Renewable & Appropriate Energy Laboratory
RAEL

The Science and Policy of Sustainable Energy

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Science Envoy for the U. S. State Department

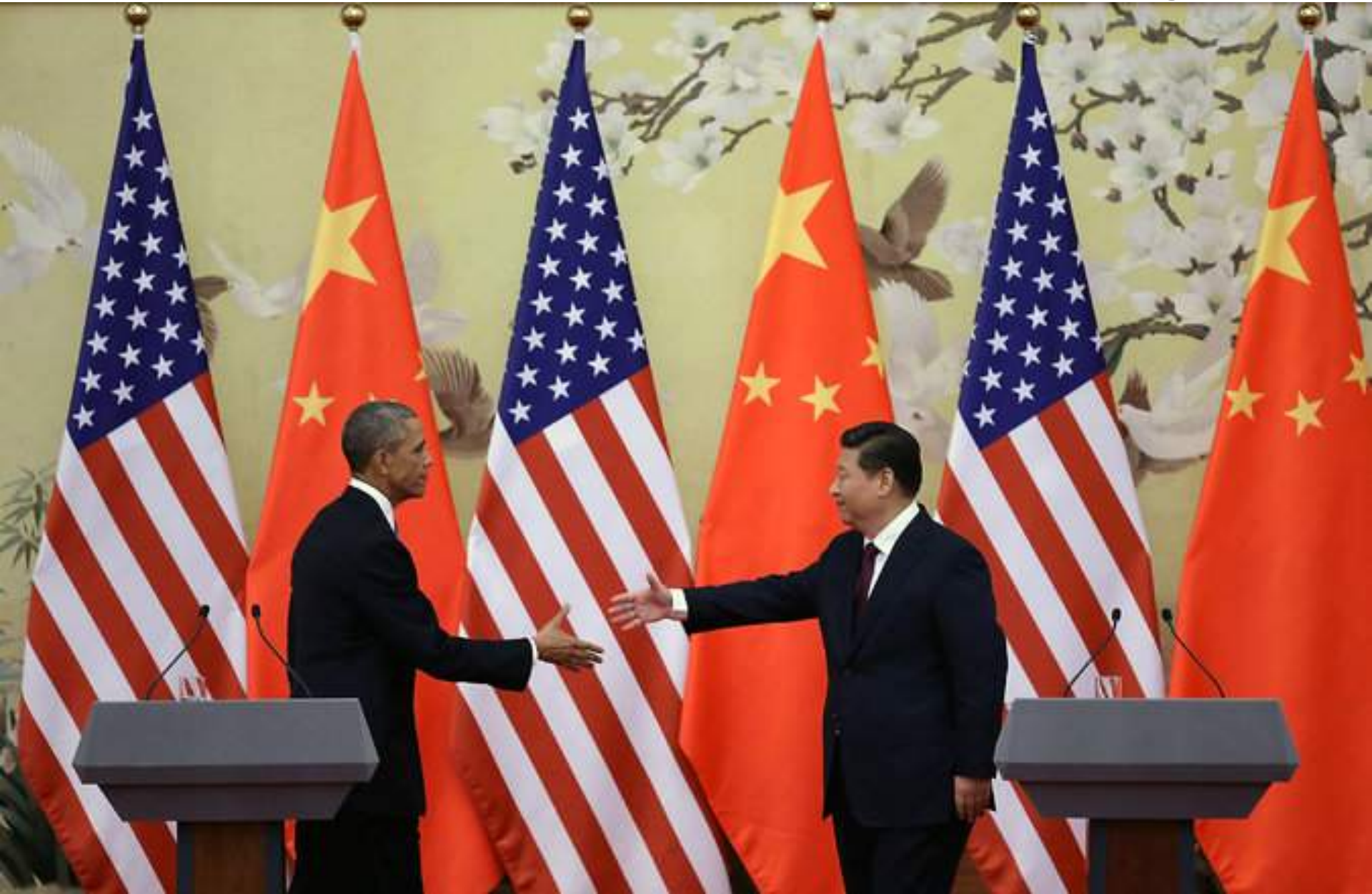
Economic Challenges for Energy, Madrid, Spain - February 15, 2017

Takeaway message:

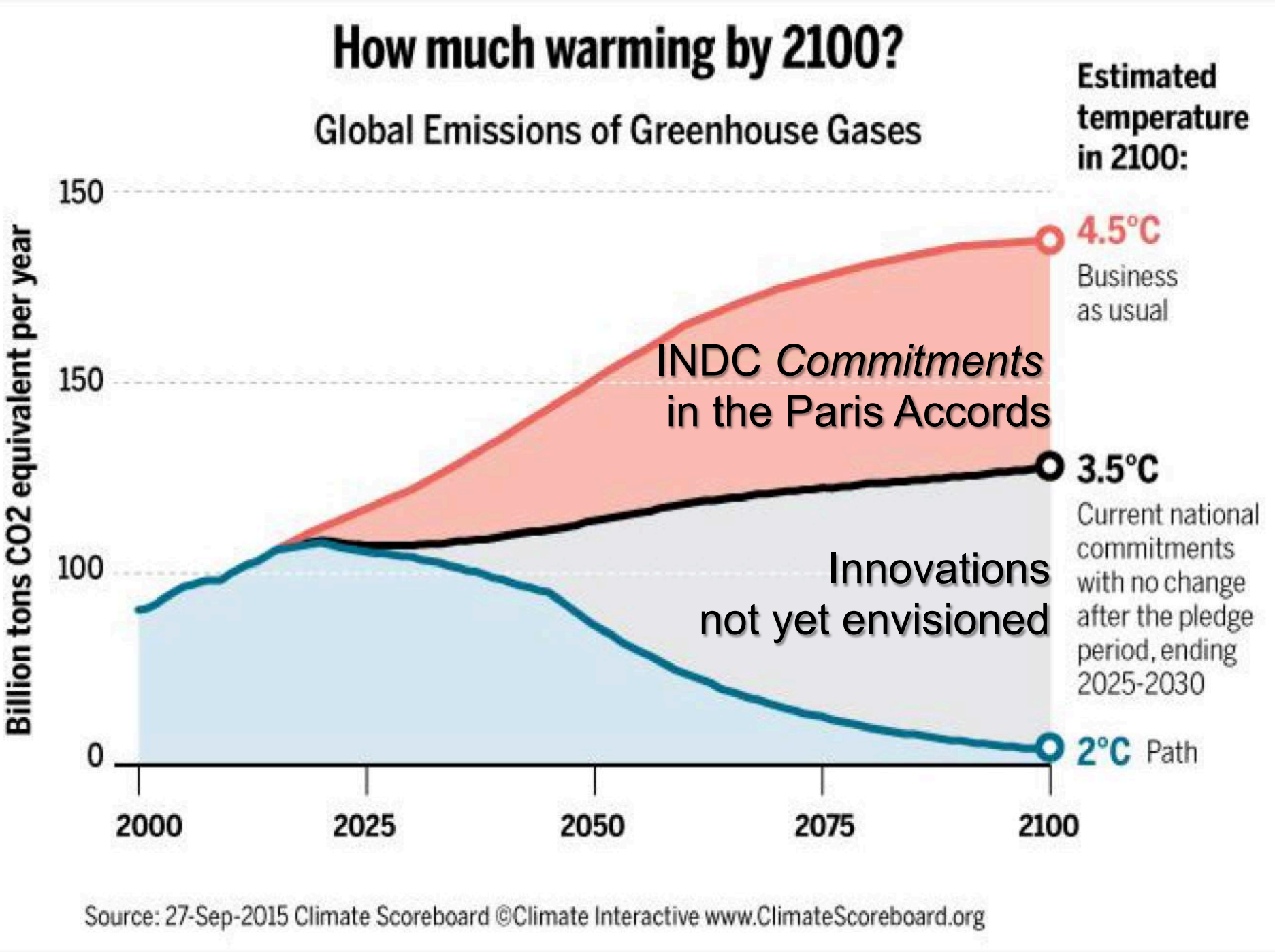
Scientific and technical transformations are critical to enabling a sustainable energy system, but it is the energy-information nexus that provides the 'killer app' for innovation and change

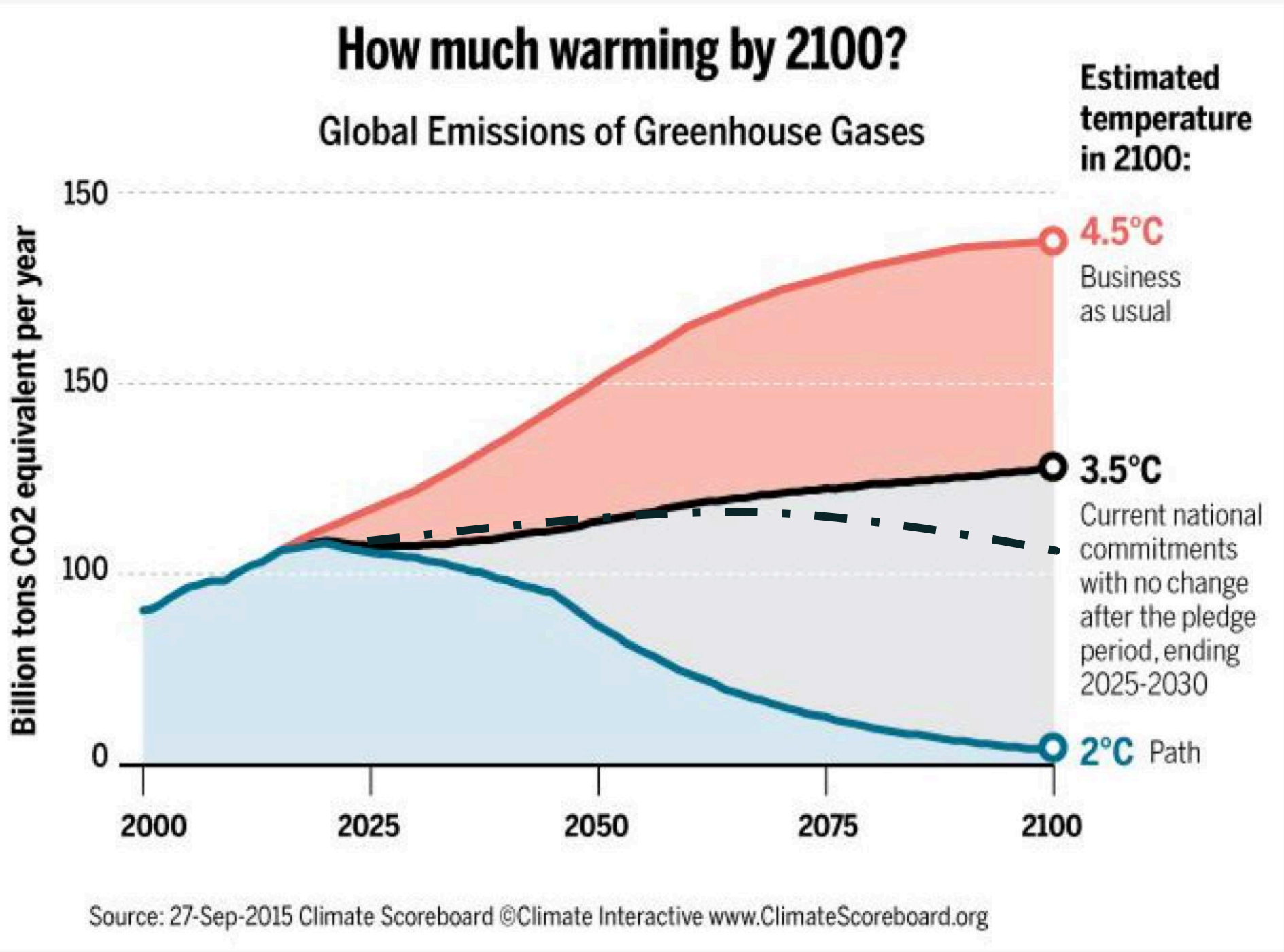
This is true on-grid *and* off-grid in developing nations

A revolution in climate politics
U.S.- China Joint Announcement on Climate Change, 2014




Paris, Franc
PRESIDENT
SECRET


How much warming by 2100?
Global Emissions of Greenhouse Gases
Billion tons CO2 equivalent per year
150
150
100
0
2000
2025
2050
2075
2100
Estimated temperature in 2100:
4.5°C
Business as usual
INDC Commitments in the Paris Accords
3.5°C
Current national commitments with no change after the pledge period, ending 2025-2030
Innovations not yet envisioned
2°C Path
Source: 27-Sep-2015 Climate Scoreboard ©Climate Interactive www.ClimateScoreboard.org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The Journal of Alternative Facts 01 (2017) 01–20

JAF
THE JOURNAL OF
alternative
FACTS

The Journal of Alternative Facts

We Have All the Best Climates, Really, They're Great

Iwas A. Scientistonce *

* and now I have all my research approved by a public relations office

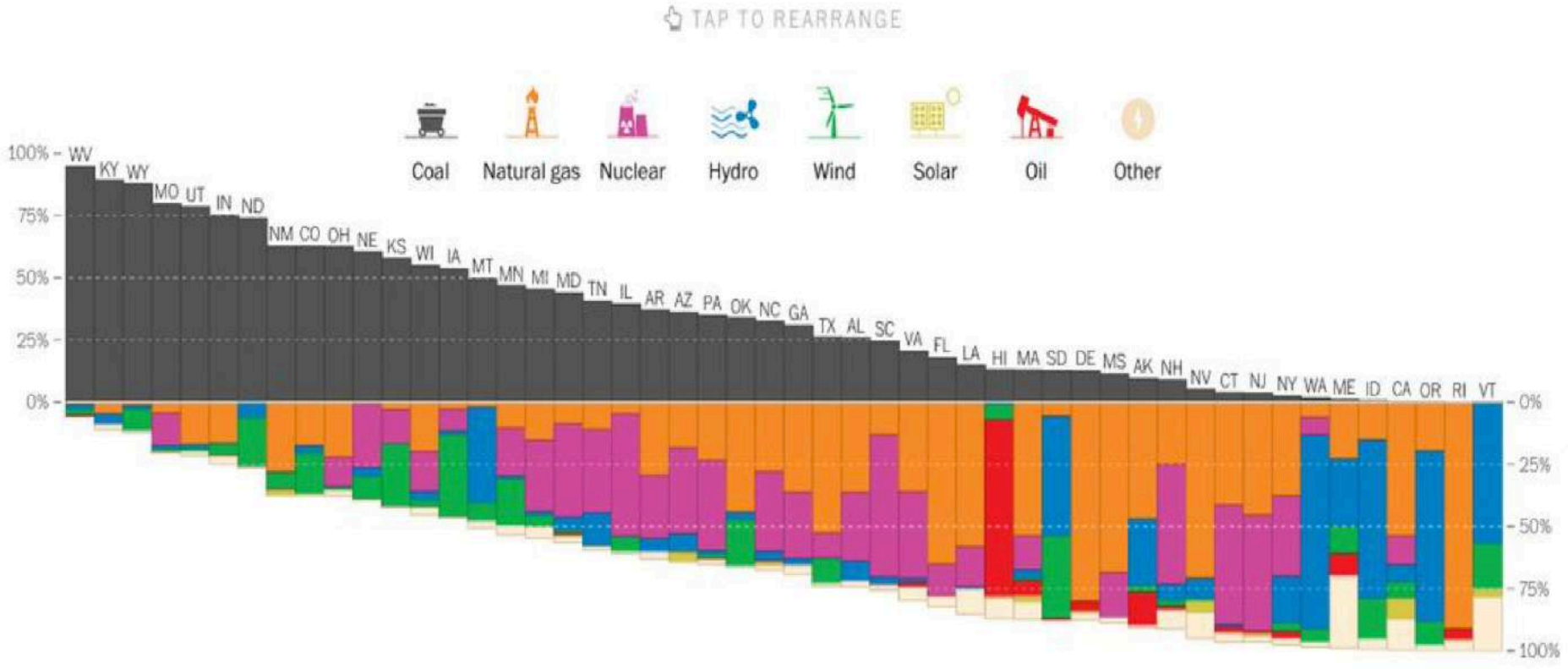
Abstract

The research presented in this paper is really the best research that you will ever see. We have methods, the best methods, and we used them to study climate. As you may already know, the Earth, led by America, has all the best climates. In this paper we refute prior work by out-of-touch scientists who insist that the climate is changing – why would it change, when it's so great already? It is not getting warmer. In fact, our findings show that you were cold at least one day last year. Our (really fantastic) data also reveals that America has all the best CO2 levels, really great levels. In our discussion, we reveal that there is no reason to believe a bunch of scientists who spent all their time learning and studying "facts" instead of being out in the real world making jobs. Our alternative facts definitively prove that scientists are losers. Finally, we had peer reviews, by all the best people, our people, because politicians know the most about science, the very best things about science.

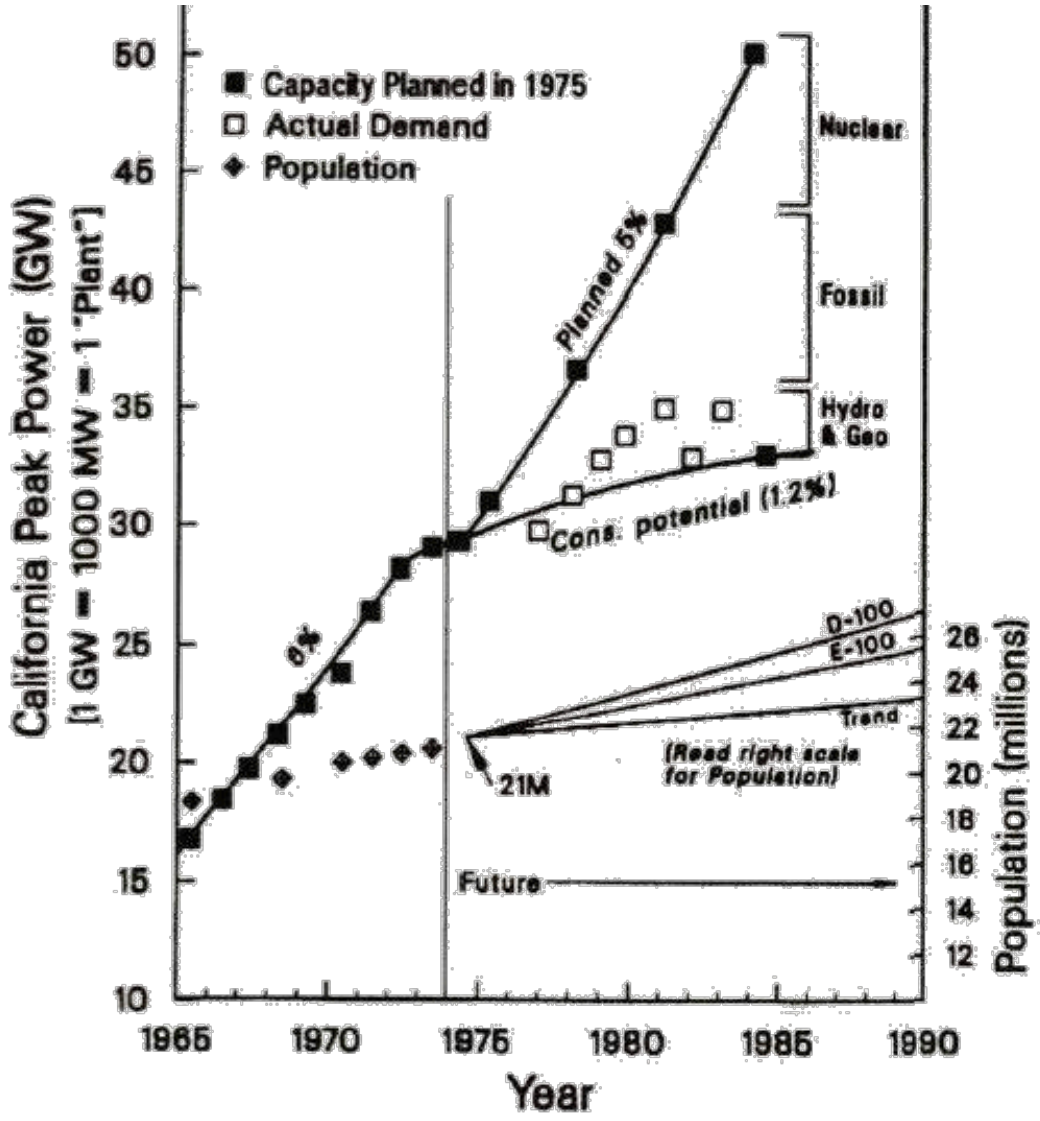
Keywords: climate, "data", "facts", #makeclimategreatagain, "science"

Electricity generation by power source, January to May 2015

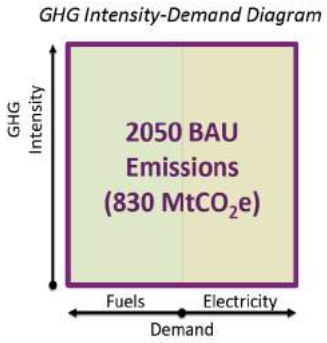
Local electric utilities take advantage of the power sources most accessible to them: coal mines, dammed rivers, new supplies of natural gas or nuclear plants to generate the bulk of the nation's electricity. This shows the source of electricity generation in each state in 2015.



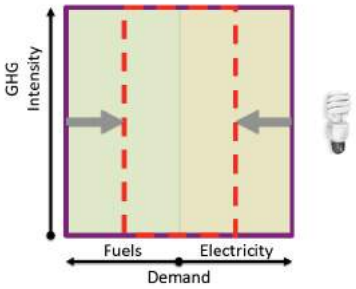
CA Peak Power: Testimony by Goldstein and Rosenfeld (Dec. 1974)



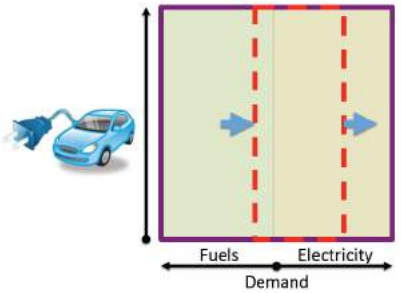
Four Actions to Reduce Emissions



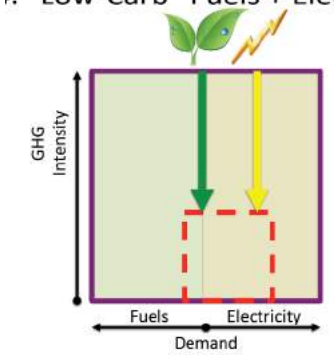
1. Efficiency



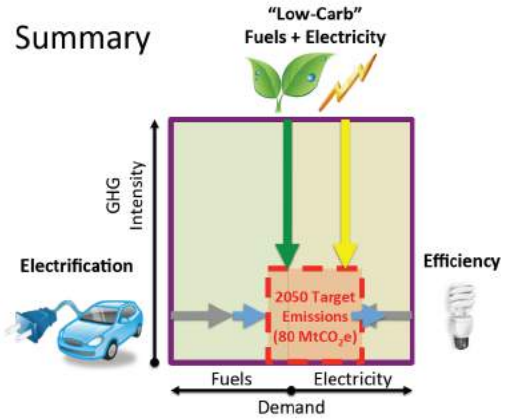
2. Electrification



3. "Low-Carb" Fuels + Electricity

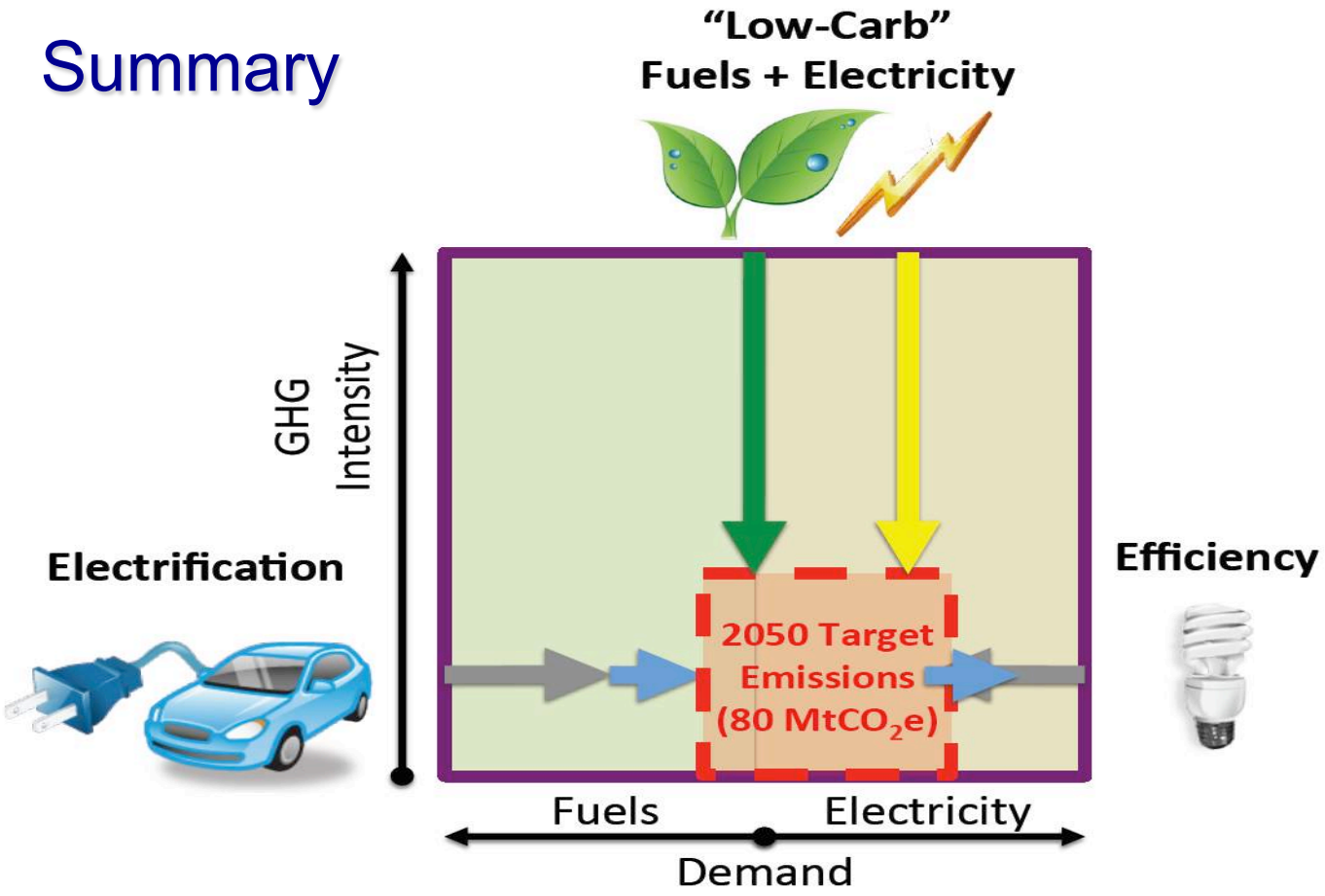


Summary

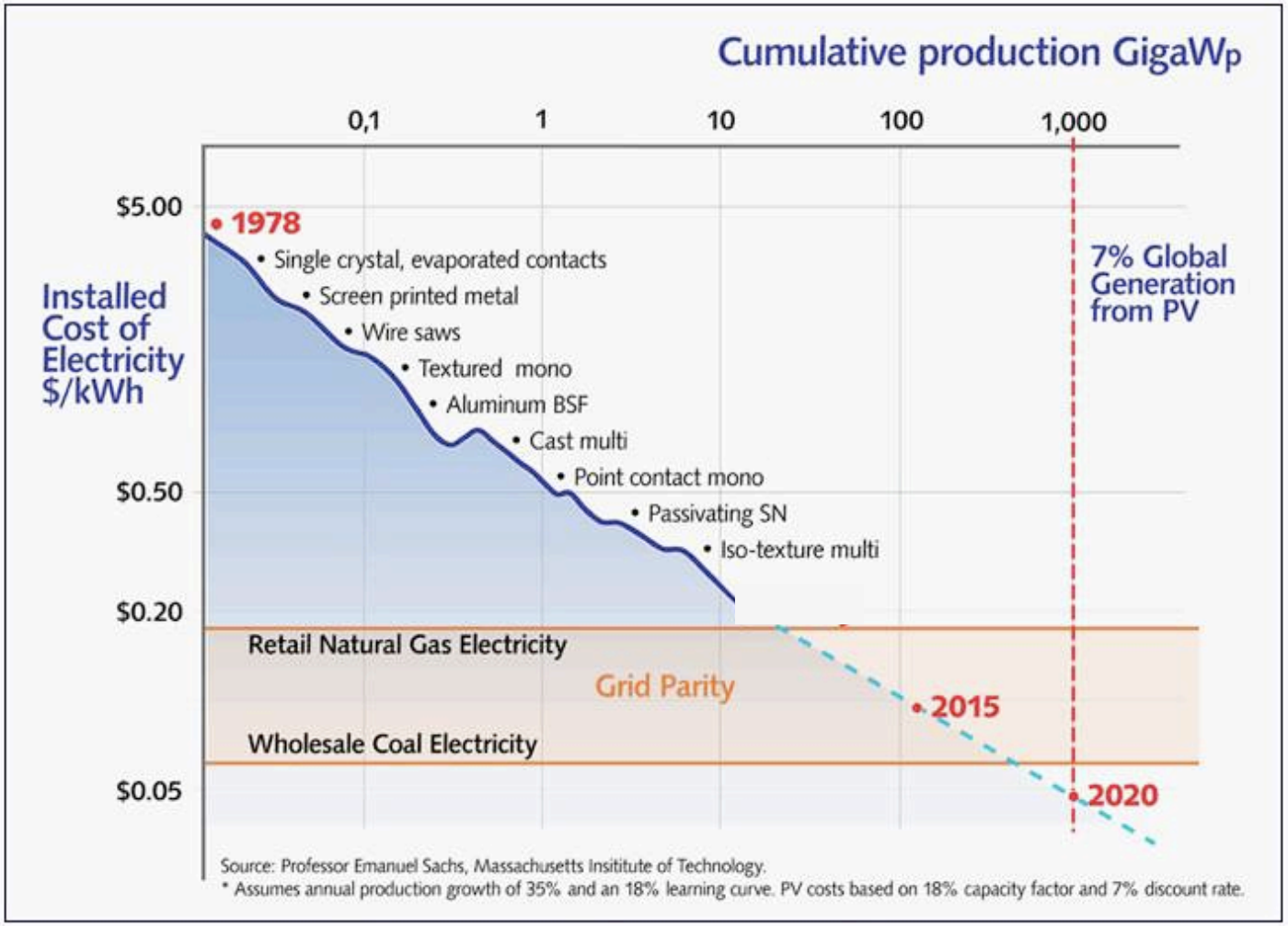


http://rael.berkeley.edu

Summary


"Low-Carb"
Fuels + Electricity
GHG
Intensity
Electrification
Efficiency
2050 Target
Emissions
(80 MtCO2e)
Fuels
Electricity
Demand

