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Materials and Sustainable Energy

David Keffer
Dept. of Materials Science & Engineering
The University of Tennessee
Knoxville, TN 37996-2100
dkeffer@utk.edu
http://clausius.engr.utk.edu/

Governor’s School
University of Tennessee, Knoxville
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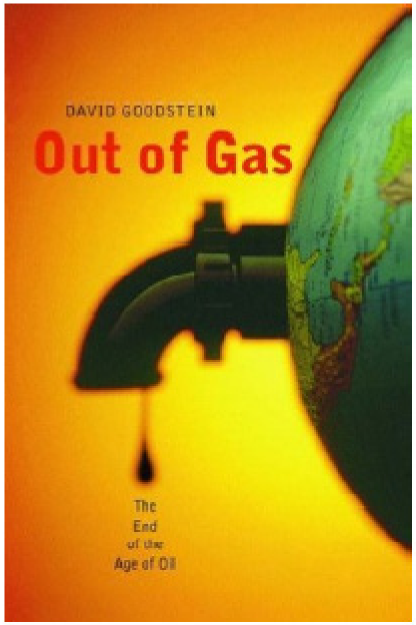
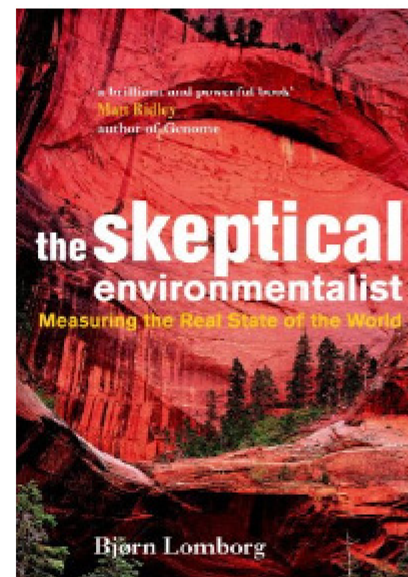
Multiscale Materials Modeler

Motivations



David Goodstein's *Out of Gas* (2004).

In *Out of Gas,* Caltech physicist David Goodstein describes an impending energy crisis brought on by The End of the Age of Oil. This crisis is coming soon, he predicts: the crisis will bite, not when the last drop of oil is extracted, but when oil extraction can't meet demand – perhaps as soon as 2015 or 2025. Moreover, even if we magically switched all our energy guzzling to nuclear power right away, Goodstein says, the oil crisis would simply be replaced by a *nuclear crisis in just twenty years or so, as uranium* reserves also became depleted.



Bjørn Lomborg's *The Skeptical Environmentalist* (2001).

In The Skeptical Environmentalist, Bjørn Lomborg paints a completely different picture. "Everything is fine." Indeed, "everything is getting better." Furthermore, "we are not headed for a major energy crisis," and "there is plenty of energy."

How could two smart people come to such different conclusions?

Sustainable Energy - Without the Hot Air by David MacKay

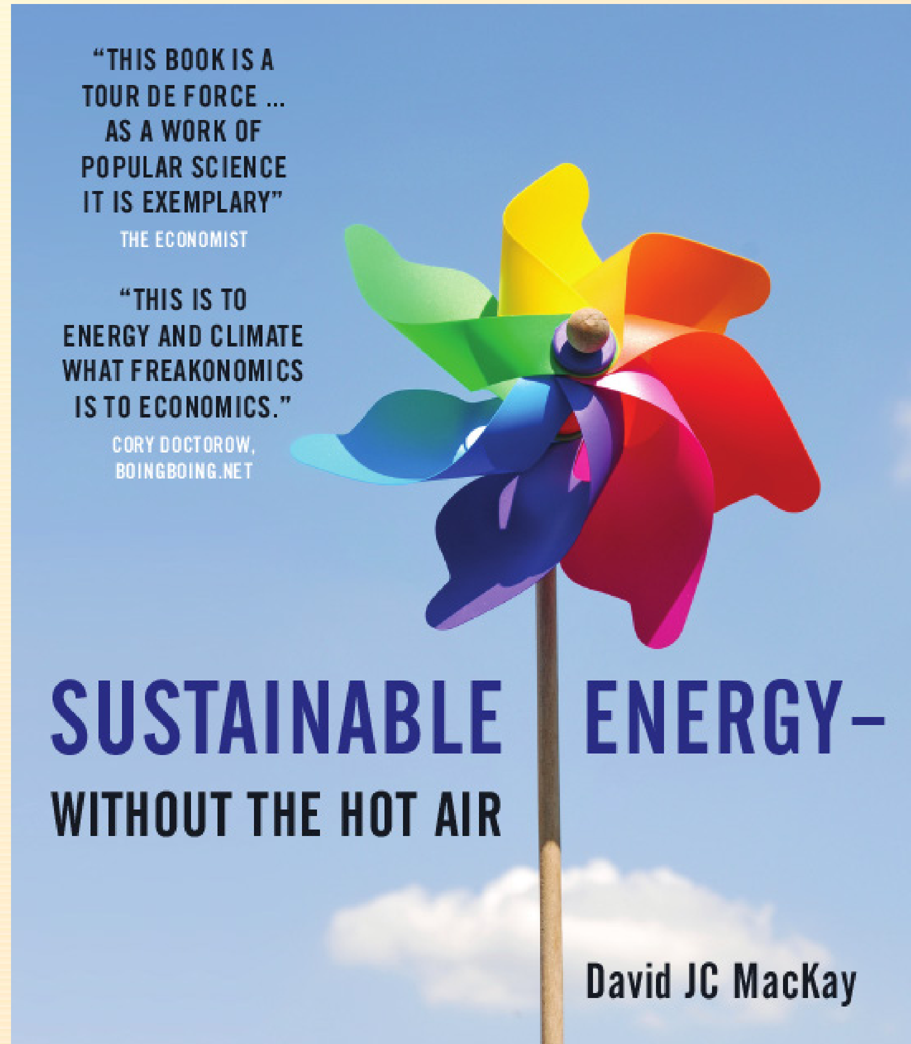
This lecture adopts the approach advocated by David MacKay.

His book is intended for a lay audience with technical appendices.

It examines national energy consumption and potential energy production from sustainable resources on a national scale.

Book can be freely accessed:

http://www.withouthotair.com/



Approach & Motivations

The discussion of an energy crisis requires numbers, not adjectives.

The numbers will be big because the problem is global.

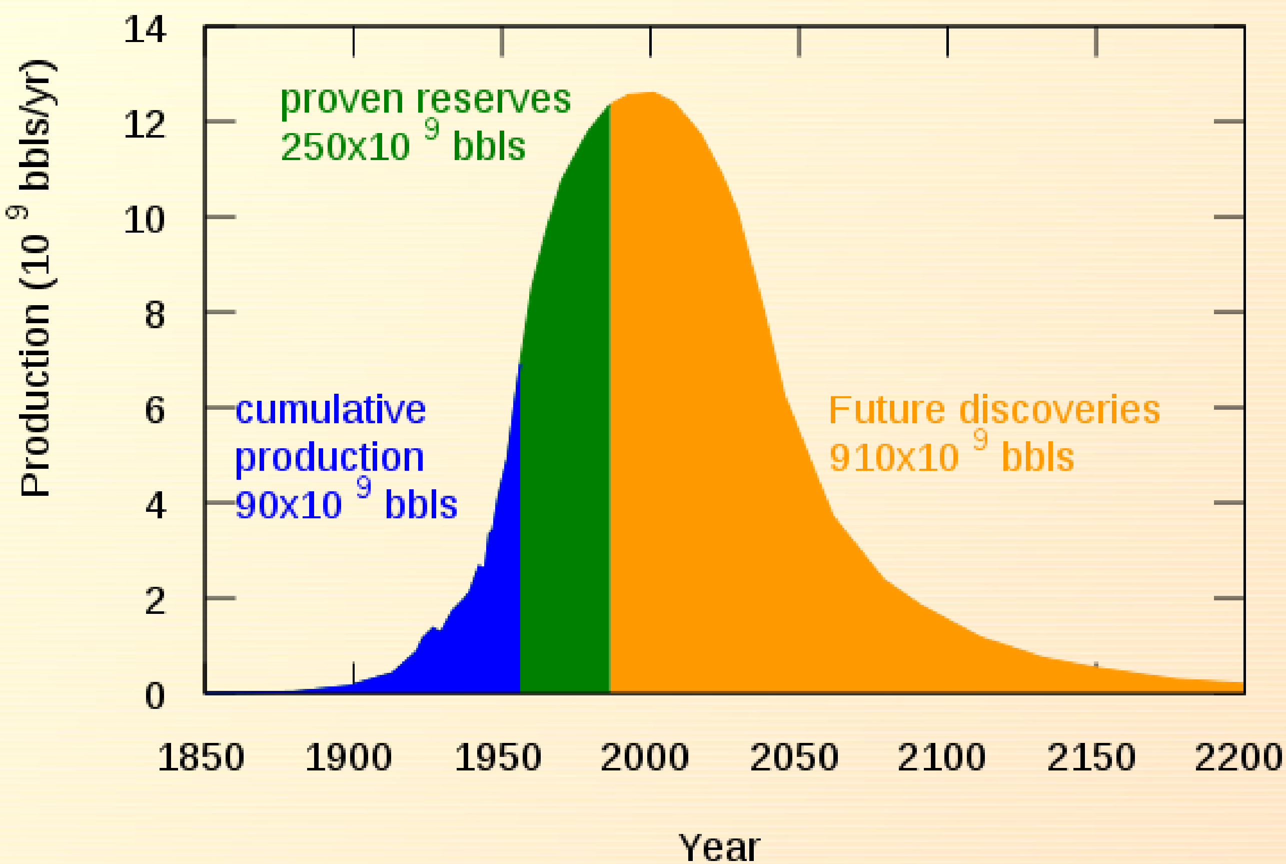
If everyone does a little, we will achieve only a little.

What is required are country-sized changes in energy usage.

