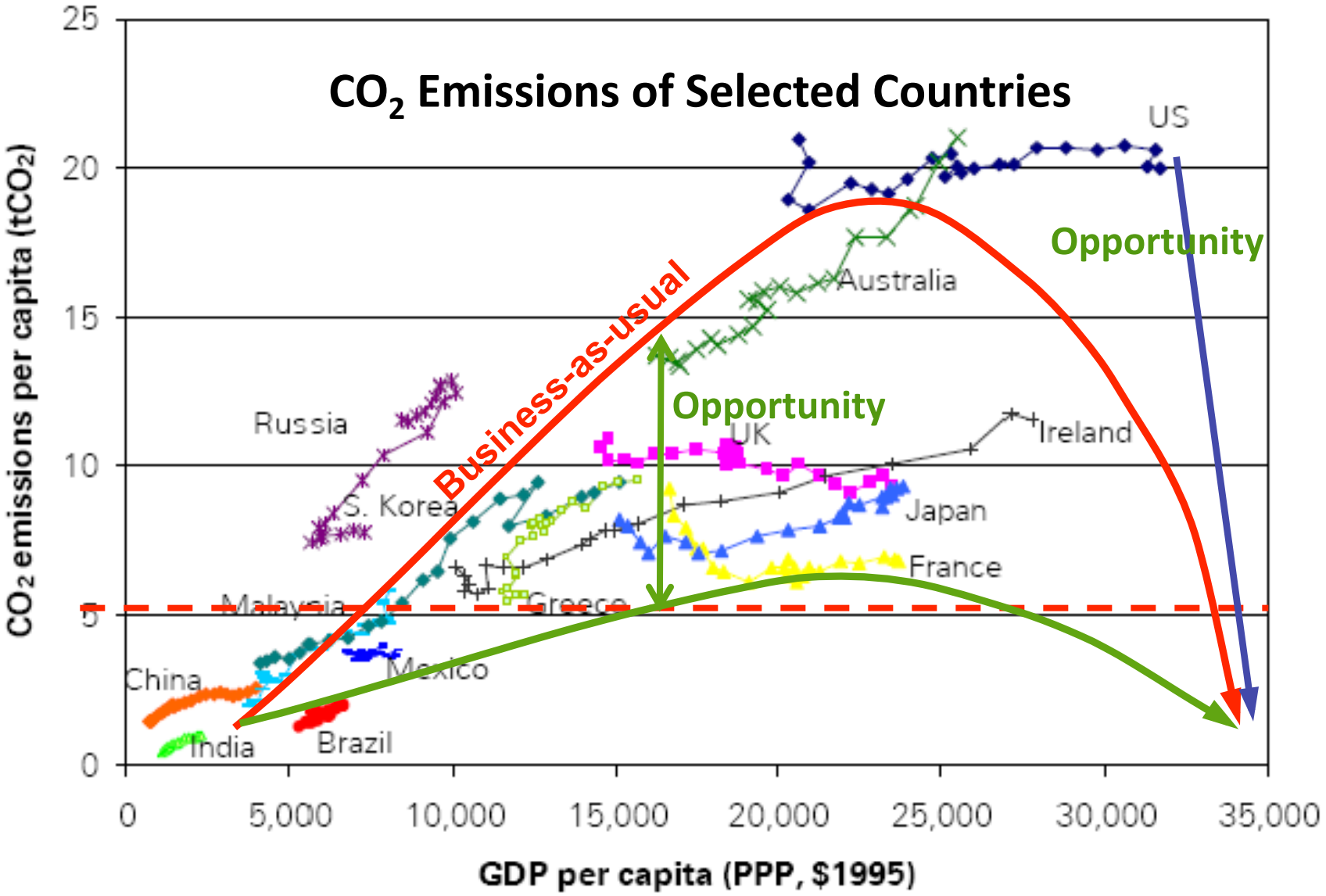
http://arpa-e.energy.gov/





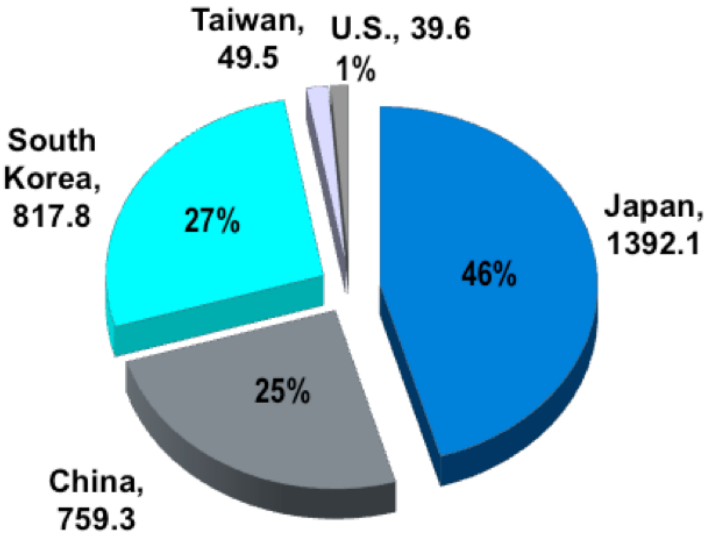


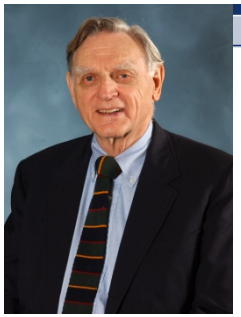
OPPORTUNITY



WAKE UP CALL

Lithium-ion battery manufacturing volumes in 2009 (millions of cells/year)





THE ENRICO FERMI AWARD

2009

John Goodenough, U. Texas at Austin

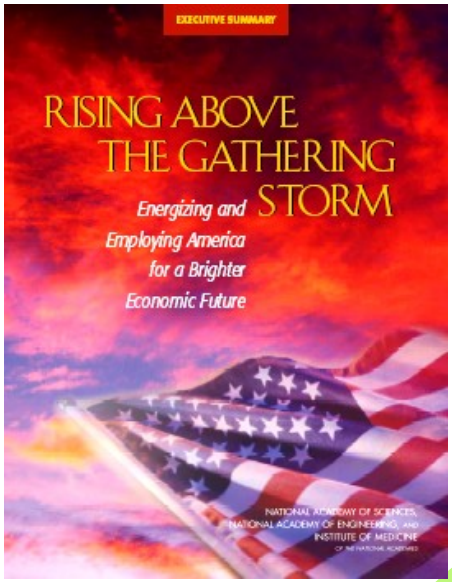
WAKE UP CALL

We import 60% of our oil.
Need to make that 0%!

Energy Innovation is at the core of our

- **National Security**
- **Economic Security**
- **Environmental Security**

CREATION OF ARPA-E



2006
Rising Above the Gathering Storm
(National Academies)

2007
America COMPETES Act

American Recovery and Reinvestment Act of 2009 (Recovery Act)

$400M appropriated for ARPA-E
President Obama launches ARPA-E in a speech at NAS on April 27, 2009

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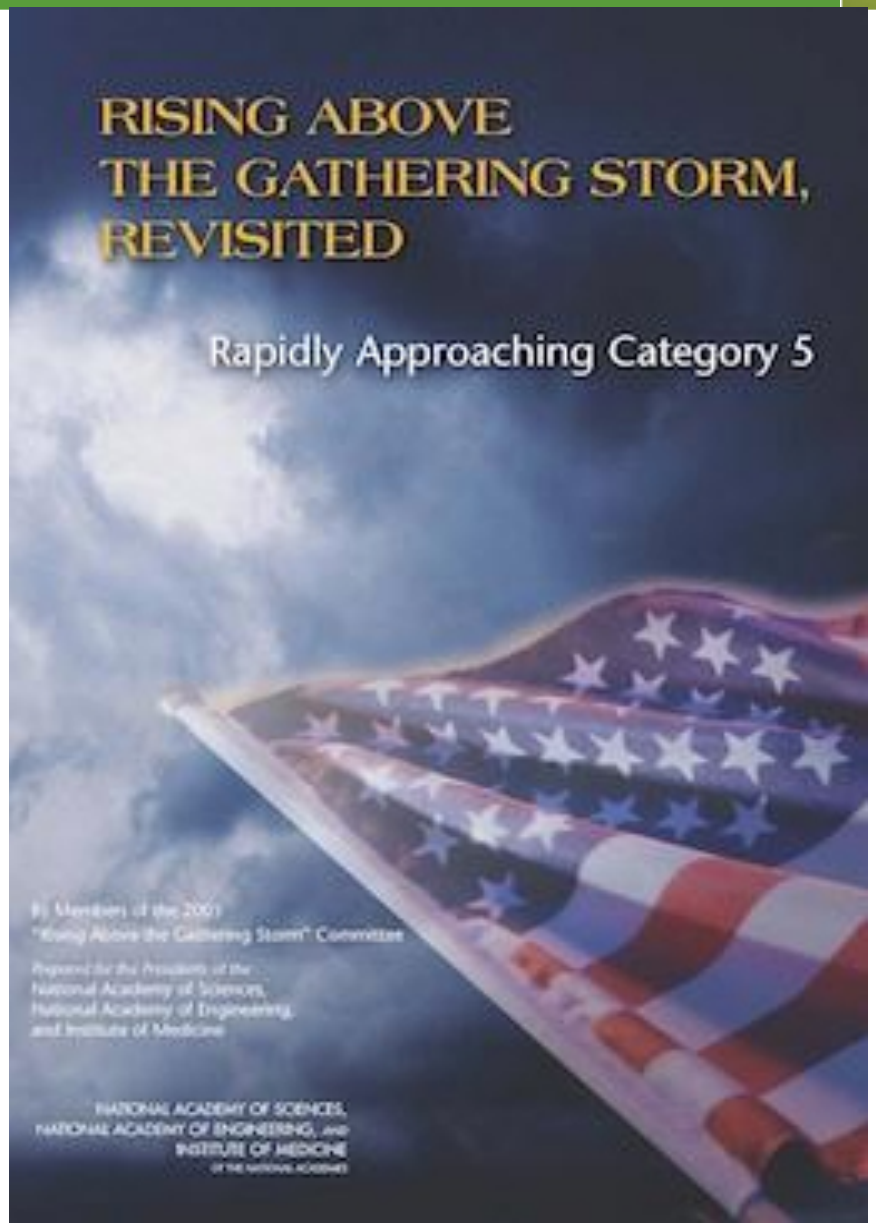
Gathering Storm committee concluded that a primary driver of the future economy and concomitant creation of jobs will be *innovation*, largely from advances in science and engineering.