Solar cost decreases 10% per year



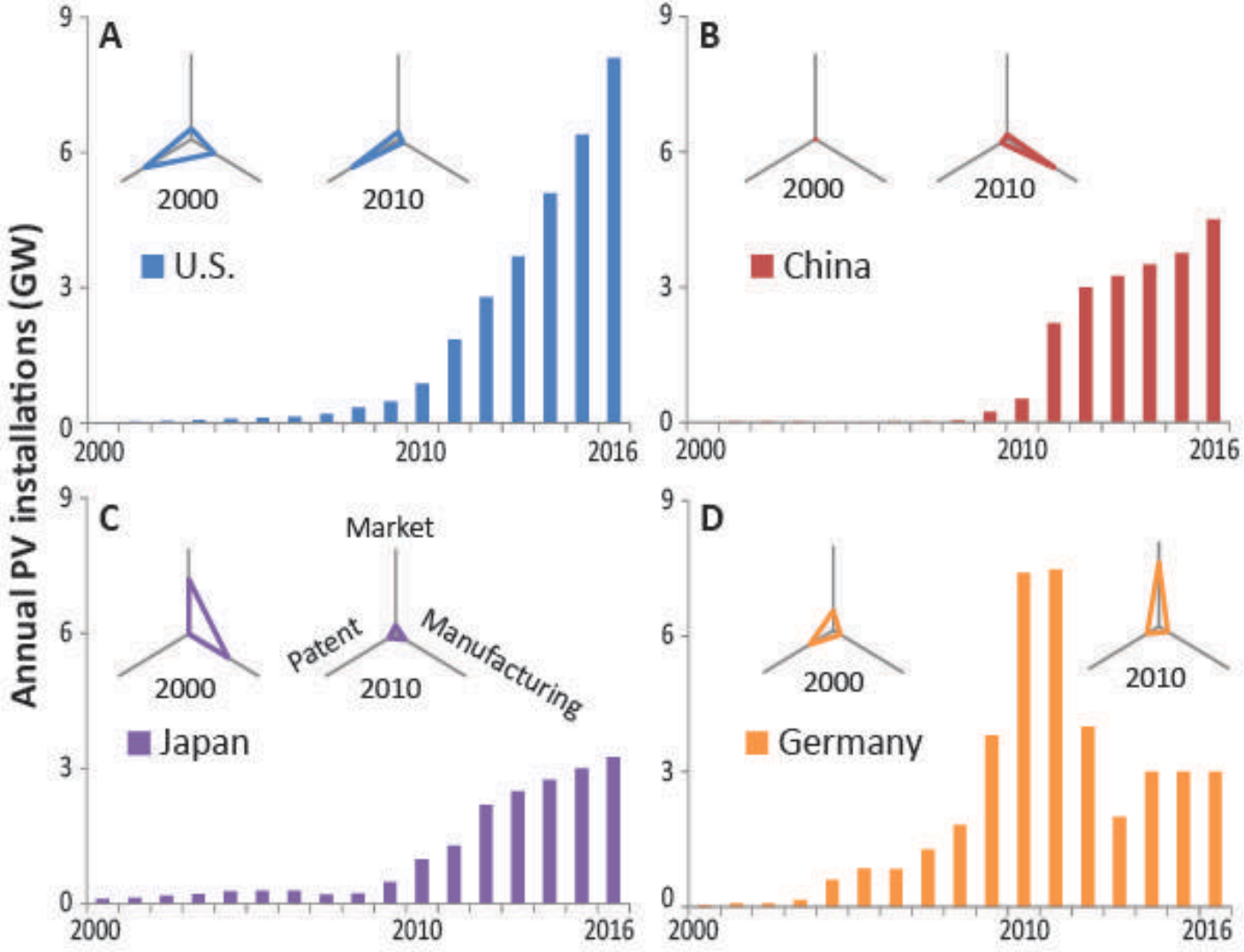
June 2, 2016: Dubai Electricity and Water Authority (DEWA)

800 MW of solar at 2.54 UScents/kWh

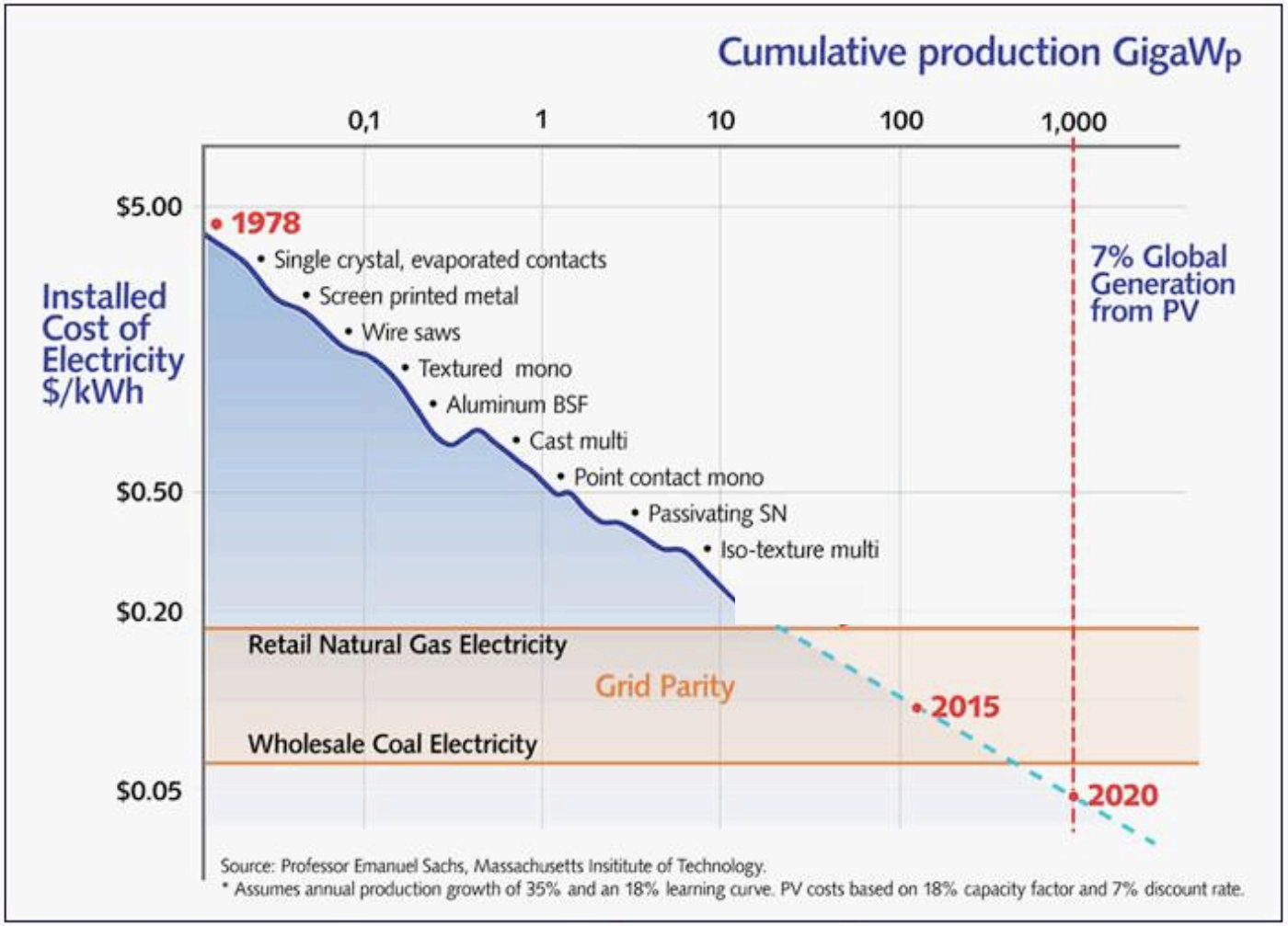
Location: Mohammed bin Rashid Al Maktoum Solar Park

Dubai's goal: lowest carbon footprint of any city in the world

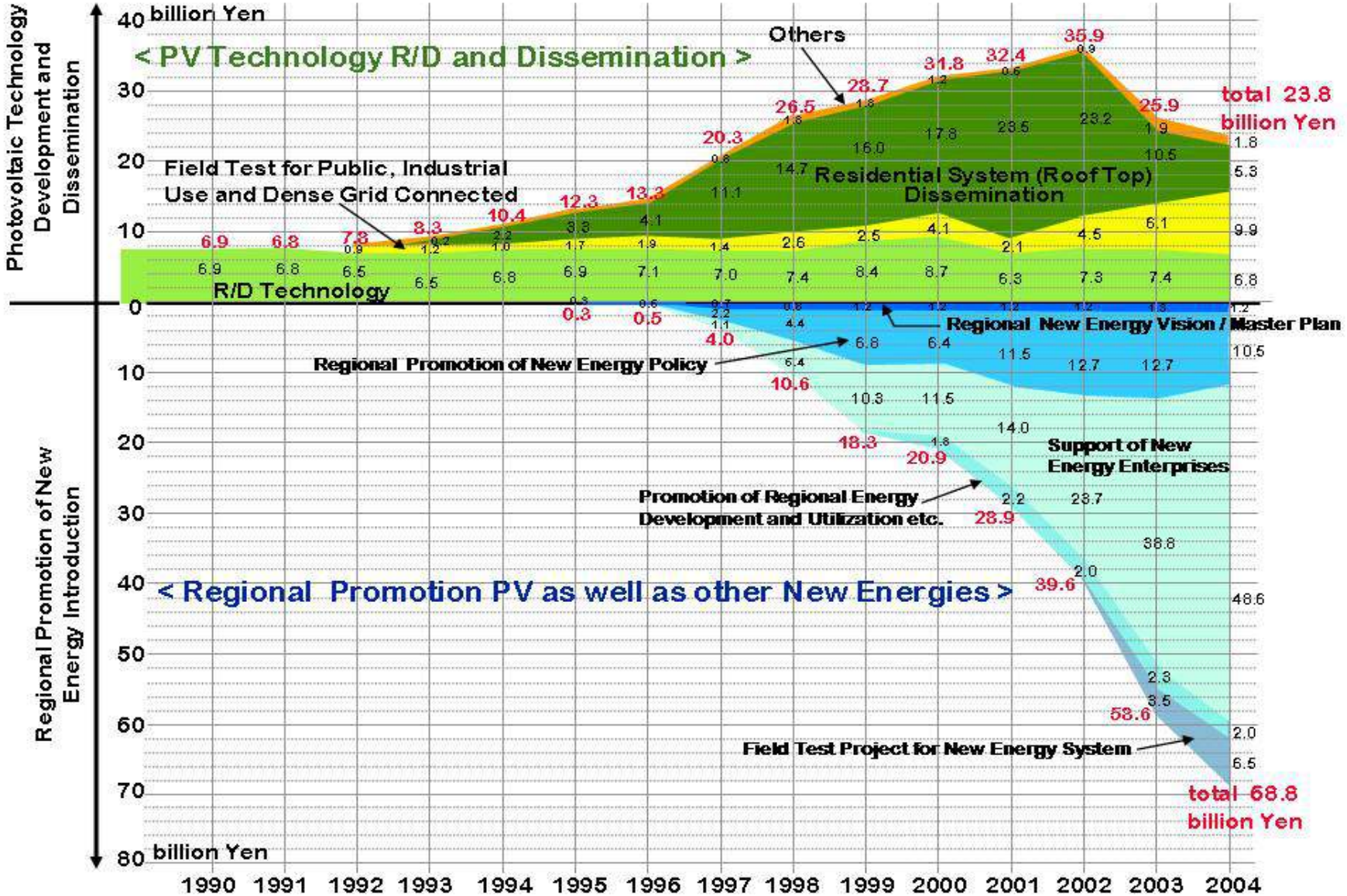
The Solar Energy Industry is an International Partnership



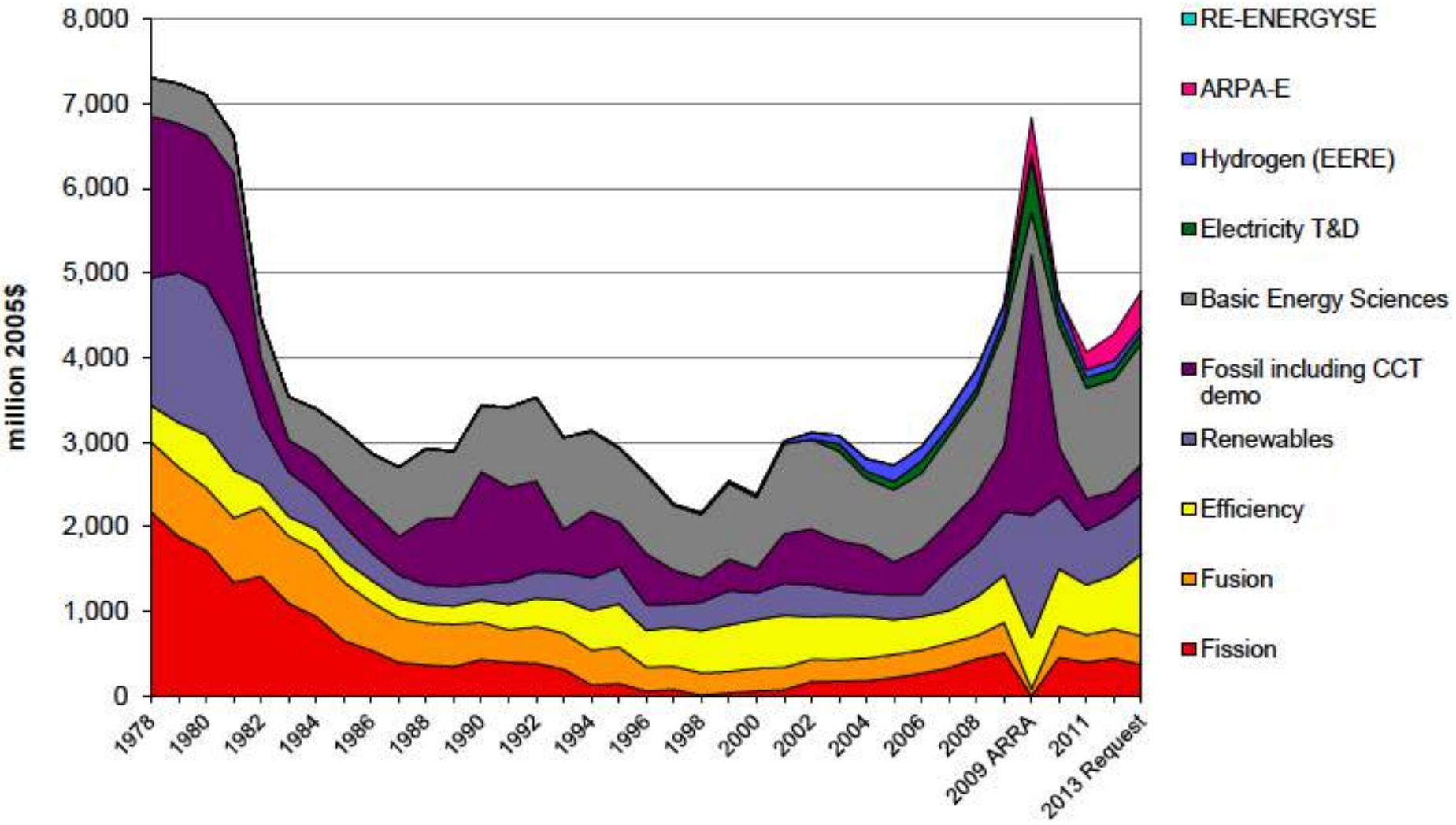
Solar cost decreases 10% per year



Japanese “Sunshine” Program
way too much detail, but technology push/demand pull is clear

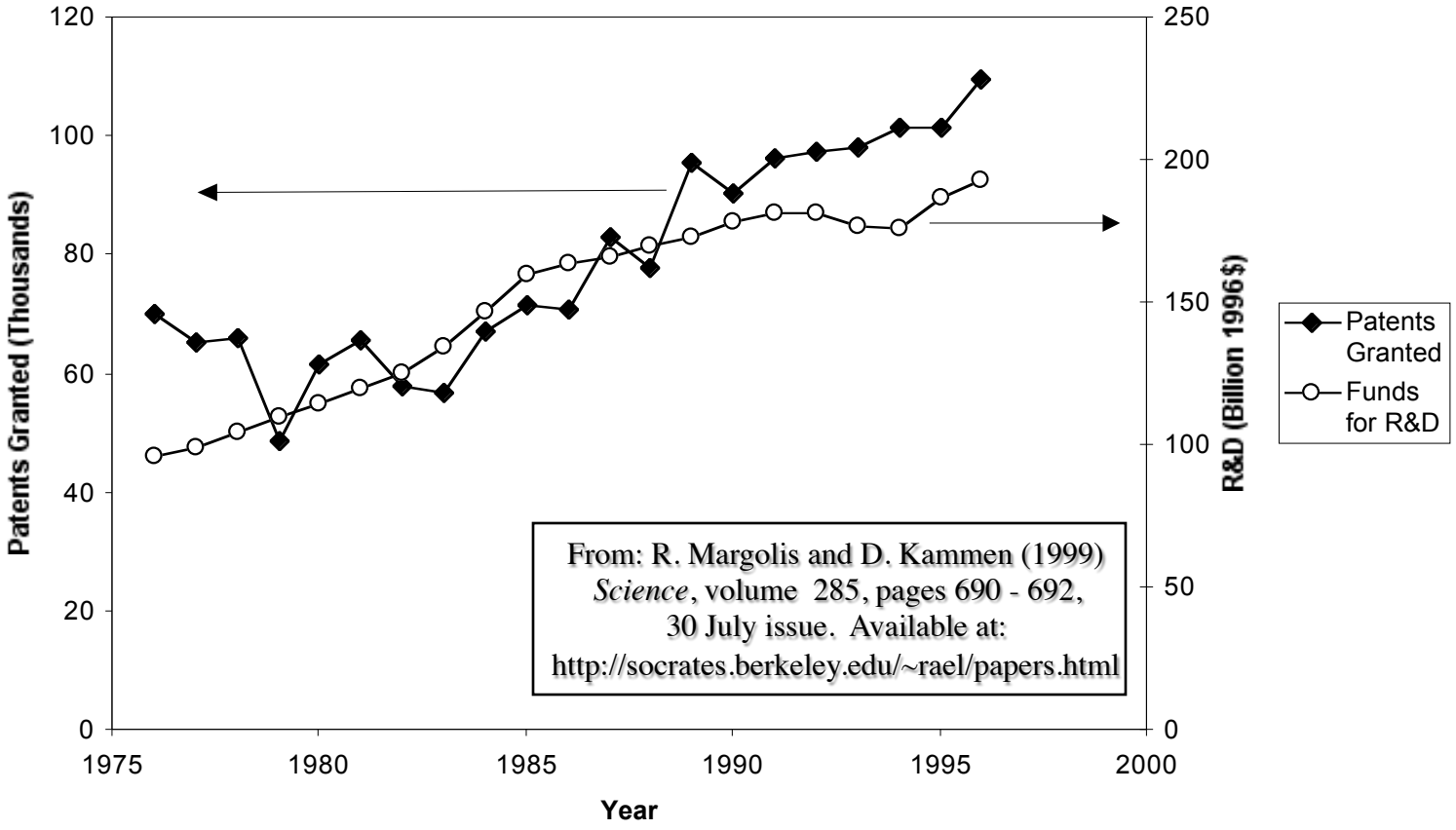


U.S. DOE Energy RD&D
FY1978-FY2013 Request



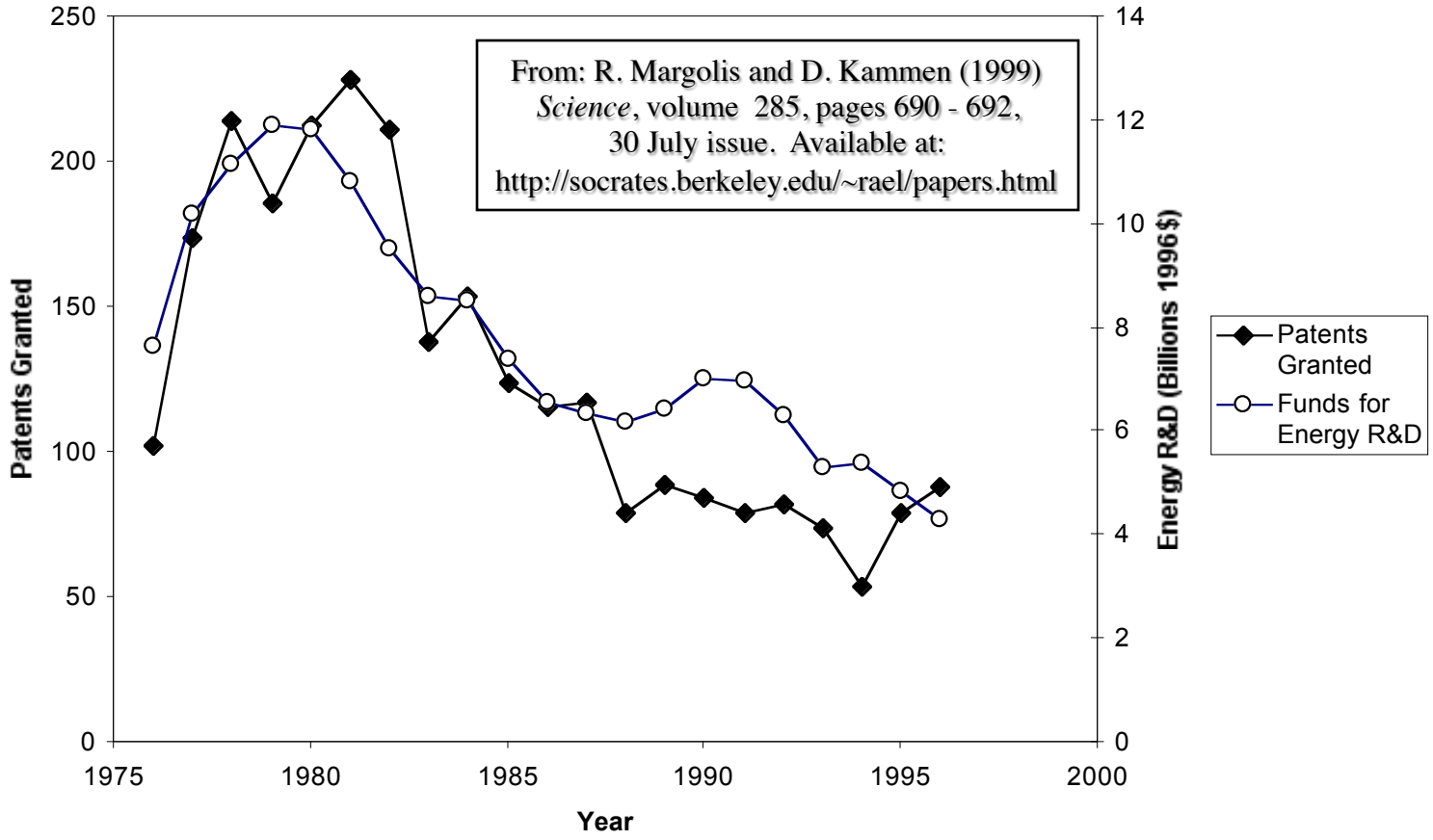
Federal R&D Policy Can be Effective

Figure 1. Total U.S. patents granted and total U.S. investments in R&D.

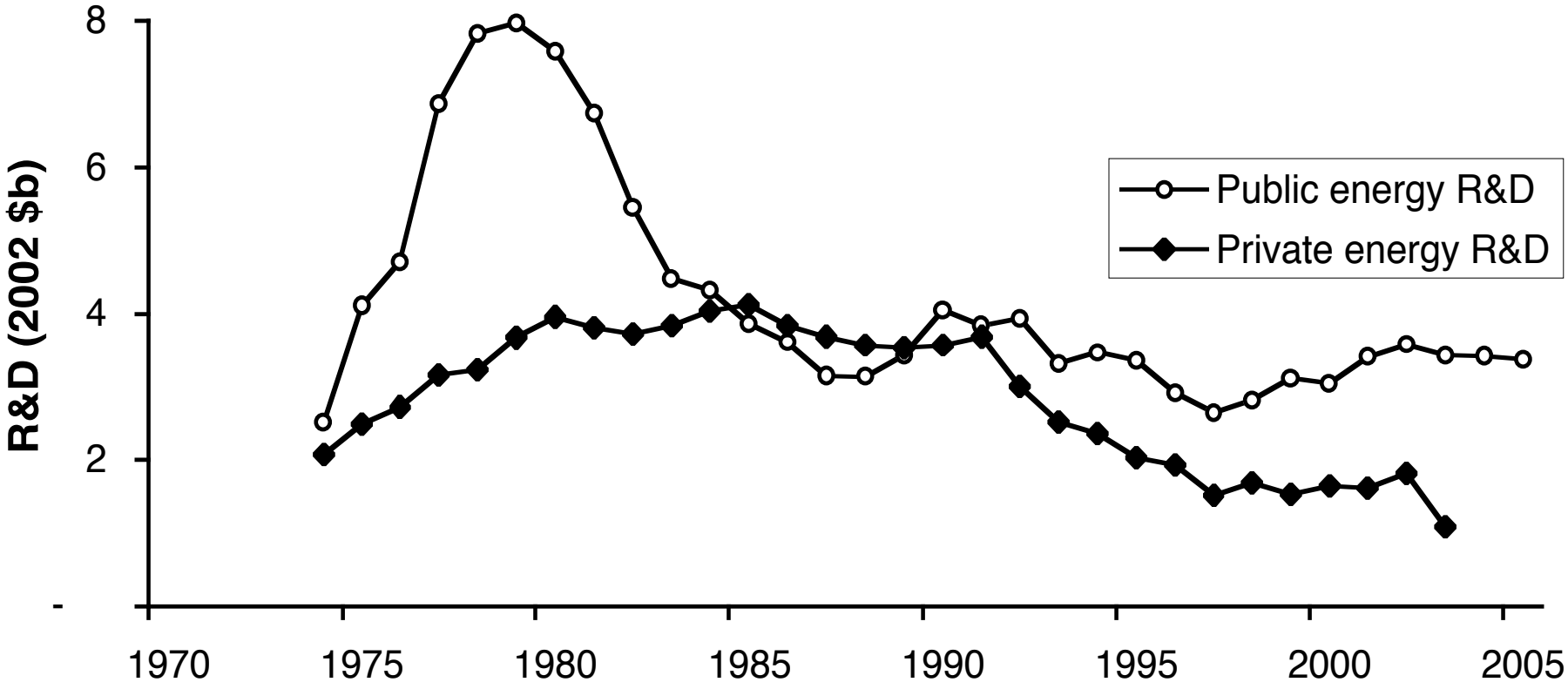


Lack of Federal R&D policy…
leads to lack of support for energy options

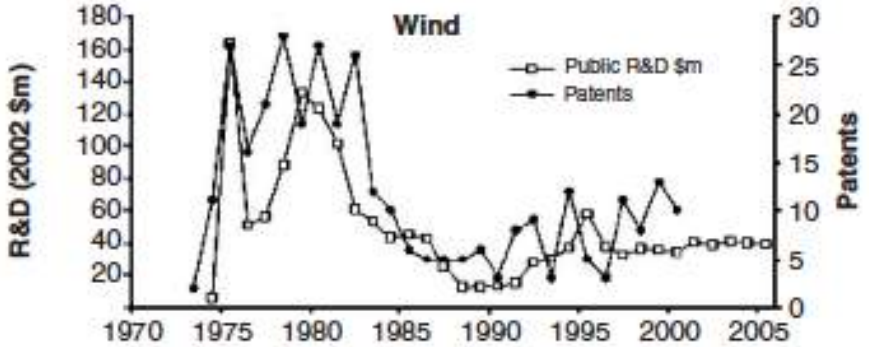
Figure 2. U.S. energy technology patents and total U.S. energy R&D.