Motivations

- fossil fuels are a finite resource
- energy security (many fossil fuels are located in politically unstable regions of the world, like the Middle East)
- fossil fuels probably cause climate change

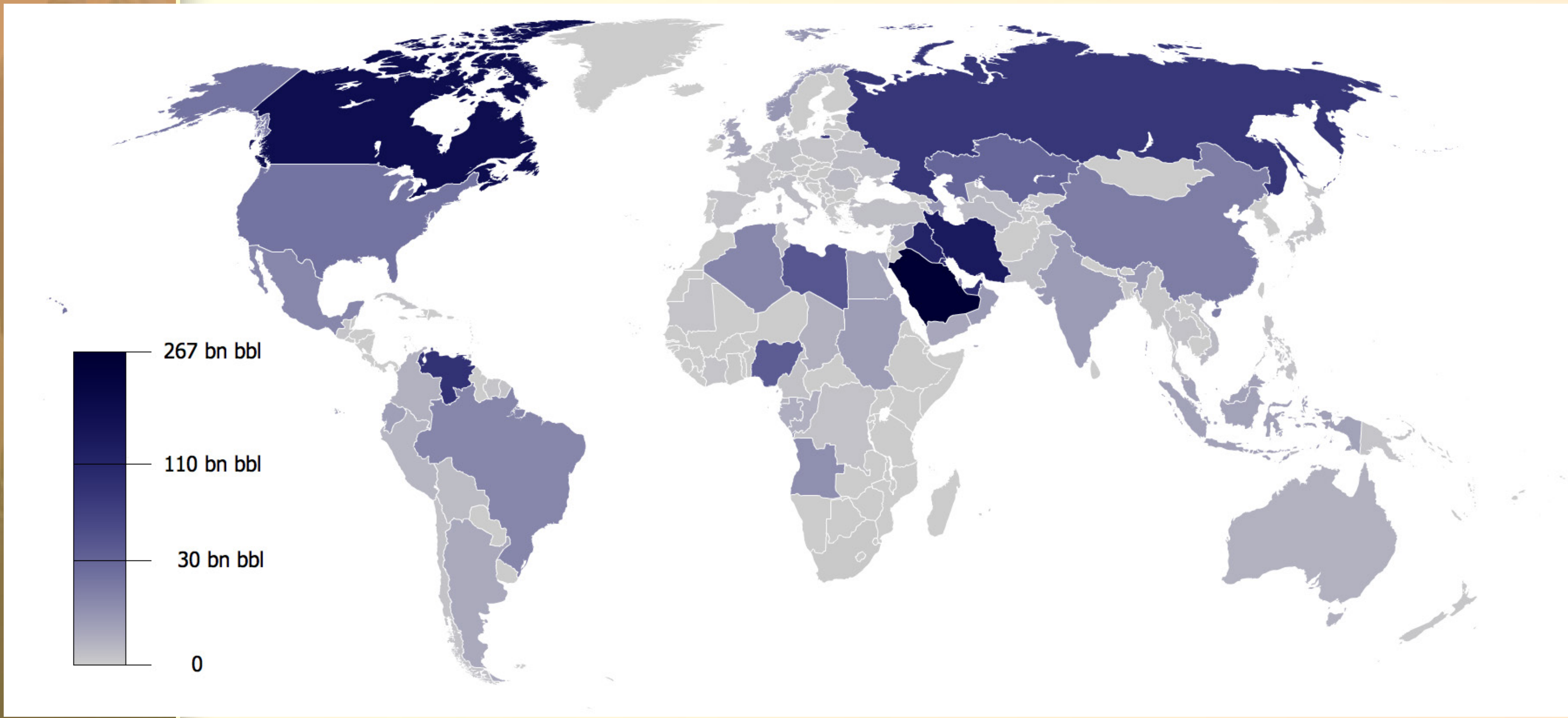
Motivations



Fossil fuels are a finite resource: Peak Oil

http://en.wikipedia.org/wiki/Peak_oil

Motivations



Energy Security

http://en.wikipedia.org/wiki/Peak_oil

Motivations

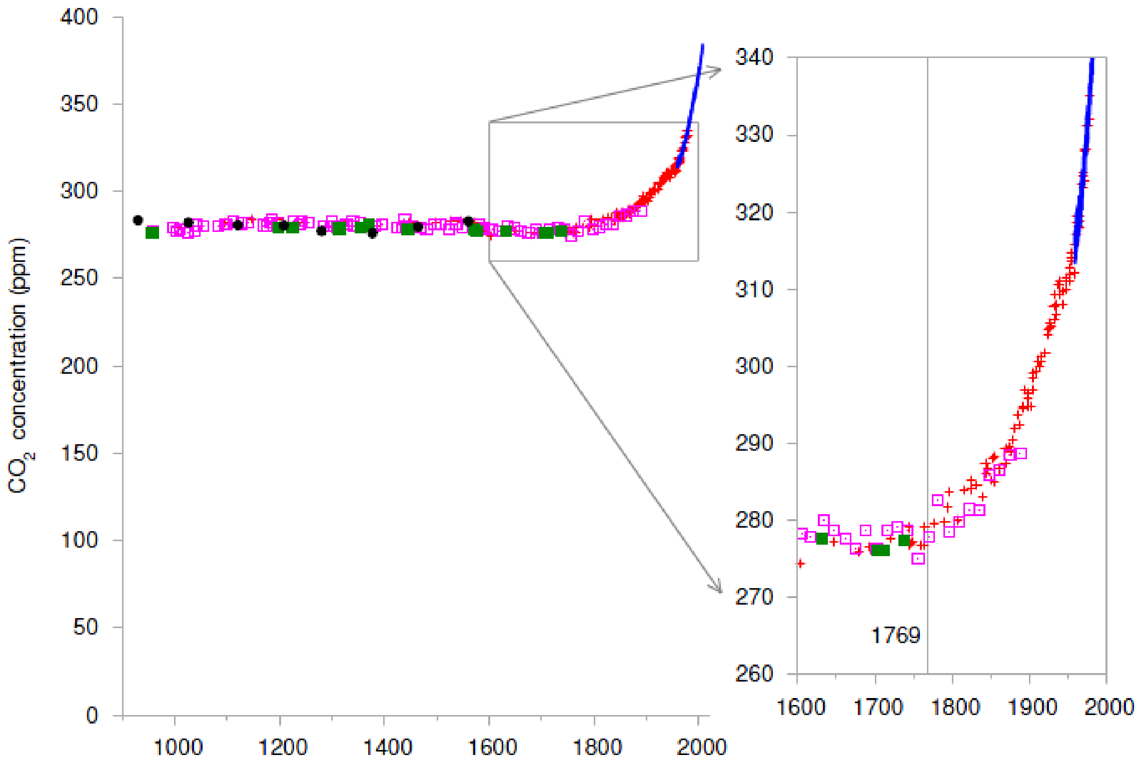


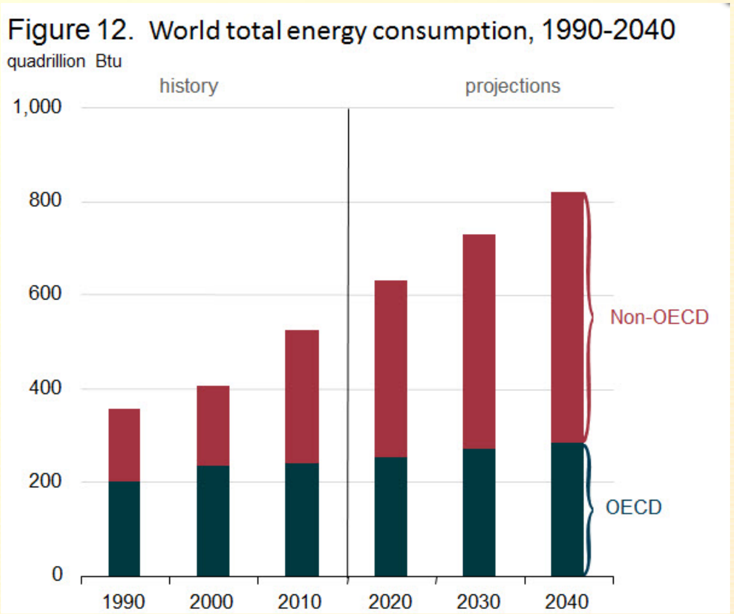
Figure 1.4. Carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards).

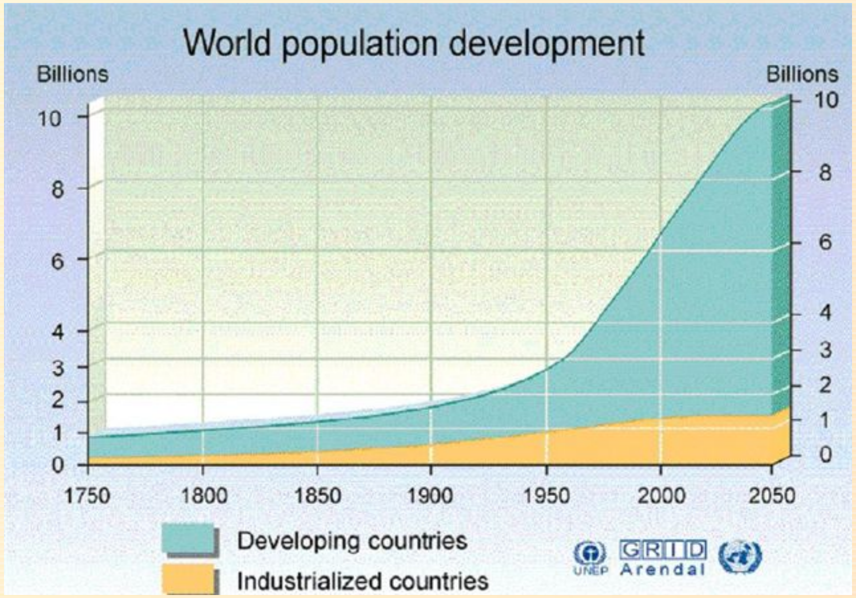
I think something new may have happened between 1800 AD and 2000 AD. I've marked the year 1769, in which James Watt patented his steam engine. (The first practical steam engine was invented 70 years earlier in 1698, but Watt's was much more efficient.)

Climate Change

Atmospheric carbon dioxide concentrations over the past 1100 years.

Motivations





Global Energy Demand is Rising

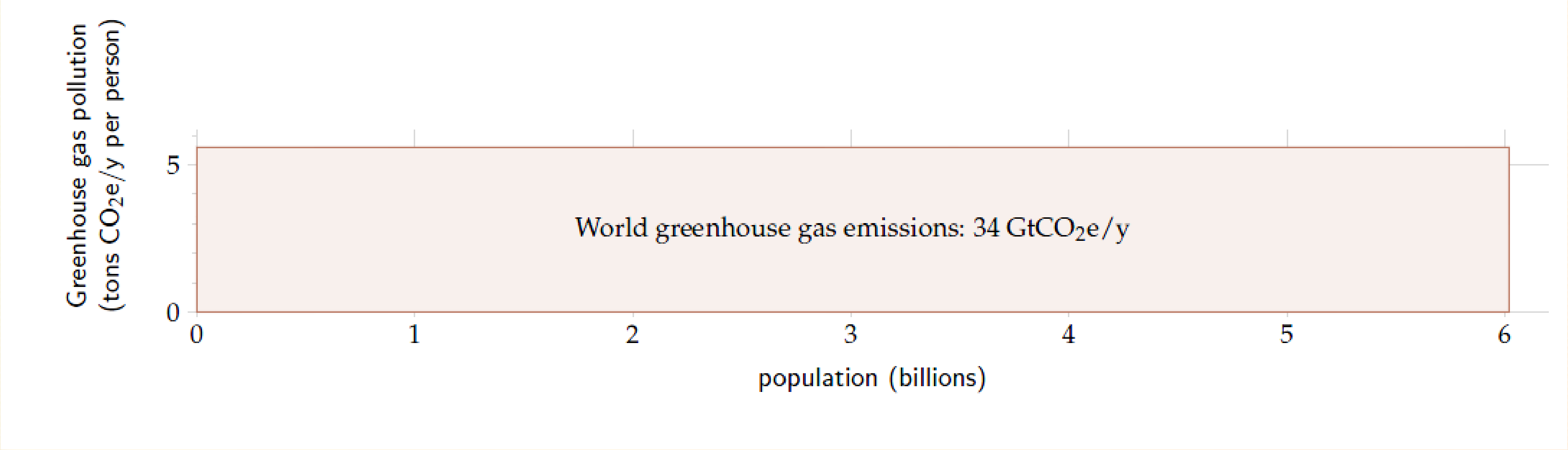
http://www.eia.gov/forecasts/ieo/world.cfm

Primary Cause: World population from 1750 to 2050.

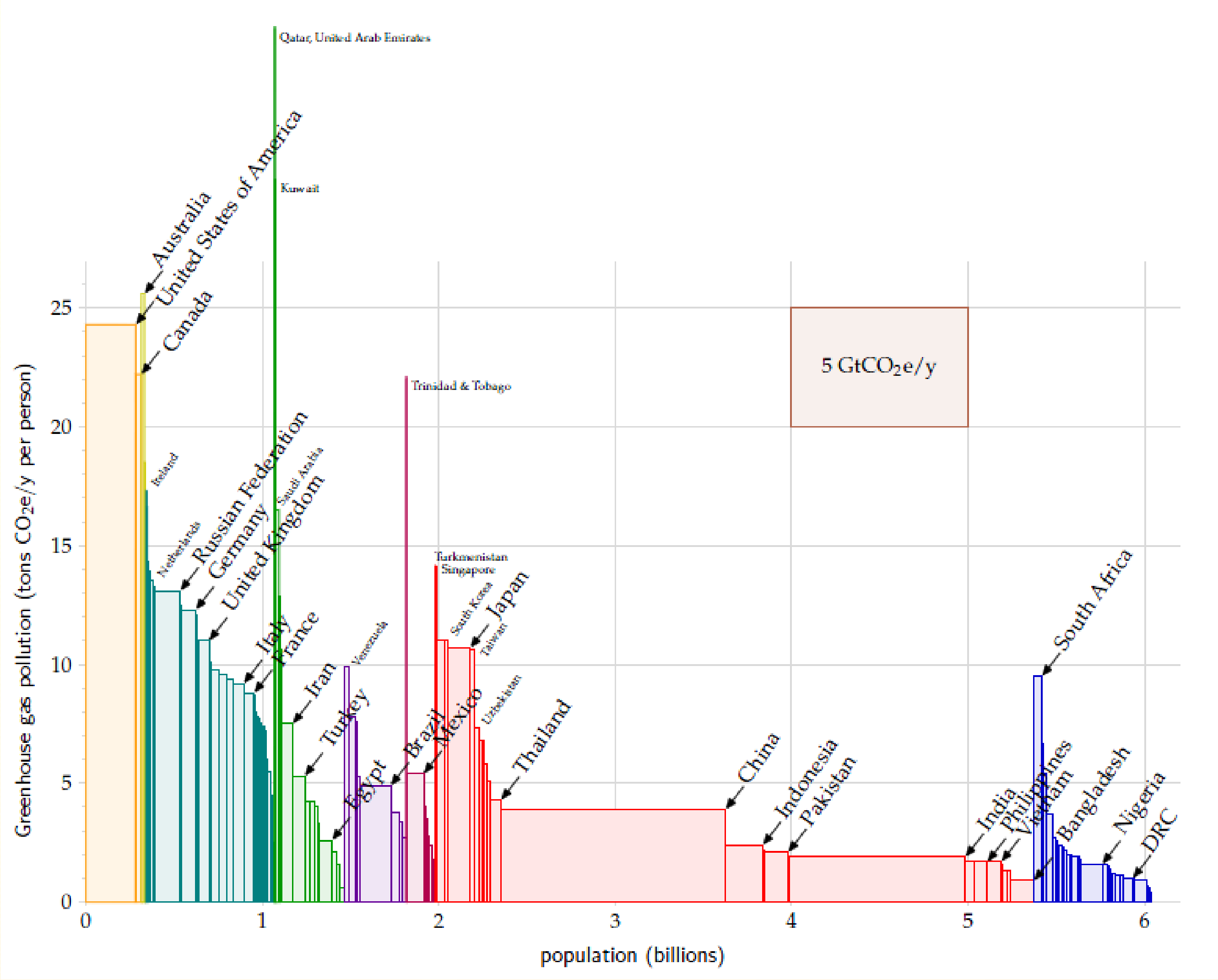
Motivations

Americans have a special responsibility to lead the search for sustainable energy sources due to current and historical usage.

Global Greenhouse gas pollution
34 Gigatons of CO_2 equivalent per year
Hypothetically spread uniformly over the global population.

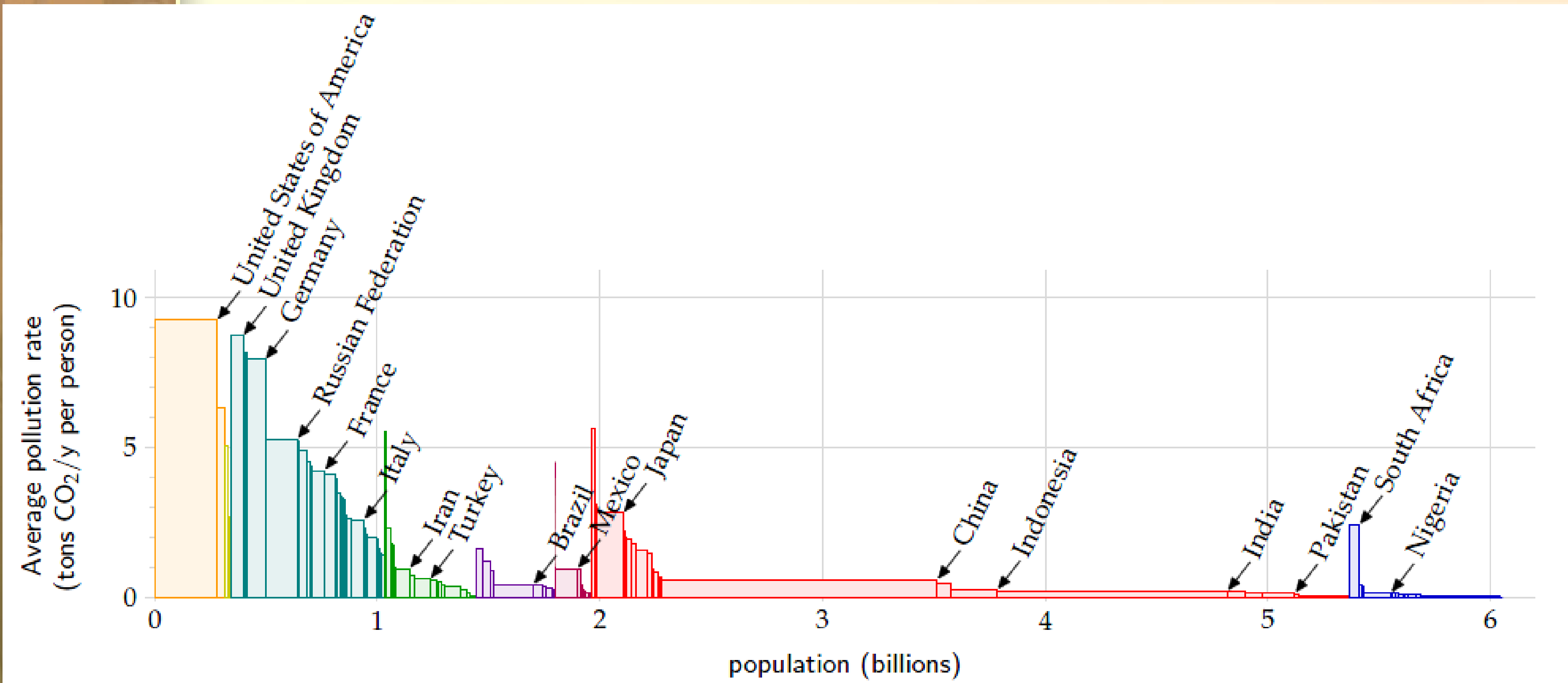


Motivations: Uneven current usage



Greenhouse gas pollution by country

Motivations: Uneven historical usage



Cumulative Greenhouse gas pollution by country from 1880-2004.

Motivations Energy is the main generator of GHG

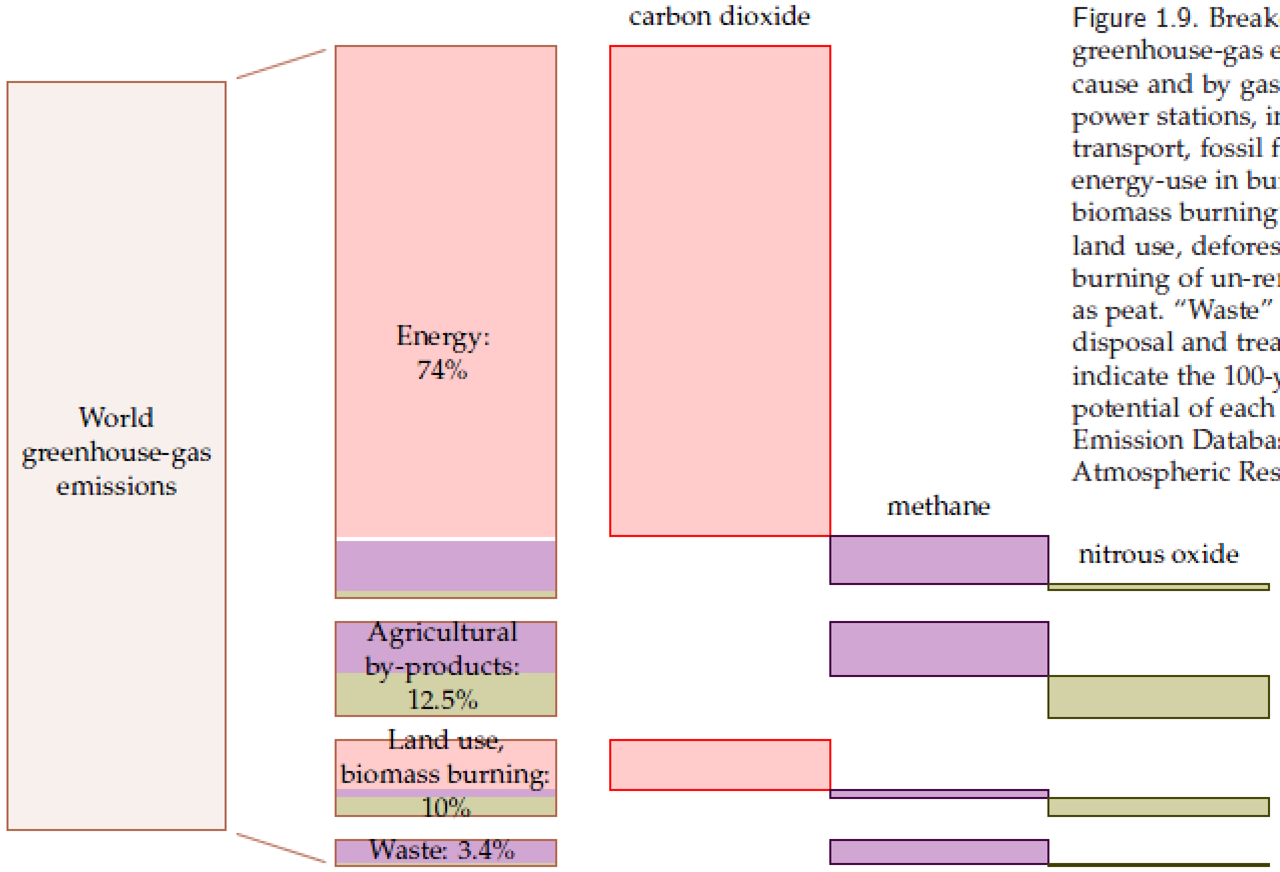


Figure 1.9. Breakdown of world greenhouse-gas emissions (2000) by cause and by gas. "Energy" includes power stations, industrial processes, transport, fossil fuel processing, and energy-use in buildings. "Land use, biomass burning" means changes in land use, deforestation, and the burning of un-renewed biomass such as peat. "Waste" includes waste disposal and treatment. The sizes indicate the 100-year global warming potential of each source. Source: Emission Database for Global Atmospheric Research.

Breakdown of Greenhouse gas pollution by cause and species.

The Balance Sheet

consumption

Some key forms of consumption for the left-hand stack will be:

- transport
  - cars, planes, freight
- heating and cooling
- lighting
- information systems and other gadgets
- food
- manufacturing

production

In the right-hand sustainable-production stack, our main categories will be:

- wind
- solar
  - photovoltaics, thermal, biomass
- hydroelectric
- wave
- tide
- geothermal
- nuclear? (with a question-mark, because it's not clear whether nuclear power counts as "sustainable")

Two lists: one of energy consumption, one of conceivable production
Can we conceivably live on sustainable energy?

Scientific consensus on global warming?

American Physical Society

In November 2007, the American Physical Society (APS) adopted an official statement on climate change:

Emissions of greenhouse gases from human activities are changing the atmosphere in ways that affect the Earth's climate. Greenhouse gases include carbon dioxide as well as methane, nitrous oxide and other gases. They are emitted from fossil fuel combustion and a range of industrial and agricultural processes. The evidence is incontrovertible: Global warming is occurring. If no mitigating actions are taken, significant disruptions in the Earth's physical and ecological systems, social systems, security and human health are likely to occur. We must reduce emissions of greenhouse gases beginning now.
Because the complexity of the climate makes accurate prediction difficult, the APS urges an enhanced effort to understand the effects of human activity on the Earth's climate, and to provide the technological options for meeting the climate challenge in the near and longer terms. The APS also urges governments, universities, national laboratories and its membership to support policies and actions that will reduce the emission of greenhouse gases.

An established, global scientific consensus exists, despite uncertainties.

Scientific consensus on global warming?

Not everyone believes that "climate change" is real, or caused by man or even bad.

- Myth 1 Average global temperature (AGT) has increased over the last few years.
  - Fact 1 Within error bounds, AGT has not increased since 1995 and has declined since 2002, despite an increase in atmospheric CO2 of 8% since 1995.
- Myth 2 During the late 20th Century, AGT increased at a dangerously fast rate and reached an unprecedented magnitude.
  - Facts 2 The late 20th Century AGT rise was at a rate of 1-20 C/century, which lies well within natural rates of climate change for the last 10,000 yr. AGT has been several degrees warmer than today many times in the recent geological past.
- Myth 3 AGT was relatively unchanging in pre-industrial times, has sky-rocketed since 1900, and will increase by several degrees more over the next 100 years (the Mann, Bradley & Hughes "hockey stick" curve and its computer extrapolation).
  - Facts 3 The Mann et al. curve has been exposed as a statistical contrivance. There is no convincing evidence that past climate was unchanging, nor that 20th century changes in AGT were unusual, nor that dangerous human warming is underway.
- Myth 4 Computer models predict that AGT will increase by up to 60 C over the next 100 years.
  - Facts 4 Deterministic computer models do. Other equally valid (empirical) computer models predict cooling.
- Myth 5 Warming of more than 20 C will have catastrophic effects on ecosystems and mankind alike.
  - Facts 5 A 20 C change would be well within previous natural bounds. Ecosystems have been adapting to such changes since time immemorial. The result is the process that we call evolution. Mankind can and does adapt to all climate extremes.

http://www.abovetopsecret.com/forum/thread525791/pg1, retrieved April 13, 2011

What is sustainability?

Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of 'needs', in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

from The U.N. Report of the Brundtland Commission, *Our Common Future*, *1987.*

Full text of the Brundtland Report available at http://worldinbalance.net/agreements/1987-brundtland.php

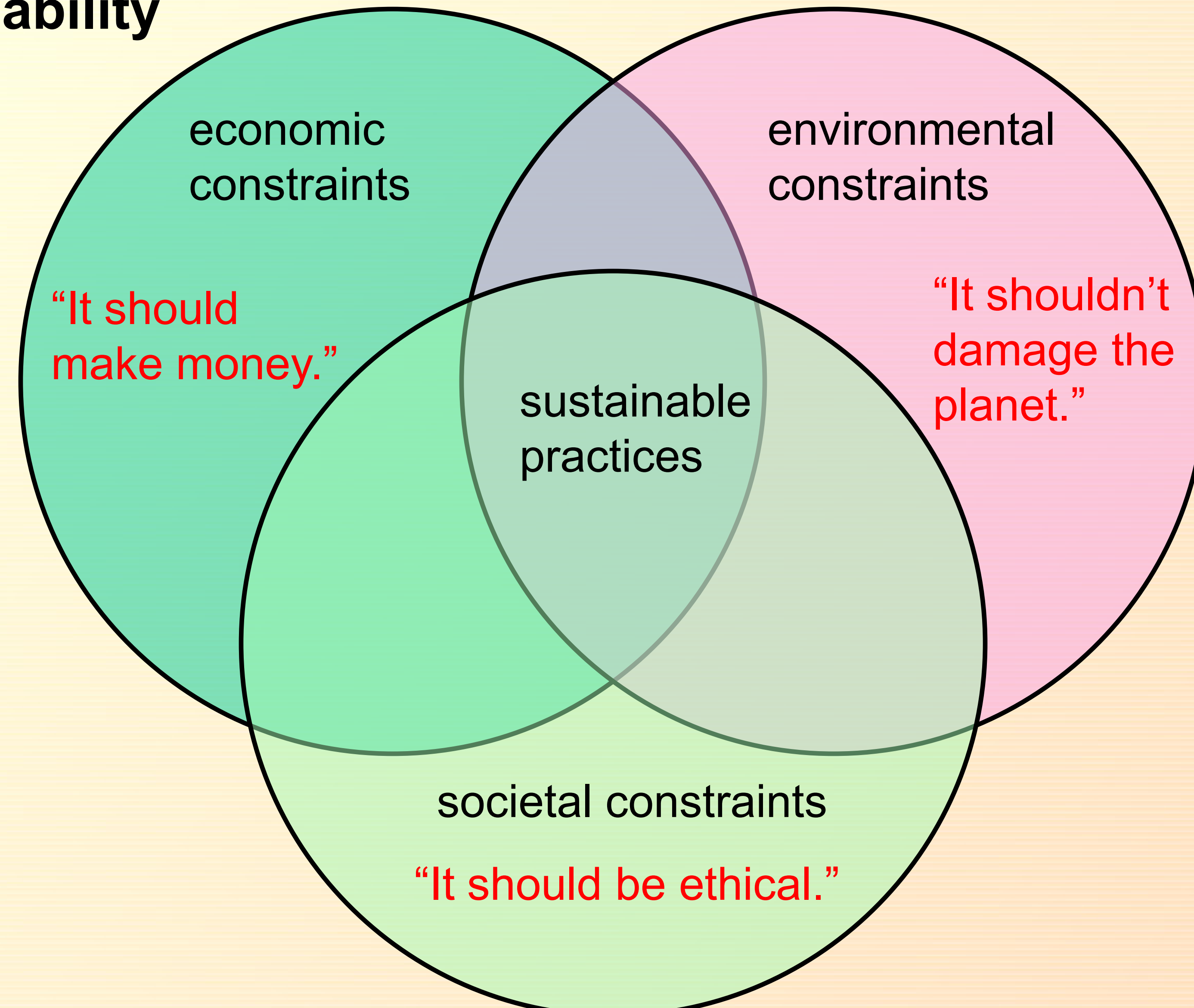
What is sustainability?

"Sustainability is the art of living well within ecological limits."
- Tim Jackson, Prof. of Sustainable Development, University of Surrey

"Sustainability is a 21st century business imperative."
- Edward G. Madzy, Director of Product Regulations and Product Stewardship, BASF Corporation

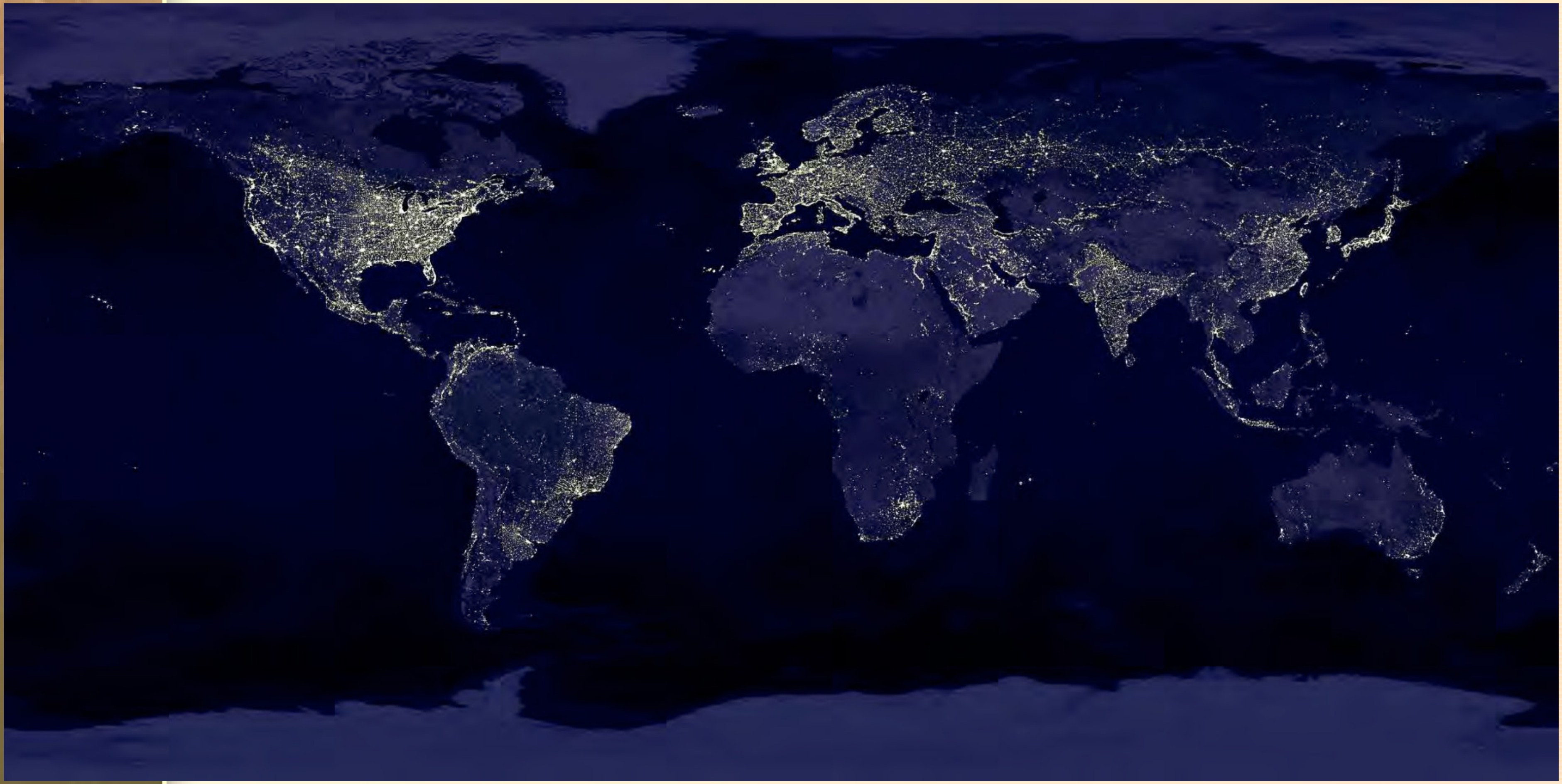
"Sustainability should be viewed as both a responsibility and an opportunity."
- Len Sauers, Vice President for Global Sustainability, Procter & Gamble

Sustainability



Interdisciplinary problem: Materials Scientists play critical role.

Strategies for Solutions: Thinking BIG



http://www.pppl.gov/colloquia_pres/WC13MAY09_JMinervini2.pdf

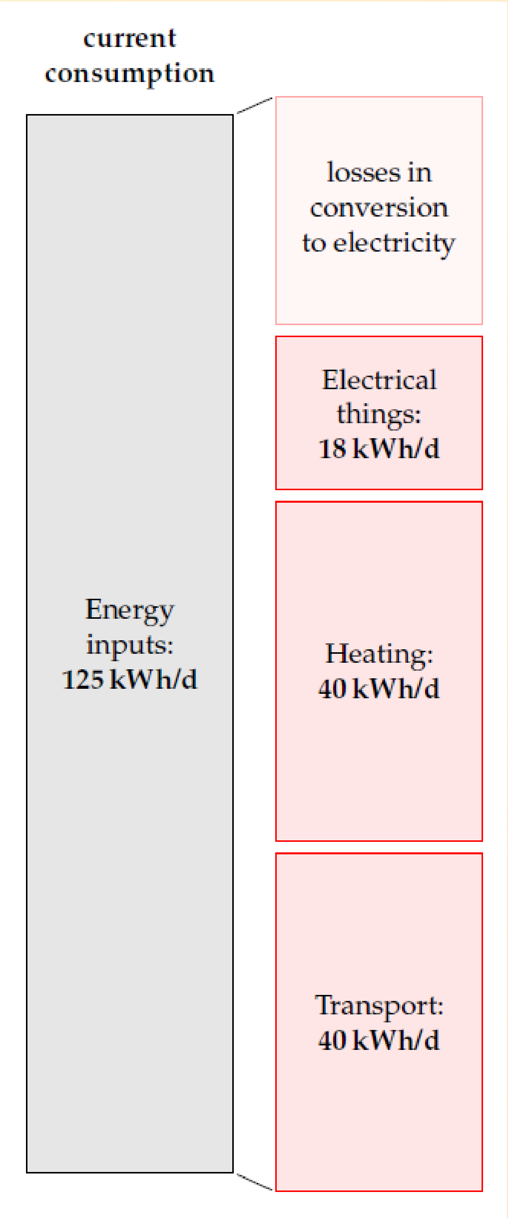
Strategies: BIG

BIG Changes are required

Demand can be reduced
- reduce the population
- change our lifestyle
- keep population & lifestyle, reduce energy intensity through efficiency and technology

Supply can be increased
- sustainable, clean coal?
- sustainable, nuclear fission?
- buy, beg or steal renewable energy from other countries

Simplify the picture
- transport
- heating
- electricity
- conversion losses



Strategies: Thinking BIG

Potential Directions

Better Transport (Chapter 20)

- electrify transportation
- more mass transit
- more bicycles
- advanced design of electric cars

Smarter Heating (Chapter 21)

- better building design
- heat pumps
- lower thermostat settings

Efficient Electricity Use (Chapter 22)

- turning off idle devices (stand by devices account for 8% of residential electricity use)
- use of energy efficient devices/bulbs
- reduce transmission losses in electrical lines

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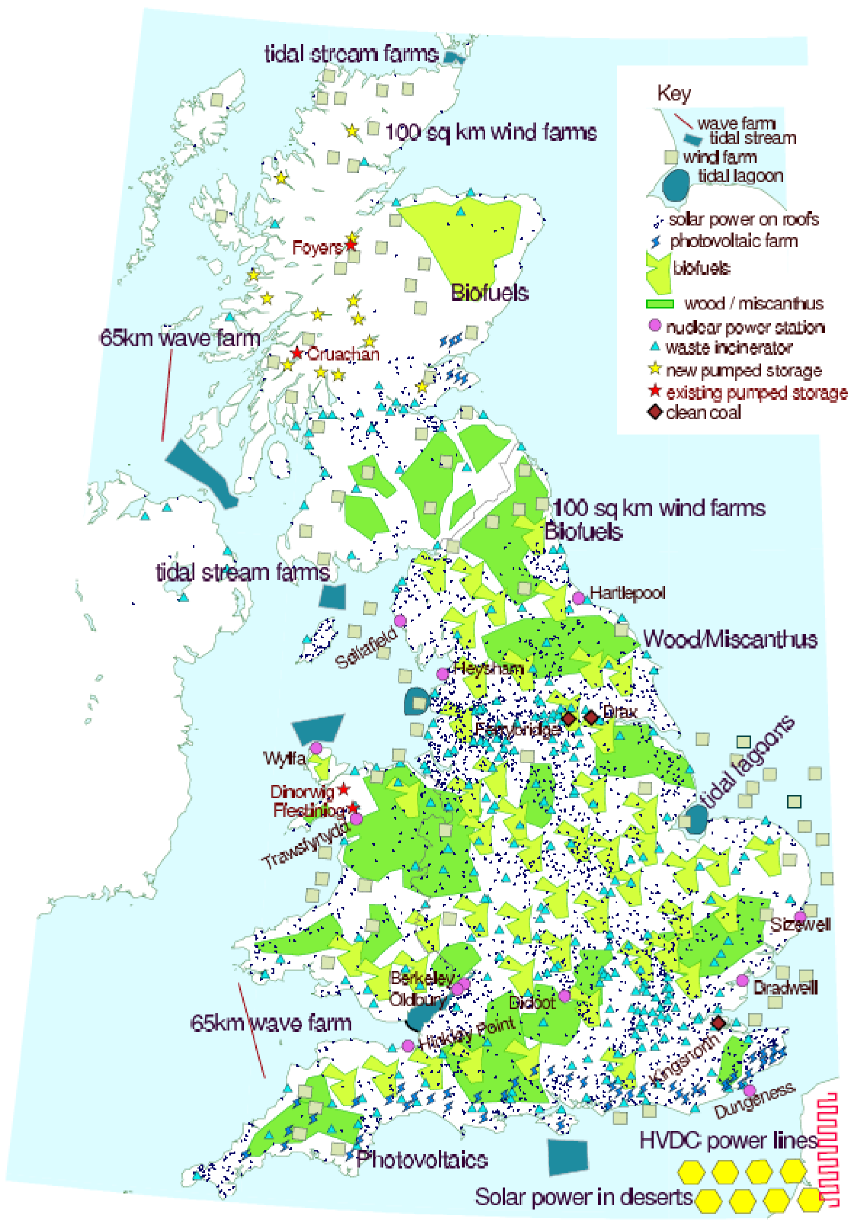
A Strategy

Plan M: the Middle plan

This model contains all technologies.

It is physically feasible. There is enough area around England for each of the technologies.



Solar in deserts: 16 kWh/d

Clean coal: 3

Nuclear: 16 kWh/d

Tide: 3.7

Wave: 0.3

Hydro: 0.2

Waste: 1.1

Pumped heat: 12 kWh/d

Wood: 5 kWh/d

Solar HW: 1

Biofuels: 2

PV: 2

Wind: 8

Concentrated Solar Power

What is Concentrated Solar Power?

Concentrated solar power (CSP) are systems that use lenses or mirrors to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat which drives a heat engine (usually a steam turbine) connected to an electrical power generator.
CSP should not be confused with photovoltaics, where solar power is directly converted to electricity without the use of steam turbines.

Advantages

- Uses steam turbines (conventional technology)
- No expensive solar PV cells
- 12 to 18 cents per kWh
- needs a desert

Commercial electricity ~ 9 cents/kWh (Knoxville, TN, November, 2010)

http://en.wikipedia.org/wiki/Concentrated_solar_power

Concentrated Solar Power

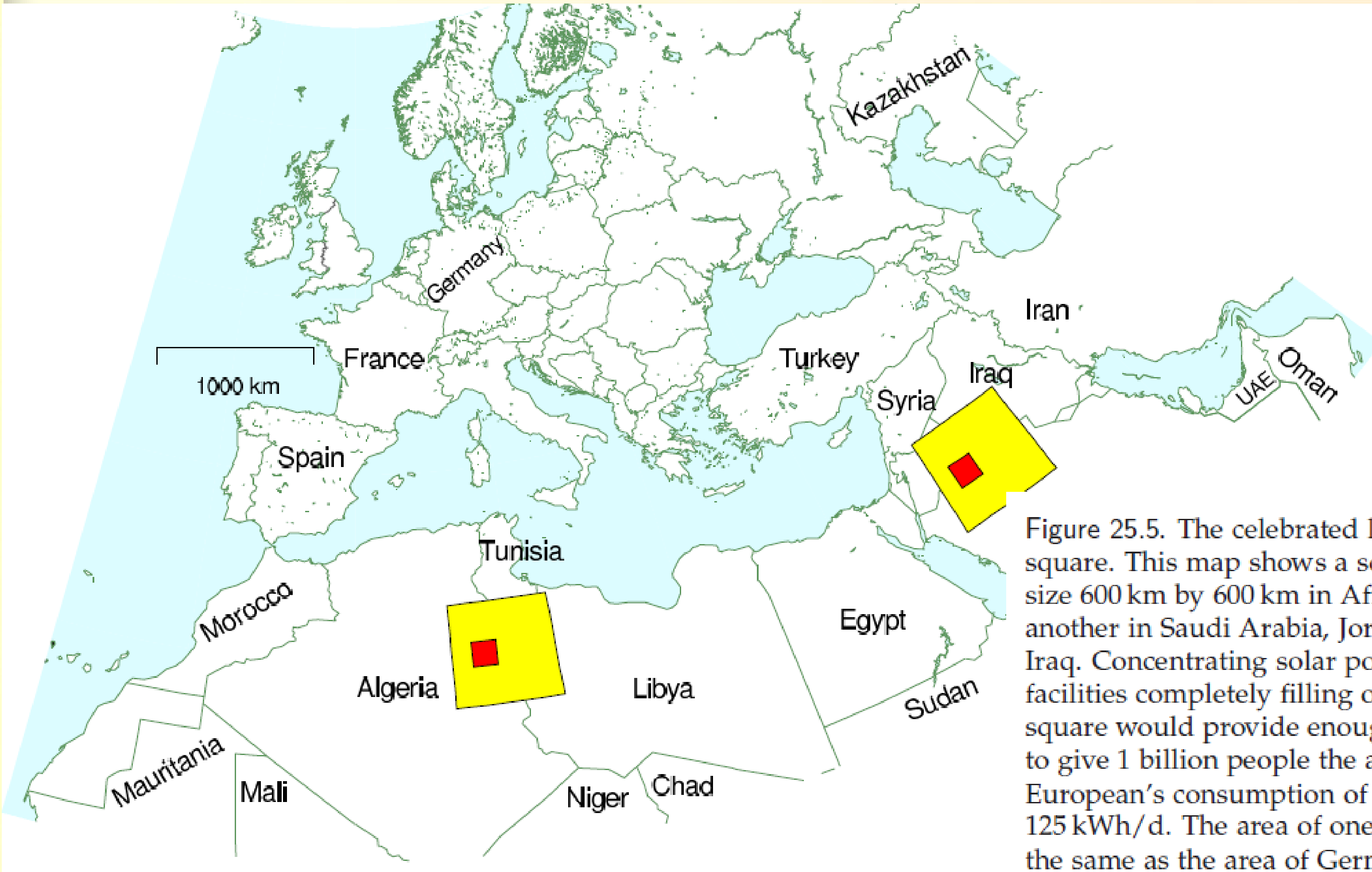


Figure 25.5. The celebrated little square. This map shows a square of size 600 km by 600 km in Africa, and another in Saudi Arabia, Jordan, and Iraq. Concentrating solar power facilities completely filling one such square would provide enough power to give 1 billion people the average European's consumption of 125 kWh/d. The area of one square is the same as the area of Germany, and 16 times the area of Wales. Within each big square is a smaller 145 km by 145 km square showing the area required in the Sahara – one Wales – to supply all British power consumption.

- Each yellow square could provide 125 kWh/day/person for 10^9 people. Place them near water, since they can desalinate water.

Solar Power Materials Slide

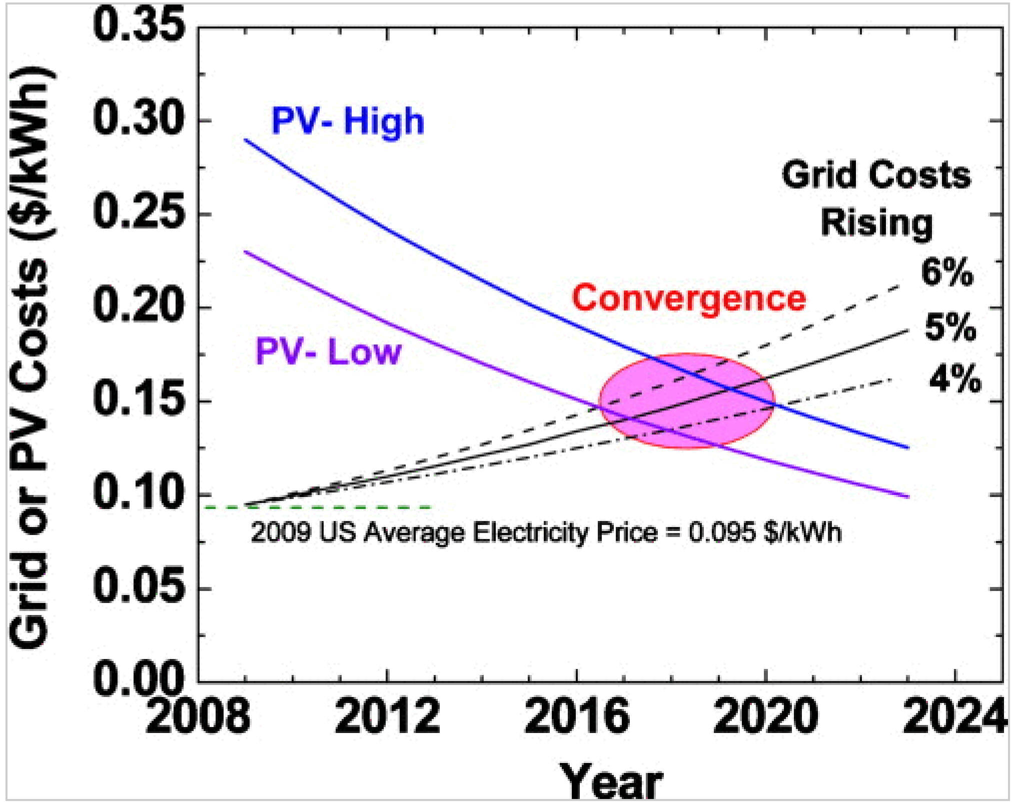


FIG. 1.

(Color online) Projected convergence of the cost of electricity produced by PV and the conventional grid prices.

Citation: J. Vac. Sci. Technol. A **29**, 030801 (2011); http://dx.doi.org/10.1116/1.3569757

Materials research is a critical element in bringing down PV costs.

Improving Solar Power Generation through Materials

Advanced photon management: The importance of this topic is self-evident as this phrase was used in conjunction with the discussion of nearly every technology. Typically, advances and improvements in efficiency involve materials that are applied externally to the cell, allowing them to be developed independently without impacting cell designs that are highly optimized.

(1) *Antireflection coatings.* Multilayer or nanostructured antireflection coatings can extend photon collection both across the spectrum and at diffuse angles
(2) *Increasing the path length through the absorber.* Texturing, microstructures, or nanostructure based on plasmonics divert photons coming normal to the surface to more oblique angles, increasing the probability of absorption
(3) *Optical field enhancement.* Plasmonic enhancement of the optical field in the vicinity of a metal nanoparticle is used to increase optical absorption
(4) *Downshifting.* This is the process of converting high-energy UV and blue photons and downconverting their energy where quantum efficiency values typically approach 100%
(5) *Downconversion.* Often called photon splitting, this is the process of transforming one high-energy photon into two photons that still have the energy to create electron-hole pairs
(6) *Upconversion.* This is the reverse process whereby two low energy photons are combined to produce one high-energy photon that is capable of generating an electron-hole pair.

This is a materials problem.

Photovoltaic manufacturing: Present status, future prospects, and research needs
Colin A. Wolden et al., J. Vac. Sci. Technol. A **29**, 030801 (2011);

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Energy Usage in Homes: Design & Materials

Comparison: Knoxville, Tennessee, USA 3 new homes

Home 2:
Built by Contractor
w/ conventional materials
w/ conventional design
immediately retrofit to be energy efficient

Home 1:
Built by Contractor
with conventional materials
with conventional design

Home 3:
Built by from the beginning to be energy efficient
Energy efficient design
Energy efficient materials

Images & Slides:
Jeff Christian
Oak Ridge
National Laboratory

Energy Usage in Homes: Design & Materials

Comparison: Knoxville, Tennessee, USA 3 new homes

TVA Near Zero Energy House, HERs Index = 32

- Advanced 2 X 6 Framing with DOWsis
- R-49 attic with LP Techshield radiant barrier sheathing
- R-7. Triple layer windows from Serious Materials
- R-10 vertical slab stem wall insulation
- One Amana 2-ton HP, SEER 16, HSPF=9.5, zone control
- Fantech Energy Recovery Ventilator
- Advanced GE appliances
- Energy Star pin based High performance lighting design
- Solar drain-back water heater
- 2.5 kWh Solar PV system
- Greywater waste heat recovery
- Appliance waste heat recovery
- 65-70% heating energy savings

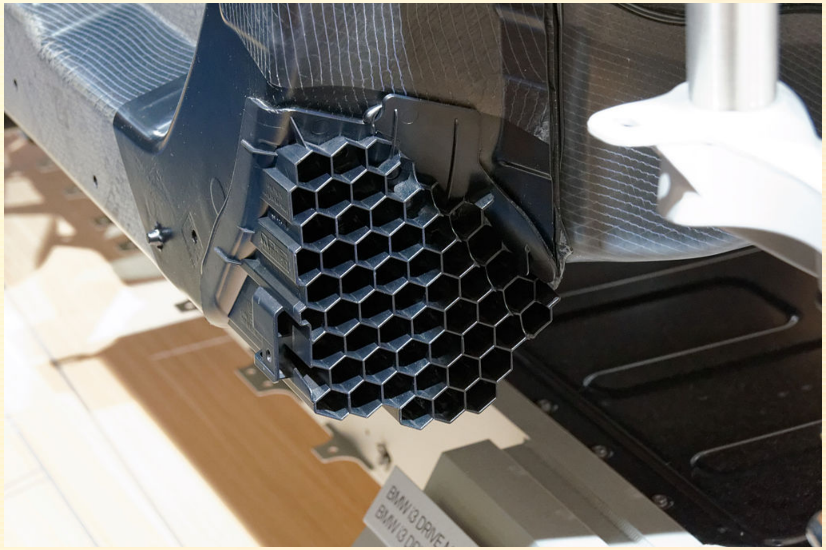
Images & Slides:
Jeff Christian
Oak Ridge
National Laboratory

Note: HERS = home energy rating system

Materials for Transportation

The White House - Office of the Press Secretary
August 28, 2012
Obama Administration Finalizes Historic 54.5 MPG Fuel Efficiency Standards

WASHINGTON, DC – The Obama Administration today finalized groundbreaking standards that will increase fuel economy to the equivalent of 54.5 mpg for cars and light-duty trucks by Model Year 2025.



Honeycomb structure made of injection-molded plastic fixed onto a carbon-fiber-reinforced polymer chassis on a BMW i3.

This is a materials problem.

http://en.wikipedia.org/wiki/Carbon-fiber-reinforced_polymer#Automotive_engineering

Reducing Transmission Losses

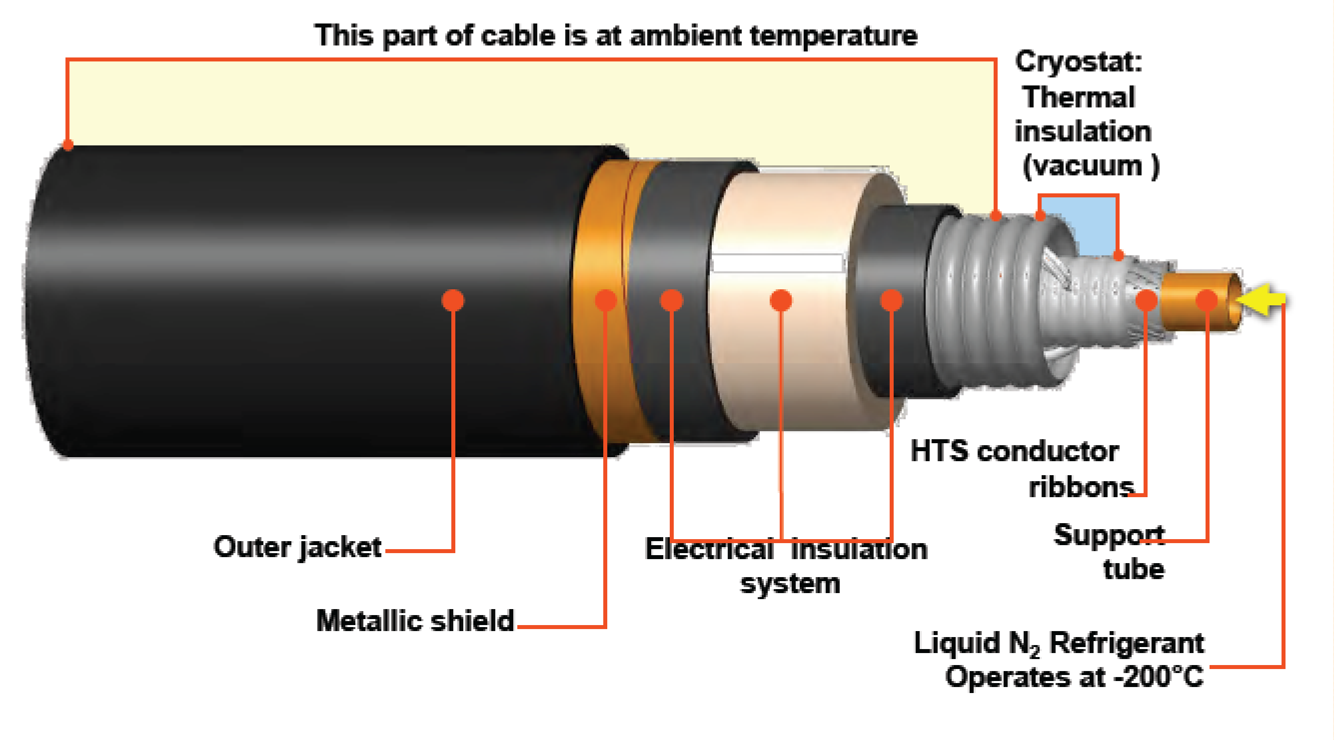
Transmission Losses

- Transmitting electricity at high voltage reduces the fraction of energy lost to resistance.
- For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor.
- At extremely high voltages, more than 2 MV between conductor and ground, corona discharge losses are so large that they can offset the lower resistance loss in the line conductors.
- Transmission and distribution losses in the USA were estimated at 6.6% in 1997[13] and 6.5% in 2007.[13]

http://en.wikipedia.org/wiki/Electric_power_transmission

Reducing Transmission Losses

How much can transmission and distribution losses be reduced
High-temperature superconductors promise to revolutionize power distribution by providing lossless transmission of electrical power. The development of superconductors with transition temperatures higher than the boiling point of liquid nitrogen has made the concept of superconducting power lines commercially feasible, at least for high-load applications. It has been estimated that the waste would be halved using this method, since the necessary refrigeration equipment would consume about half the power saved by the elimination of the majority of resistive losses.



http://www.pppl.gov/colloquia_pres/WC13MAY09_JMinervini2.pdf
http://en.wikipedia.org/wiki/Electric_power_transmission

Sustainable Fossil Fuels?

Sustainable Coal

Target: 1000 years

- 1600 Gt of coal
- 6 billion people
- contains 6 kWh/day/person
- due to conversion losses, provides 2.2 kWh/day/person
- with clean coal technology, provides 1.6 kWh/day/person

Conclusion Clean coal is only a temporary solution.

The End of Business as usual: How long will coal last?

- 1600 Gt of coal
- population increase
- coal demand increase at 3.4% per year
- 60 years of coal left ~2070
- the impact will be felt well before 2070.

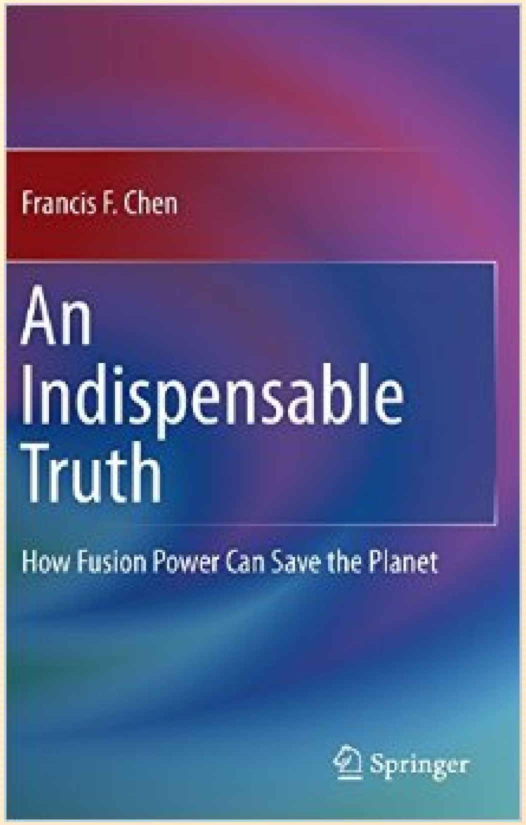
New **materials** are needed to economically capture CO_2.

Fusion Power

What if fusion of deuterium became a reality?

- 33 grams of deuterium in every ton of ocean water
- 1 gram of deuterium via fusion yields 100,000 kWh
- 230 million tons of ocean water per person

- For a population of 60 billion (not six billion)
- For one million years
- 30,000 kWh/day/person



It is a worthwhile gamble to continue to pursue harnessing nuclear fusion for energy.

