Can we ever get to a zero-emission world?

iSEE Congress 2016

UIUC, 09/12/16

Steven E. Koonin, PhD
Founding Director, NYU’s Center for Urban Science and Progress (CUSP)
Professor of Information, Operations & Management Sciences, NYU Stern School of Business
Professor of Civil and Urban Engineering, NYU Tandon School of Engineering
Professor of Physics, NYU Faculty of Arts and Sciences
Climate / Energy is a complex and nuanced subject

Science of Natural Systems

Climate science
• How has the climate changed?
• Why does it change? Role of human influences (GHGs, Aerosols)?
• How will it change in the future?

Ecosystem impacts
• Temperature, extreme weather, sea level rise, migration of species, ocean acidification

Societal impacts (negative and positive)
• Agriculture, migration, disease, flood, ...

Required output: understanding, confident projections (models) over decades

Challenges: incomplete observations; small changes in a complex chaotic system;

Certainties, uncertainties

Societal Response

Possible Responses
1. Adapt
2. Reduce GHG emissions
   – Reduce energy demand, emissions-lite supply
   – Technology, economics, behavior, perceptions, politics
3. Geoengineer

Considerations
• Efficacy (time, scale), costs (direct and opportunity), collateral benefits, unintended consequences, public acceptability

Values
• Environment vs development, intergenerational/international equity, risk tolerance
Climate / Energy is a complex and nuanced subject

Science of Natural Systems

Climate science
- How has the climate changed?
- Why does it change? Role of human influences (GHGs, Aerosols)?
- How will it change in the future?

Ecosystem impacts
- Temperature, extreme weather, sea level rise, migration of species, ocean acidification

Societal impacts (negative and positive)
- Agriculture, migration, disease, flood, ...

Required output: understanding, confident projections (models) over decades

Challenges: incomplete observations; small changes in a complex chaotic system;

Societal Response

Possible Responses
1. Adapt
2. Reduce GHG emissions
   - Reduce energy demand, emissions-lite supply
   - Technology, economics, behavior, perceptions, politics
3. Geoengineer

Considerations
- Efficacy (time, scale), costs (direct and opportunity), collateral benefits, unintended consequences, public acceptability

Values
- Environment vs development, intergenerational/international equity, risk tolerance
Half of the CO$_2$ we emit stays in the atmosphere for centuries.
Cumulative global CO$_2$ emissions
The long CO$_2$ lifetime is highly problematic.
Science dimensions of reducing human influences

RCPs = UN IPCC emissions/concentration scenarios

Human influence

Influence at 2100
Severe emission constraints merely to stabilize human influences at “safe” levels

NO oil, NO gas, NO coal post-2075 (absent sequestration or biological offsets)

What are the socio-technical pathways /barriers to that goal?
Effect of the COP21 INDCs*
*Intended Nationally Determined Contributions

Paris agreement: has 5-year reviews with self-reporting; non-binding, no enforcement
Global contexts to 2050

• Demographic
  – Growing population (7.3B to ~9.7B)
  – “Older” Developed World, “Younger” Developing World
  – Urbanization (50M per year; 50% → 70% urban)

• Economic
  – Development of Most Of the World
  – Growing demand for resources (energy demand + 50-60%)
  – Leveling of the playing field (US out-of-wack by factor of 4)
Energy Use vs. GDP, both per capita (1980-2010)

Source: EIA
Global contexts to 2050

• Demographic
  – Growing population (7.3B to ~9.7B)
  – “Older” Developed World, “Younger” Developing World
  – Urbanization (50M per year; 50% to 70% urban)

• Economic
  – Development of MOW
  – Growing demand for resources (energy demand + 50-60%)
  – Leveling of the playing field (US out-of-wack by factor of 4)

• Energy
  – Fossil fuels are most common (80%), most reliable, cheapest form of energy
  – They won’t be “running out” for a long time
Global context – energy demand is rising
The total recoverable oil-resource base is estimated at 9 trillion barrels (including 2.5 trillion barrel of GTL/CTL) of which we have so far produced 1.1 Tb
Global contexts to 2050

- **Demographic**
  - Growing population (7.3B to ~9.7B)
  - “Older” Developed World, “Younger” Developing World
  - Urbanization (50M per year; 50% to 70% urban)