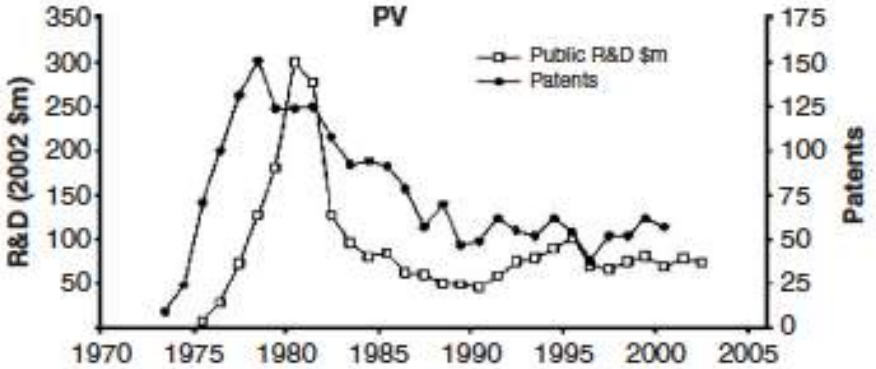


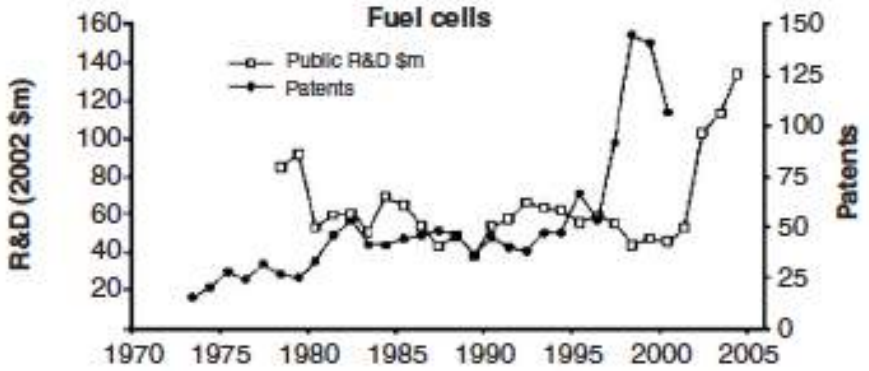
If you think US public sector energy R&D funding is doing poorly …

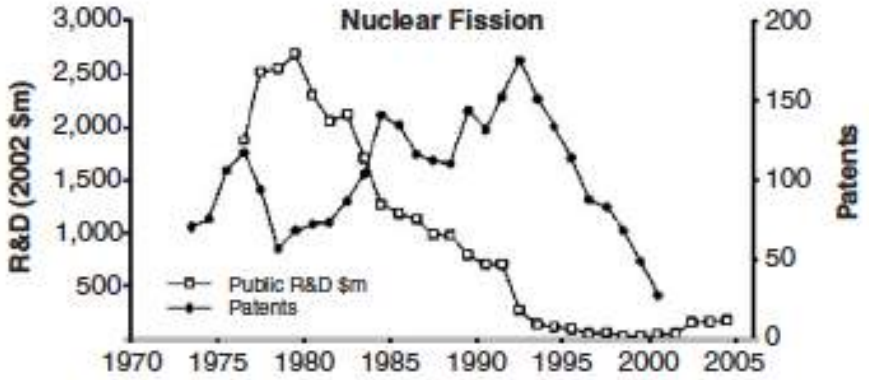


Kammen & Nemet (2005)









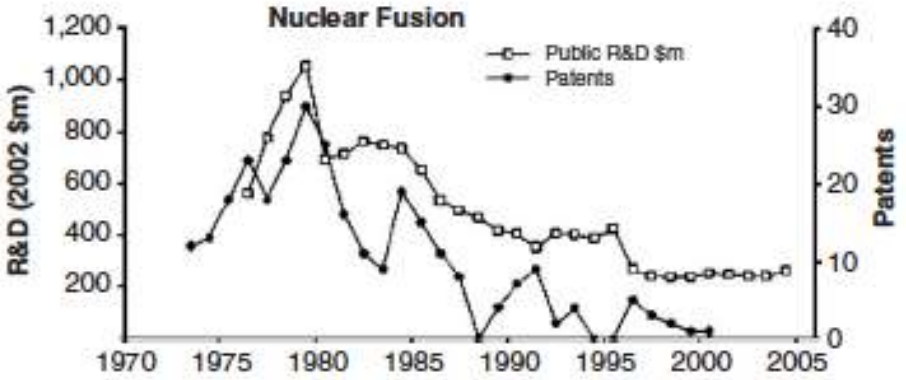
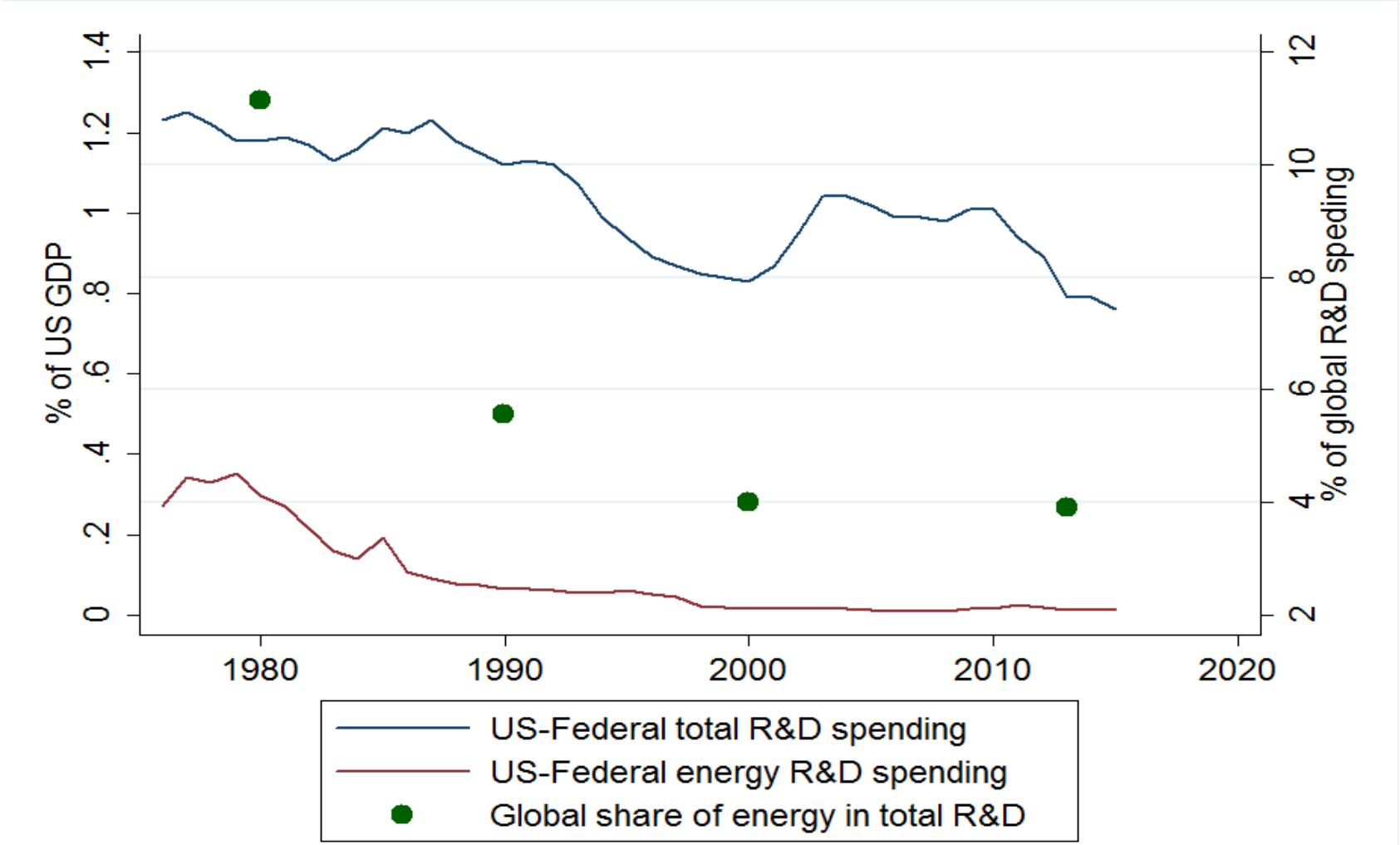
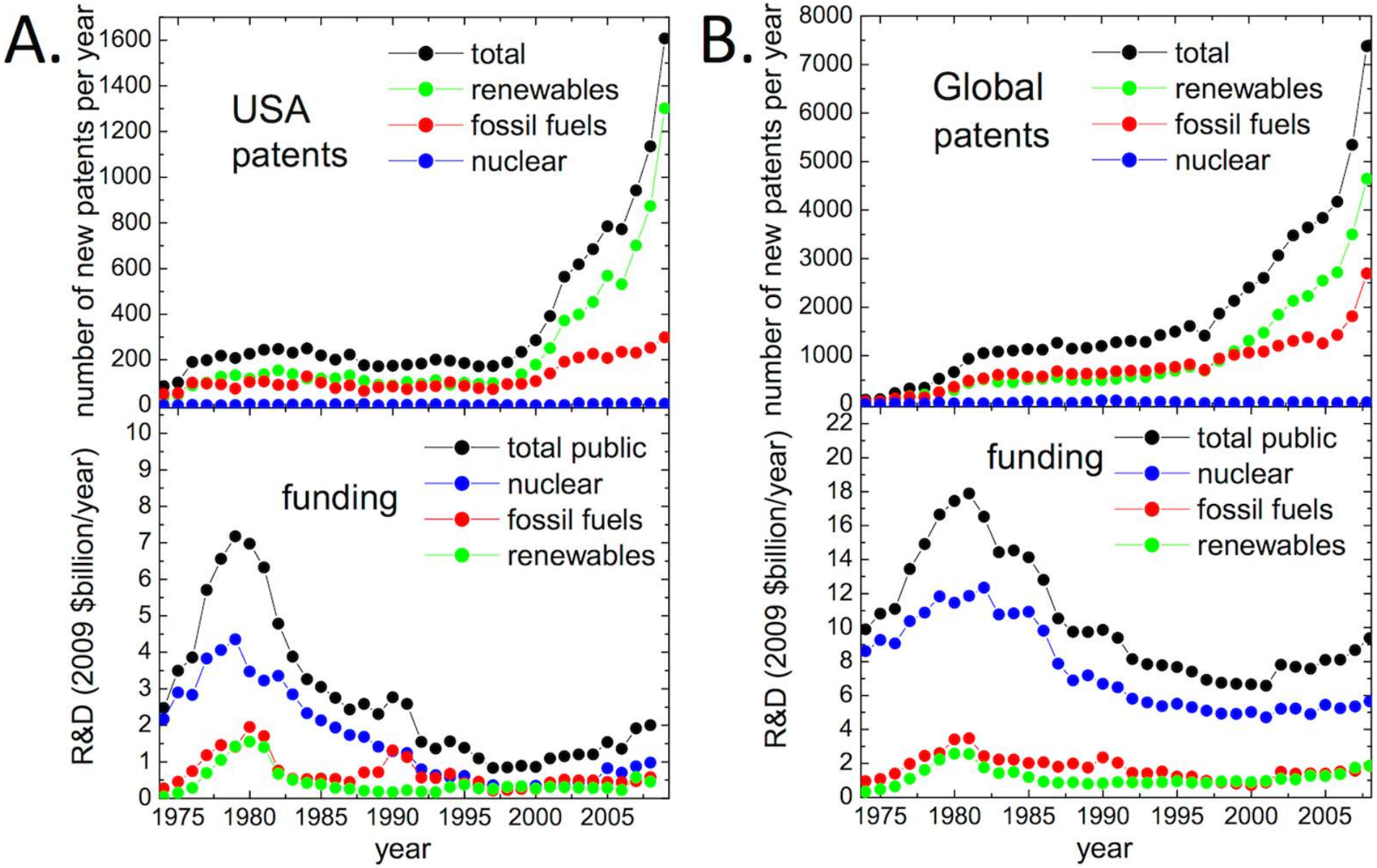


Fig. 7. Patenting and federal R&D. Patenting is strongly correlated with federal R&D. To provide comparisons with U.S. R&D funding, foreign patents are excluded. The data include granted patents in the U.S. patent system filed by U.S. inventors only. Patents are dated by their year of application to remove the effects of the lag between application and approval. This lag averages 2 years.

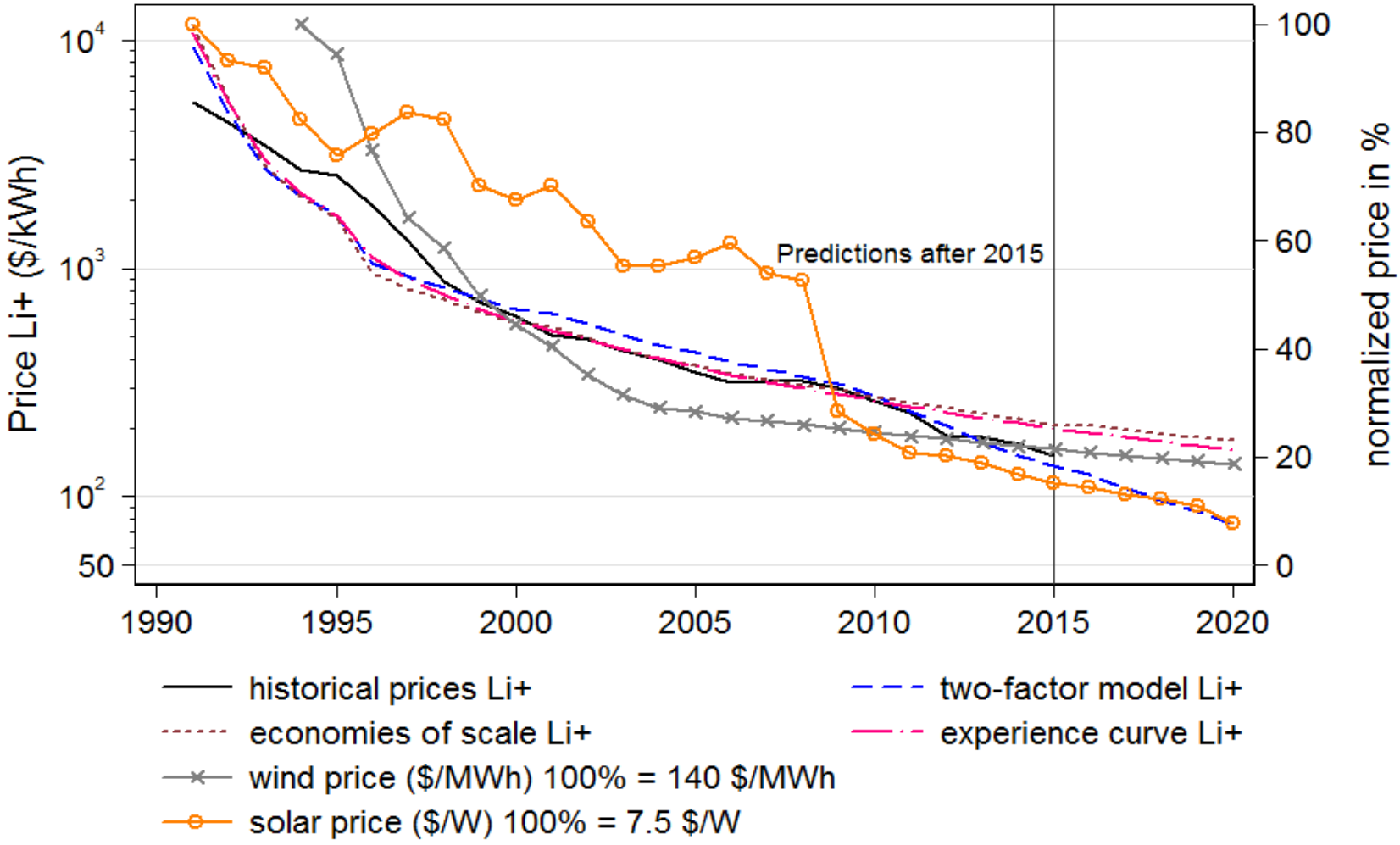
Nemet and Kammen, 2007

Investing in Innovation (or Not)

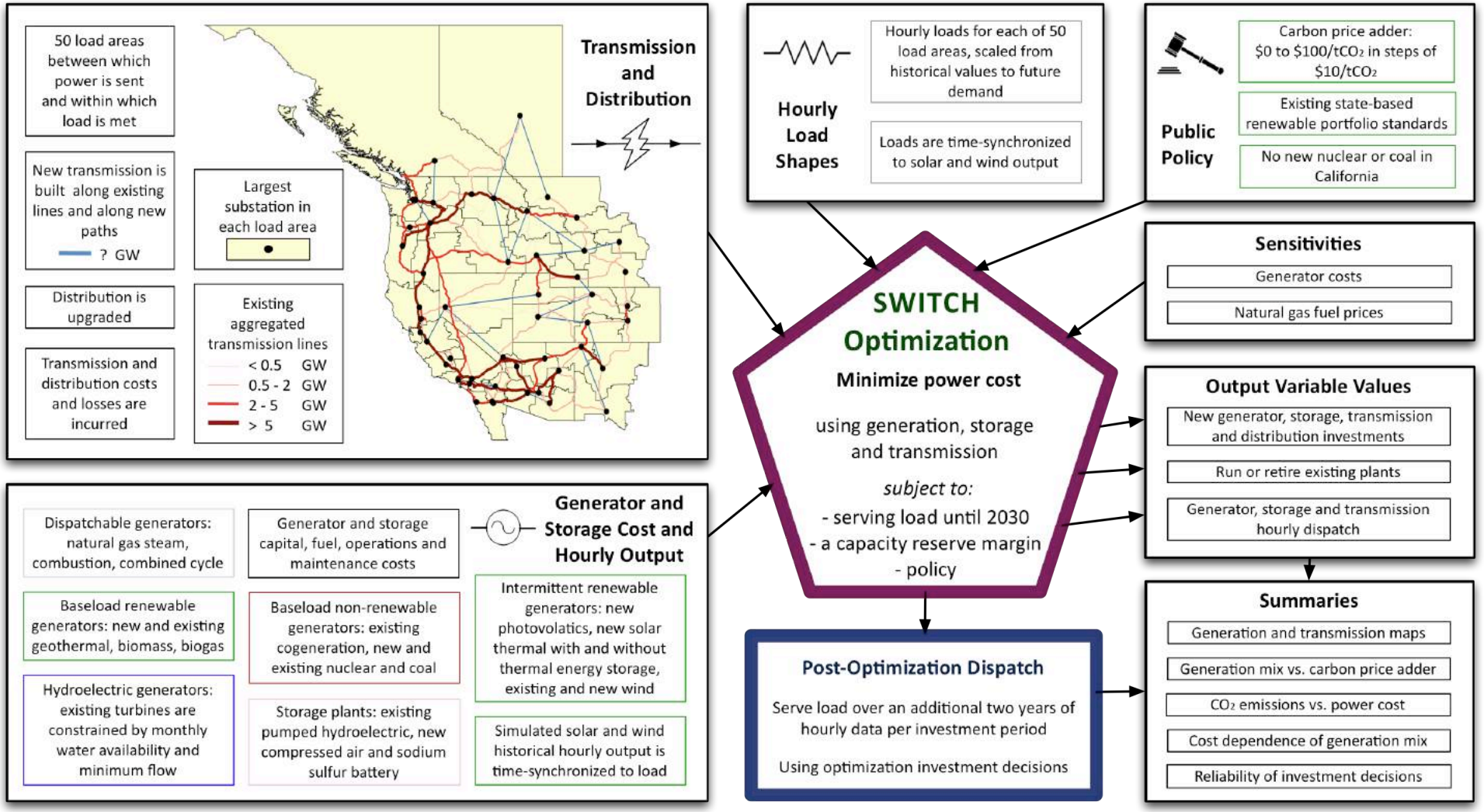




Trancik, et al, PLoS, 2014


Price Li+ ($/kWh)
normalized price in %
Predictions after 2015
historical prices Li+
economies of scale Li+
wind price ($/MWh) 100% = 140 $/MWh
solar price ($/W) 100% = 7.5 $/W
two-factor model Li+
experience curve Li+

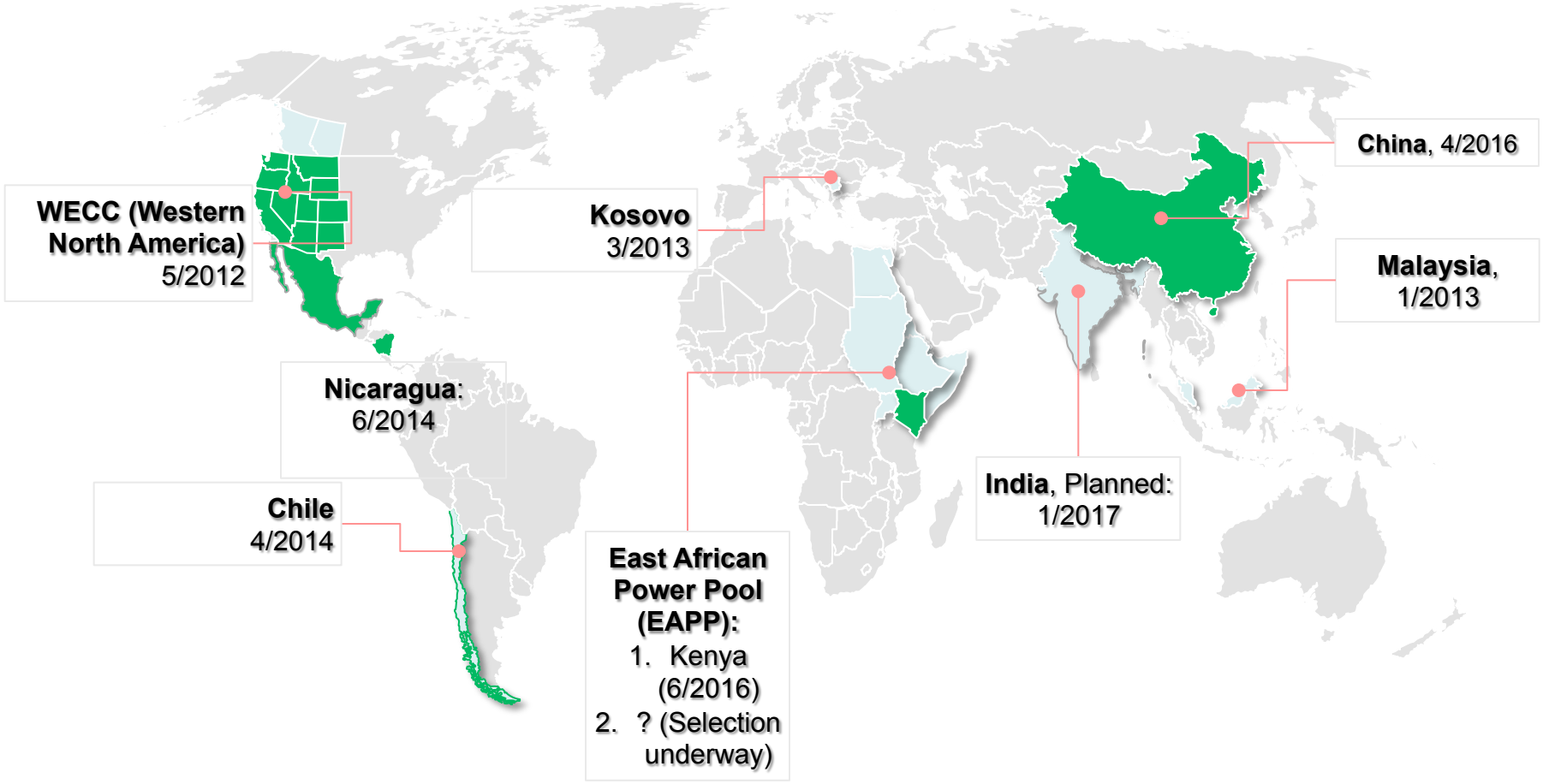
The SWITCH-WECC Model



Optimization and data framework of the western North American SWITCH model.