While only 4% of the nation's work force is composed of scientists and engineers, this group disproportionately creates jobs for the other 96%.



Released
September 23, 2010

The unanimous view of the committee members …… our nation's outlook has worsened. While progress has been made in certain areas – for example, launching ARPA-E – the latitude to fix problems being confronted has been severely diminished by the growth of the national debt over this period from $8 trillion to $13 trillion.

Finally, many other nations *have* been markedly progressing, thereby affecting America's relative ability to compete effectively for new factories, research laboratories, administrative centers – and *jobs*. While this progress by other nations is to be both encouraged and welcomed, so too is the notion that Americans wish to continue to be among those peoples who do prosper.

The only promising avenue for achieving this latter outcome, in the view of the *Gathering Storm* committee and many others, is through *innovation*. Fortunately, this nation has in the past demonstrated considerable prowess in this regard.

FACTOIDS & QUOTES

- Among the manufacturers of photovoltaics, wind turbines and advanced batteries, the top 10 global firms by market capitalization include 2, 1, and 1 US firms, respectively. The other firms are from China, Denmark, France, Germany, India, Spain, Taiwan and the U.K.

- A Japanese company produces over 75% of the world's nickel-metal hydride batteries used in vehicles

- US spends more on potato chips than energy R&D, and more on dog food R&D than the R&D in the electrical power sector

"In today's integrated and digitized global market, where knowledge and innovation tools are so widely distributed. . . . : whatever can be done, will be done. The only question is will it be done by you or to you." Thomas L. Friedman, Author, "The World Is Flat"

"The greatest long-term threat to U.S. national security is not terrorists wielding a nuclear or biological weapon, but the erosion of America's place as a world leader in science and technology." Gordon England, Former Deputy Secretary of Defense

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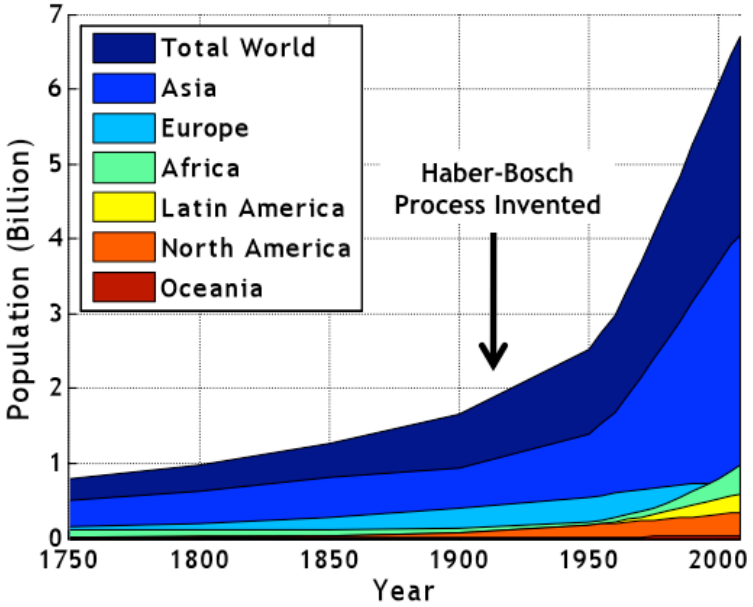
"Gentlemen, we have run out of money. It is time to start thinking."

Sir Ernest Rutherford, Nobel Laureate (Physics)

HAS THE WORLD FACED SUCH A CHALLENGE BEFORE?

1898: "Calling upon Science to save the world from impending starvation," Sir William Crookes, President, British Assoc. for the Advancement of Science.

Guano Islands, South America

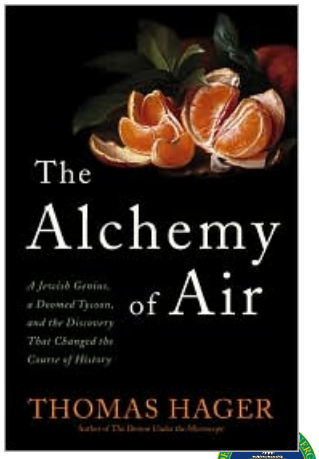


1908: Fritz Haber (Chemist) discovered a catalyst that would combine atmospheric nitrogen with hydrogen to form ammonia. Catalyst - Uranium!!

Haber

Bosch

1913: Carl Bosch (BASF) developed process to mass produce ammonia and made fertilizers.



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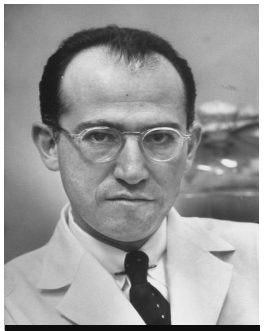
HAVE WE FACED SUCH A CHALLENGE BEFORE?

Norman Borlaug

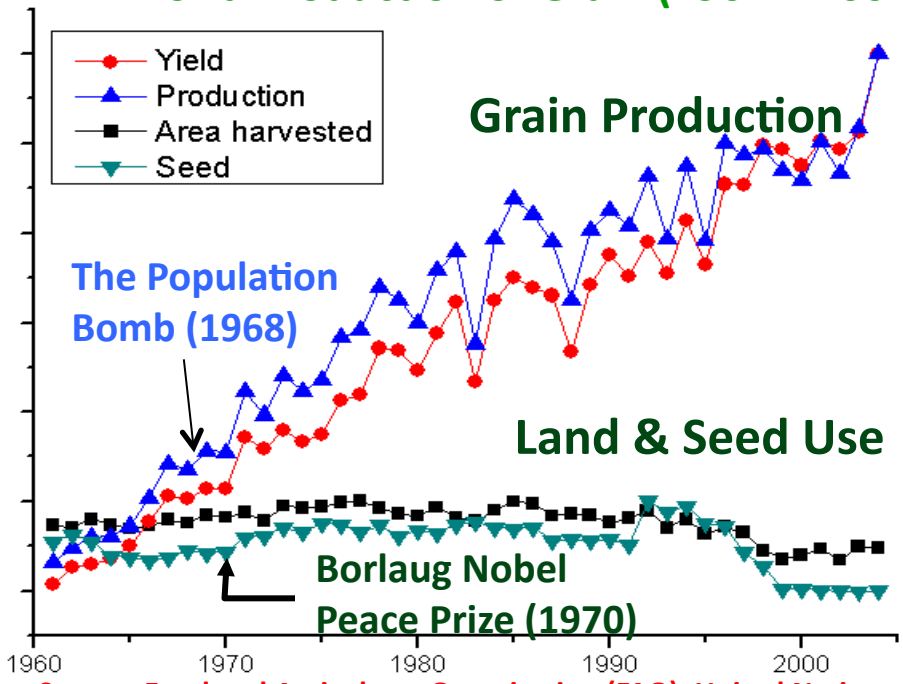
Dwarf Strain of Wheat



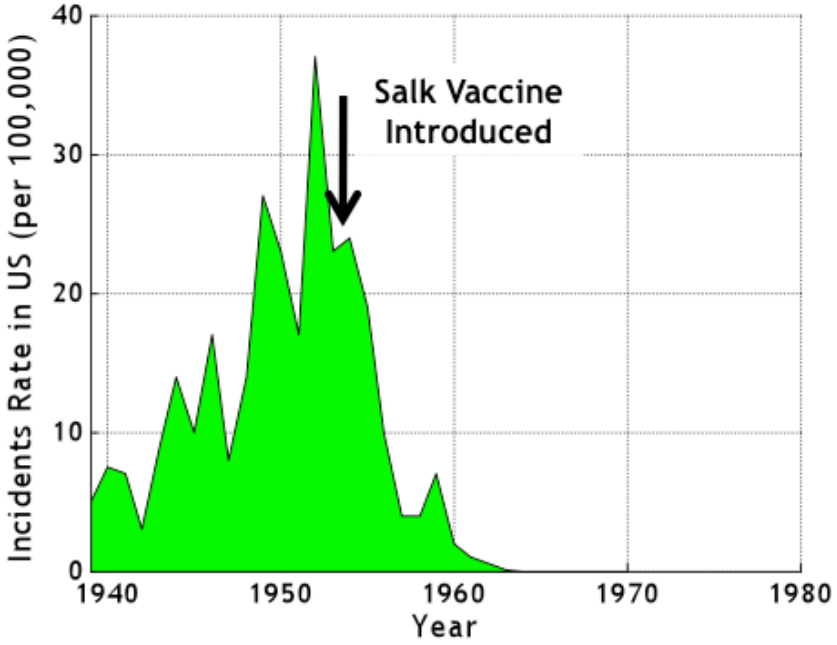
Jonas Salk

Polio Vaccination

World Production of Grain (1961 – 2004)