- **Economic**
  - Development of MOW
  - Growing demand for resources (energy demand + 50-60%)
  - Leveling of the playing field (US out-of-wack by factor of 4)

- **Energy**
  - Fossil fuels are most common (80%), most reliable, cheapest form of energy
  - They won’t be “running out” for a long time

- **Environmental**
  - Growing environmental impacts (“The only humans who don’t pollute …”)
  - Push to reduce human influences on climate (GHG emissions)

- **Technology progress**
  - informatics, robotics, materials/manufacturing, biological

- **Greater regulation, globalization of people, goods, ideas, capital**
Energy

• There is plenty, but GHGs

• The challenges are severe

• It will change slowly

• In a NO fossil-fuel world (NO coal, oil, gas)
  – Efficiency in transport, stationary
  – Decarbonize electricity
    • wind/solar (intermittency, cost)
    • Nuclear (waste, scale)
    • CCS (cost, integrity)

  – Decarbonize transport (electrify LDVs, vehicles, biofuels/hydrogen for HDVs)

  – What to do about space and process heat?
  – Nuclear waste storage, seismic hazard assessment, U/Th resources
  – Weather correlations for wind/solar
  – Geothermal (deep, resource, drilling, …)
  – New resource businesses (rare earths, but earth abundant requiring)

  – Severe cutback in geosciences research, demand for students

US 2014 ~ 18 t
Global Anthropogenic GHG Emissions by Sector 2005

- Energy: 64.5%
- Electricity and Heat: 28%
- Transportation: 12.20%
- Other Fuel Combustion: 8.50%
- Manufacturing and Construction: 11.80%
- Fugitive Emissions: 4%
- Agriculture: 13.80%
- Land-Use Change and Forestry: 12.20%
- Industrial Processes: 4.30%
- Waste: 3.20%
- International Bunkers: 2.10%
Projecting energy is perilous, but there are some givens

- A zero-emissions world doesn’t violate physical laws
  - But it likely violates economic and political laws
- Cost, scale, and carbon constraint are the most important (but not the only) considerations
  - e.g., low tolerance for electricity outages
- Energy system will change slowly
  - Large capital investments, long lifetimes, commodities produced by private sector, interoperability
- It’s a local discussion
  - Resource endowment, existing infrastructure, climate, mix of activities

What works in NYC won’t work in Niger
Evolution of the US energy supply

U.S. Primary Energy Consumption Estimates by Source, 1850-2010

US Wind Capacity 2015 – 69 GW; 1999- 2.5 GW
US Wind Generation – 2014 - ~ 5%
US Solar Capacity 2014 – 22.7 GW
US Solar Generation 2015– 0.6%

Source: U.S. Energy Information Administration Annual Energy Review, Tables 1.3, 10.1, and E1
Annual NYC energy consumption

\[ \text{PJ} = 10^{15} \text{ J} \text{ (US annual is 100,000 PJ)} \]

- **Transport (total = 158 PJ)**
  - LDVs are 125 PJ (gasoline, ethanol)
  - HDVs are 23 PJ (21.6 diesel, 1.4 CNG in buses/trucks/rail)
    - 30% of buses in 2013 were diesel hybrids
  - Subway + commuter rail = 9.9 PJ electricity

- **Stationary Electricity = 181 PJ**
  - 5.8 GW avg, 13 GW peak
  - Street + traffic lights = 0.8 PJ

- **Heating (oil, gas, steam for water/space) = 304 PJ**
Decarbonization strategy

- Cost effective efficiency is good for all seasons, and becomes increasingly feasible with technology improvements, but ...
  - Lack of capital funds; principal-agent disconnects; rebound

- Decarbonize transport
  - Light-duty vehicles (LDVs)
  - Heavy-duty vehicles (HDVs)

- Decarbonize electricity (baseload, peak)

- Decarbonize heat (space, water, industry)
Decarbonizing transport

• Vehicle efficiency through mass reduction, autonomy, connectivity
• Fuel choices are electricity, cellulosic biofuels, hydrogen
• LDVs will likely go electric
  – Gradual transition from ICE to HEV to PHEV to BEV
    • stock of 240 M; 14M sold /yr; 120k PHEV + BEV sold in 2014
  – Batteries are (marginally) good enough now; Charging infrastructure partially in place
  – Small increase in generation required, mostly at night
    • ICE: 30 mpg = ¼ mile/MJ; BEV: 4 miles/kWh; all NYC LDVs require 31 PJ of electricity, or +16%
Projected Reductions in the Fuel Consumption of Large Cars and Small Trucks through Technology