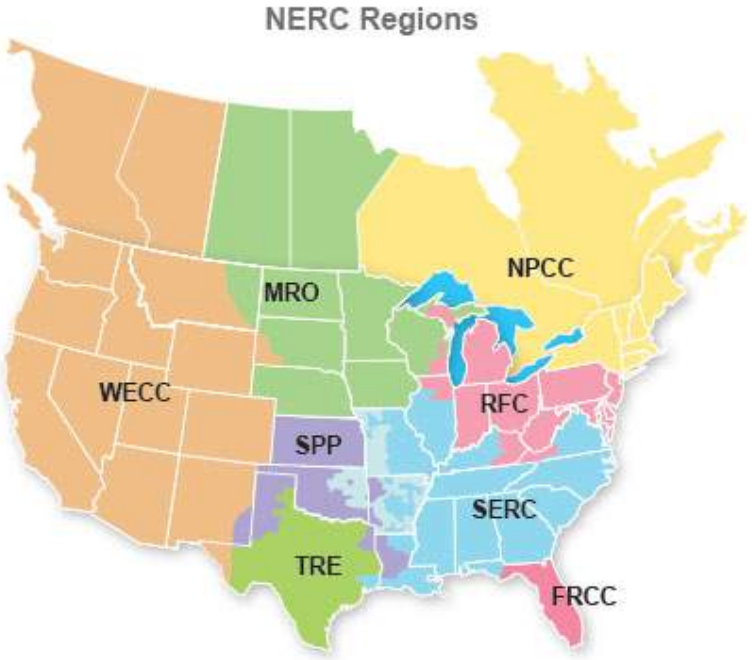
http://rael.berkeley.edu/switch

Power System Models
http://rael.berkeley/edu/project/SWITCH



SWITCH Electricity Supply Model

http://rael.berkeley.edu/project/SWITCH



- **Capacity expansion deterministic linear program**

- **Minimizes total cost of the power system:**
  - **Generation investment and operation**
  - **Transmission investment and operation**

Geographic:
- Western Electricity Coordinating Council
- 50 load areas

Temporal:
- 4 investment periods: 2016-2025 (“2020”); 2026-2035 (“2030”); 2036-2045 (“2040”); 2046-2055 (“2050”);
- 72 distinct hours simulated per period
  - Dispatch simulated simultaneously with investment decisions

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SWITCH – high resolution power systems & PROGRESS – first pass modeling tool

$$min\text{-}(c\downarrow i)\ .NPV\ \sum i,k=1\uparrow n,m\ TC\downarrow k\ (c\downarrow i)$$

Dispatch

$$Total\ Cost\ TC\downarrow k = Capital\ Cost\downarrow i * Capacity\ (c\downarrow i) + [Variable\ Cost\downarrow i * Capacity\ (c\downarrow i) *\ CF\downarrow i * hours]$$

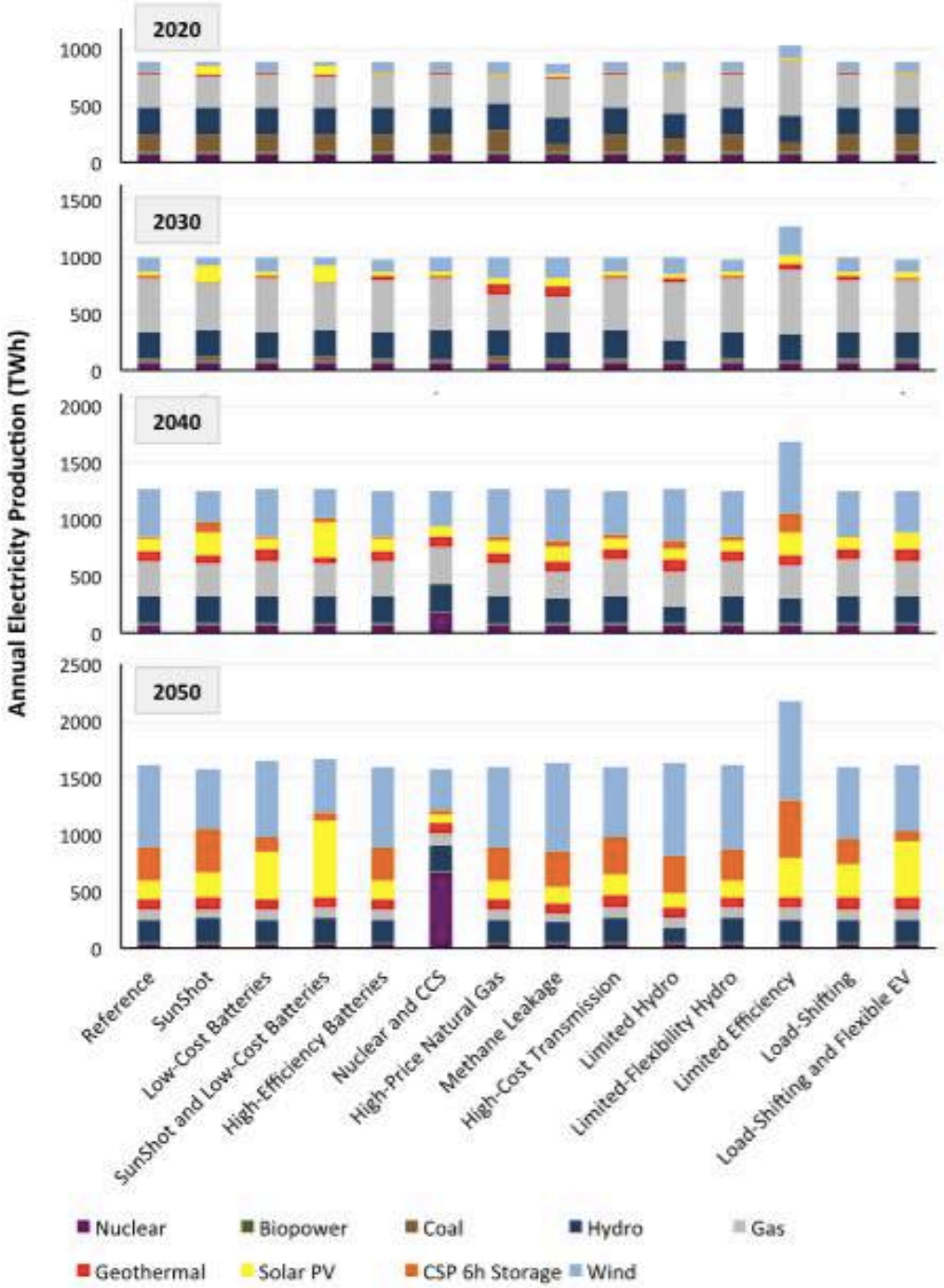
$$\sum i=1\uparrow n\ Capacity\ (c\downarrow i) * Peak\ Contribution\downarrow i \geq Annual\ Peak\ Demand * [1 + Reserve\ Margin]$$

Installed capacity

$$\sum i=1\uparrow n\ [Capacity\ (c\downarrow i) *\ CF\downarrow i * hours] \geq Annual\ Load$$

$$Annual\ Load * Spill\ Factor \geq \sum i=1\uparrow n\ [Capacity\ (c\downarrow i) *\ CF\downarrow i * hours]$$

$$Total\ Resource\ Potential\downarrow i \geq \sum k=1\uparrow m\ Capacity\ (c\downarrow i)$$


2020
2030
2040
2050
Annual Electricity Production (TWh)
0
500
1000
1500
2000
2500
Reference
SunShot
Low-Cost Batteries
SunShot and Low-Cost Batteries
High-Efficiency Batteries
Nuclear and CCS
High-Price Natural Gas
Methane Leakage
High-Cost Transmission
Limited Hydro
Limited-Flexibility Hydro
Limited Efficiency
Load-Shifting
Load-Shifting and Flexible EV
Nuclear
Biopower
Coal
Hydro
Gas
Geothermal
Solar PV
CSP 6h Storage
Wind

2030/2050 Path Dependence Using SWITCH

How to plan efficiently?

- Today until 2030 and then until 2050?
- Or today until 2050?

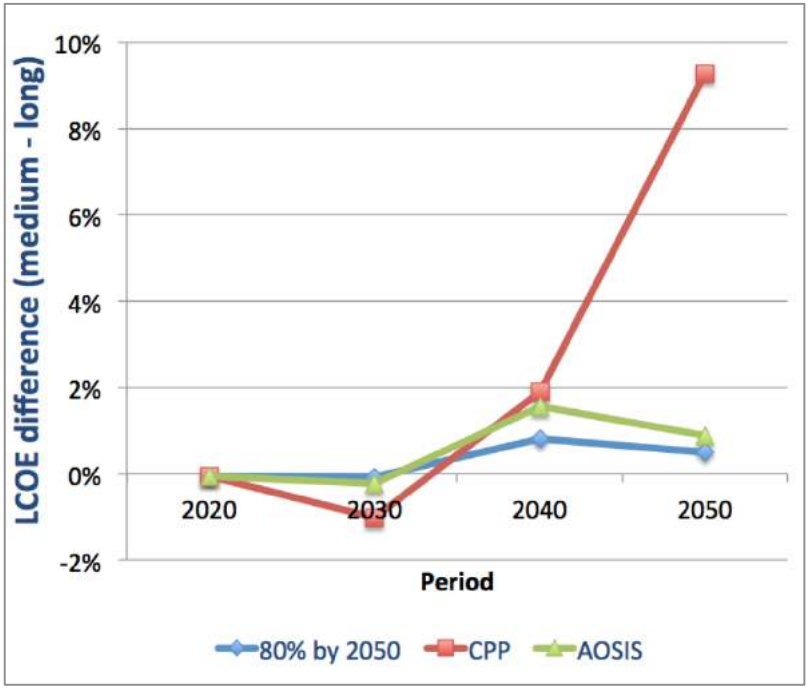
Carbon cap scenarios:

- 80% reduc. by 2050
- 1.5°C
- CA executive order (40% lower in 2030)
- Clean Power Plan

Preliminary Findings

Planning until 2030 for CPP results in:

- Later coal retirements
- Minor/no savings in periods 2020 and 2030
- More costly in 2040 and 2050
- CPP 9% more expensive in 2050



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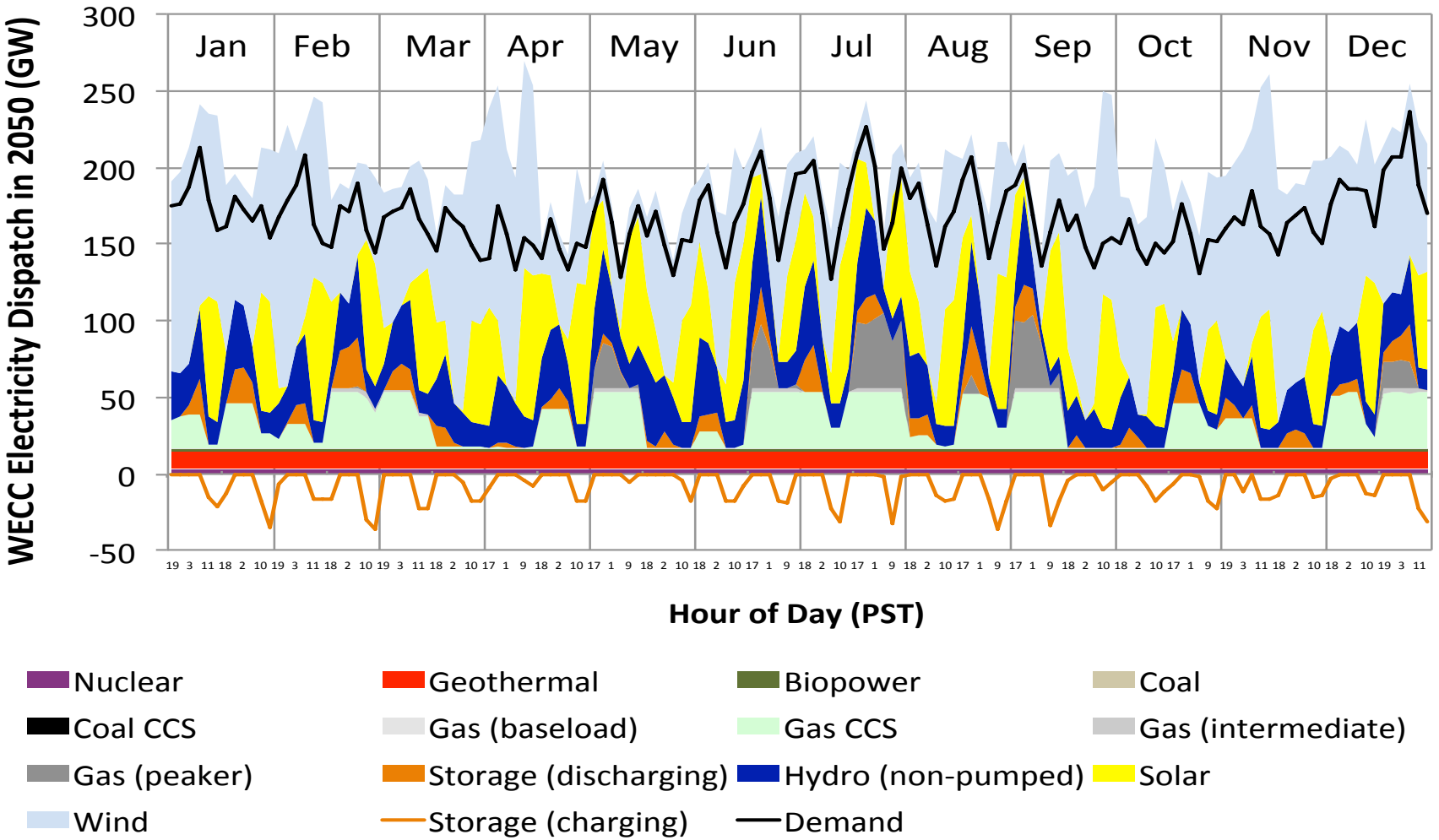
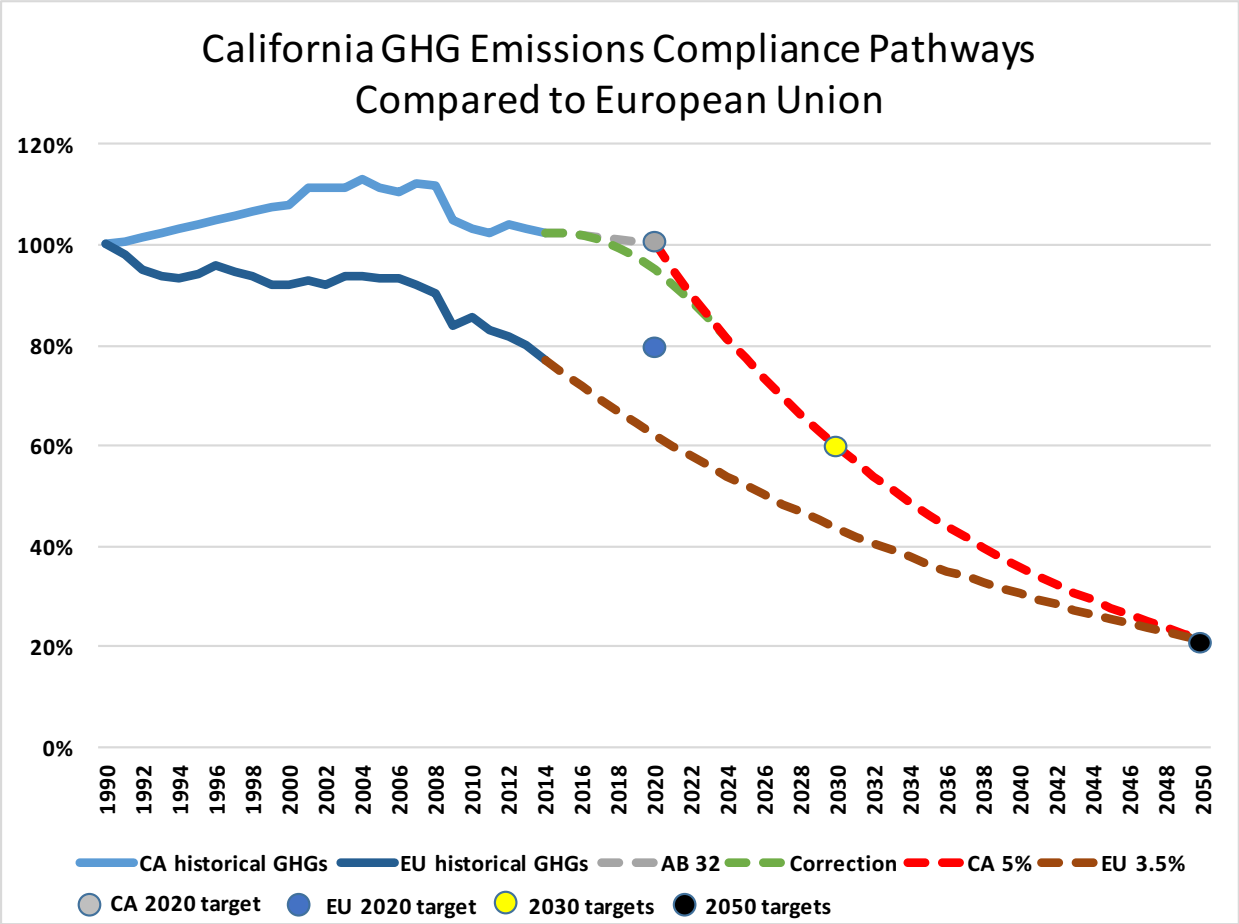
Dispatch in 2050: Flexibility and variable renewables dominate

- Storage almost exclusively moves solar to the night
- Geothermal only remaining substantial baseload





Meeting the 2030 and 2050 targets will require 5% average annual abatement across the entire CA economy

The EU, by contrast, already met the same 2020 target 10 years earlier and needs 3.5% annual abatement to meet the 2050 target

5% is equivalent to GHG reductions during the Great Recession (‘08-’10); CA must do this every year while growing the economy

Environmental Science & Technology

Policy Analysis

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SWITCH-China: A Systems Approach to Decarbonizing China's Power System

Gang He,*[,†,‡,§] Anne-Perrine Avrin,[‡,§] James H. Nelson,[⊥] Josiah Johnston,[‡,§] Ana Mileva,[⊥] Jianwei Tian,[#] and Daniel M. Kammen*[,‡,§,∥]

[†]Department of Technology and Society, College of Engineering and Applied Sciences, Stony Brook University, Stony Brook, New York 11794, United States

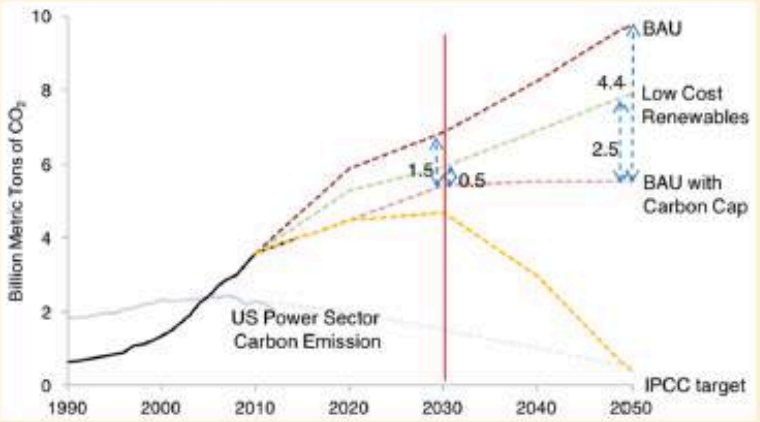
[‡]Renewable and Appropriate Energy Laboratory, [§]Energy and Resources Group, and [∥]Goldman School of Public Policy, University of California, Berkeley, California 94720, United States

[⊥]Energy and Environmental Economics, Inc. (E3), San Francisco, California 94104, United States

[#]China National Institute of Standardization, Beijing 100191, P.R. China

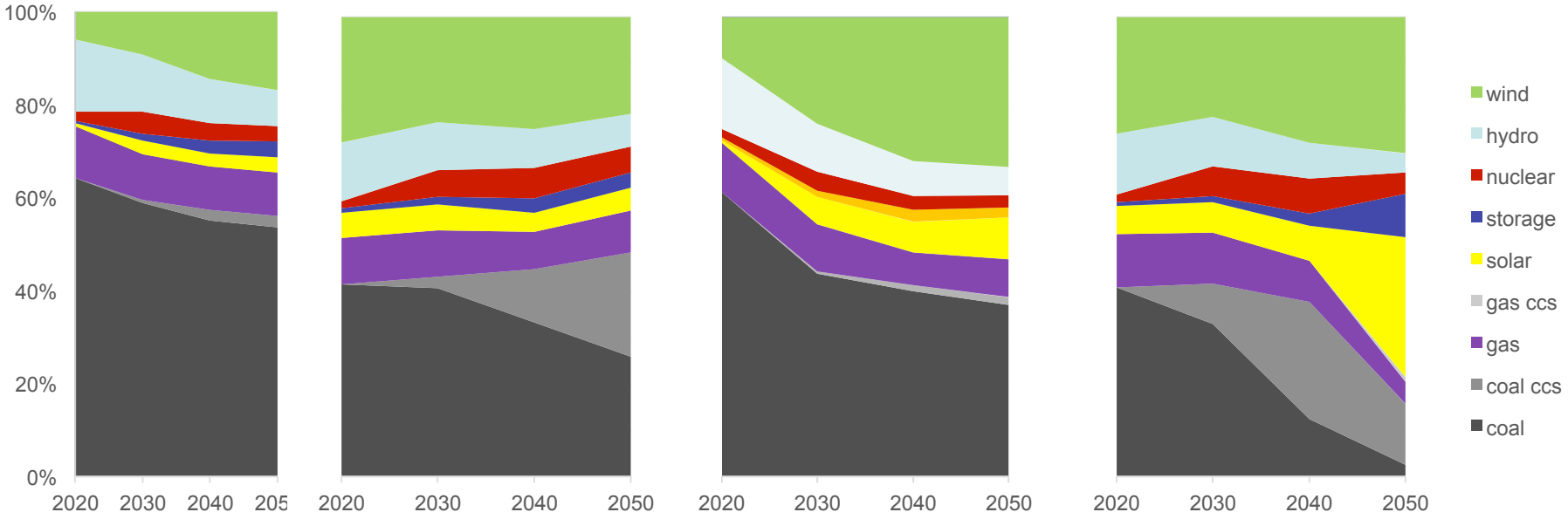
Supporting Information

ABSTRACT: We present an integrated model, SWITCH-China, of the Chinese power sector with which to analyze the economic and technological implications of a medium to long-term decarbonization scenario while accounting for very-short-term renewable variability. On the basis of the model and assumptions used, we find that the announced 2030 carbon peak can be achieved with a carbon price of ~\$40/tCO_2. Current trends in renewable energy price reductions alone are insufficient to replace coal; however, an 80% carbon emission reduction by 2050 is achievable in the Intergovernmental Panel on Climate Change Target Scenario with an optimal electricity mix in 2050 including nuclear (14%), wind (23%), solar (27%), hydro (6%), gas (1%), coal (3%), and carbon capture and sequestration coal energy (26%). The co-benefits of carbon-price strategy would offset 22% to 42% of the increased electricity costs if the true cost of coal and the social cost of carbon are incorporated. In such a scenario, aggressive attention to research and both technological and financial innovation mechanisms are crucial to enabling the transition at a reasonable cost, along with strong carbon policies.



In China even aggressive wind, solar and storage learning alone is not enough to phase out coal

http://rael.berkeley.edu/project/SWITCH



Business as Usual

BAU with Carbon cap

Current aggressive solar and wind continued

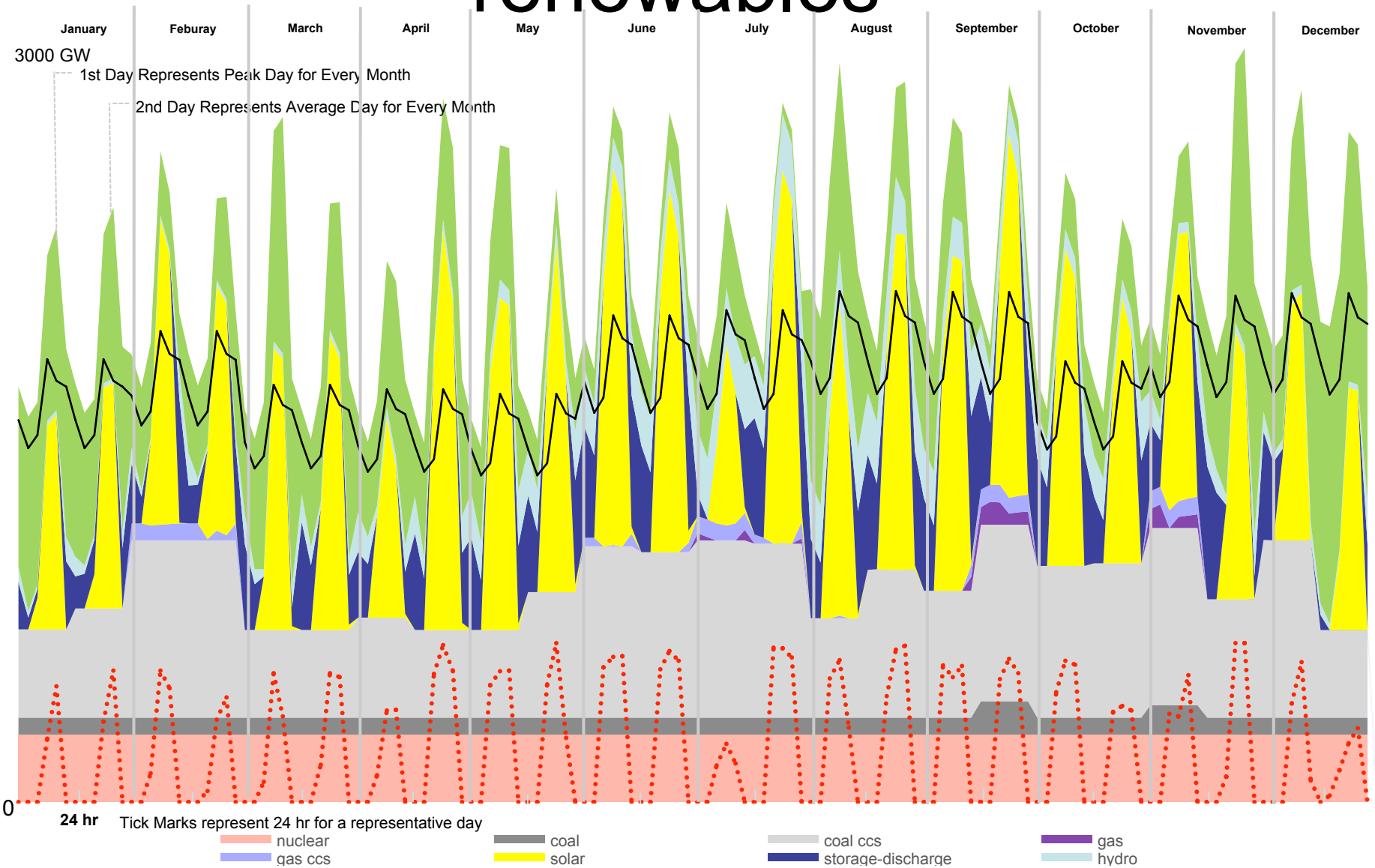
IPCC 2050 (80% cut in carbon)

SWITCH-China: A Systems Approach to Decarbonizing China's Power System

Gang He,[*,†,‡,§] Anne-Perrine Avrin,[‡,§] James H. Nelson,[⊥] Josiah Johnston,[‡,§] Ana Mileva,[⊥] Jianwei Tian,[#] and Daniel M. Kammen[*,‡,§,∥]

Figure 4. Generation, transmission, and storage capacity needed to achieve an 80% carbon reduction in 2050. All represented lines are new transmission expansion. Inner Mongolia emerges as a major center of clean energy generation thanks to the combination of its location (a few hundred kilometers from major demand centers) and high-quality renewable energy resources.