Source: Food and Agriculture Organization (FAO), United Nations



PACE AND SCALE OF INNOVATIONS NEEDED IN ENERGY TECHNOLOGIES

Game Changers from 20th Century

100 years

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

20 years

Imagine all of this happening in the next 20 years…

- Solar electricity generation at cost lower than that produced from fossil fuels ($1/W fully installed)
- Real-time optimization, security and storage for grid with two-way dispatchable electric power
- Carbon capture and utilization at net cost lower than its market price
- Car batteries with 3X energy density and 4X lower cost
- Transportation fuels from sunlight, CO_2 and/or agricultural waste at cost lower than petroleum
- 50-80% reduction in energy consumption in homes and buildings with energy use awareness and behavioral impact
- Low-cost desalination of water
- Low-cost and safe nuclear energy

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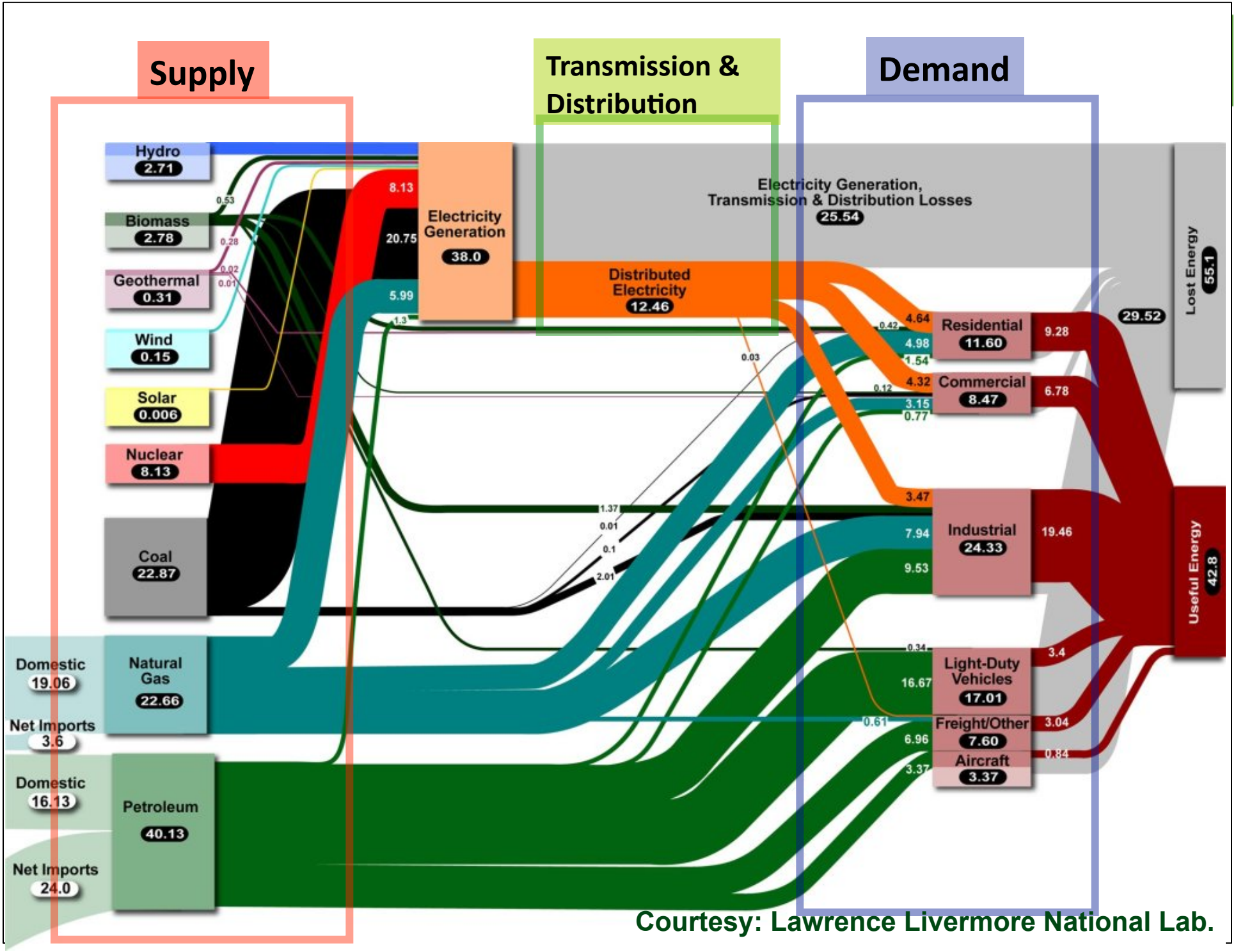
ARPA-E Mission

To overcome the long-term and high-risk technological barriers in the development of energy technologies.

1. To enhance the economic and energy security of the United States through the development of energy technologies that result in—

- *reductions of imports of energy from foreign sources;*
- *reductions of energy-related emissions, including greenhouse gases;*
- *improvement in the energy efficiency of all economic sectors;*

2. To ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies.

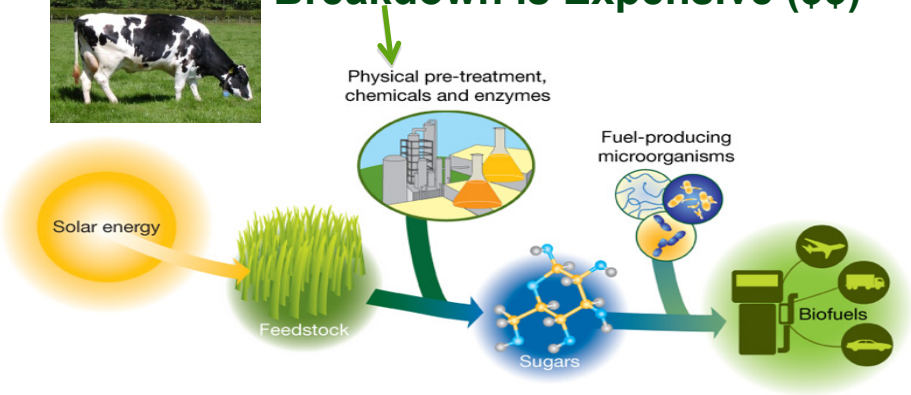


Courtesy: Lawrence Livermore National Lab.

EXAMPLES FROM FIRST ROUND OF FUNDING

Cellulosic Biofuels

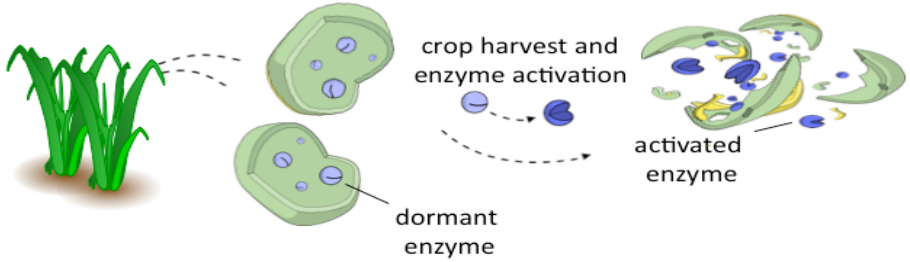
Artificial Cellulose Breakdown is Expensive ($$)



Agrivida

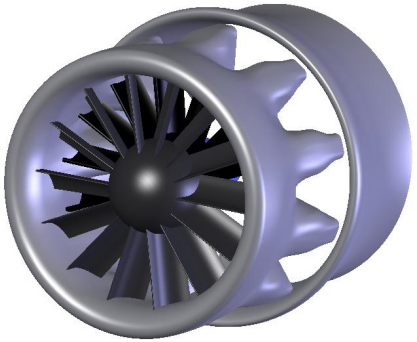
GreenGenes™ Technology

Putting the cow inside the plant!



Plant produces all the enzymes & chews itself from the inside!!

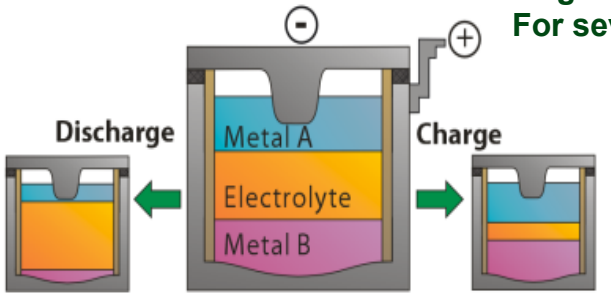
Breakthrough High Efficiency Mixer/ Ejector Wind Turbine (MEWT) – FloDesign Wind Turbine Corp.



- Mimic jet engines, not propellers, for wind turbine
- 40% lower cost expected vs. horizontal axis wind turbines (HAWT)