Source: National Research Council with data adapted by a National Petroleum Council study committee; joint study by the Environmental Protection Agency and National Highway Traffic Safety Administration (EPA/NHTSA).
Estimated Supply Impacts of Meeting 50% of Today’s LDV Demand by Various Alternative Fuels
Relation of Fuel Prices to Crude Oil Price, 2000–2011

Data from EIA and Nebraska Energy Office
Decarbonizing transport

- Vehicle efficiency through mass reduction, autonomy, connectivity
- Vehicle choices are electricity, cellulosic biofuels, hydrogen
- LDVs will likely go electric
  - Gradual transition from ICE to HEV to PHEV to BEV
    - stock of 240 M; 14M sold /yr; 120k PHEV + BEV sold in 2014
    - Batteries are (marginally) good enough now; Charging infrastructure partially in place
    - Small increase in generation required, mostly at night
      - ICE: 30 mpg = ¼ mile/MJ; BEV: 4 miles/kWh; all NYC LDVs require 31 PJ of electricity, or +16%
- HDVs could go biodiesel, electricity, hydrogen
  - Fleet nature makes fueling infrastructure less of an issue
Biomass can provide significant carbon

![Graph showing annual US carbon emissions in Mt C for different sectors: Fuel, Fossil, Agriculture, and Biomass. The biomass bar is labeled as 15% of Transportation Fuels and the biomass potential bar.](image)
Decarbonizing transport

• Vehicle efficiency through mass reduction, autonomy, connectivity
• Fuel choices are electricity, cellulosic biofuels, hydrogen
• LDVs will likely go electric
  – Gradual transition from ICE to HEV to PHEV to BEV
    • stock of 240 M; 14M sold /yr; 120k PHEV + BEV sold in 2014
  – Batteries are (marginally) good enough now; Charging infrastructure partially in place
  – Small increase in generation required, mostly at night
    • ICE: 30 mpg = ¾ mile/MJ; BEV: 4 miles/kWh; all NYC LDVs require 31 PJ of electricity, or +16%
• HDVs could go biodiesel, electricity, hydrogen
  – Fleet nature makes fueling infrastructure less of an issue
• Some consequences of doing this nationally or globally
  – Low oil demand creates lower prices, extending decarbonization transition
  – Higher vehicle costs, lower fuel costs
  – Stability of transport fuel costs
  – Is there enough biomass for biodiesel with growing global transport?
  – Oil reserve assets become essentially worthless
Decarbonizing electricity

• It’s much more than cost of electricity and emissions
  – Intermittency, dispatchability, land, water, local environment, ...
Power demand is highly variable and there’s no practical storage.
Baseload Power Systems Cost Comparison

Cost of Electricity (2010$/MWh)

Fuel Cost Assumptions:
- Coal - $1.64/MMBtu
- Nuclear - $9.7/MWh*
- NG - $4.8/MMBtu

Capacity Factor Assumptions:
- PC Today - 85%
- IGCC Today - 80%
- NGCC - 85%
- Nuclear - 90%

Sources:
- NETL 2nd Gen - Multiple NETL technology pathway study reports
Additions to U.S. Electricity Generation Capacity, 1985–2035 (total US capacity ~ 1.1 TW, so 100-year turnover time)

Source: EIA
Decarbonizing electricity

• It’s much more than cost of electricity and emissions
  – Intermittency, dispatchability, land, water, local environment, ...
• Methane halves CO$_2$ relative to coal, but likely climate neutral
Cheap gas is changing the US energy system

- On 9/6/16, gas was $2.88
- Gas <$8 beats fission
- Gas <$~$3 beats renewables (without backup costs)
- Cheap gas in the US has brought back manufacturing, converted gas imports to exports
- Bankruptcies in coal (Peabody, Arch, ...), renewables (Abengoa, SunEdison, ...)