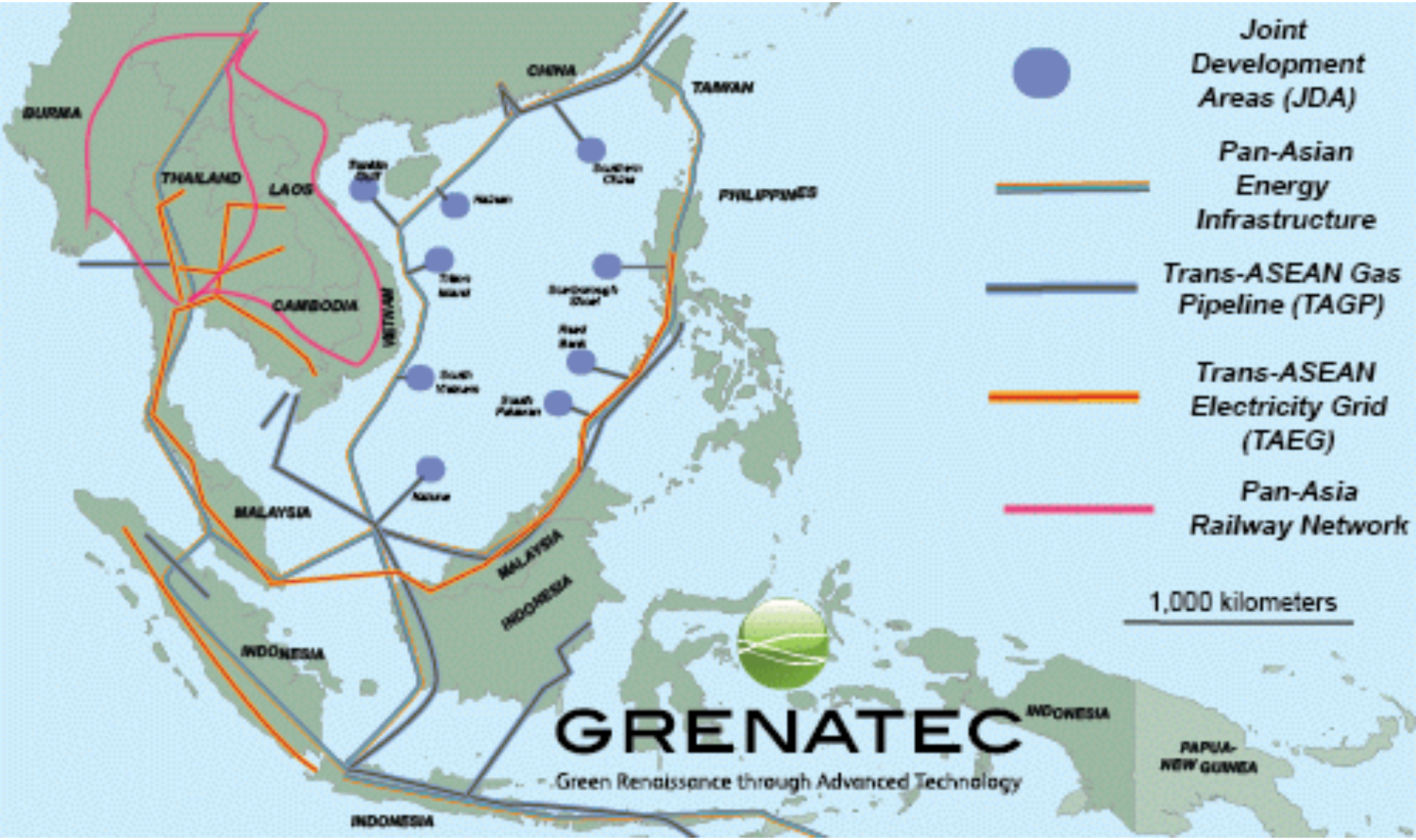
China: dispatch challenge for coal and renewables



Source: He, Avrin, Nelson, Johnston, Mileva, Tian, and Kamme

National Grid Plan in About 2020

- UHVAC corridors connecting North and Central grids
- UHVAC synchronous grid interconnecting North, Central and East grids
- UHVDC transfer long distance power
- Expected capacity of UHV：above 200GW


Joint Development Areas (JDA)
Pan-Asian Energy Infrastructure
Trans-ASEAN Gas Pipeline (TAGP)
Trans-ASEAN Electricity Grid (TAEG)
Pan-Asia Railway Network
1,000 kilometers
BURMA
THAILAND
LAOS
CAMBODIA
VIETNAM
CHINA
TAIWAN
PHILIPPINES
MALAYSIA
INDONESIA
PAPUA-NEW GUINEA
GRENATEC
Green Renaissance through Advanced Technology

The mathematical model of a planning problem

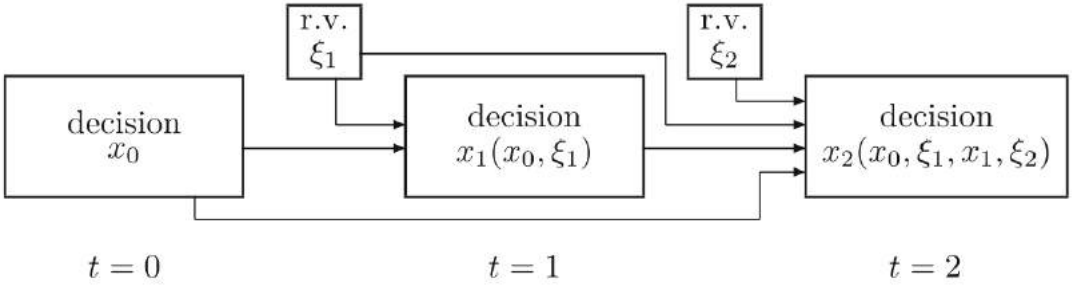
- Given a control variable *x,* the model maximizes discounted utility over a long term horizon.
- A planning problem is by nature a dynamic model, given the time dependencies on the equation of motion of the state variable *y*.
- In general planning problems are modeled as large scale static optimization mathematical programs.

$$\max_{\hat{x}} \quad \sum_{t=0}^{\infty} \beta^t u(x_t)$$

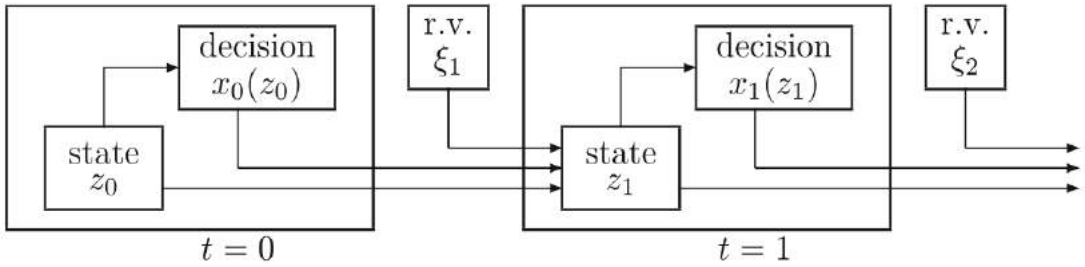
$$\text{subject to} \quad y_{t+1} = F(y_t, x_t, \rho, t)$$

Modeling alternatives

- Stochastic Programming



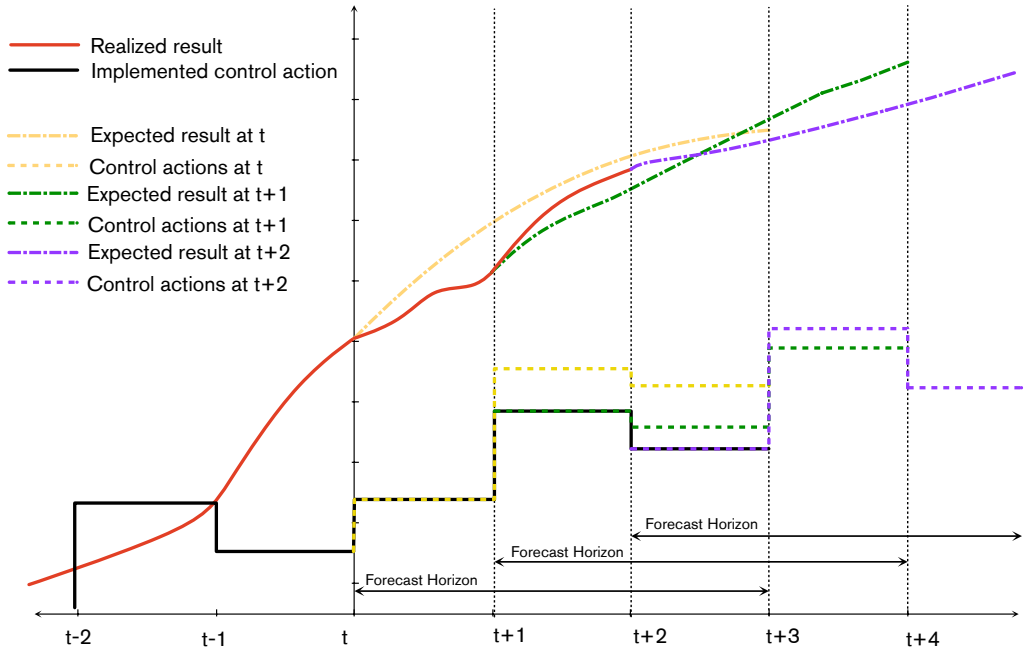
Dynamic Programming



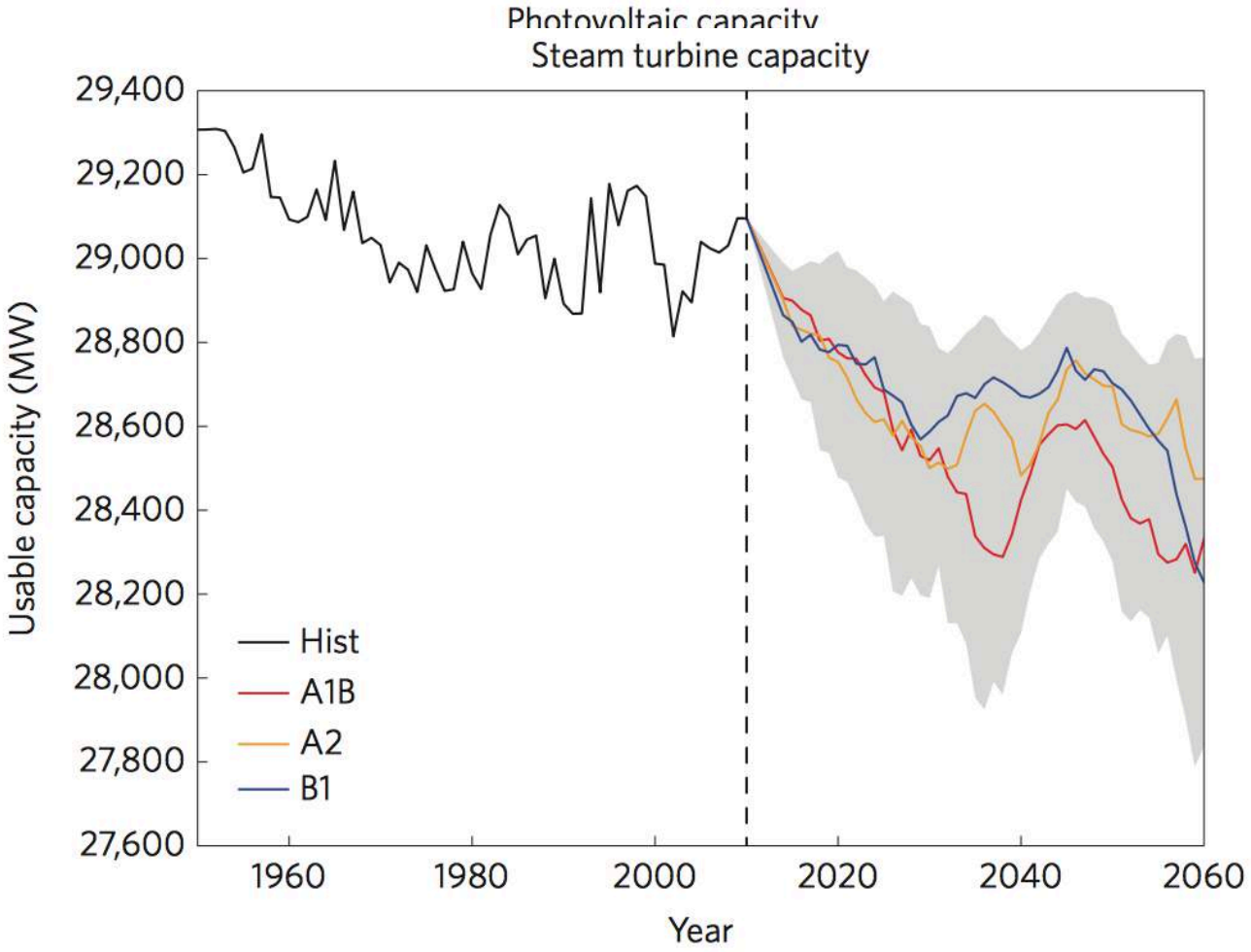
The difference between model results are mostly due to the assumptions on the exogenous process and the impact on the decisions (learning vs total uncertainty)

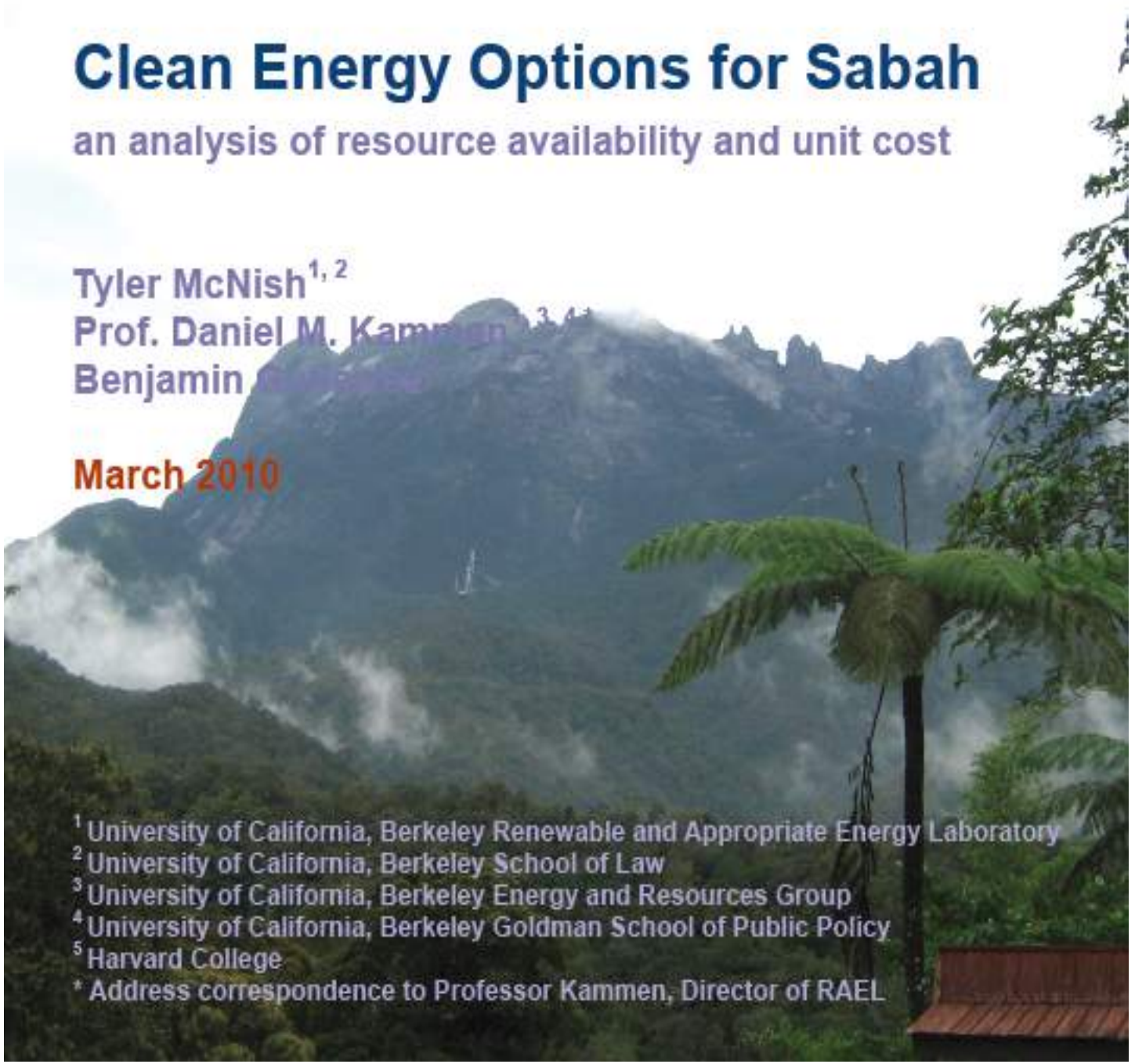
The role of learning in modeling

- The decision maker can anticipate their own learning before making the decision.
- In the classical receding horizon problem, there is no anticipates learning.
- This difference is modeled by optimizing after taking the expected value of future periods



Bartos and Chester, “Impacts of Climate Change on Electric Power Supply in the Western United States.” Nature Climate, August 2015





http://rael.berkeley.edu/node/609

By Jennifer Pinkowski Tuesday, Feb. 22, 2011

Borneo Says No to Dirty Energy

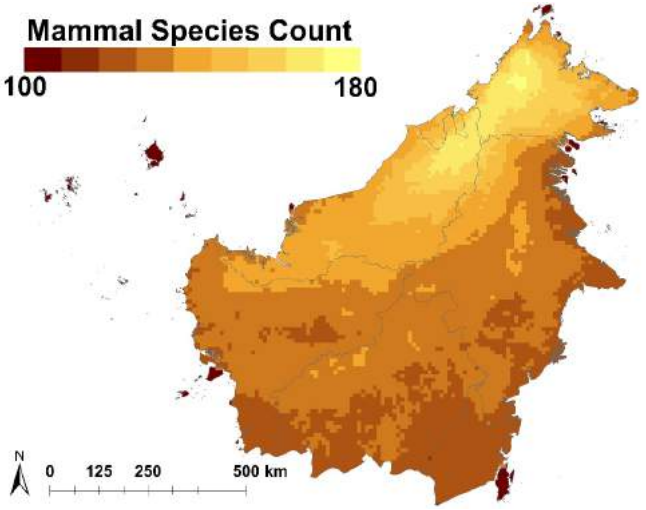
TIME Science

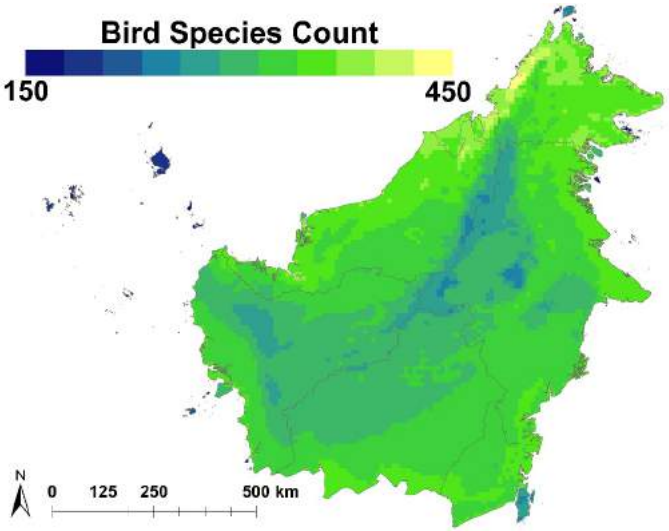
UNDER 2°

Renewable & Appropriate Energy Laboratory
RAEL

Borneo Says No to Dirty Energy

Two-thirds of Bornean Bird, Mammal, Tree and Insect Species may lose habitat forever due to reservoirs





Renewable & Appropriate Energy Laboratory
RAEL

JABATAN PEGUAM BESAR NEGERI SARAWAK
(SARAWAK STATE ATTORNEY-GENERAL'S CHAMBERS)
TINGKAT 15 & 16,
WISMA BAPA MALAYSIA,
PETRA JAYA, 93502 KUCHING,
SARAWAK, MALAYSIA.

Telefon: 082-441957/440736
Faks: 082-440525/444537
Laman Web: www.sag.sarawak.gov.my

Our Ref. : CS/MYY/001(WS)/3-2015 Date : 15th March, 2016

Your Ref. : Please advice

Messrs Harrison Ngau & Co. Advocates
Lot 1046, 1st Floor,
Shang Garden Commercial Centre,
Jalan Bulan Sabit, 98000 Miri,
Sarawak

By Fax 085-421236 only

Dear Sirs,

Re: In the High Court in Sabah and Sarawak at Miri
Suit No. MYY-21NCvC-1/3-2015
Plaintiffs : Tama Wing Kalang & 3 Ors
Defendants : Superintendent of Lands and Surveys Miri Division & 2 Ors

We refer to the above matter and "The Land (Native Customary Rights) (No.53) 2014 Direction".

2. We are please to inform you that the above mentioned Direction has been revoked vide "The Land Native Customary Rights (No.2) (Revocation) Direction 2016" published on 18th February, 2016 in the Sarawak Government Gazette under G.N. 569. We forward herewith a copy of the Gazette for your record and further action.

Thank you.

"BERSATU BERUSAHA BERBAKTI"
"AN HONOUR TO SERVE"

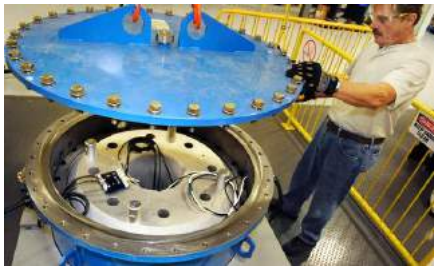
[MA XIANG RUI]

Energy Storage is Not Just Batteries

Natural gas (without & with storage)

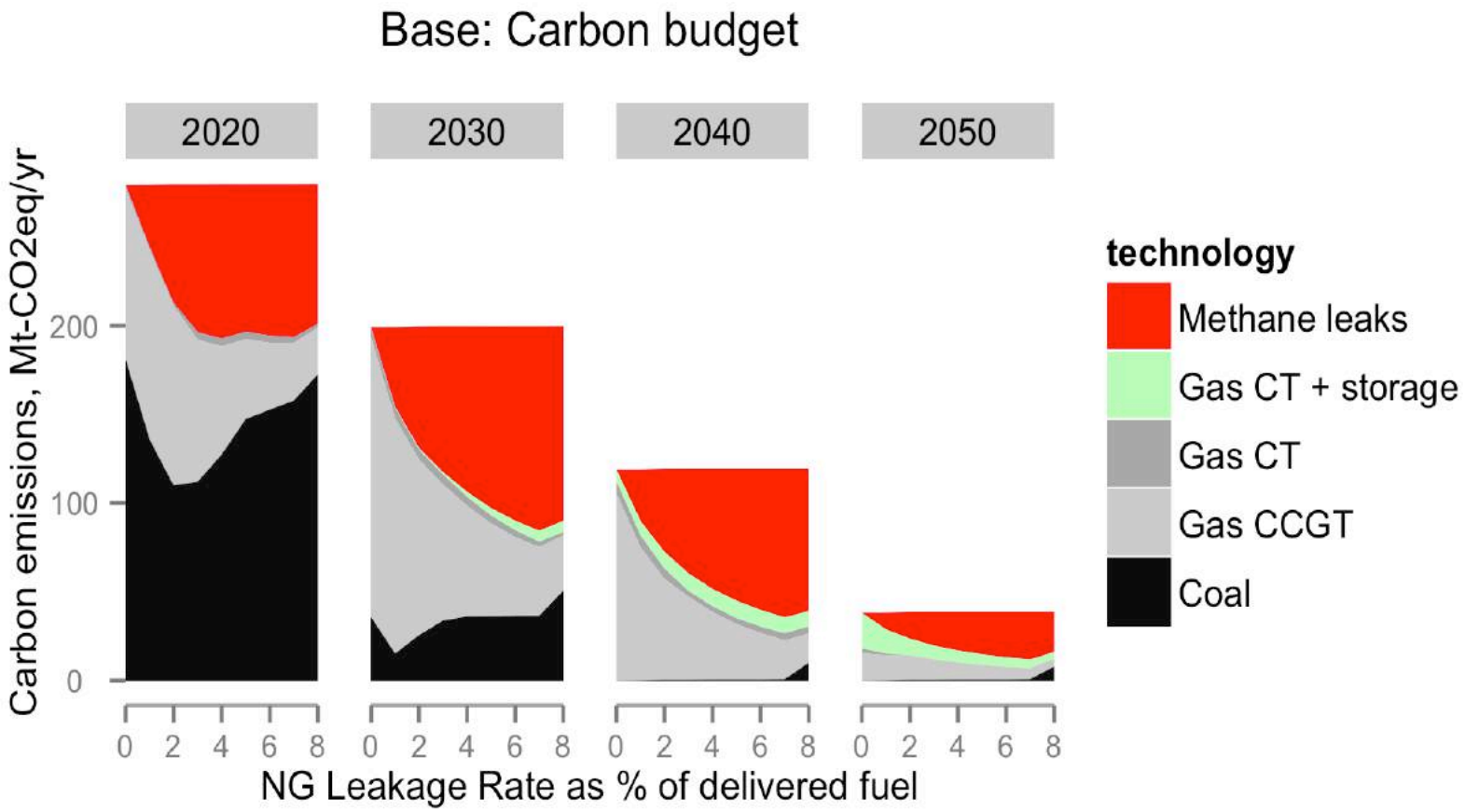
Traditional and pumped hydropower

Flywheels



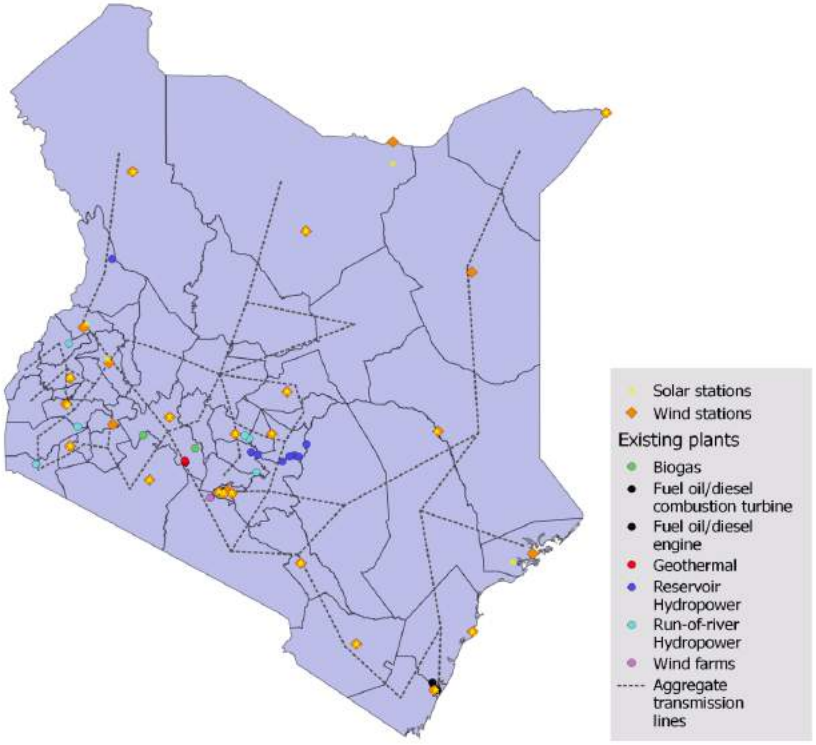
Flow batteries

Example: the impact of Natural Gas Leakage on carbon budgets



Johnstone and Kammen, 2017 in press

Results - Kenya



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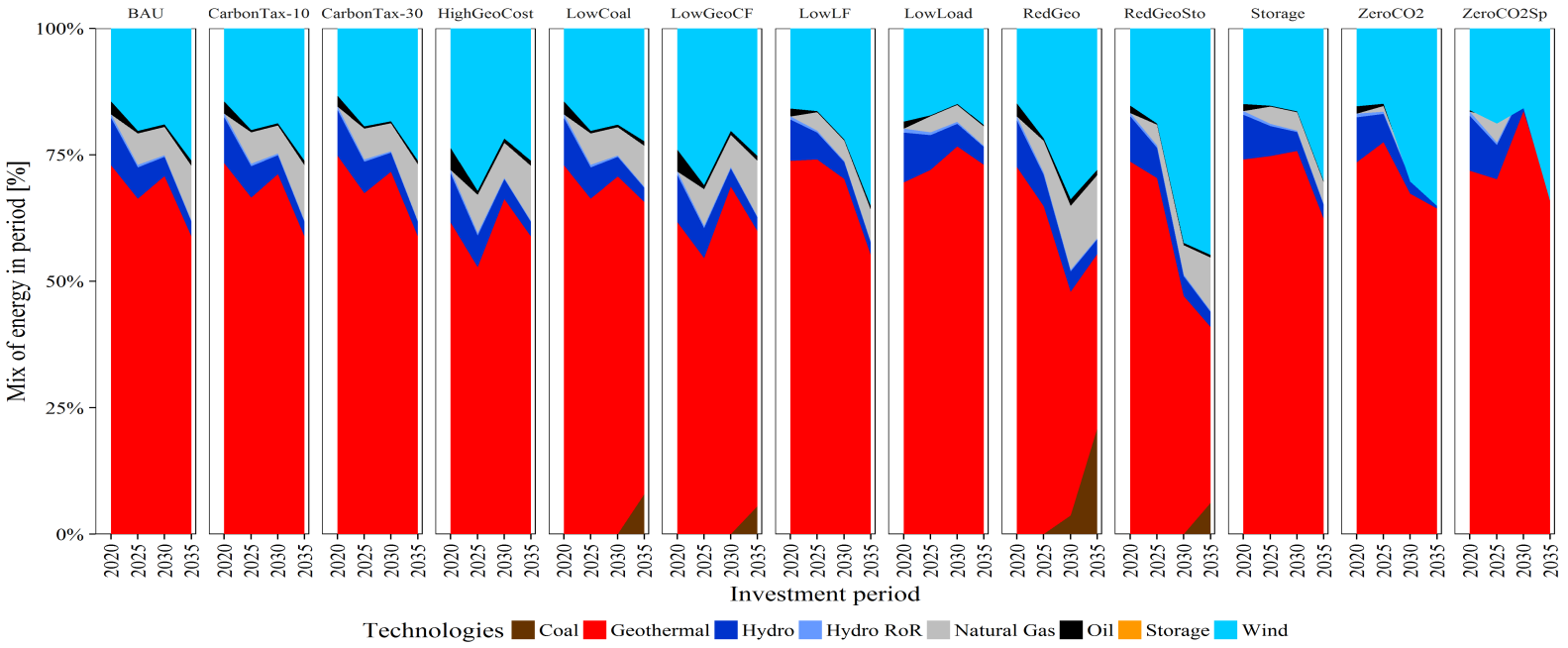
East African Rift Valley is currently the world's most active geothermal development zone

- 10MW test well at Olkaria field in Hell's Gate National Park, Kenya
- KenGen's first plant commissioned in 1985 (45MW) – now over 300MW at Olkaria

Results – Kenya (Energy mix for each scenario)