Today, fusion research has become a **materials** problem!

What structural materials are sufficiently durable to sustain damage from high energy neutrons for an acceptable lifetime?

Fluctuation and Storage

Energy supply from renewable sources fluctuates on a daily and yearly basis

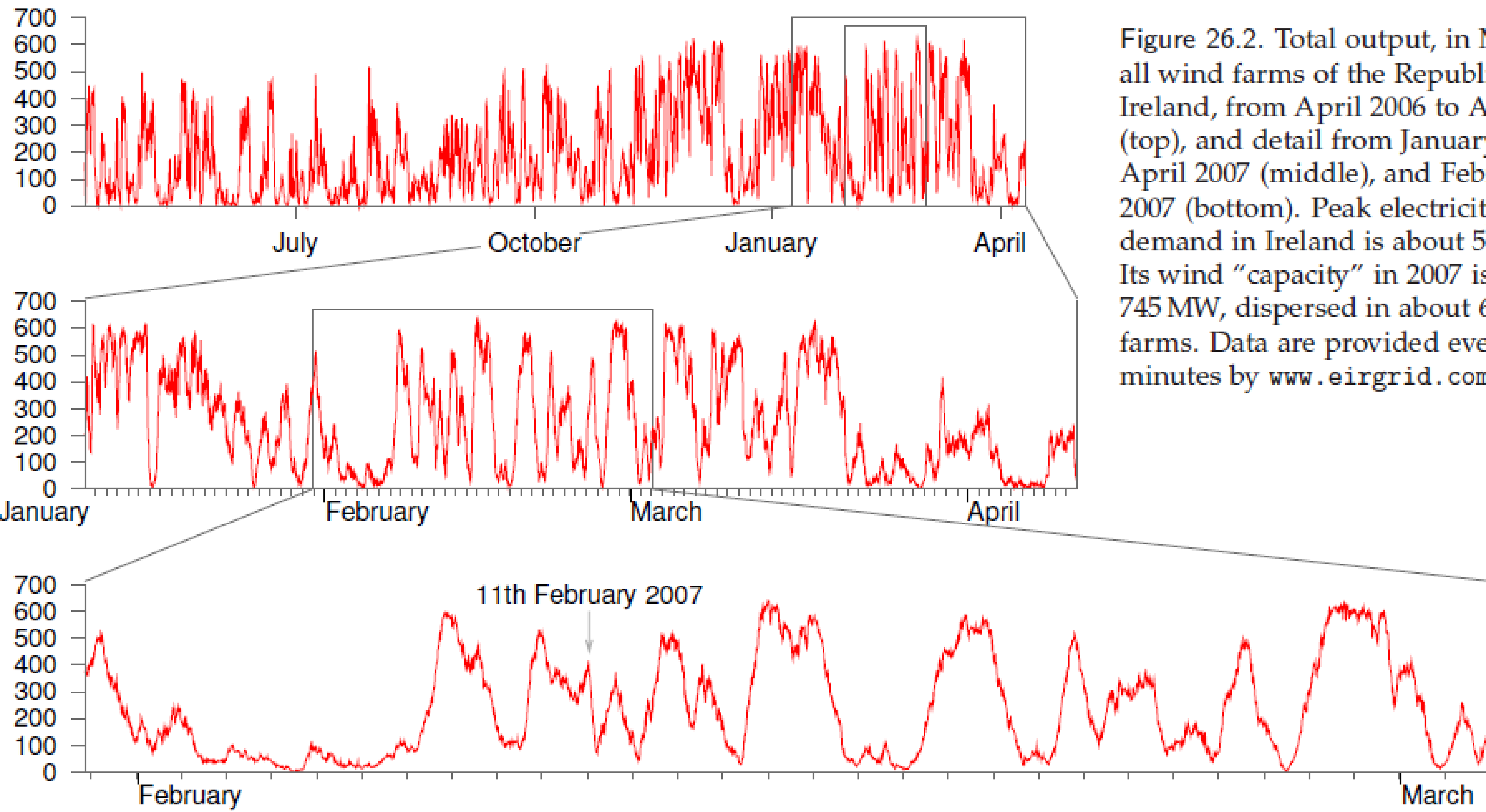


Figure 26.2. Total output, in MW, of all wind farms of the Republic of Ireland, from April 2006 to April 2007 (top), and detail from January 2007 to April 2007 (middle), and February 2007 (bottom). Peak electricity demand in Ireland is about 5000 MW. Its wind "capacity" in 2007 is 745 MW, dispersed in about 60 wind farms. Data are provided every 15 minutes by www.eirgrid.com.

We need national-sized storage strategies.

Fluctuation and Storage

- Network of electric vehicles (Vehicle to Grid) Technology

Vehicle-to-grid (**V2G**) describes a system in which plug-in electric vehicles, such as electric cars (BEVs) and plug-in hybrids (PHEVs), communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate.[1][2]
Vehicle-to-grid can be used with such *gridable* vehicles, that is, plug-in electric vehicles (BEVs and PHEVs), with grid capacity. Since most vehicles are parked an average of 95 percent of the time, their batteries could be used to let electricity flow from the car to the power lines and back, with a value to the utilities of up to $4,000 per year per car.[3]

A major component of the vehicle-to-grid storage system is the availability of low cost, high performance electric batteries. This is a **materials** problems.

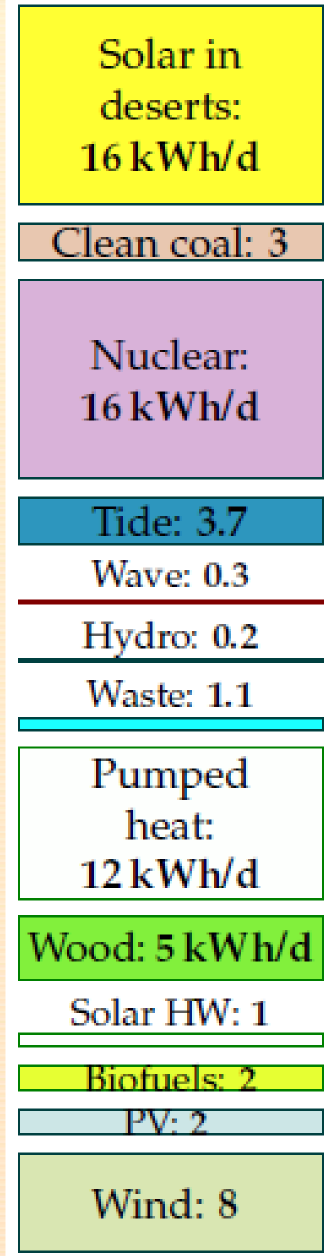
http://en.wikipedia.org/wiki/Vehicle-to-grid

Putting Costs in Perspective

Plan M: the Middle plan

Installation cost per kWh/day/person.

	cost (billion pounds)	power kWh/d/p	cost/power (billion pounds/kWh/d/p)
onshore wind	27	4.2	6.428571
offshore wind	36	3.5	10.28571
photovoltaic farms	190	2	95
solar hot water	72	1	72
waste incinerators	8.5	1.1	7.727273
heat pumps	60	12	5
wave farms	6	0.3	20
tidal barrage	15	0.8	18.75
tidal lagoons	2.6	0.7	3.714286
tidal farm	21	2.2	9.545455
nuclear power	60	16	3.75
clean coal	16	3	5.333333
concentrating solar power in deserts	340	16	21.25



Putting Costs in Perspective

Other things that cost a billion

$46 billion/year – US war on drugs
$700 billion/year – US expenditure on foreign oil
$120 billion/year – US wars in Iraq and Afghanistan
$40 billion/year – US federal highway maintenance
£10 billion/year – UK spent on food that is not eaten
$40 billion/year – Exxon profits (2006)

The global cost of averting dangerous climate change (if we act now) is $440 billion/year

£ 0.012 billion/per year: UK government investment in renewable energy research and development

There is money out there.
We spend it on short-sighted endeavors.

What to do now?

Carbon Pollution
The price of carbon dioxide must be set sufficiently high that people stop burning coal without capture.

Energy Supply
We cannot rely on the free market to drive energy sustainability.
The free market makes short-term decisions for short-term investments.
We need government legislation and green taxes.

Greening the tax system
It is cheaper to buy a new microwave or dvd player than it is to have the old one repaired. In part because labor is taxed higher than material goods. If the tax on goods was higher, the option of repairing a device would be more economically attractive.

Investment in Research and Development
Energy technologies take decades to develop. An increase in research money is needed immediately.

What to do now?

Simple action	possible saving
Put on a woolly jumper and turn down your heating's thermostat (to 15 or 17 °C, say). Put individual thermostats on all radiators. Make sure the heating's off when no-one's at home. Do the same at work.	20 kWh/d
Read all your meters (gas, electricity, water) every week, and identify easy changes to reduce consumption (e.g., switching things off). Compare competitively with a friend. Read the meters at your place of work too, creating a perpetual live energy audit.	4 kWh/d
Stop flying.	35 kWh/d
Drive less, drive more slowly, drive more gently, car-pool, use an electric car, join a car club, cycle, walk, use trains and buses.	20 kWh/d
Keep using old gadgets (e.g. computers); don't replace them early.	4 kWh/d
Change lights to fluorescent or LED.	4 kWh/d
Don't buy clutter. Avoid packaging.	20 kWh/d
Eat vegetarian, six days out of seven.	10 kWh/d

32 Saying yes

Because Britain currently gets 90% of its energy from fossil fuels, it's no surprise that getting off fossil fuels requires big, big changes – a total change in the transport fleet; a complete change of most building heating systems; and a 10- or 20-fold increase in green power.

Given the general tendency of the public to say "no" to wind farms, "no" to nuclear power, "no" to tidal barrages – "no" to anything other than fossil fuel power systems – I am worried that we won't actually get off fossil fuels when we need to. Instead, we'll settle for half-measures: slightly-more-efficient fossil-fuel power stations, cars, and home heating systems; a fig-leaf of a carbon trading system; a sprinkling of wind turbines; an inadequate number of nuclear power stations.

We need to choose a plan that adds up. It *is* possible to make a plan that adds up, but it's not going to be easy.

We need to stop saying no and start saying yes. We need to stop the Punch and Judy show and get building.

If you would like an honest, realistic energy policy that adds up, please tell all your political representatives and prospective political candidates.