A “gas world” has lower CO$_2$, but CH$_4$ leaks and loss of aerosol cooling result in essentially no reduction in radiative forcing.
Decarbonizing electricity

• It’s much more than cost of electricity and emissions
  – Intermittency, dispatchability, land, water, local environment, ...
• Methane halves CO₂ relative to coal, but likely climate neutral
• Baseload
  – Nuclear
    • U resource; Repository integrity; Seismic hazard; Water availability? Acceptance? SMRs?
  – Carbon Capture and Storage fueled by coal/gas
    • Costs? Reservoir integrity (<0.3% /yr leak rate for hundreds of years)
  – Biomass
    • If we use it for power, can’t use if for fuel; BioCCS net carbon negative
• Renewables
  – Hydro essentially tapped out nationally
  – Solar/wind have limited potential (20%-30% of generation)
    • Weather stats (variability, covariability)
    • Land use; local environmental impacts
    • Need massive storage and extra generation in the absence of fossil backup
    • Transmission infrastructure; frequency regulation
  – Geothermal
    • Deep resource characterization / access; cost?
  – Storage a key enabling technology
Wind/solar electricity is currently more costly

Solar costs dropping rapidly, but deployment still driven by
- Financial incentives
- Tax credits
- Feed-in tariffs
- Loan guarantees
- Portfolio standards

Fossil backup requirement has unintended GHG consequences
Additional transmission to make wind viable
Solar takes land

• Long Island Solar Farm
  – 200 acres (81 ha) for 5 MW average (37 MW peak)
• Indian Point 2 GW average power
  – Equivalent to 32000 ha, or a 5.5 mile circle
  – Ecological, logistical impacts?
  – Need 3 of these for NYC baseload
Decarbonizing heat

• Residential
  – Solar for hot water, space heating by building design
  – Carbon-free electricity to heat is inefficient
    • NYC electricity goes to + 1.5X to 15 GW average!
  – Heat pumps are inappropriate in cold climate, urban areas
  – Carbon-free district heating in urban areas
    • SMRs, biomass

• Industrial
  – Biomass?
  – ????

Source: DOE Buildings Energy Data Book
Building Energy Efficiency

Source Energy Use Intensity, Office Buildings, New York City
Source: Local Law 84 Disclosure Data, Kontokosta 2013

N = 1,150
Mean = 219.5
s.d. = 101.7

Source Energy Use Intensity, Multi-Family Buildings, New York City
Source: Local Law 84 Energy Disclosure Data, Kontokosta 2013

N = 7,505
Mean = 137.9
s.d. = 46.8

Kontokosta 2013
And in the rest of the world ...

Energy is central to nearly every major challenge, and opportunity the world faces today. Be it jobs, security, climate change, food production or increasing incomes, access to sustainable energy for all is essential for strengthening economies, protecting ecosystems and achieving equity.

Worldwide, about 1.2 billion people have no access to electricity and the development benefits it brings, and 1 billion more have access only to unreliable electricity networks. Nearly 3 billion people rely on traditional biomass (such as wood and charcoal) for cooking and heating.

- UN Foundation
Informal poll

With which of the following do you agree?

- CO$_2$ levels will exceed **450** ppm during the 21$^{st}$ century
- CO$_2$ levels will exceed **550** ppm during the 21$^{st}$ century
- CO$_2$ levels will exceed **650** ppm during the 21$^{st}$ century
- CO$_2$ levels will exceed **750** ppm during the 21$^{st}$ century

Mauna Loa CO$_2$ in August 2016 = 402.25 ppm
Koonin’s “not so fast” strategy

- Clarify the policy discussion and the science that underpins it
  - Sustain and bolster climate observations
  - A scientific “red team” exercise to accurately portray uncertainties
  - Reframe the discussion to “values”; don’t use alleged certainty as a club
Koonin’s “not so fast” strategy

• Clarify the policy discussion and the science that underpins it
  – Sustain and bolster climate observations
  – Reframe the discussion to “values”; don’t use alleged certainty as a club
  – A scientific “red team” exercise to accurately portray uncertainties

• Pursue “easy” emissions reductions
  – Cost-effective efficiencies; Leverage credible side benefits (local environment, energy security)
  – RD&D for low-cost, emissions-free technologies
    • Fission, solar, storage/grid management, biofuels, CCS, fusion, …

• Reduce emissions further if/when
  – the science becomes more certain or
  – a values consensus emerges or
  – zero-emissions technologies become more feasible
Americans’ Level of Worry About National Problems — 2014 Rank Order

Next, I’m going to read a list of problems facing the country. For each one, please tell me if you personally worry about this problem a great deal, a fair amount, only a little, or not at all? First, how much do you personally worry about ... [RANDOM ORDER]?