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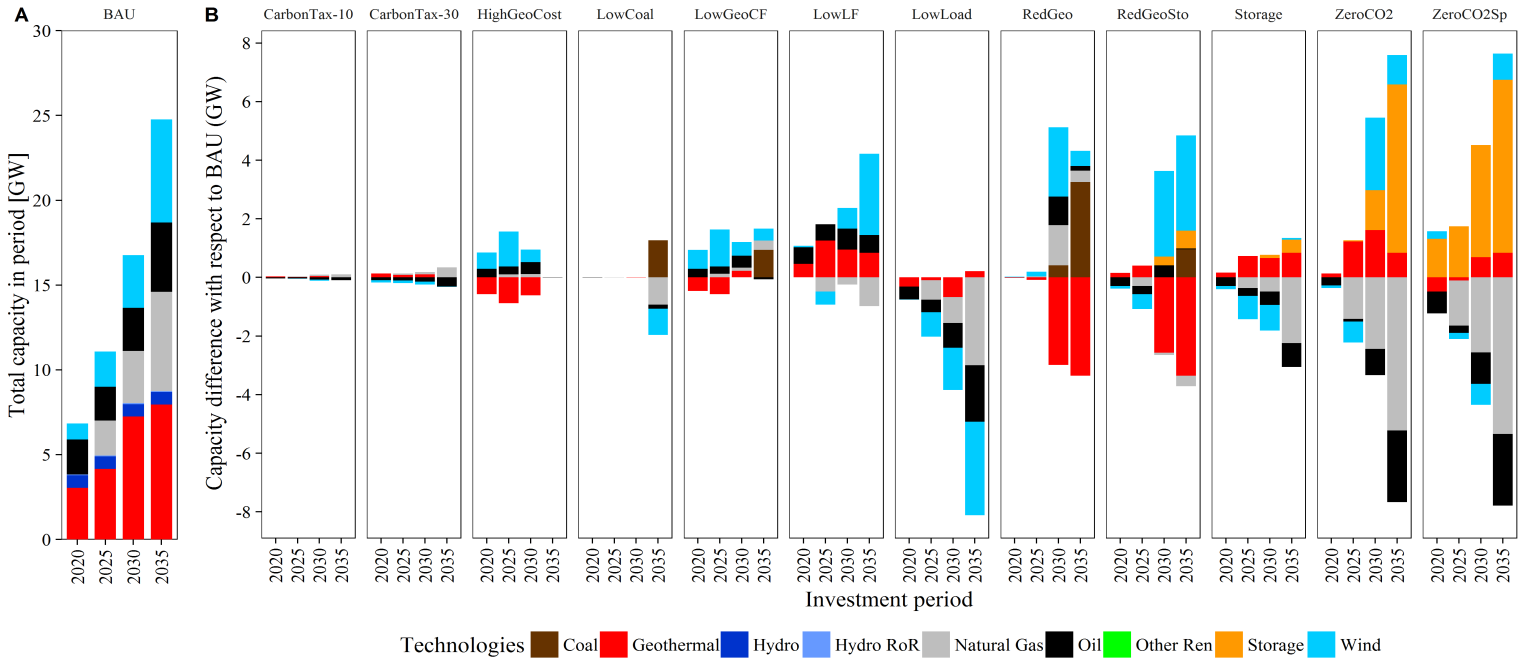
Kenya (Cumulative generation capacity expansion)



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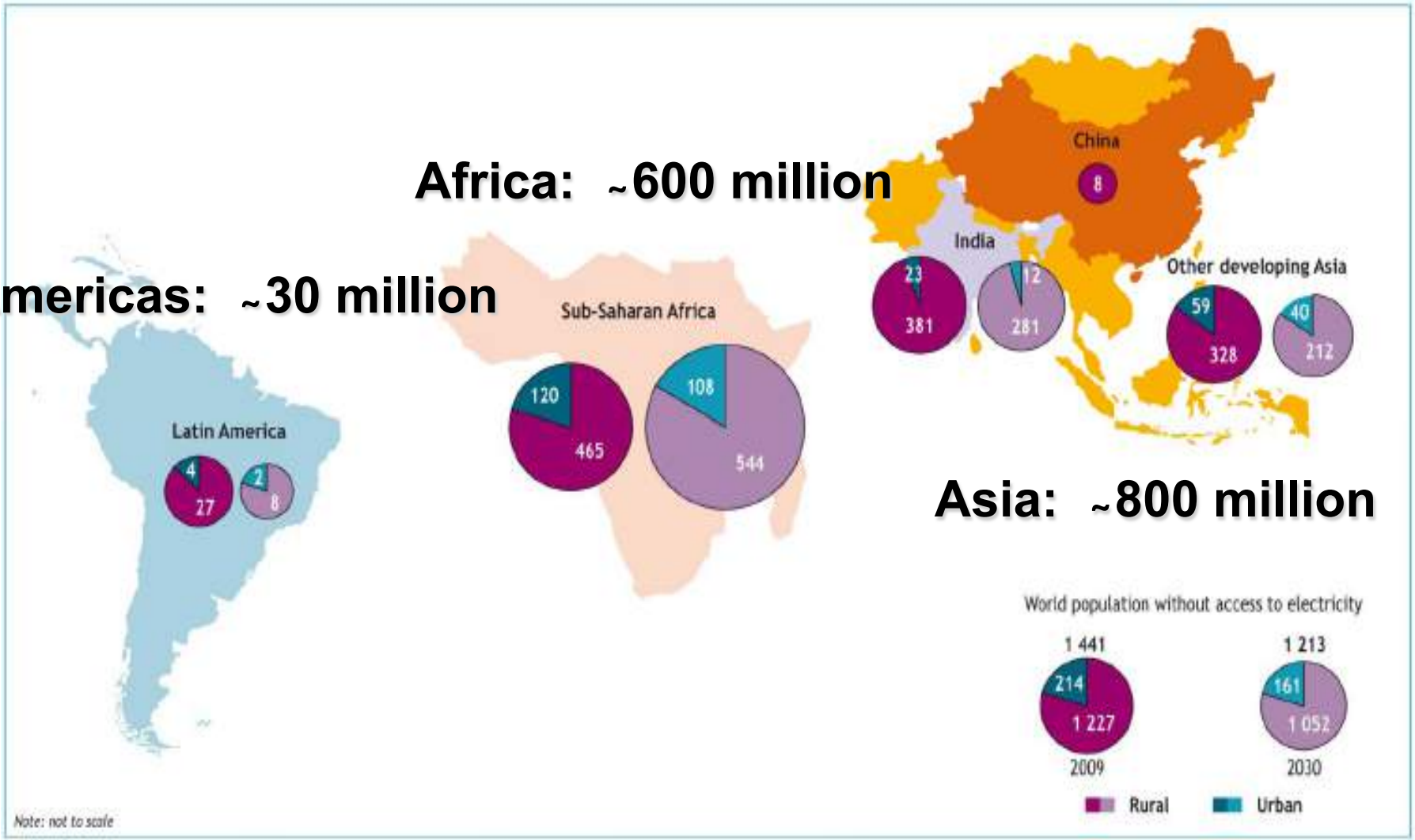
Unelectrified People (and fuel based lighting users) in Asia is Even Higher than in Africa



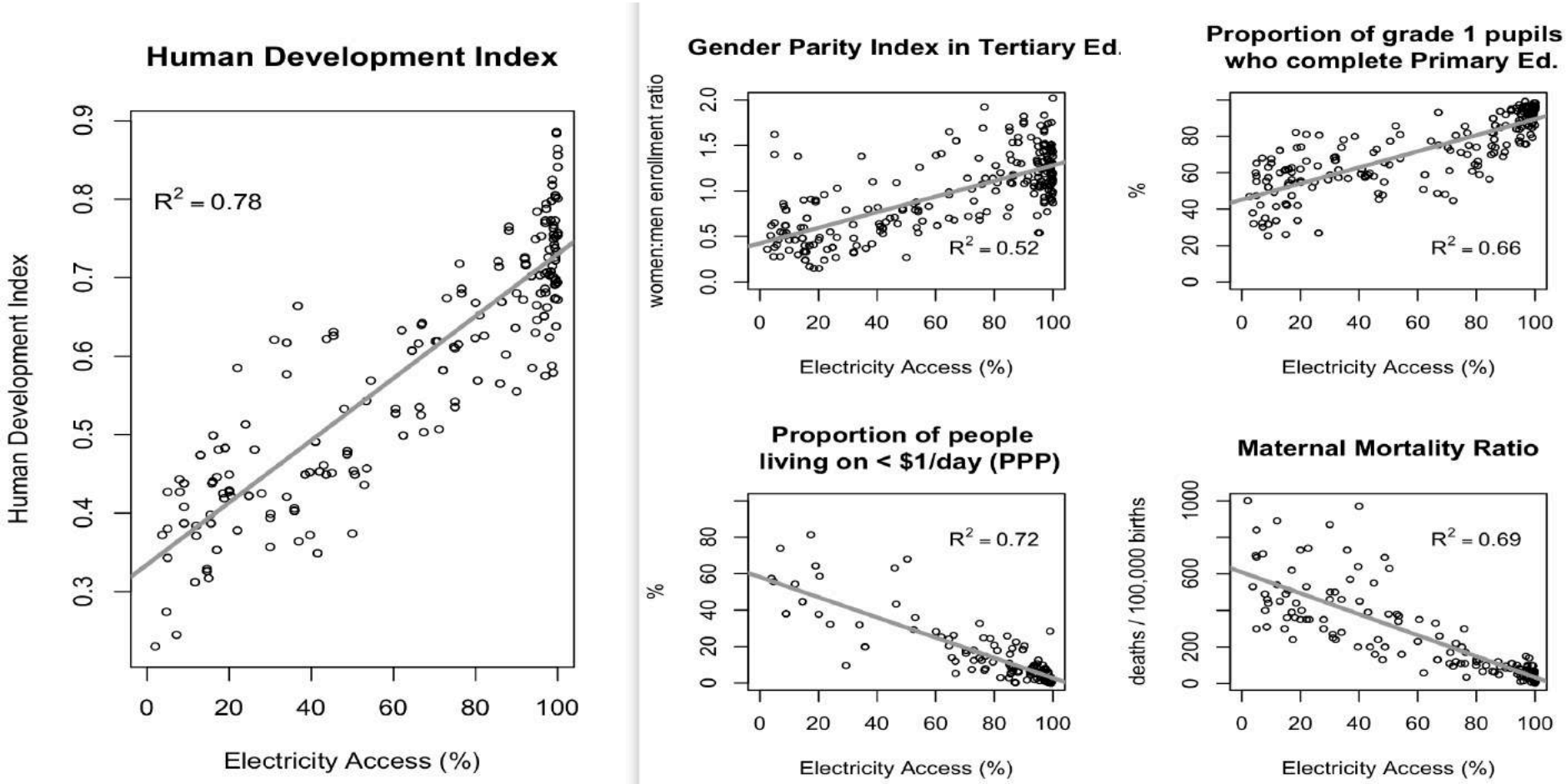
Source: IEA, 2010 World Energy Outlook

Fuel Based Lighting:
Displacing the Incumbent in Low-Income Areas

Fuel Based Lighting : Expensive, Unhealthy, and Inefficient

Kerosene for lighting is a $25 billion per year industry globally (source: UNEP, 2013)

Quantitative Assessments of the Sustainable Development Indicators

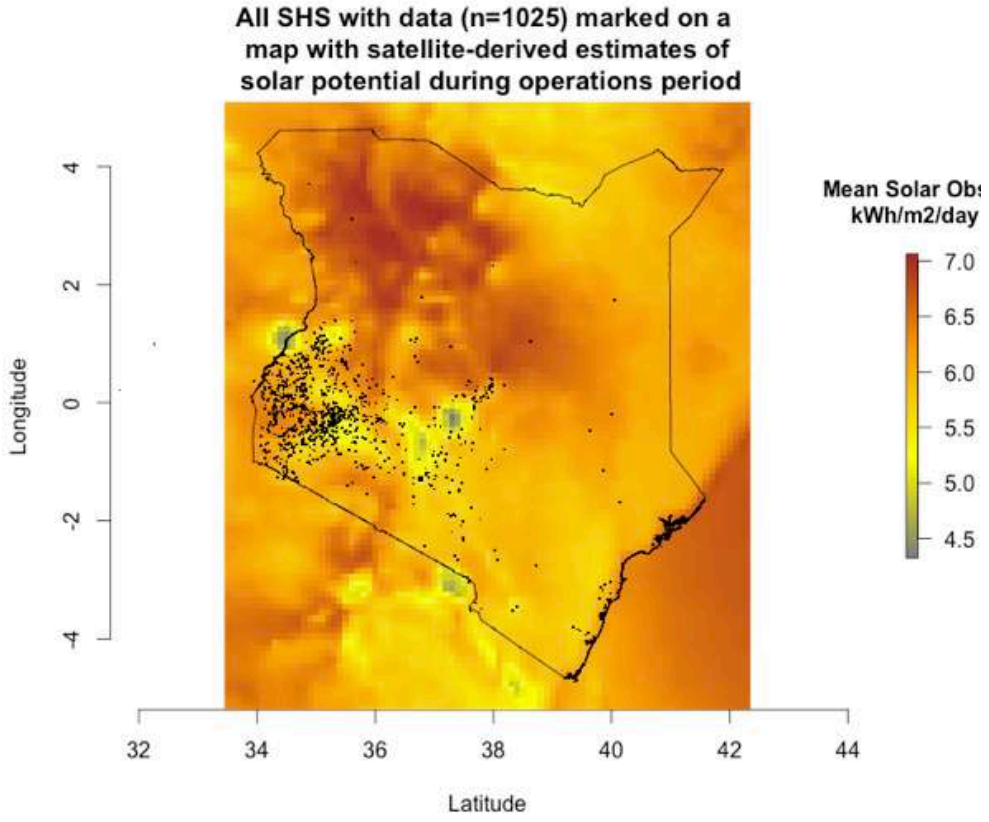


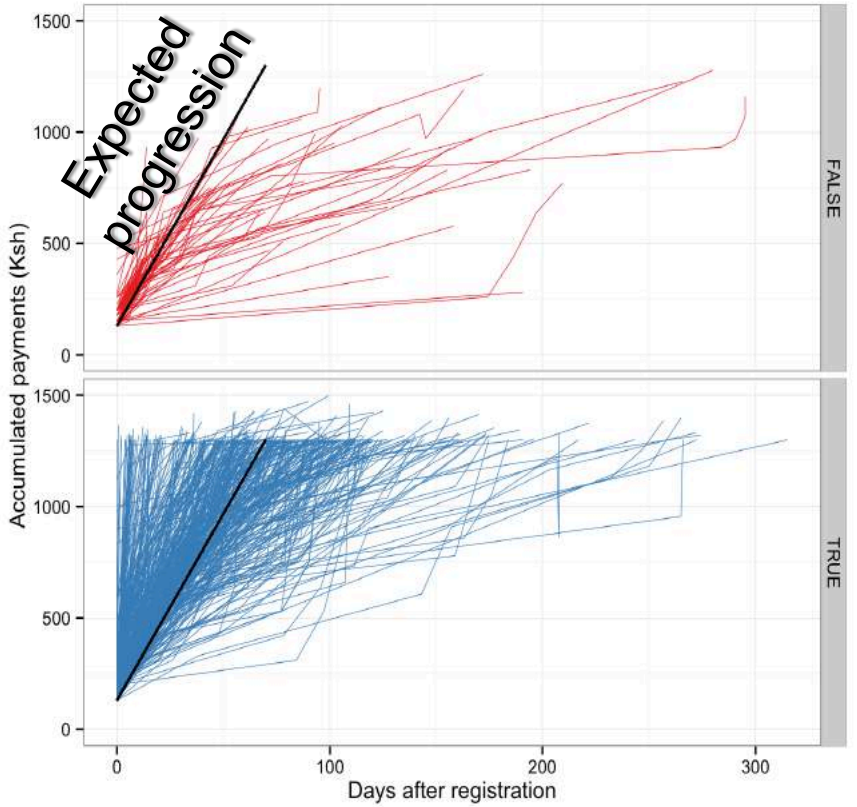
Alstone, Gershenson & Kammen, *Nature Climate Change*, 2015

Off-grid Electricity Enabled by Storage and Efficient Lights, but …

Impossible without secure mobile money

Information Technology Enables Transformative Energy Access Technologies





Information Technology Enables Transformative Energy Access Technologies

The Tragedy of the Commons

The population problem has no technical solution; it requires a fundamental extension in morality.

Garrett Hardin

At the end of a thoughtful article on the future of nuclear war, Wiesner and York (*1*) concluded that: "Both sides in the arms race are . . . confronted by the dilemma of steadily increasing military security. *It is our considered professional judgment that this dilemma has no technical solution.* If the great powers continue to look for solutions in the area of science and technology only, the result will be to worsen the situation."

sional judgment. . . ." Whether they were right or not is not the concern of the present article. Rather, the concern here is with the important concept of a class of human problems which can be called "no technical solution problems," and, more specifically, with the identification and discussion of one of these.

It is easy to show that the class is not a null class. Recall the game of tick-tack-toe. Consider the problem, "How can I win the game of tick-tack-toe?" It is well known that I cannot, if I as-

What Shall We Maximize?

Population, as Malthus said, naturally tends to grow "geometrically," or, as we would now say, exponentially. In a finite world this means that the per capita share of the world's goods must steadily decrease. Is ours a finite world?

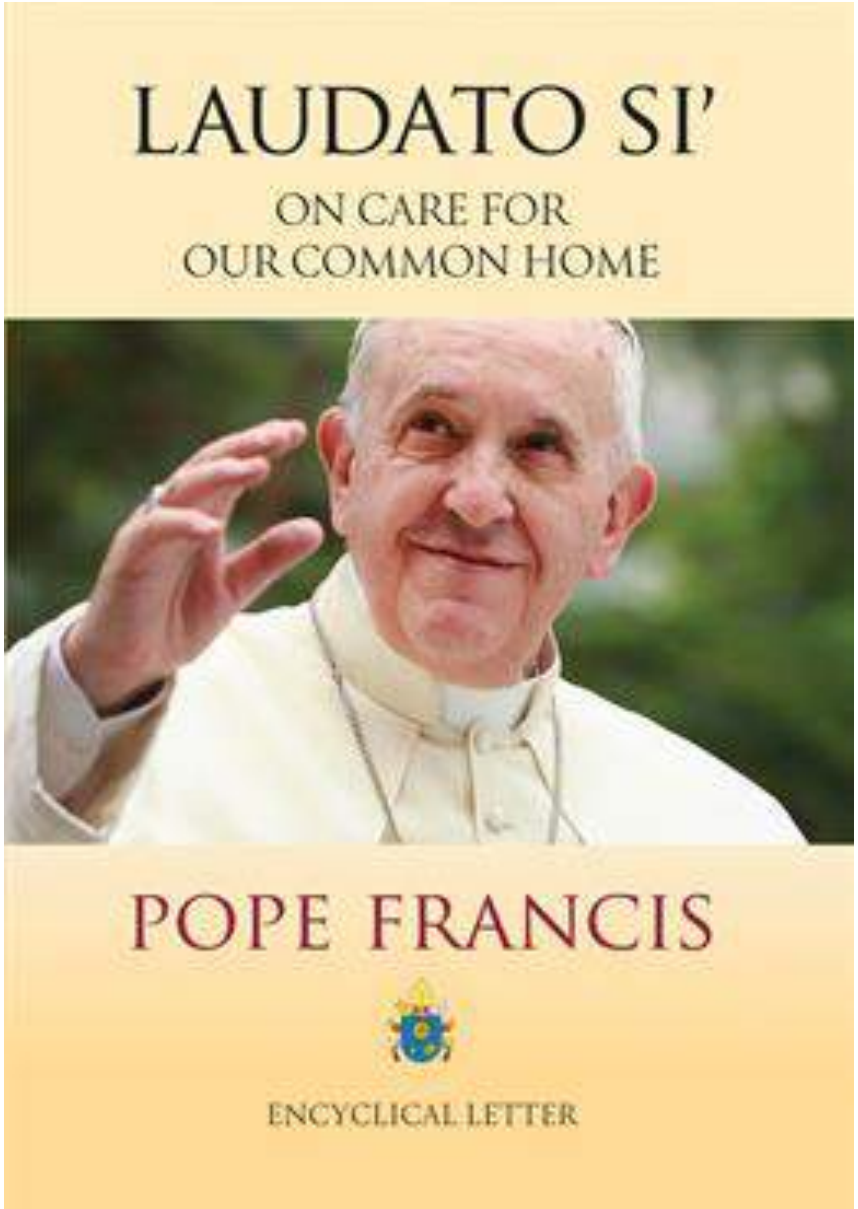
A fair defense can be put forward for the view that the world is infinite; or that we do not know that it is not. But, in terms of the practical problems that we must face in the next few generations with the foreseeable technology, it is clear that we will greatly increase human misery if we do not, during the immediate future, assume that the world available to the terrestrial human population is finite. "Space" is no escape (*2*).

A finite world can support only a finite population; therefore, population growth must eventually equal zero. (The case of perpetual wide fluctuations above and below zero is a trivial variant that need not be discussed.) When this condition is met, what will be the situation of mankind? Specifically, can Bentham's goal of "the greatest good for the greatest number" be realized?

No—for two reasons, each sufficient

Science, New Series, Vol. 162, No. 3859 (Dec. 13, 1968), 1243-1248.

Laudato Si
Encyclical Letter on Care for our Common Home



Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density

Christopher Jones*,† and Daniel M. Kammen*,†,‡,§

†Energy and Resources Group, ‡Goldman School of Public Policy, and §Department of Nuclear Engineering, University of California, Berkeley, California 94720, United States

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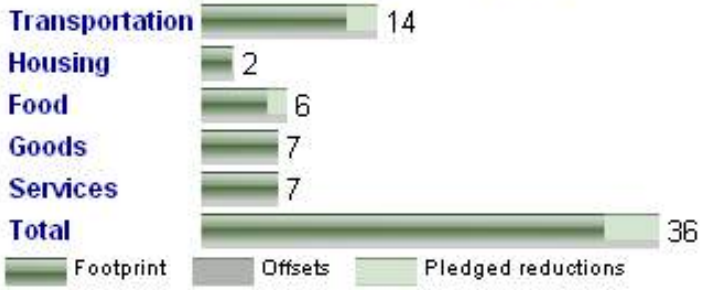
  Heavy civil general engineering construction company...
- The Living Christmas Company

Carbon Footprint Summary (tons CO_2e / year)



Climate Action Plan Summary

MY CURRENT FOOTPRINT	41	100%
Pledged reductions	5	12%
Offsets	0	0%
MY NEW FOOTPRINT	36	88%

financial savings per yr	$2223
10 year net savings	$20321
Payback	0.9

1) Click view / hide 2) Pledge 3) Save

Assumptions

Pledge all

			mt CO2e/yr reduced	$ / yr saved	10 year net savings
✔	view	Buy a More Efficient Vehicle	1.86	$500	$3000
✔	view	Telecommute to Work	1.07	$528	$5280
	view	Ride my Bike	0.58	$156	$1560
	view	Take Public Transportation	0.47	$156	$1560
	view	Practice Eco-Driving	0.93	$249	$2490
	view	Maintain my Vehicles	0.71	$190	$1900
	view	Reduce Air Travel	0.45	$100	$1000
	view	Offset Remaining Transportation Footprint	13.07	$-261	$-2610
✔	view	Switch to CFLs	0.18	$63	$721
	view	Turn Down Thermostat in Winter	0.52	$95	$950
	view	Turn up Thermostat in Summer	0.15	$54	$540
	view	Choose an Energy Star Refrigerator	0.05	$17	$140
	view	Dry your Clothes on the Line	0.22	$75	$750
	view	Purchase Green Electricity	0	$0	$0

Environmental Science & Technology

Policy Analysis

pubs.acs.org/est

Spatial Distribution of U.S. Household Carbon Footprints Reveals Suburbanization Undermines Greenhouse Gas Benefits of Urban Population Density

Christopher Jones*,† and Daniel M. Kammen*,†,‡,§

†Energy and Resources Group, ‡Goldman School of Public Policy, and §Department of Nuclear Engineering, University of California, Berkeley, California 94720, United States

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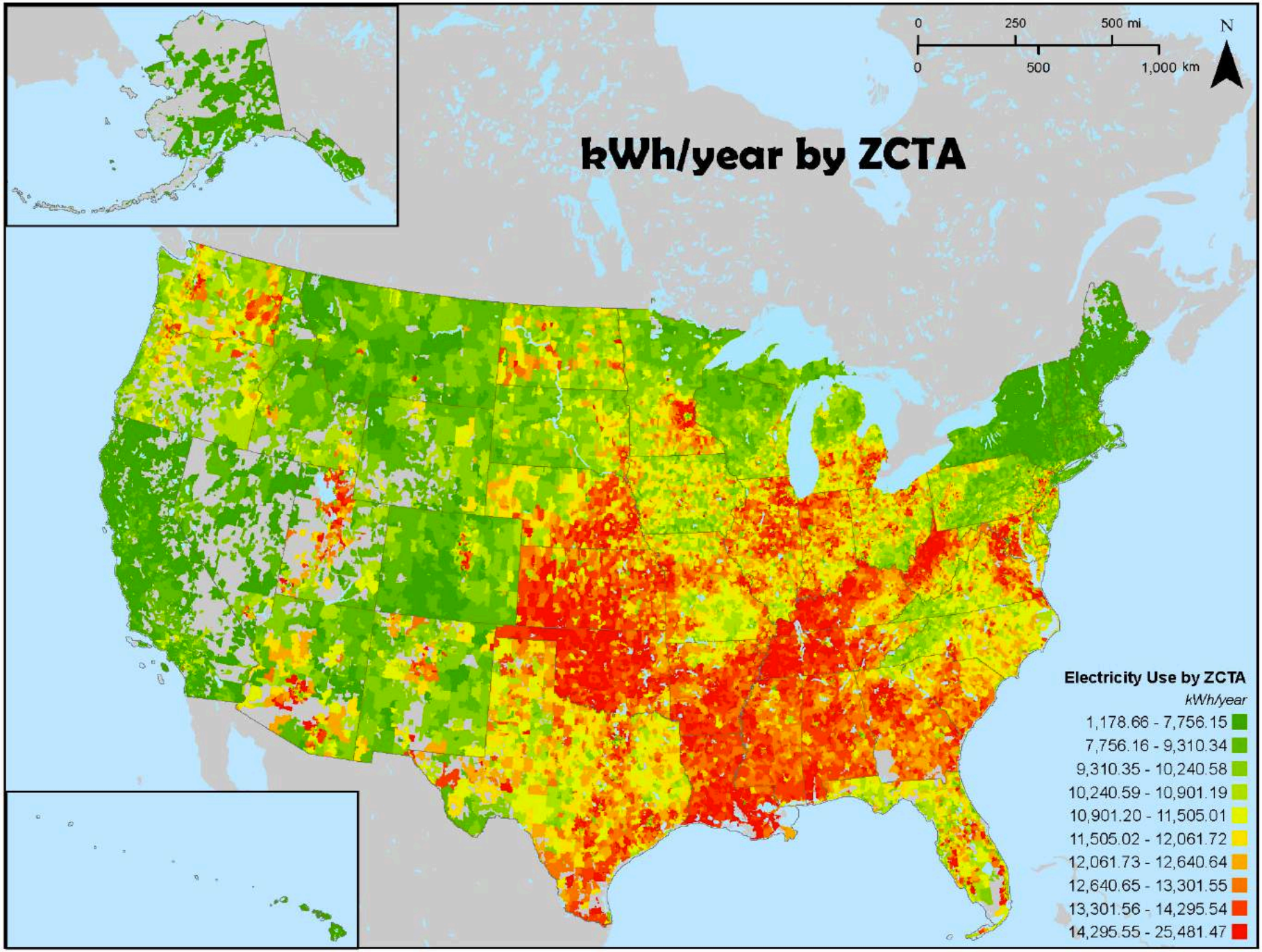
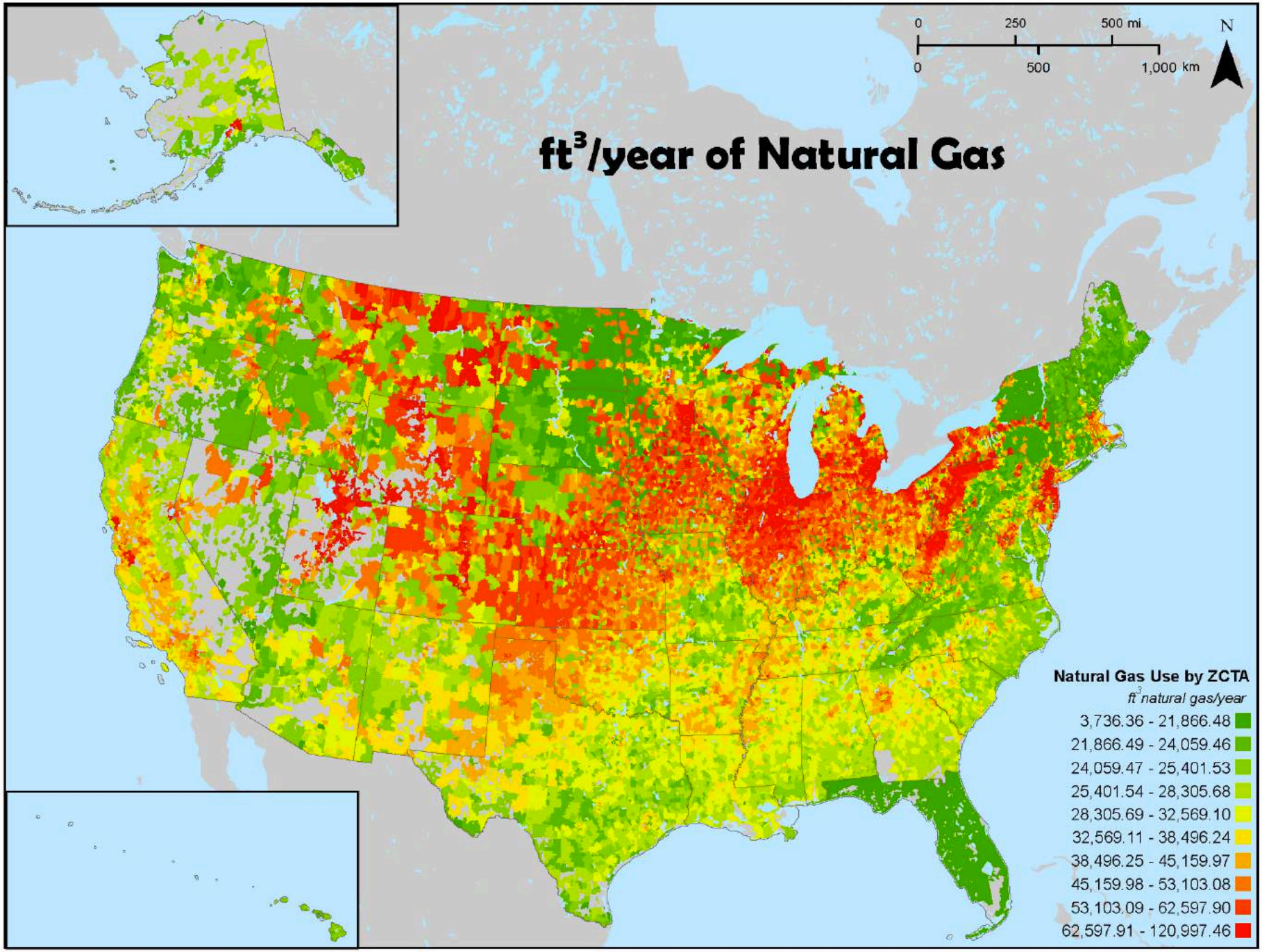
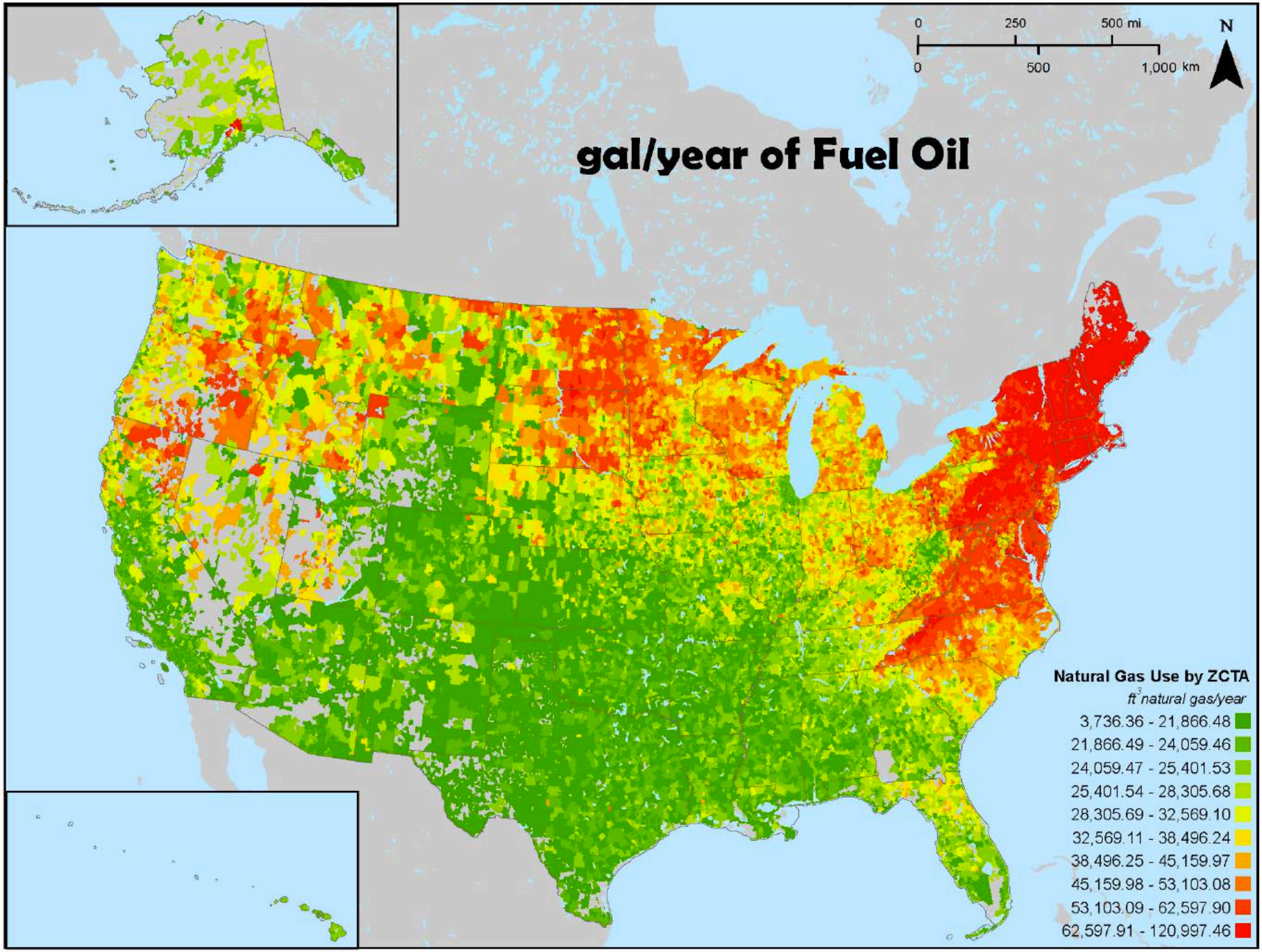
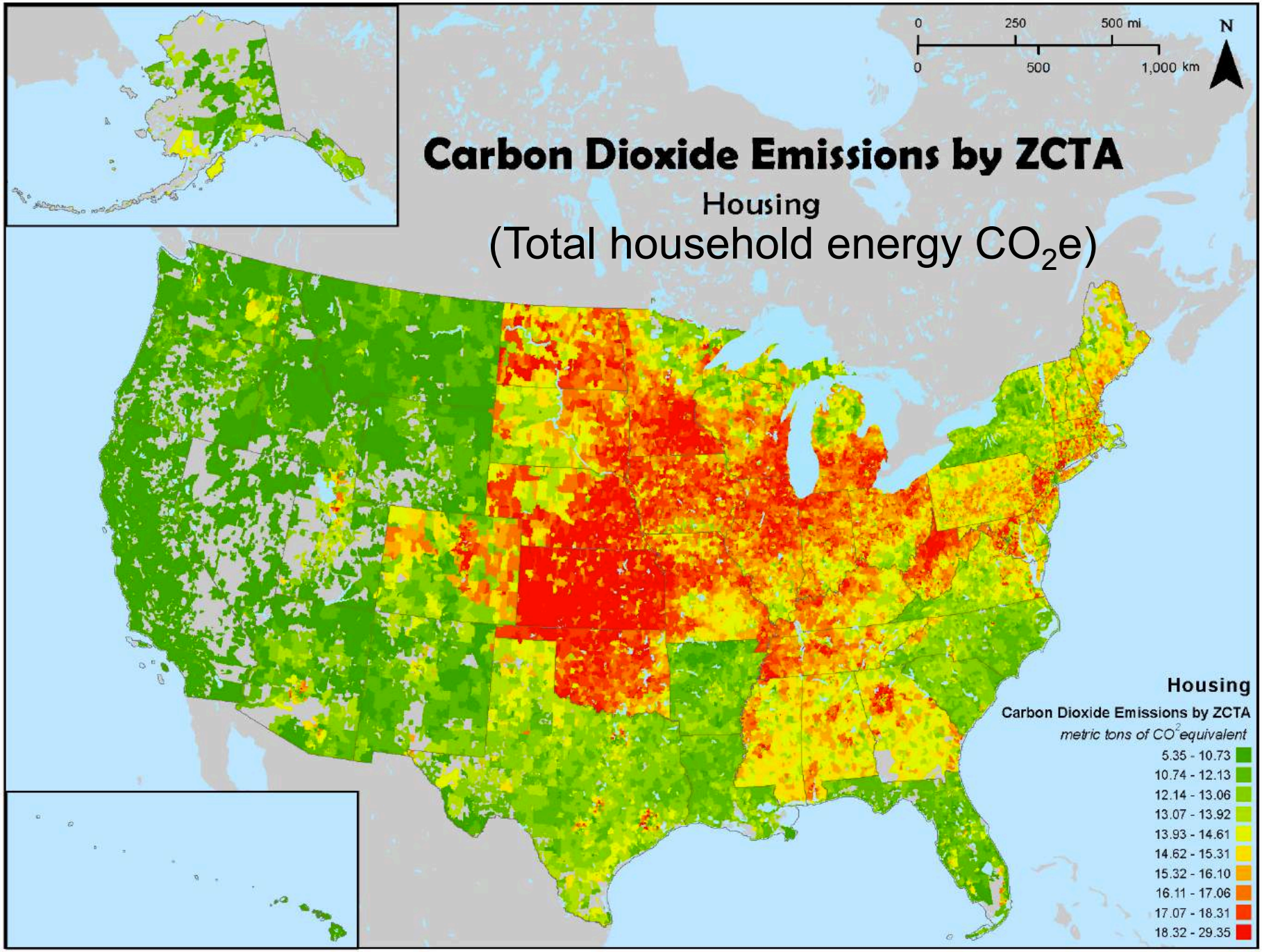
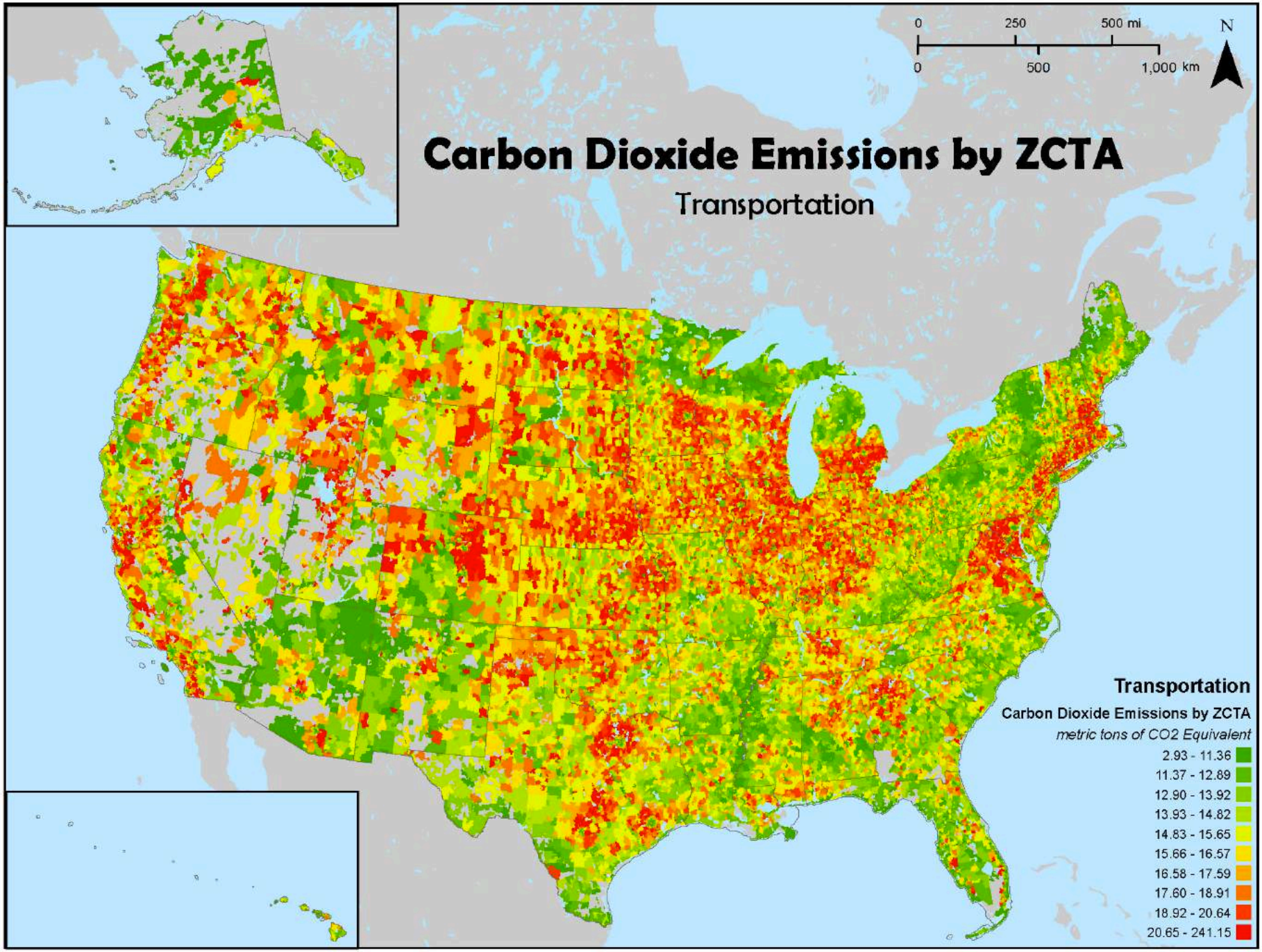
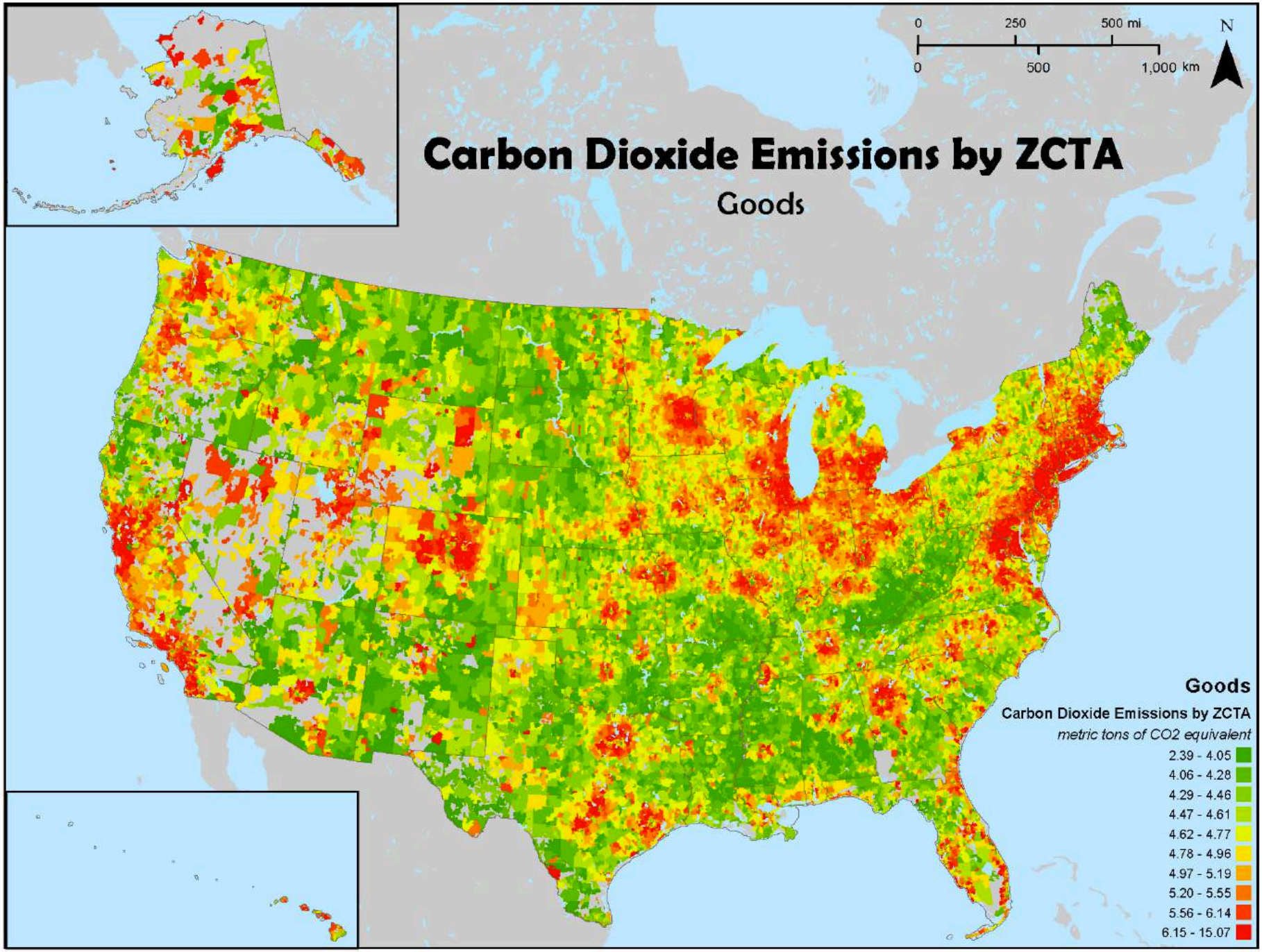

0
250
500 mi
0
500
1,000 km
N
kWh/year by ZCTA
Electricity Use by ZCTA
kWh/year
1,178.66 - 7,756.15
7,756.16 - 9,310.34
9,310.35 - 10,240.58
10,240.59 - 10,901.19
10,901.20 - 11,505.01
11,505.02 - 12,061.72
12,061.73 - 12,640.64
12,640.65 - 13,301.55
13,301.56 - 14,295.54
14,295.55 - 25,481.47

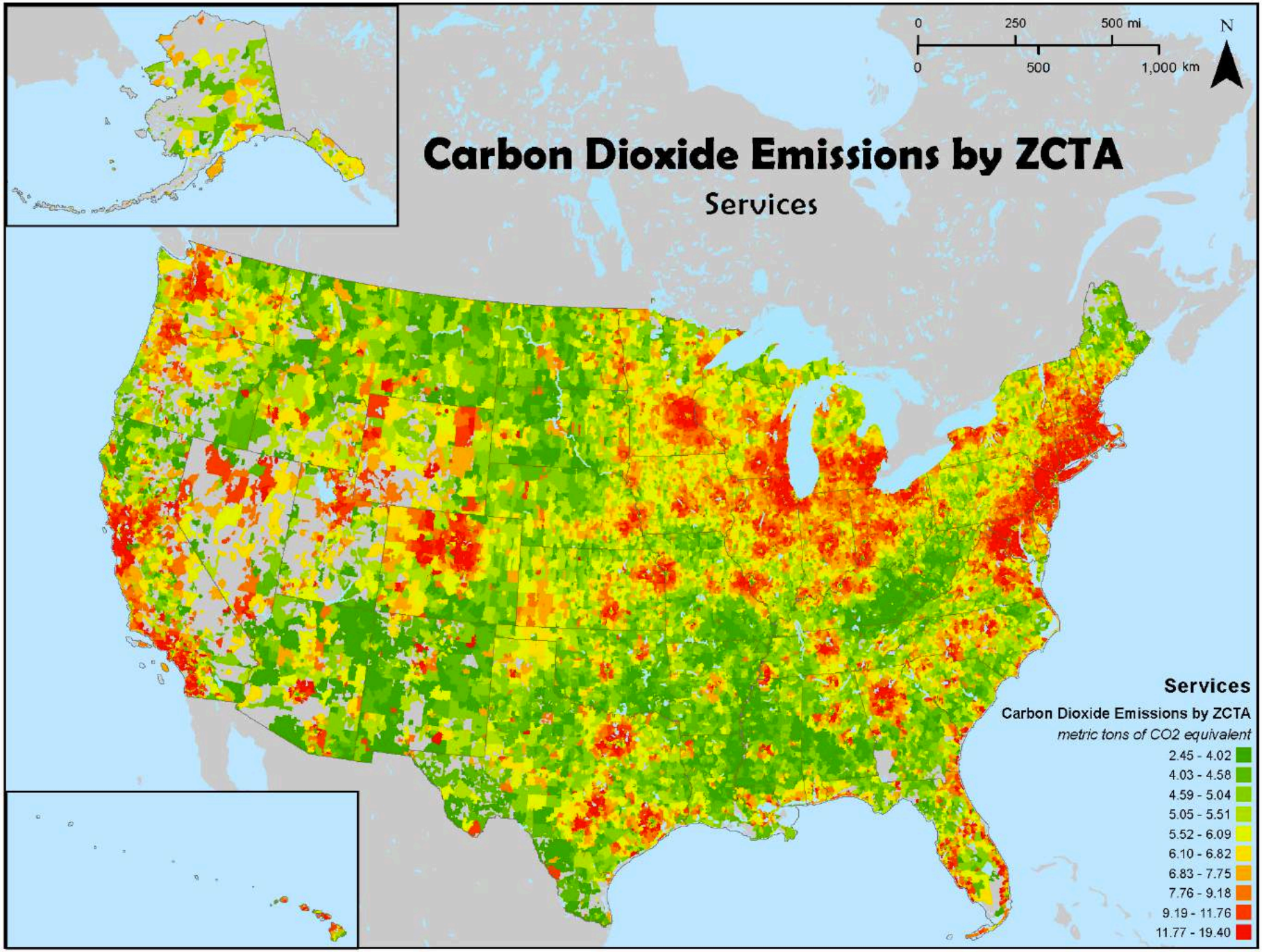

0
250
500 mi
0
500
1,000 km
N
ft³/year of Natural Gas
Natural Gas Use by ZCTA
ft³ natural gas/year
3,736.36 - 21,866.48
21,866.49 - 24,059.46
24,059.47 - 25,401.53
25,401.54 - 28,305.68
28,305.69 - 32,569.10
32,569.11 - 38,496.24
38,496.25 - 45,159.97
45,159.98 - 53,103.08
53,103.09 - 62,597.90
62,597.91 - 120,997.46

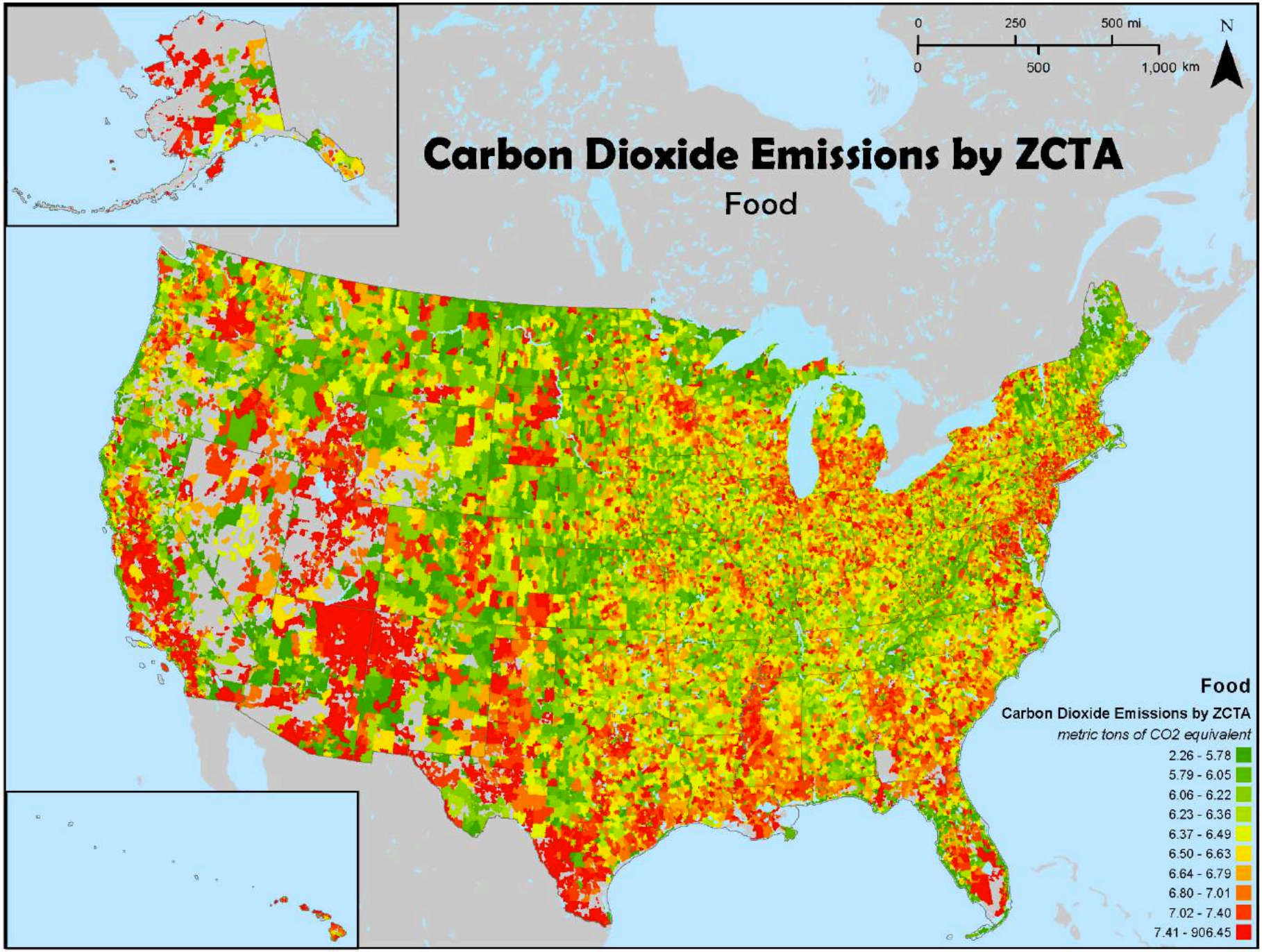

0
250
500 mi
0
500
1,000 km
N
gal/year of Fuel Oil
Natural Gas Use by ZCTA
ft³ natural gas/year
3,736.36 - 21,866.48
21,866.49 - 24,059.46
24,059.47 - 25,401.53
25,401.54 - 28,305.68
28,305.69 - 32,569.10
32,569.11 - 38,496.24
38,496.25 - 45,159.97
45,159.98 - 53,103.08
53,103.09 - 62,597.90
62,597.91 - 120,997.46