Grid-Level Electricity Storage - MIT

Megawatts of storage For several hours



Potential Cost: $50/kW-hr

Lithium Ion Laptop Battery: $2000/kW-hr
Lithium Ion Car Battery: $1000/kW-hr

What is an ARPA-E Project

High impact on ARPA-E mission areas

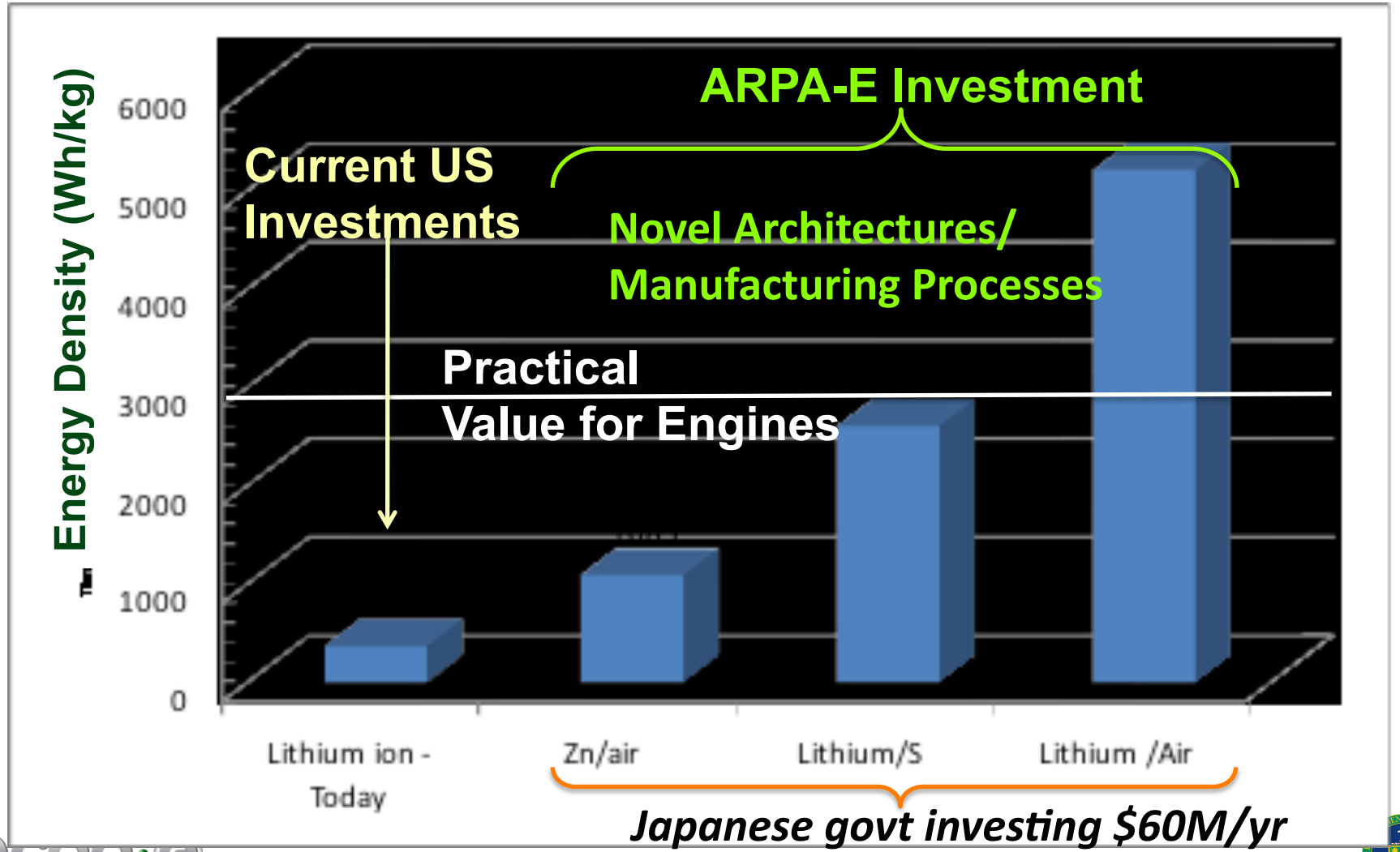
New technologies, devices and prototype systems that:

- do not exist in today's energy market;
- too risky for private sector investment;
- if successful:
  - *could make today's technologies obsolete;*
  - *could have large commercial impact;*
  - *could produce new learning curves and new markets;*

- Best-in-class people & teams containing scientists and engineers;
- Attract the US intellectual horsepower to energy R&D

Strong impact of ARPA-E funding relative to private sector

Batteries for Electrical Energy Storage for Transportation (BEEST)



BATTERIES FOR ELECTRICAL ENERGY STORAGE FOR TRANSPORTATION (BEEST)

Program Director: David Danielson (PhD Materials Sci, MIT; General Catalyst)

- Cell-level energy density: 400 W-hr/kg (2.5X higher)
- Cost: $250/kW-hr (4X lower)
- New architectures & manufacturing processes

Upside

Ultra-High Energy

Recapping Stanford (Capacitive)

PolyPlus (Li-Air)

Missouri Inst of Sci/Tech

Sion Power (Li-S)

ReVolt (Zn-Air Flow)

MIT (Flow Batt)

Pellion (Mg-Ion)

Mfg Innovations

AMAT/A123/ LBNL (Li Ion Mfg)

Planar Energy Devices (Solid State Li-Ion)

Infrastructure Compatible High Energy Materials

Time to Market

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LOW-COST CARBON CAPTURE

Program Director: Mark Hartney (PhD Chem Engr, UC Berkeley, DARPA, Lincoln Labs, Bell Labs, Flex Tech)

Today: CO_2 +

Today's CO_2 Binding Chemicals

Bind, Isolate & Release →

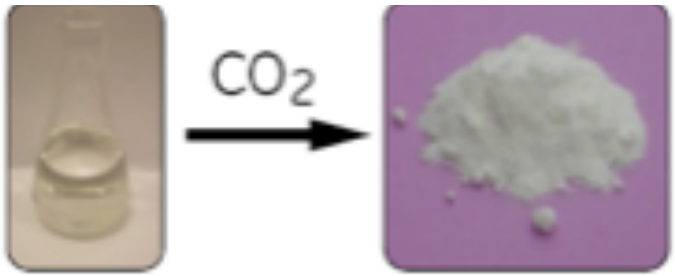
Cost: $70-100/t$CO_2$
Cost Above Price = Loss!

↑ **High-Temperature Heat**

Market Price of CO_2: ≈ $30/t$CO_2$

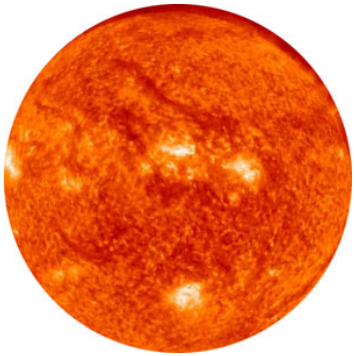
Carbon Capture in Solid Form

Potential Cost = $25-30/t$CO_2$



Electrofuels Program

<1% efficient



Photosynthesis

Biomass

Algae

EtOH
Advanced
biofuels

Pyrolysis
oils

Biodiesel
Advanced
biofuels

Electrons/
Reducing equivalents

Up to 90% efficient

Chemical
Catalysis

Biological
Catalysis

Syngas
CH_3OH
CH_4
Advanced fuels?

Advanced
Fuels

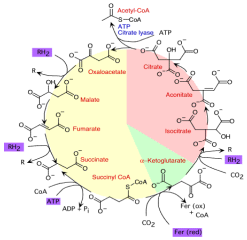
Electrofuels approach is non-photosynthetic, modular, and solutions can be mixed- and- matched

Assimilate Reducing Equivalents

Reducing equivalents: *other than reduced carbon or products from Photosystems I & II*

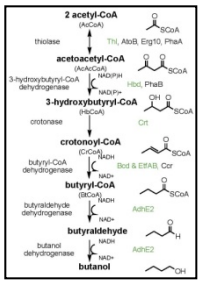
H_2S H_2 Direct Current NH_3 Fe^{2+}

Fix CO_2 for Biosynthesis

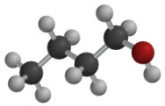


Pathway for carbon fixation: *reverse TCA, Calvin- Benson, Wood-Ljungdahl, hydroxpropionate/hydroxybutyrate, or newly designed biochemical pathways*

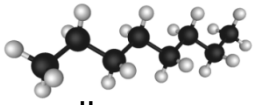
Generate Energy Dense Liquid Fuel



Fuel synthesis *metabolic engineering to direct carbon flux to fuel products*



butanol

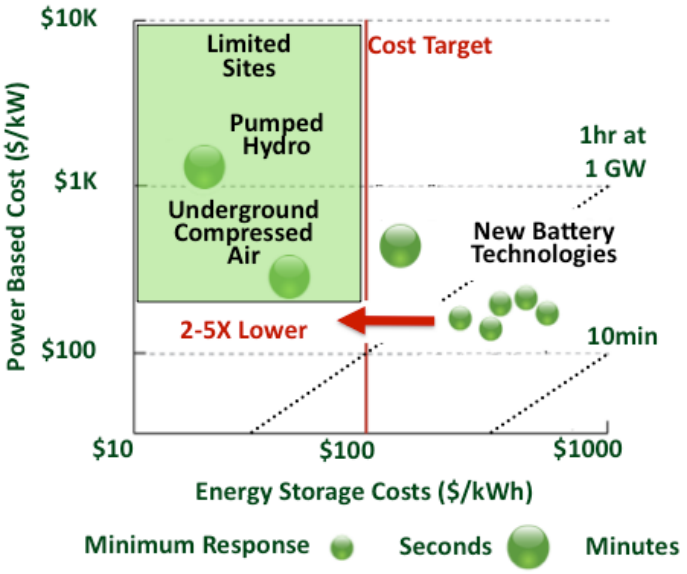


alkanes

+ numerous possibilities

ROUND 3 PROGRAMS

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)



Program Director: Mark Johnson (Prof. of Mat Sci, NCSU)

Building Energy Efficiency Through Innovative Thermo-devices (BEETIT)