<table>
<thead>
<tr>
<th>Problem</th>
<th>Great deal %</th>
<th>Fair amount %</th>
<th>A little/not at all %</th>
</tr>
</thead>
<tbody>
<tr>
<td>The economy</td>
<td>59</td>
<td>29</td>
<td>11</td>
</tr>
<tr>
<td>Federal spending and the budget deficit</td>
<td>58</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>The availability and affordability of healthcare</td>
<td>57</td>
<td>20</td>
<td>23</td>
</tr>
<tr>
<td>Unemployment</td>
<td>49</td>
<td>28</td>
<td>23</td>
</tr>
<tr>
<td>The size and power of the federal government</td>
<td>48</td>
<td>20</td>
<td>31</td>
</tr>
<tr>
<td>The Social Security system</td>
<td>46</td>
<td>29</td>
<td>24</td>
</tr>
<tr>
<td>Hunger and homelessness</td>
<td>43</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>Crime and violence</td>
<td>39</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>The possibility of future terrorist attacks in the U.S.</td>
<td>39</td>
<td>24</td>
<td>37</td>
</tr>
<tr>
<td>The availability and affordability of energy</td>
<td>37</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>Drug use</td>
<td>34</td>
<td>29</td>
<td>37</td>
</tr>
<tr>
<td>Illegal immigration</td>
<td>33</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>The quality of the environment</td>
<td>31</td>
<td>35</td>
<td>34</td>
</tr>
<tr>
<td>Climate change</td>
<td>24</td>
<td>25</td>
<td>51</td>
</tr>
<tr>
<td>Race relations</td>
<td>17</td>
<td>26</td>
<td>56</td>
</tr>
</tbody>
</table>

Question asked of a half sample
March 6-9, 2014

GALLUP
Koonin’s “not so fast” strategy

• **Clarify the policy discussion and the science that underpins it**
  – Sustain and bolster climate observations
  – Reframe the discussion to “values”; don’t use alleged certainty as a club
  – A scientific “red team” exercise to accurately portray uncertainties

• **Pursue “easy” emissions reductions**
  – Cost-effective efficiencies; Leverage credible side benefits (local environment, energy security)
  – RD&D for low-cost, emissions-free technologies
    • Fission, solar, storage/grid management, biofuels, CCS, fusion, ...

• **Reduce emissions further if/when**
  – the science become more certain *or*
  – a values consensus emerges *or*
  – zero-emissions technologies become more feasible

• **Pursue adaptation vigorously**
  – It is **effective** (we manage to muddle through)
  – It is **agnostic** (indifferent to natural vs human-caused)
  – It is **proportional** (adapt more if the change is greater)
  – It is **local** (politically palatable; does not require global consensus)
  – It is **autonomous** (it will happen/ is happening on its own)
  – Modes of adaptation (“wedges”)? What are we adapting to?

• **Develop geoengineering as a last-resort option**
  – Research program? Feasibility tests? Governance?
Bottom line thoughts

• It is unlikely that we can get to a zero-emission world (by 2100)
  – Human influences on the climate will continue to grow through this century
  – If human influences are already deteriorating the climate, we’re in for at least another century

• R&D essential to prepare for a contingent future

• Society will adapt to a climate changing under human and natural influences

• It would be good to know if we can have geoengineering options “on the shelf”
COMMENTS/QUESTIONS??
Political climate-speak

The Agreement sets a goal of keeping warming well below 2 degrees Celsius and for the first time agrees to pursue efforts to limit the increase in temperatures to 1.5 degrees Celsius. It also acknowledges that in order to meet that target, countries should aim to peak greenhouse gas emissions as soon as possible. – *White House Fact Sheet on Paris Agreement*

**Implicit assumptions**

1. There is an agreed-upon baseline [± <0.5°C] against which to judge warming
2. GHG emissions are the sole control knob for warming
3. We know how the climate will respond to GHGs to within 25%
4. Warming of 2°C (1.5°C) will be net detrimental
As a result, we see

• “Certainty” statements by political figures and science administrators
  
  – *Kerry:* The science of climate change is leaping out at us like a scene from a 3D movie. It’s warning us; it’s compelling us to act. *And let there be no doubt in anybody’s mind that the science is absolutely certain.* It’s something that we understand with absolute assurance of the veracity of that science.
  