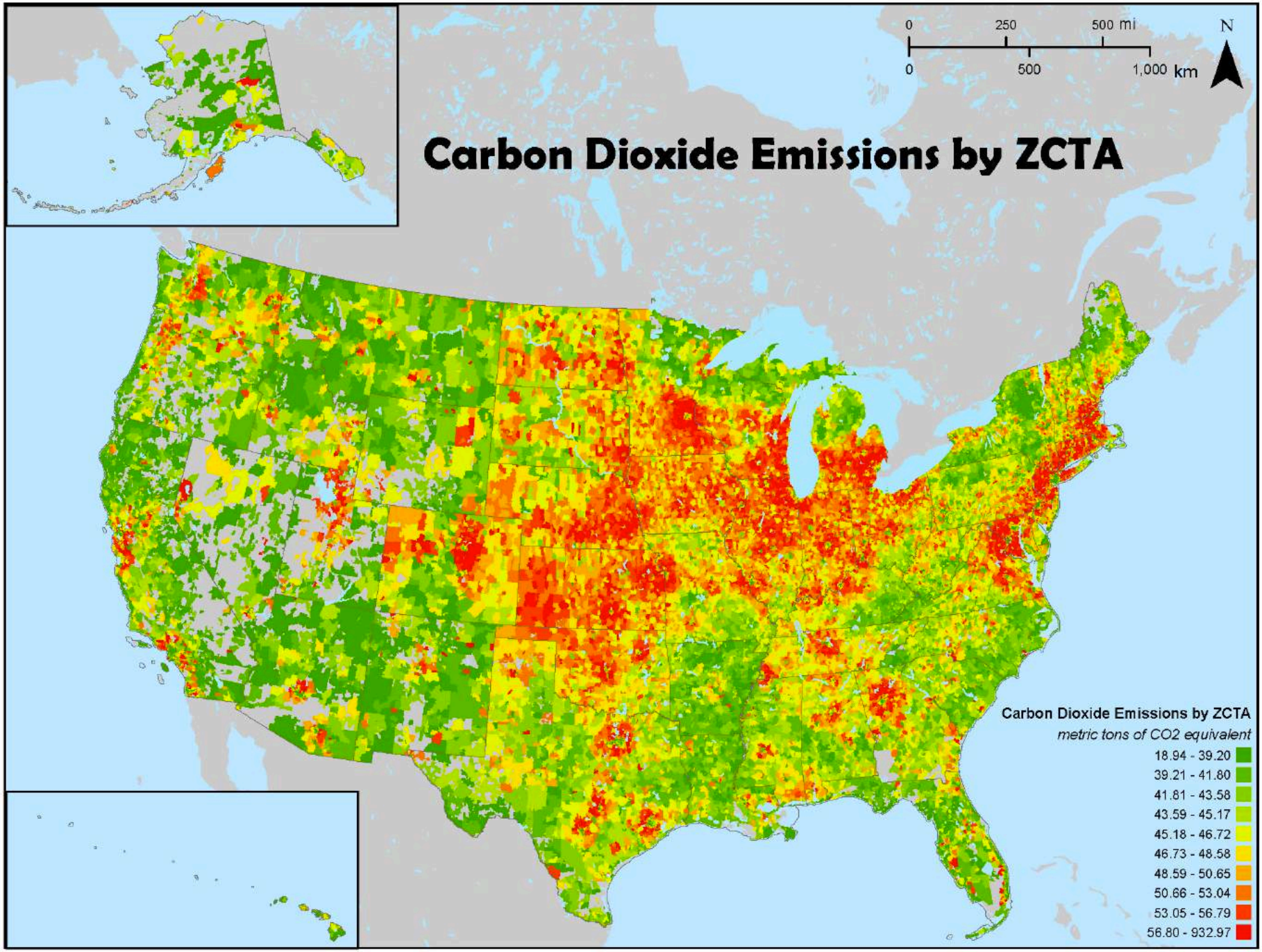

0
250
500 mi
0
500
1,000 km
N
Carbon Dioxide Emissions by ZCTA
Housing
(Total household energy CO_2e)
Housing
Carbon Dioxide Emissions by ZCTA
metric tons of CO^2 equivalent
5.35 - 10.73
10.74 - 12.13
12.14 - 13.06
13.07 - 13.92
13.93 - 14.61
14.62 - 15.31
15.32 - 16.10
16.11 - 17.06
17.07 - 18.31
18.32 - 29.35


0
250
500 mi
0
500
1,000 km
N
Carbon Dioxide Emissions by ZCTA
Transportation
Transportation
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 Equivalent
2.93 - 11.36
11.37 - 12.89
12.90 - 13.92
13.93 - 14.82
14.83 - 15.65
15.66 - 16.57
16.58 - 17.59
17.60 - 18.91
18.92 - 20.64
20.65 - 241.15

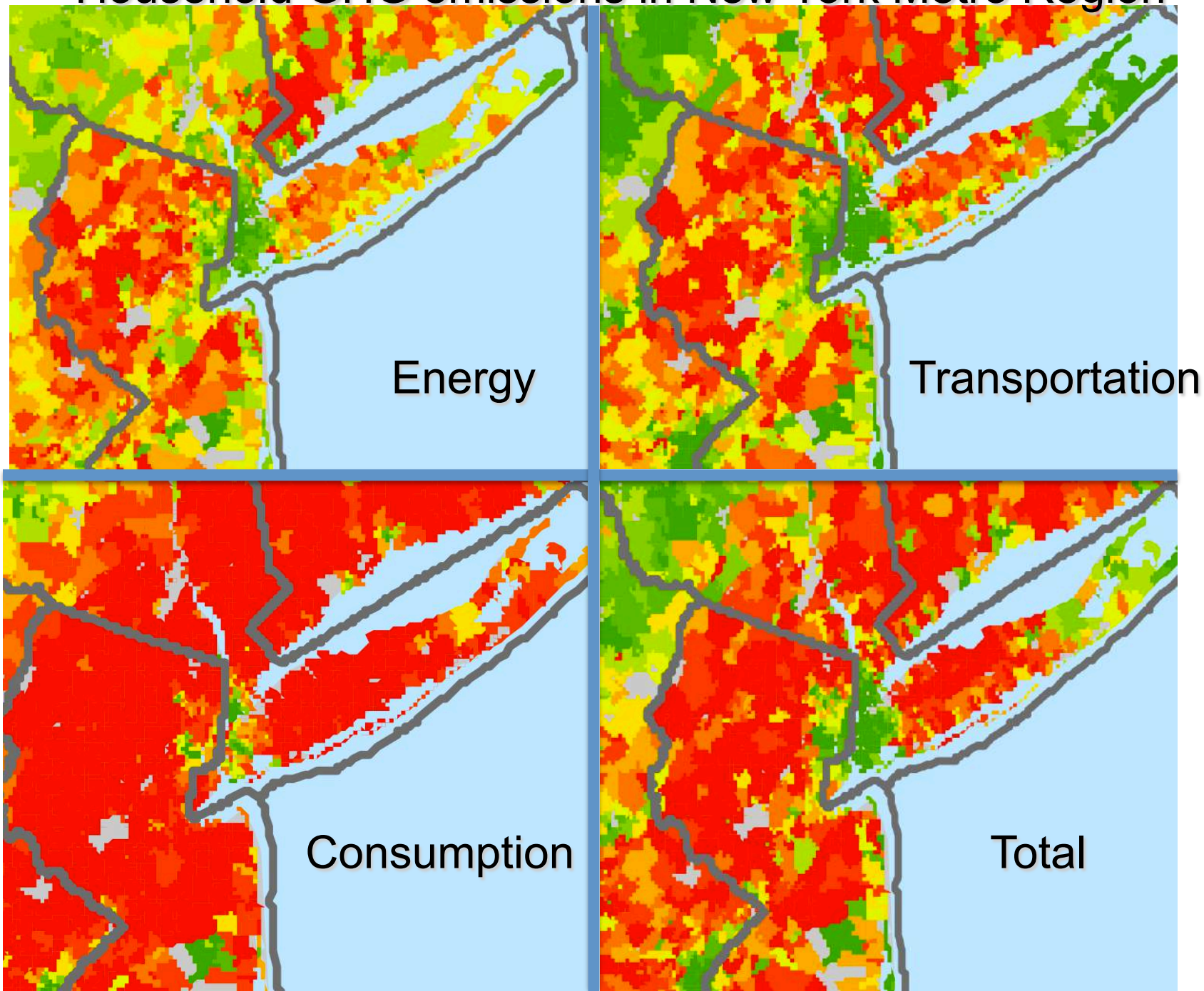

0
250
500 mi
0
500
1,000 km
N
Carbon Dioxide Emissions by ZCTA
Goods
Goods
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 equivalent
2.39 - 4.05
4.06 - 4.28
4.29 - 4.46
4.47 - 4.61
4.62 - 4.77
4.78 - 4.96
4.97 - 5.19
5.20 - 5.55
5.56 - 6.14
6.15 - 15.07

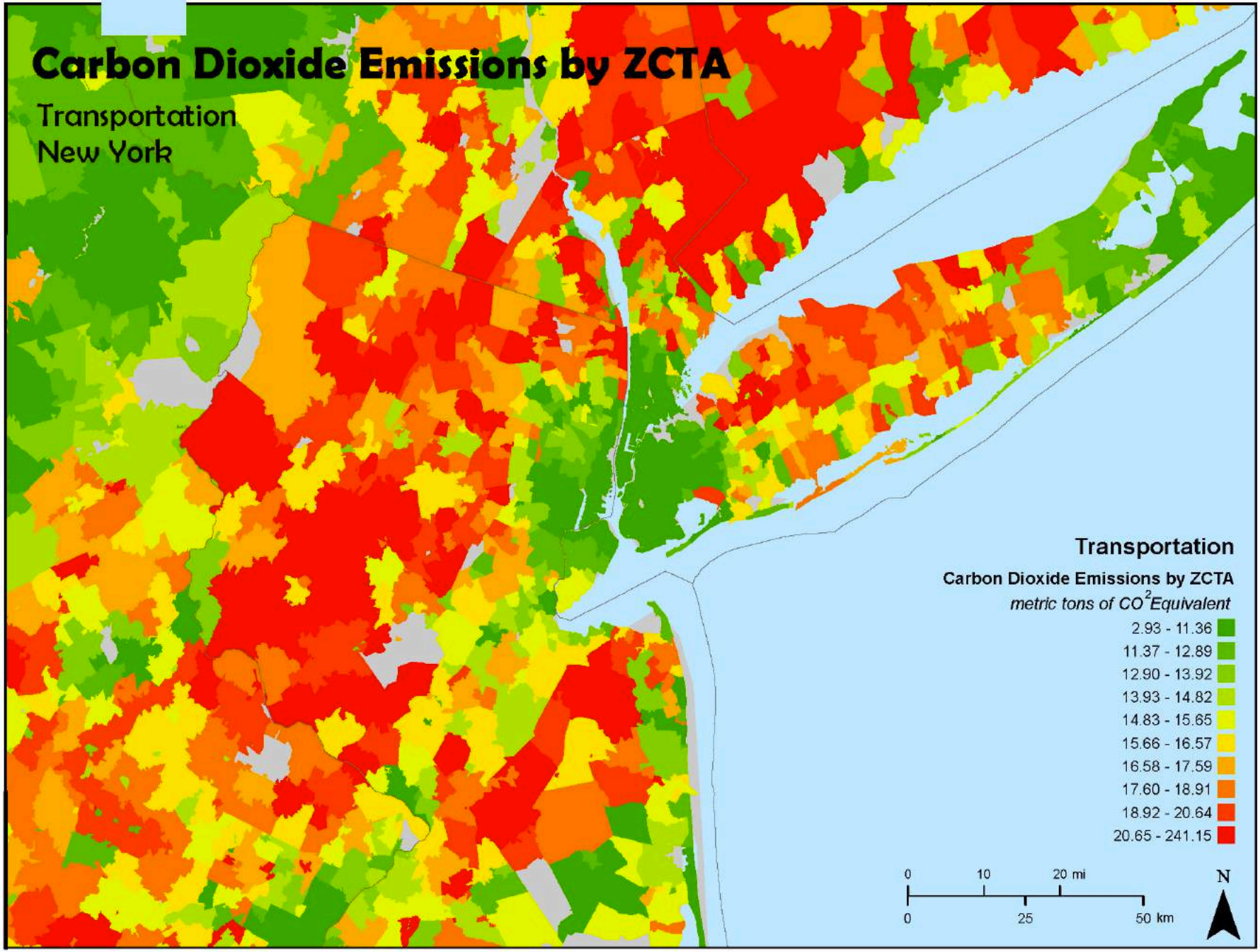

0
250
500 mi
0
500
1,000 km
N
Carbon Dioxide Emissions by ZCTA
Services
Services
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 equivalent
2.45 - 4.02
4.03 - 4.58
4.59 - 5.04
5.05 - 5.51
5.52 - 6.09
6.10 - 6.82
6.83 - 7.75
7.76 - 9.18
9.19 - 11.76
11.77 - 19.40


0
250
500 mi
0
500
1,000 km
N
Carbon Dioxide Emissions by ZCTA
Food
Food
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 equivalent
2.26 - 5.78
5.79 - 6.05
6.06 - 6.22
6.23 - 6.36
6.37 - 6.49
6.50 - 6.63
6.64 - 6.79
6.80 - 7.01
7.02 - 7.40
7.41 - 906.45

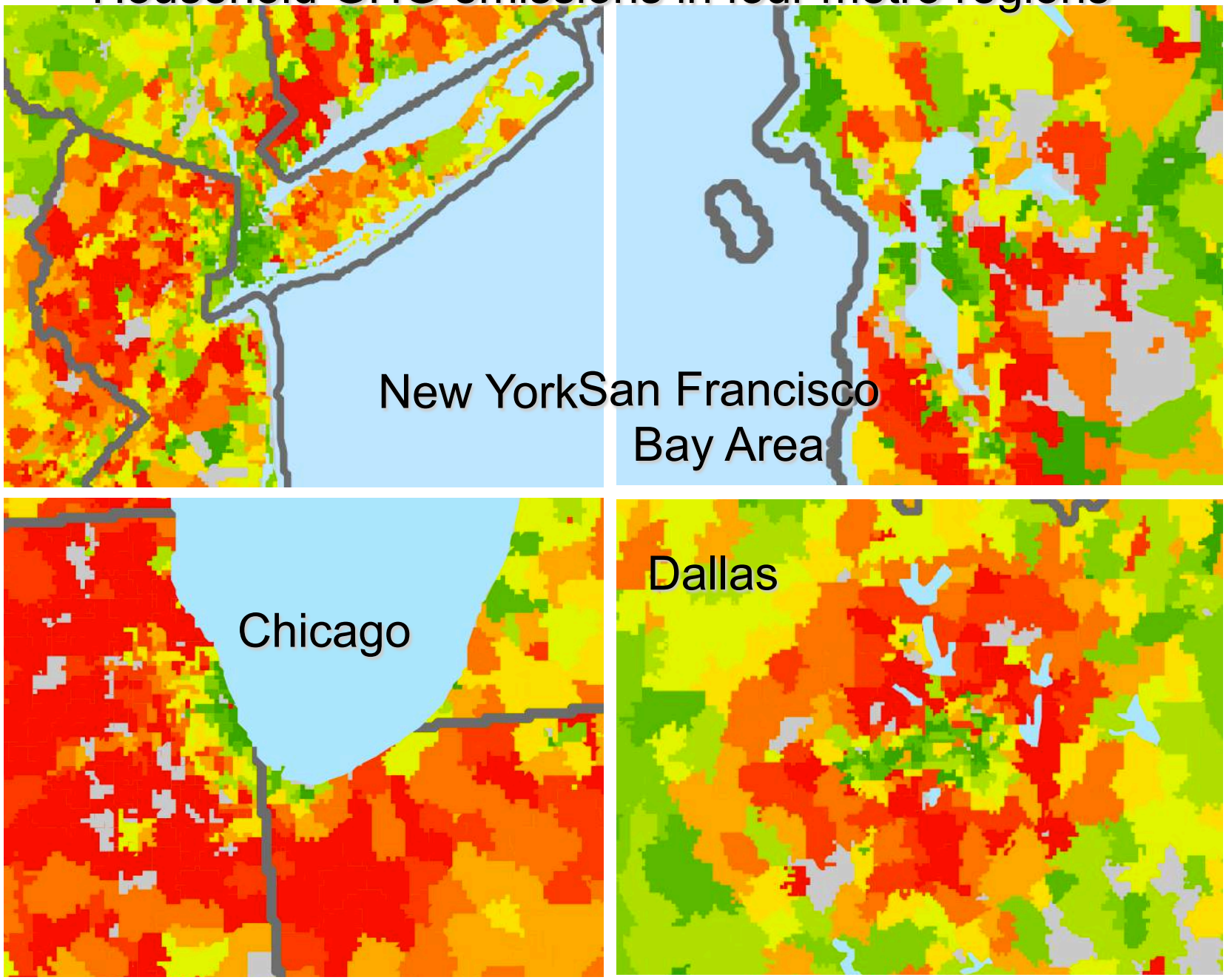

0 250 500 mi
0 500 1,000 km
N
Carbon Dioxide Emissions by ZCTA
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 equivalent
18.94 - 39.20
39.21 - 41.80
41.81 - 43.58
43.59 - 45.17
45.18 - 46.72
46.73 - 48.58
48.59 - 50.65
50.66 - 53.04
53.05 - 56.79
56.80 - 932.97

Household GHG emissions in New York Metro Region

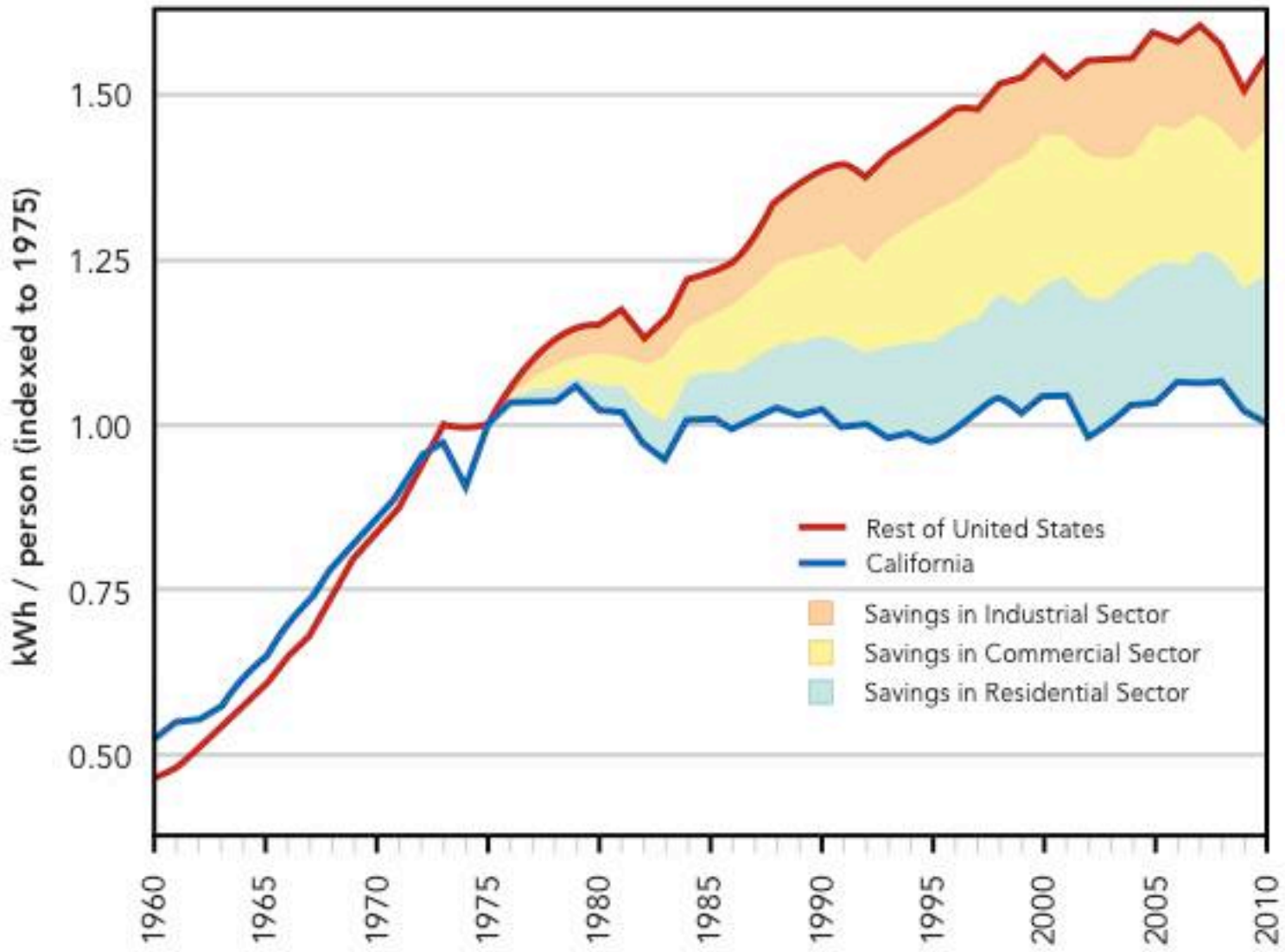


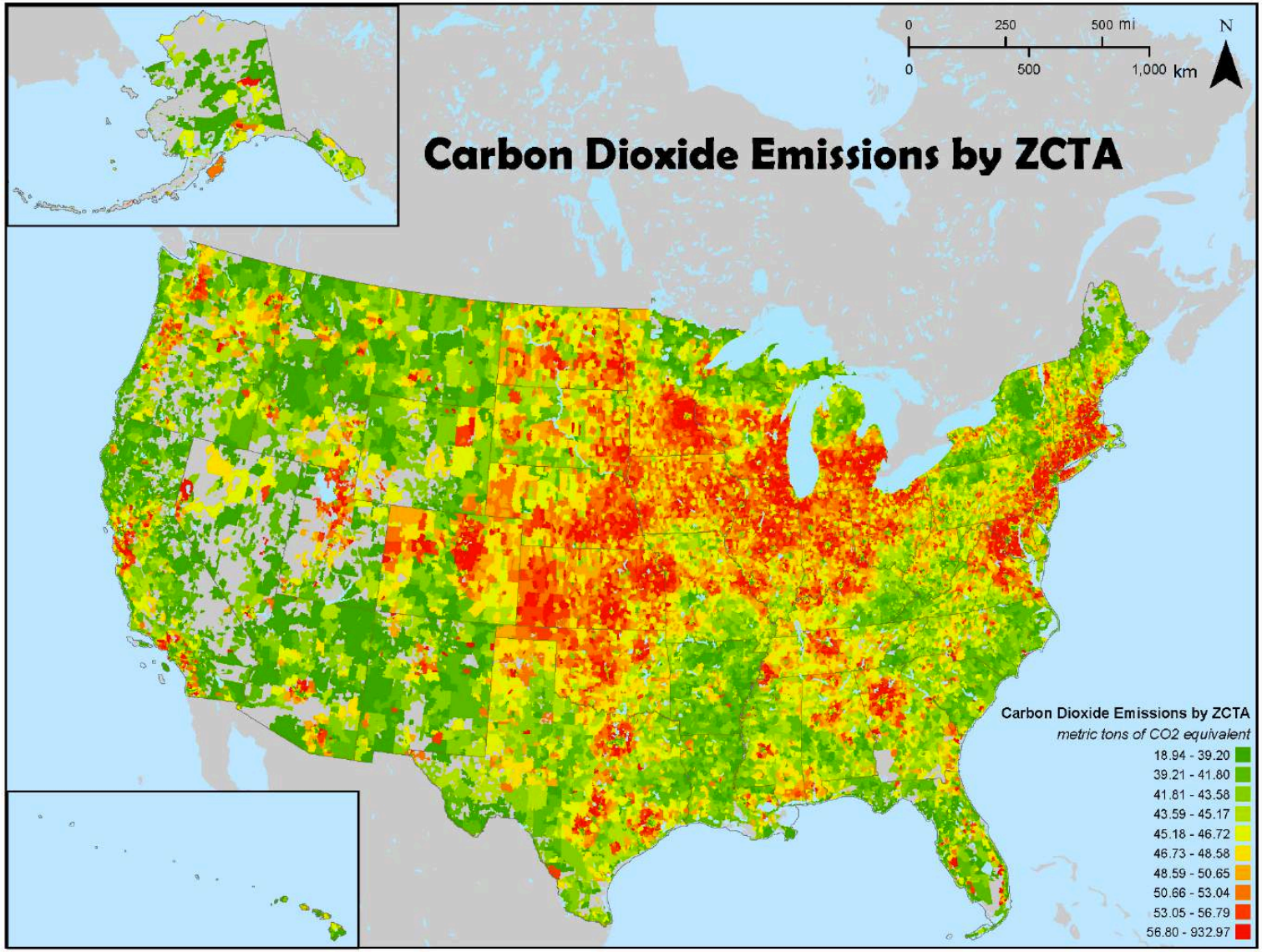

Carbon Dioxide Emissions by ZCTA
Transportation
New York
Transportation
Carbon Dioxide Emissions by ZCTA
metric tons of CO2 Equivalent
2.93 - 11.36
11.37 - 12.89
12.90 - 13.92
13.93 - 14.82
14.83 - 15.65
15.66 - 16.57
16.58 - 17.59
17.60 - 18.91
18.92 - 20.64
20.65 - 241.15
0
10
20 mi
0
25
50 km
N

Household GHG emissions in four metro regions



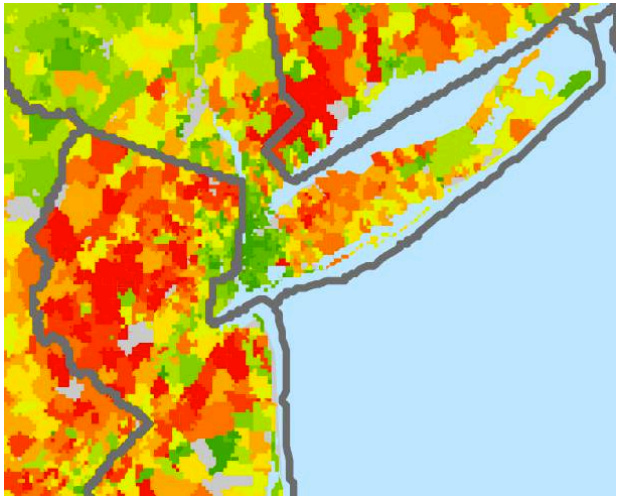
California Advancing Energy Efficiency



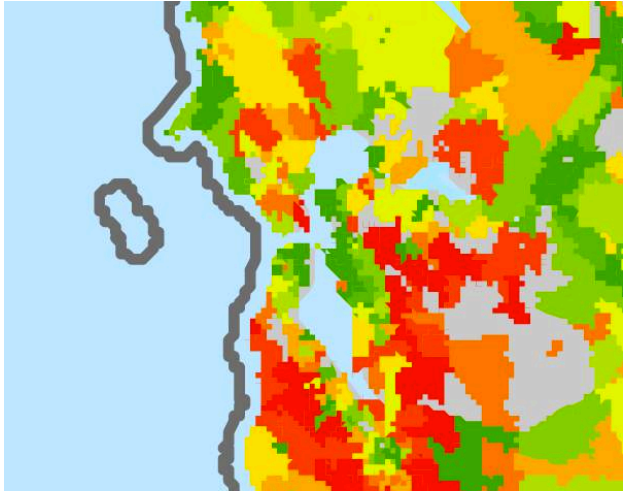


Jones and Kammen, 2014

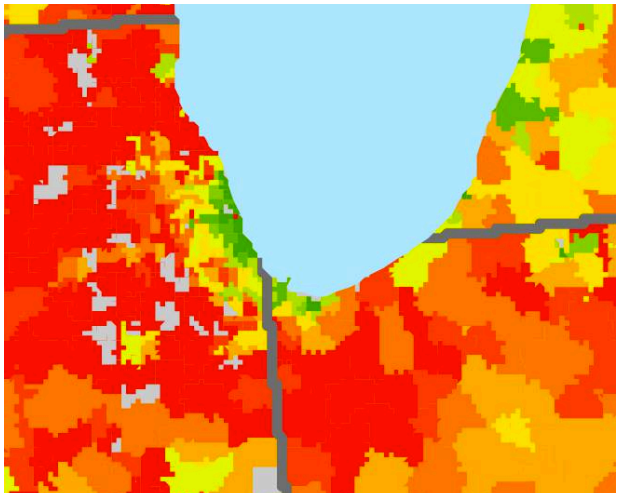
http://coolclimate.berkeley.edu/maps



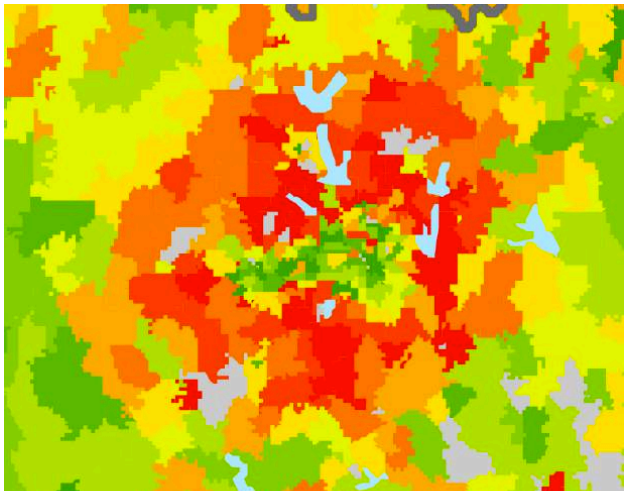
New York



San Francisco
Bay Area



Chicago



Dallas

Jones and Kammen, 2014

http://coolclimate.berkeley.edu/maps

Takeaway message:

Scientific and technical transformations are critical to enabling a sustainable energy system, but it is the energy-information nexus that provides the 'killer app' for change