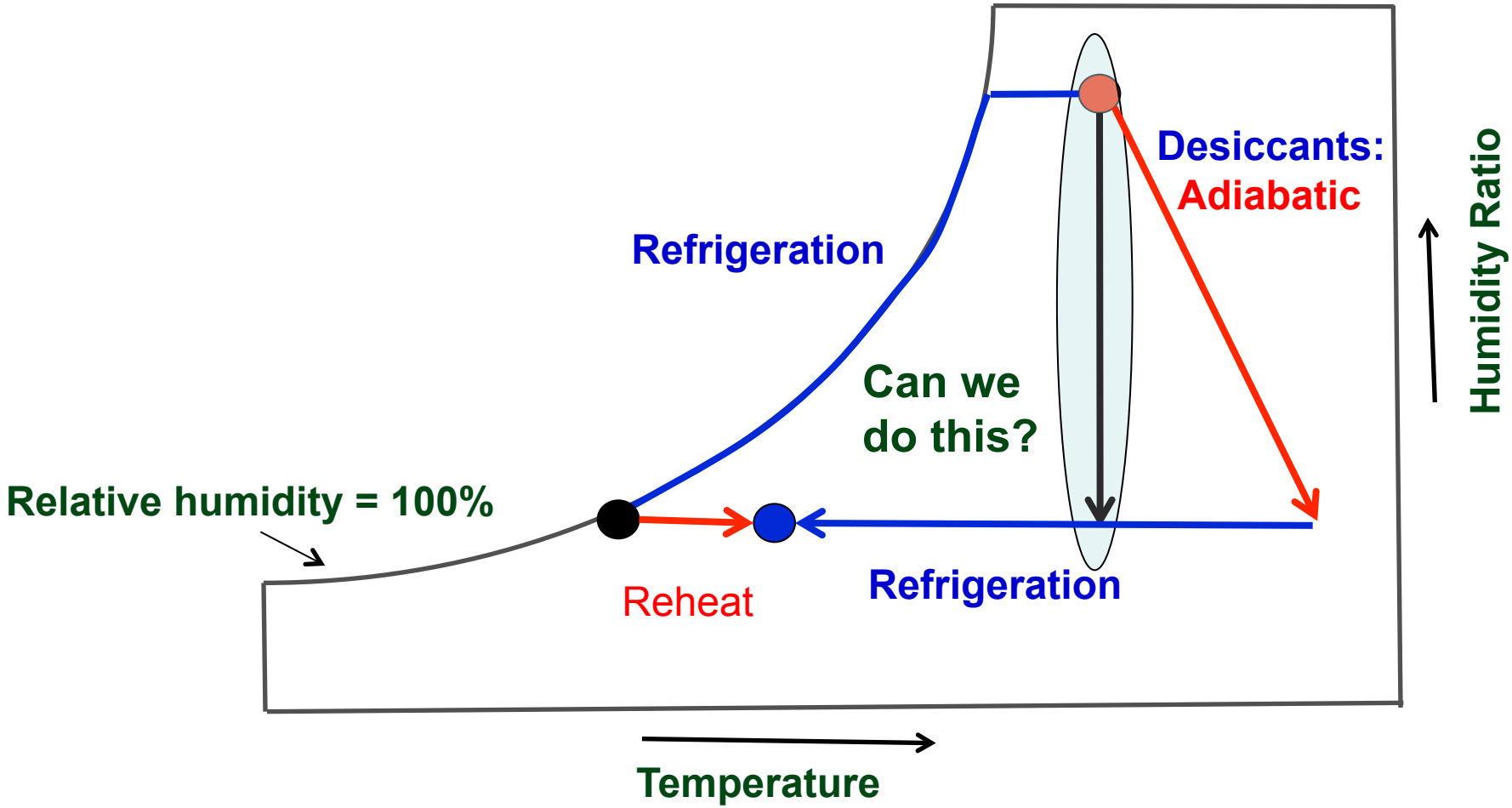
Program Director: Ravi Prasher (Formerly Intel, PhD-ASU)

Power Electronics

Program Director: Rajiv Ram (Professor, EECS Dept, MIT)

Announced: March 2, 2010
Awardees Selected: July, 2010
All Awards Made: September, 2010

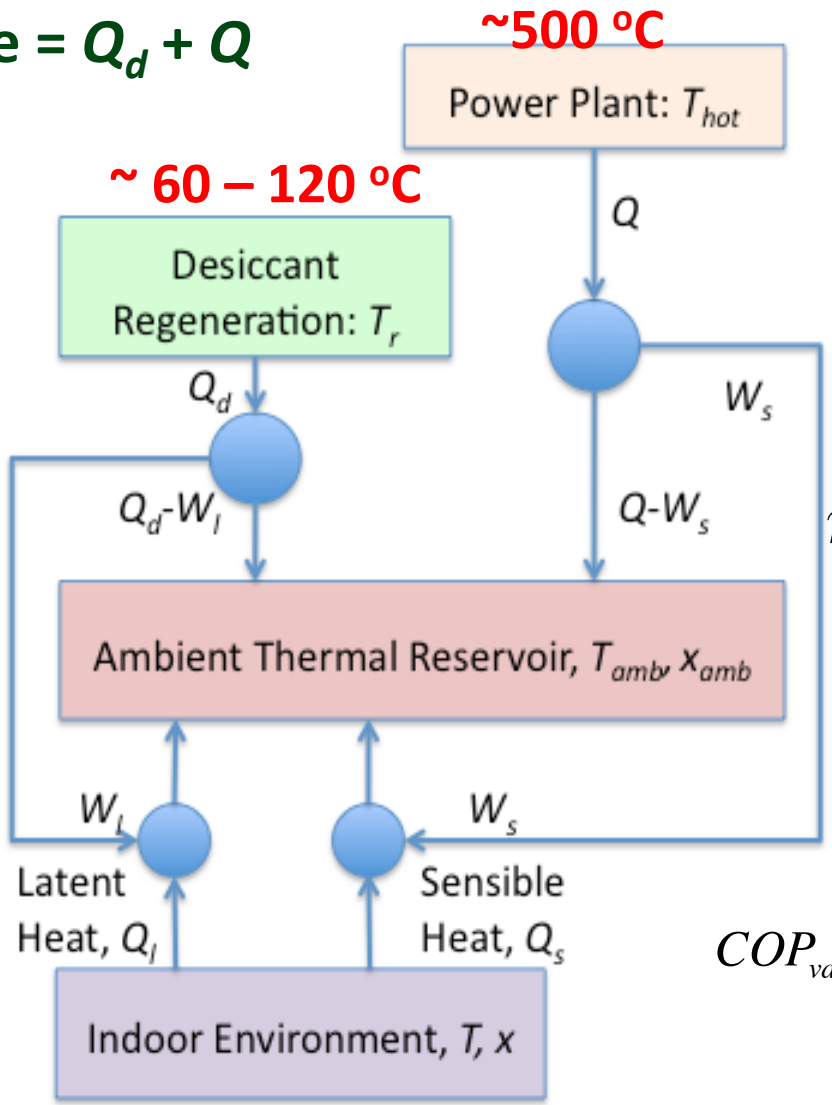
Current Cooling Practice



Can we achieve cost effective isothermal dehumidification?

Air Conditioning System at Thermodynamic Limit

Primary Energy Use = $Q_d + Q$



Latent Heat

$$COP_{latent} = \frac{Q_l}{Q_d} = \frac{Q_l}{W_l / \eta_{Carnot}}$$

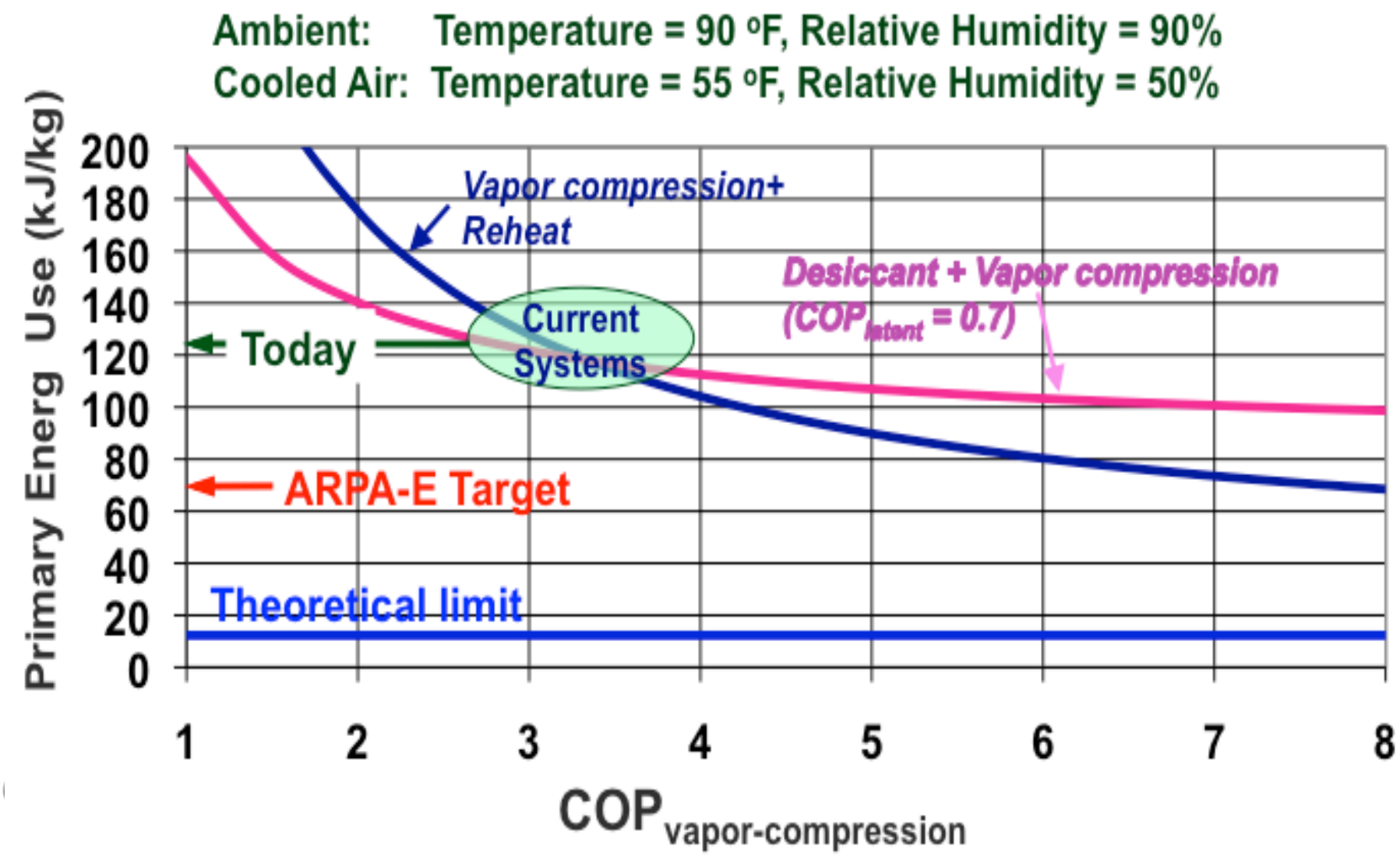
Sensible Heat

$$\eta_{Carnot} = \frac{W_s}{Q} = 1 - \frac{T_{amb}}{T_{hot}}$$

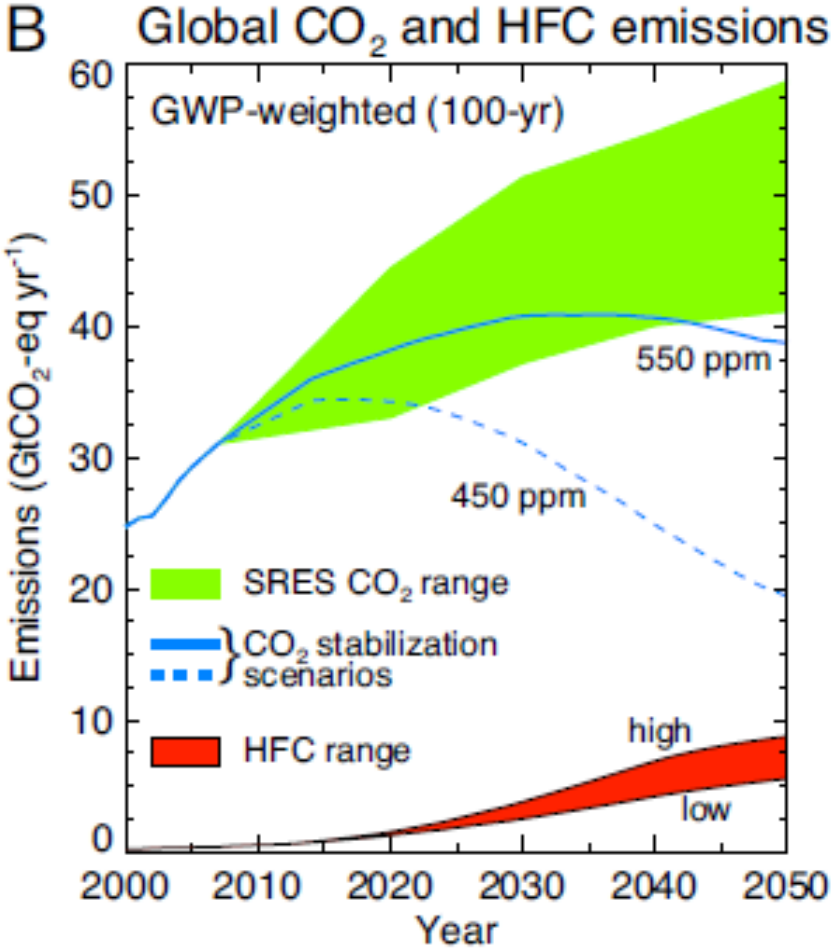
Ideal COP_{latent} = ~ 2.5-6.5
Real COP = ~ 0.7 – 1.0

$$COP_{vapor-compression} = \frac{Q_s}{W_s}$$

How far are we from the limit?



HFC Emissions: Air conditioning & Refrigeration



Alternatives with GWP ≤ 1

- CO_2
- Magnetocaloric
- Thermoacoustic
- Thermoelectric
- …….

*Source: Velders et al, PNAS **106**, 10949 (2009), http://www.pnas.org/content/suppl/2009/06/22/0902817106.DCSupplemental/0902817106SI.pdf#nameddest=ST2*

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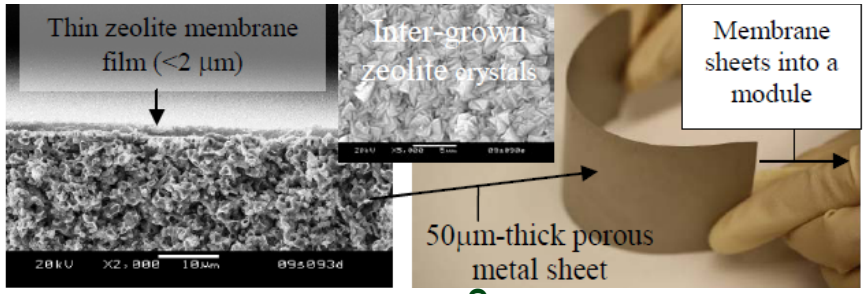
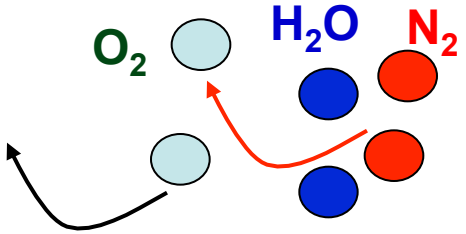
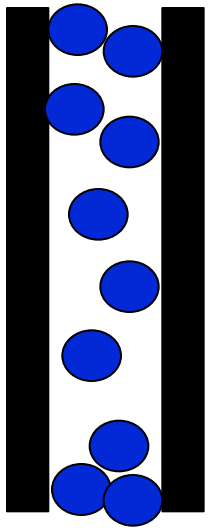
High-Efficiency, on-Line Membrane Air Dehumidifier Enabling Sensible Cooling for Warm and Humid Climates

Team	ADMA Products, Inc, PNNL, Texas A&M





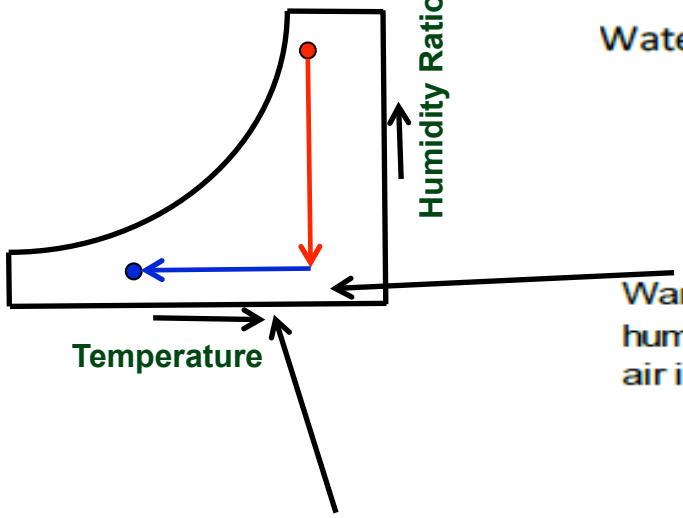


Adsorption

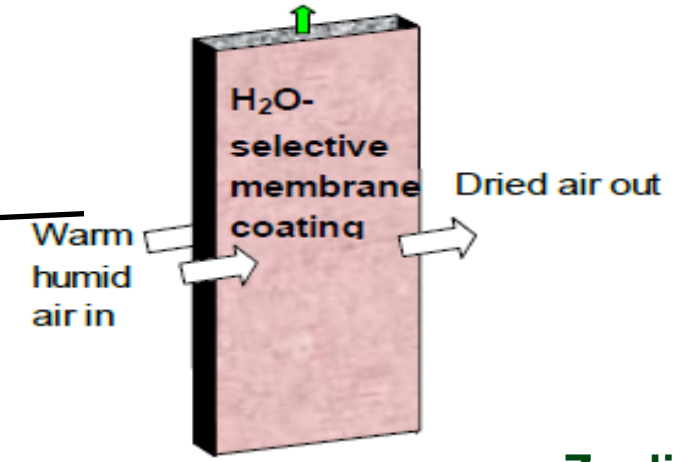
Diffusion

Desorption

Zeolite pore (0.3 – 0.4 nm)



Refrigeration unit

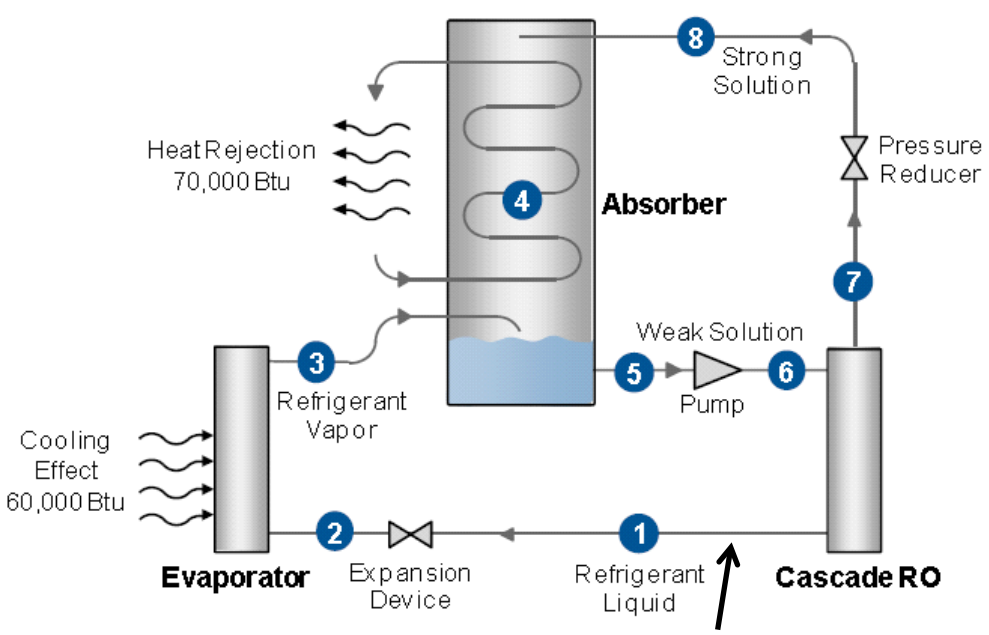


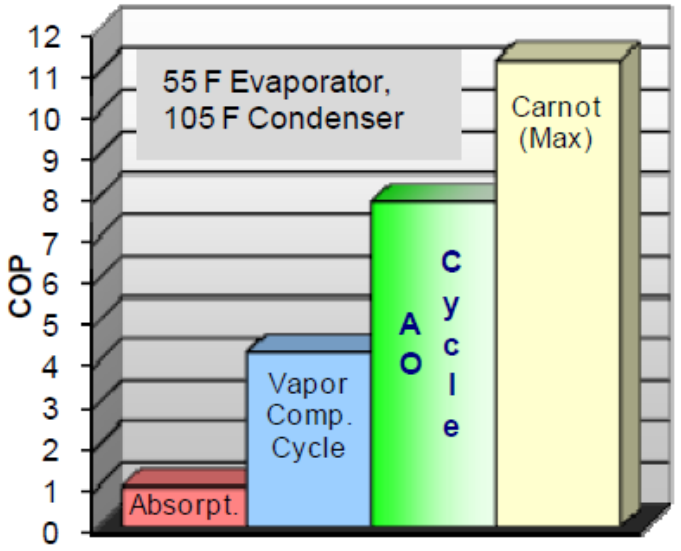
Can potentially beat FOA target by ~50%

The Absorption – Osmosis Cooling Cycle

Team	Battelle Memorial Institute, Dynamic Solutions, LLC

LiBr strong solution





Water

Water (Refrigerant) & LiBr (absorbent)

Can potentially beat BEETIT target by > 50%

DEPARTMENT OF ENERGY

Advanced Research Projects Agency - Energy

Loan Programs Office

American Recovery & Reinvestment Act Office

Office of the Secretary
Dr. Steven Chu, Secretary

Daniel B. Poneman,
Deputy Secretary*

Chief of Staff

Federal Energy Regulatory Commission

Inspector General

Office of the Under Secretary For Nuclear Security/ Administrator for National Nuclear Security Administration
Thomas P. D'Agostino

- Deputy Administrator for Defense Nuclear Nonproliferation
- Deputy Administrator for Naval Reactors
- Associate Administrator for Defense Nuclear Security
- Associate Administrator for Infrastructure & Environment
- Deputy Administrator for Defense Programs
- Deputy Under Secretary for Counter-terrorism
- Associate Administrator for Emergency Operations
- Associate Administrator for Management & Administration

Office of the Under Secretary for Science

Dr. Steven E. Koonin
Under Secretary for Science

Office of Science

- Advanced Scientific Computing Research
- Basic Energy Sciences
- Biological & Environmental Research
- Fusion Energy Science
- High Energy Physics
- Nuclear Physics
- Workforce Development for Teachers & Scientists

Office of the Under Secretary

Dr. Kristina M. Johnson
Under Secretary

- Assistant Secretary For Energy Efficiency And Renewable Energy
- Assistant Secretary for Electricity Delivery and Energy Reliability
- Assistant Secretary for Nuclear Energy
- Assistant Secretary For Environmental Management
- Assistant Secretary for Fossil Energy
- Legacy Management
- Civilian Radioactive Waste Management

- Energy Information Administration
- Bonneville Power Administration
- Southwestern Power Administration
- Southeastern Power Administration
- Western Area Power Administration

- Management
- Health Safety & Security
- Hearings & Appeals

- Assistant Secretary for Policy & International Affairs
- Assistant Secretary for Congressional & Intergovernmental Affairs
- General Counsel
- Chief Financial Officer
- Chief Human Capital Officer
- Chief Information Officer
- Intelligence & Counterintelligence
- Public Affairs
- Economic Impact & Diversity

* The Deputy Secretary also serves as the Chief Operating Officer

12 JUL 10

ARPA-E Team (Now Recruiting)

Program Team 3-4 yr term

Eric Toone

Dave Danielson

Mark Hartney

Rajeev Ram

Mark Johnson

Ravi Prasher

Karma Sawyer

Commercialization Team

Sanjay Wagle

Srini Mirmira

Leshika Samarasinghe

Strategic Outreach

Shannon Barrett

Operations Team

Shane Kosinski

Tony DiGiovanni

Matt Dunne

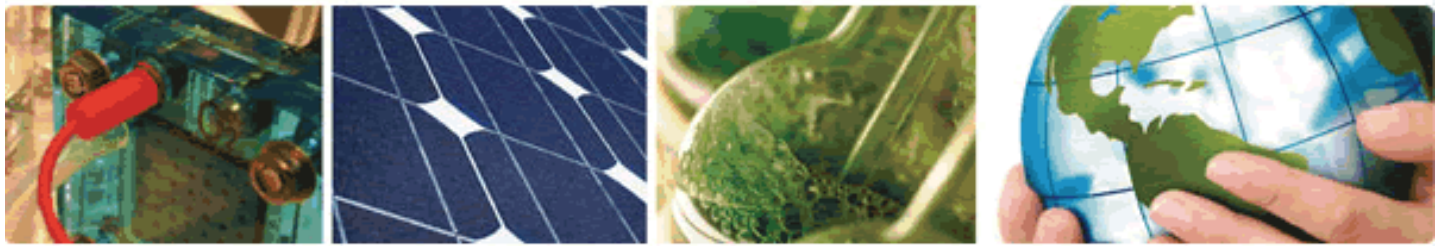
ARPA-E Fellows Program

Recent best/brightest PhDs in science/engineering & technical entrepreneurs will form a think tank to identify new approaches and scenarios for technology/markets/social engagement

…engage with the next generation and get them excited and educated in energy and environment

ARPA-E ENERGY INNOVATION SUMMIT

MARCH 1ST – 3RD, 2010
GAYLORD CONVENTION CENTER
WASHINGTON, DC



- **2 months preparation**
- **1700 attendees**
- **Integrating relevant communities**
  - *Scientists & engineers*
  - *Technology entrepreneurs*
  - *Other DOE Offices and federal agencies*
  - *Investors*
  - *State and regional clean tech incubators*
  - *White House, Congress and policy makers*

Technology Showcase

- *ARPA-E Funded technologies;* ***AND***
- *Finalists that ARPA-E could not fund*

arpa·e Energy Innovation Summit

Supporting America's Breakthrough Energy Innovators

February 28-March 2, 2011 • Washington, DC

About the Summit

The ARPA-E Energy Innovation Summit 2011 will convene the key players in the nation's energy innovation community to spur the networks that will bring about the next Industrial Revolution in clean energy technologies. » read more

Register | Showcase | Sponsor

HOSTED BY: arpa·e U.S. DEPARTMENT OF ENERGY

PRESENTED BY: CTSI Clean Technology and Sustainable Industries Organization

Purpose

- Showcase the next generation of clean energy technologies
- Connect technologists, entrepreneurs, and investors
- Provide insights that enable entrepreneurs to commercialize breakthrough technologies
- Introduce ARPA-E's leadership, program areas, and initial breakthrough technology projects

» Register Now!

Gaylord National Hotel & Convention Center

Special discounted room rates for attendees.

Book Hotel

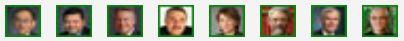
Program Highlights

Technology Showcase
See the 2010 ARPA-E award winners, finalists and additional innovative energy technologies! » Showcase Now!

Dynamic Speakers & Panelists
Bringing Disruptive Technologies to Market, Scaling and Financing Energy Technology, Views from the White House and the Hill, Building Regional Clusters, and more...

Past Keynotes:

» Steven Chu
Secretary of Energy
U.S. Department of Energy



» view last year's speakers

Participants

- Investment Professionals
- ARPA-E leadership and technical management staff
- Scientists and researchers
- Business Leaders and Entrepreneurs
- Political leaders and Congressional staff
- Energy and environmental science advocates
- DOE Applied programs and Office of Science Staff
- ARPA-E grantees/researchers
- ARPA-E non-selected "finalists"

» Learn how to participate as a sponsor

Supporting Partners

NVCA Ewing Marion KAUFFMAN

Martin Luther King (1967) :

"….We are now faced with the fact, my friends, that tomorrow is today. We are confronted with the fierce urgency of now. In this unfolding conundrum of life and history, there is such a thing as being too late."

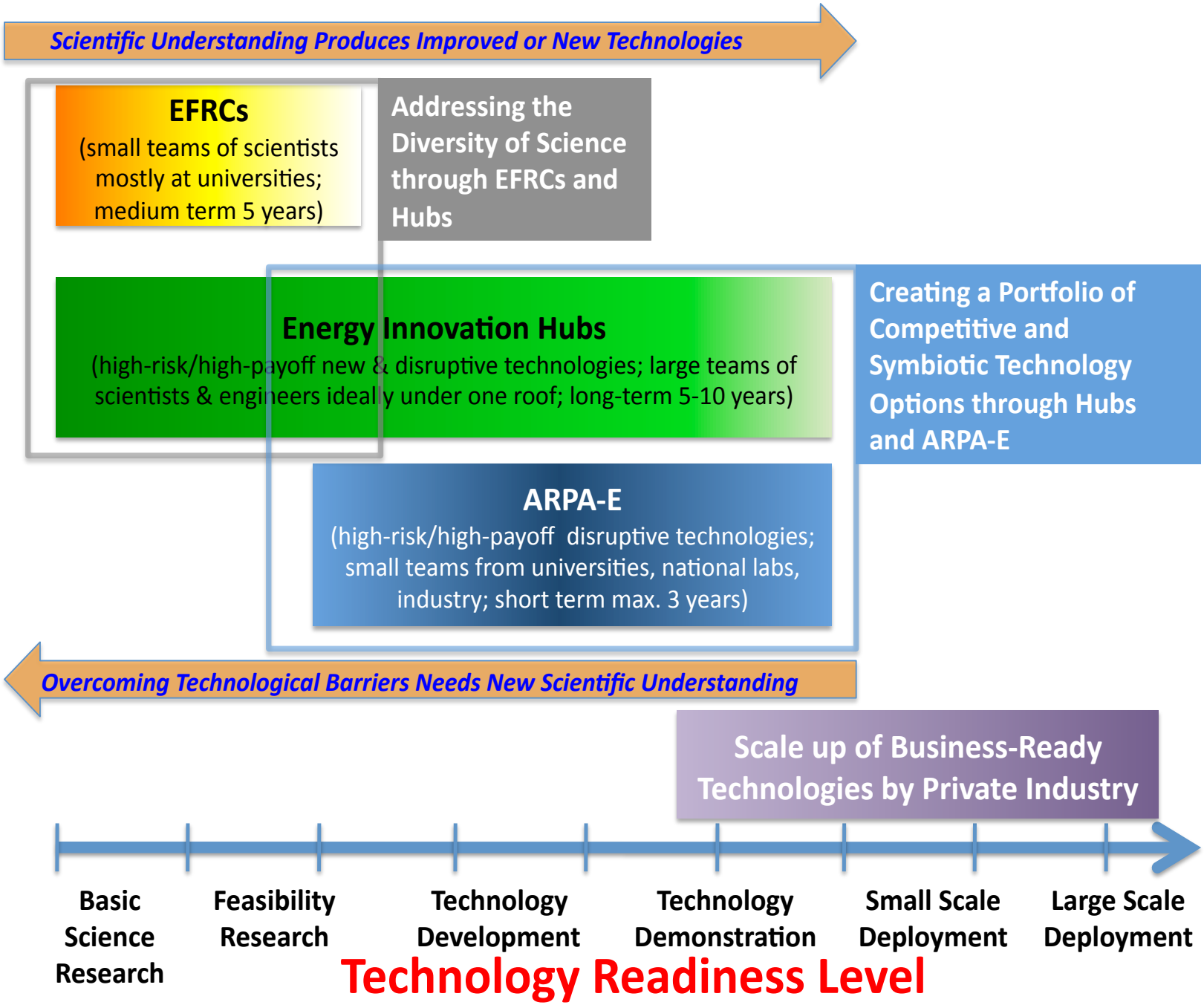
How do we measure success and manage expectations?

NOW — 3 - 5 YRS — 10+ YRS

- Attracting the best minds to energy R&D
- Follow on investment post ARPA-E award ($)
- Increase in enterprise value of company ($)
- Companies created (#)
- Initiating new technology-business ecosystems
- Accelerated market entry - Products to market (#) / Product sales ($)
- Patents filed and licensed (#)
- Papers published in top journals (#)
- World Record-setting "best-in-class" performance (#)

Home Runs

- Domestic and global sales, US market share ($)
- Avoided greenhouse gas emissions (tCO_2 equivalent)
- Reduced oil imports (barrels of oil equiv.)
- Creation of new technology/business or new industry ecosystem (#)
- Jobs created (#)
- Beating current projections and trajectories (Moving McKinsey GHG abatement cost curves, EIA & IPCC projections, etc.)


Scientific Understanding Produces Improved or New Technologies
EFRCs
(small teams of scientists mostly at universities; medium term 5 years)
Addressing the Diversity of Science through EFRCs and Hubs
Energy Innovation Hubs
(high-risk/high-payoff new & disruptive technologies; large teams of scientists & engineers ideally under one roof; long-term 5-10 years)
Creating a Portfolio of Competitive and Symbiotic Technology Options through Hubs and ARPA-E
ARPA-E
(high-risk/high-payoff disruptive technologies; small teams from universities, national labs, industry; short term max. 3 years)
Overcoming Technological Barriers Needs New Scientific Understanding
Scale up of Business-Ready Technologies by Private Industry
Basic Science Research
Feasibility Research
Technology Development
Technology Demonstration
Small Scale Deployment
Large Scale Deployment
Technology Readiness Level

ELECTROFUELS: SOLVING 4 PROBLEMS WITH 1 NOVEL SOLUTION

Program Director: Eric Toone (Robert Bass Prof of Chemistry, Duke; PhD-Toronto; Post-Doc - Harvard)

Photosynthesis: Less than 1% efficient

Electrofuels: Up to 90% efficient

CO_2

3. Greenhouse gas emissions

Non-Photosynthetic/ Modular/Mix-and-Match

Gasoline

4. 60% imported

Hydrogen

2. Difficult to store

Electricity

1. Difficult to store

H_2S

1. Waste from Oil & Natural Gas

New PIs in Energy R&D: David Baker (U. Washington), Pam Silver (Harvard), ….

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FIRST ROUND OF FUNDING

Concept Paper Phase

3700 Received

April - June 2009

Review
312 Encouraged Full Applications

June - July 2009

Full Application Phase

Panel Reviews

September – Early October 2009

Final Selection

37 Projects (avg. $4M) (2-3 years)

Announced on October 26

Award Negotiations Completed in 3 months including 3 Uses of Other Transaction Authorities

"In my 30 years of doing Government contracting…..I have never seen any government project move from selection to contracts and to actual work with such speed anywhere near what we are seeing out of ARPA-E….." CEO, Diversified Energy Corporation, Gilbert, AZ - 01/27/10

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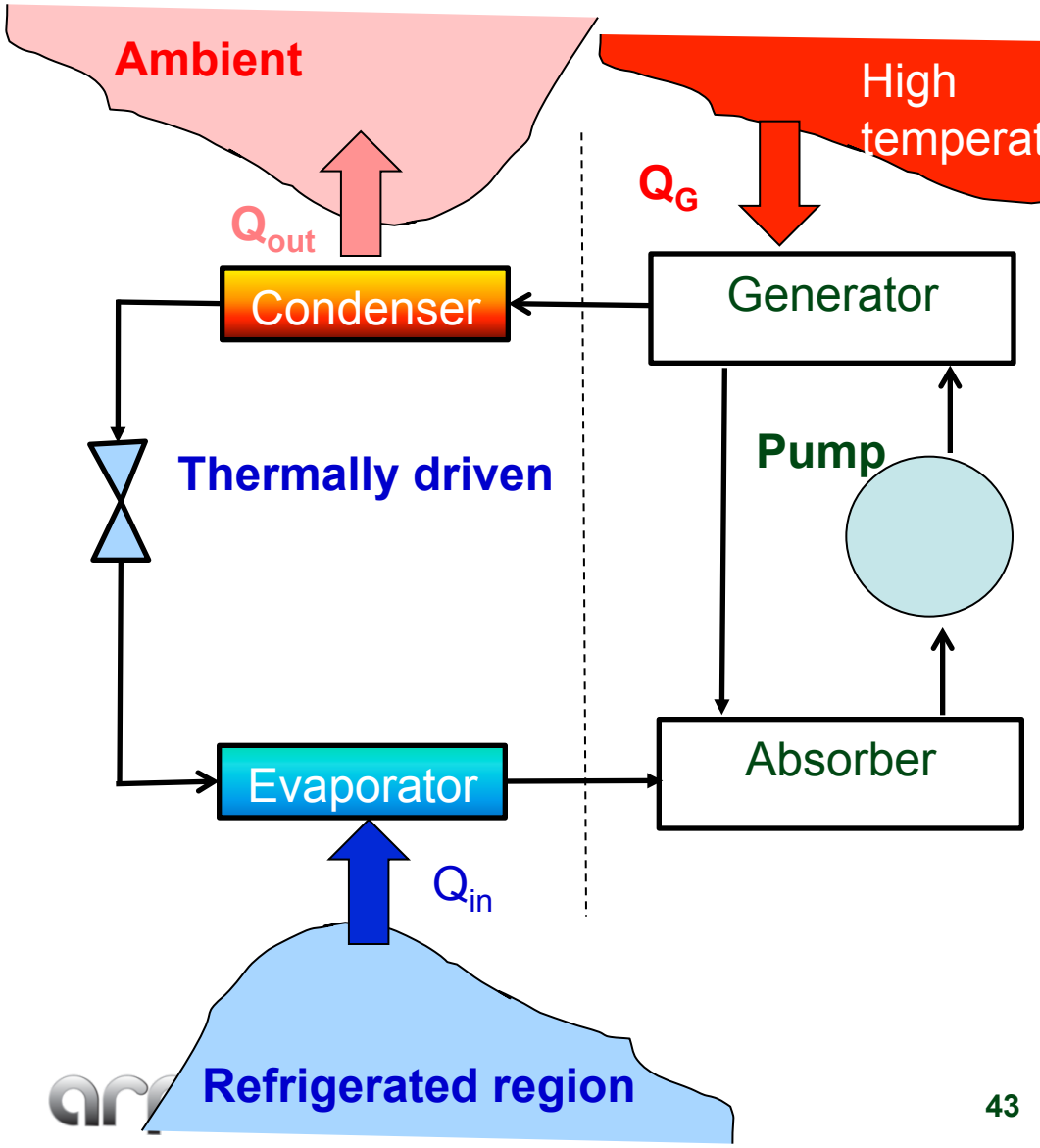
Vapor Absorption Refrigeration Cycle



Similar to Einstein Refrigerator

UNITED STATES PATENT OFFICE

ALBERT EINSTEIN, OF BERLIN, AND LEO SZILARD, OF BERLIN-WILMERSDORF, GERMANY, ASSIGNORS TO ELECTROLUX SERVEL CORPORATION, OF NEW YORK, N. Y., A CORPORATION OF DELAWARE

REFRIGERATION

INVENTORS
Albert Einstein
Leo Szilard
BY

Application filed December 16, 1927, Serial No. 240,566, and in Germany December 16, 1926.