  – *McNutt:* The time for debate has ended.

• Most extreme IPCC scenario morphed by media into “business as usual” to exaggerate impacts

• Alarmist predictions that never materialize and are soon forgotten

• Minimization of uncertainties
  
  – *The IPCC AR5 Summary for Policy Makers is discordant with the scientific report.*
ACTUAL CLIMATE CHANGE PRONOUNCEMENTS by Scientists: A brief recap

1970
WE’LL BE IN AN ICE AGE BY 2000!

1976
GLOBAL COOLING WILL CAUSE A WORLD WAR BY 2000!

1989
GLOBAL WARMING AND RISING SEA LEVELS WILL WIPE ENTIRE NATIONS OFF THE MAP BY 2000!

1990
WE HAVE FIVE TO TEN YEARS TO SAVE THE RAINFORESTS!

1999
THE HIMALAYAN GLACIERS WILL BE GONE IN TEN YEARS!

2000
SNOW WILL SOON BE A THING OF THE PAST!

2007
GLOBAL WARMING WILL CAUSE FEWER HURRICANES!

2008
THE ARCTIC WILL BE ICE-FREE BY 2013!

2012
GLOBAL WARMING WILL CAUSE MORE HURRICANES!

2014
THE SCIENCE IS SETTLED!
"On the one hand, as scientists we are ethically bound to the scientific method, in effect promising to tell the truth, the whole truth, and nothing but - which means that we must include all the doubts, the caveats, the ifs, ands, and buts. On the other hand, we are not just scientists but human beings as well. And like most people we'd like to see the world a better place, which in this context translates into our working to reduce the risk of potentially disastrous climatic change. To do that we need to get some broad-based support, to capture the public's imagination. That, of course, entails getting loads of media coverage. So we have to offer up scary scenarios, make simplified, dramatic statements, and make little mention of any doubts we might have. This 'double ethical bind' we frequently find ourselves in cannot be solved by any formula. Each of us has to decide what the right balance is between being effective and being honest. I hope that means being both."

– S. Schneider, Stanford, 1996
Why a red team? (II)

The central problem of climate science is to ask what you do and say when your data are, by almost any standard, inadequate? If I spend three years analyzing my data, and the only defensible inference is that “the data are inadequate to answer the question,” how do you publish? How do you get your grant renewed? A common answer is to distort the calculation of the uncertainty, or ignore it all together, and proclaim an exciting story that the New York Times will pick up…How many such stories have been withdrawn years later when enough adequate data became available?”
- C. Wunsch, MIT

Lack of transparency is a huge political advantage. It was really, really critical to getting the [ACA] passed. [At least one key provision was a] very clever basic exploitation of the lack of economic understanding of the American voter.
- J. Gruber. MIT
IPCC AR5: *It is extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by [humans]. *The best estimate of the human induced contribution is similar to the observed warming over this period.*
Models fail to produce historical variation

Forcing $\sim 0.4 \text{ W/m}^2$

Forcing $\sim 2.0 \text{ W/m}^2$
Manhattan Battery sea-level record

The Battery, NY  2.77 +/- 0.09 mm/yr

Source: NOAA

Data with the average seasonal cycle removed
Higher 95% confidence interval
Linear mean sea level trend
Lower 95% confidence interval

Meters


Source: NOAA
No increase in tropical cyclone activity
Comments?/Questions?

Small satellites for earth observations:
http://fas.org/irp/agency/dod/jason/smallsats-full.pdf

High Performance Computing for climate models:

Atmospheric Radiation Measurements:
http://fas.org/irp/agency/dod/jason/arm.pdf

Earthshine observations of the global albedo:

Science biofuels editorial:
http://science.sciencemag.org/content/311/5760/435

GHG Treaty Monitoring study:
http://www.osti.gov/scitech/biblio/1033495/

Energy Innovation:
Accelerating the Pace of Energy Change, with A.M. Gopstein, Issues in Science and Technology, Winter 2011

DOE Quadrennial Technology Review:

American Physical Society Climate Statement Review:
http://www.aps.org/policy/statements/climate/index.cfm

WSJ OpEd on climate science uncertainties:
http://www.wsj.com/articles/climate-science-is-not-settled-1411143565

NYT OpEd on achieving a zero-emissions world: