An energy plan the Earth can live with

Daniel Kammen

Energy and Resources Group
& Goldman School of Public Policy
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Director, Renewable and Appropriate Energy Laboratory
University of California, Berkeley

Former Science Envoy, US Department of State
Overview

• Introduction to RAEL, the Renewable and Appropriate Energy Laboratory

• Energy systems in transition

• Innovation theory for decarbonization

• Innovation practice for a healthy planet
Overview

• Introduction to RAEL, the Renewable and Appropriate Energy Laboratory
• Energy systems in transition
• Innovation theory for decarbonization
• Innovation practice for a healthy planet
Collective Frequencies and Metastability in Networks of Limit-Cycle Oscillators with Time Delay

Ernst Niebur, Heinz G. Schuster, (a) and Daniel M. Kammen (b)

Computation and Neural Systems Program, California Institute of Technology, Pasadena, California 91125
(Received 20 March 1991)

We analyze the dynamic behavior of large two-dimensional systems of limit-cycle oscillators with random intrinsic frequencies that interact via time-delayed nearest-neighbor coupling. We find that even small delay times lead to a novel form of frequency depression where the system decays to stable states which oscillate at a delay and interaction-dependent reduced collective frequency. For greater delay or tighter coupling between oscillators we find metastable synchronized states that we describe analytically and numerically.

Oscillator-phase coupling for different two-dimensional network connectivities

Ernst Niebur, Heinz G. Schuster, Daniel M. Kammen, and Christof Koch
Computation and Neural Systems Program, California Institute of Technology 216-78, Pasadena, California 91125
(Received 7 June 1991)

We investigate the dynamics of large arrays of coupled phase oscillators driven by random intrinsic frequencies under a variety of coupling schemes, by computing the time-dependent cross-correlation function numerically for a two-dimensional array consisting of 128 x 128 oscillators as well as analytically for a simpler model. Our analysis shows that for overall equal interaction strength, a sparse-coupling scheme in which each oscillator is coupled to a small, randomly selected subset of its neighbors leads to a more rapid and robust phase locking than nearest-neighbor coupling or locally dense connection schemes.

PACS number(s): 42.66. — p, 87.22. — q, 05.20. — y

Collective Oscillations in the Visual Cortex

Daniel Kammen & Christof Koch
Computation and Neural Systems
Caltech 216-78
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Philip J. Holmes
Dept. of Theor. & Applied Mechanics
Cornell University
Ithaca, NY 14853
Resources:

Website: http://rael.berkeley.edu

Twitter: @dan_kammen
RAEL: 50 PhD graduates and counting

Rick Duke, Special Advisor to Pres. Obama on Climate Change

Assoc. Prof Tracey Osborne, Geography, U of Arizona

Asst. Prof. Dan Sanchez, Extension, ESPM, UC Berkeley

Prof Charles Kirubi, Environmental Studies, Kenyatta University

Asst Prof. Gang He, Dept. Tech. & Society Stony Brook University

Assoc. Prof. Donna Green, UNSW

Rebekah Shirley, Dir. Power for All, Strathmore University, Nairobi, Kenya

Energy Extension, Christian Casillas, U of New Mexico

Asst. Prof Derek Lemoine, Economics, U. of Arizona

Prof. Katie Purvis, Environmental Chemistry, The Claremont Colleges

Prof Tonio Buonosissi, Mechanical Eng., Dir. Solar Materials Lab, MIT

Assoc. Prof. Joanna Lewis, Georgetown U

Prof Arne Jacobsen, Director, Schatz Energy Lab Humboldt State U

Prof Tracey Holloway, Atmospheric Science, U Wisc. Founder, Env. Science Women’s Network

Carla Peterman, Commissioner, California Public Commission

Prof Majid Ezzati, Dir. Global Env. Health Imperial College, London & Harvard School of Public Health

Asst Prof. Deborah Sunter, Mechanical Engineering, Tufts U. & UC Berkeley Institute of Data Sciences Fellow

Assoc. Prof. Greg Nemet, U. Wisconsin, LaFollette School of Public Affairs & Nelson Institute
Sample of Masters Students

Cyrus Wadia, Vice-President for Sustainability, Nike Corporation

Lindsey Holloway, Navajo Nation Energy Commission

Sara Kamins, Renewable Energy Integration Public Utilities Commission

Brandon Little Elk Glenn, Tribal Energy Office, Crow Nation, Montana

Sam Arons, Director of Sustainability, Lyft Corp (formerly Google)

Undergraduates

Louis Kang
ERG Minor / EECS Major
Innovation Prize of Chile ($40k)
Current: PhD student in Applied Physics, Harvard

Farah Ereiqat
ERG Minor / Env. Econ & Policy Major
Fulbright to Jordan
Current: Global water practice, IMF

Vanessa Gerber
ERG Minor / Conservation & Resource Studies Major (& Pac-12 Champion, Women’s Crew)
MA: Oxford, Environmental Change
Current: World Wildlife Fund

Maansi Shah
B.A. Urban Studies & B.S. Conservation & Resource Studies
Minors: Sustainable Design, Energy Engineering
Current: Sustainability Officer, City of Santa Monica

Kelly Jiang (current)
ERG Minor / Environmental Studies Major
Current: Power systems research at State Key Laboratory, Chongqing University, China

http://rael.berkeley.edu
Timeline

**1999**
- Founded

**2007**
- Recognized for contributions to the Nobel Peace Prize

**2009**
- Property Assessed Clean Energy
- Voted #1 World Changing Idea

**2016-18**
- RAEL’s SWITCH Model Used to Define Utility Storage Mandates
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• **Energy systems (too slowly) in transition**

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A revolution in climate politics
U.S.-China Joint Announcement on Climate Change, 2014
US & China Paris Climate Pledges Critical

Gigatons of CO₂ equivalent per year

Business as usual

2015

2020

2025

U.S.

China

E.U.

Other

Paris pledges

2030

50

55

60

65

70
How much warming by 2100?

Global Emissions of Greenhouse Gases

Estimated temperature in 2100:
- 4.5°C Business as usual
- 3.5°C Current national commitments with no change after the pledge period, ending 2025-2030
- 2°C Path

NDC Commitments to the Paris Accords

Needed Innovations

Source: 27-Sep-2015 Climate Scoreboard ©Climate Interactive www.ClimateScoreboard.org
CARBON CRUNCH

There is a mean budget of around 600 gigatonnes (Gt) of carbon dioxide left to emit before the planet warms dangerously, by more than 1.5–2°C. Stretching the budget to 800 Gt buys another 10 years, but at a greater risk of exceeding the temperature limit.

- Peaking emissions now will give us 25 years to reduce emissions to zero.
- Delaying the peak by a decade gives too little time to transform the economy.

*Data from The Global Carbon Project.
THE WHITE HOUSE
WASHINGTON

January 12, 2017

Daniel Kammen, Ph.D.
Berkeley, California

Dear Dr. Kammen:

Please accept my deepest gratitude for the distinction with which you have represented our country and my Administration as a Science Envoy.

Embodying the spirit of service and the search for shared values that speak to our common interests and humanity, you’ve helped promote the advancement of science, diplomacy, and partnership between nations and strengthen our country’s standing in the world. I want you to know how much I have appreciated your work and the role it has played in our efforts to bring about a future of greater possibility, both here at home and across the globe.

Again, thank you for endeavoring alongside me to demonstrate that there is far more that binds us than that divides us and to bring us closer to a tomorrow that reflects this essential truth. You have my very best wishes for all that lies ahead.

Sincerely,

[Signature]
But then we had a bit of an election …

The Journal of Alternative Facts

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

Iwas A. Scientistonc

* 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.
Mr. President,

I am resigning from my position as Science Envoy for the Department of State of the United States. Since 1996, I have served the Departments of Energy, the US Environmental Protection Agency, and the State Department in a number of roles. Working closely with the talented teams at State Department Headquarters and at U.S. embassies abroad, we have built significant partnerships in North and East Africa, and in the Middle East, around shared visions of national security, job creation in the U.S. and sustainable energy.

My decision to resign is in response to your attacks on core values of the United States. Your failure to condemn white supremacists and neo-Nazis has domestic and international ramifications. On this issue, I stand with the unequivocal and authoritative statements of Charlottesville Mayor Mike Signer, Virginia Governor Terry McAuliffe, Ohio Governor John Kasich, Senator John McCain, Congresswoman Ileana Ros-Lehtinen, Governor Arnold Schwarzenegger, Presidents George H.W. Bush and George W. Bush, Dr. Cornel West, Linda Sarsour, the Palestinian-American activist and one of the organizers of the Women’s March, and many others.

Particularly troubling to me is how your response to Charlottesville is consistent with a broader pattern of behavior that enables sexism and racism, and disregards the welfare of all Americans, the global community and the planet.

Examples of this destructive pattern have consequences on my duties as Science Envoy. Your decision to abdicate the leadership opportunities and the job creation benefits of the Paris Climate Accord, and to undermine energy and environmental research are not acceptable to me.

Acts and words matter. To continue in my role under your administration would be inconsistent with the principles of the United States Oath of Allegiance to which I adhere.

Character is vital in leadership. I find particularly wise the admonition of President Dwight D. Eisenhower, who cautioned that, “A people [or person] that values its privileges above principles soon loses both.”

Herein, with regret, I resign. I deeply respect and value the work of the many fine people I have encountered in our federal agencies and will miss the opportunity to work with and support them. Your actions to date have, sadly, harmed the quality of life in the United States, our standing abroad, and the sustainability of the planet.

Sincerely,

Professor Daniel M. Kammen
Science Envoy, U.S. State Department (former)
J.K. Rowling @jk_rowling
I wonder whether there’s anyone left in America who doesn’t know what an acrostic is.

Daniel M Kammen @dan_kammen
Mr. President, I am resigning as Science Envoy. Your response to Charlottesville enables racism, sexism, & harms our country and planet. pic.twitter.com/eWzDc5Yw6t

Daniel M Kammen @dan_kammen
Mr. President, I am resigning as Science Envoy. Your response to Charlottesville enables racism, sexism, & harms our country and planet.

...
California Testimony by Art Rosenfeld (Enrico Fermi’s graduate student)
California Advancing Energy Efficiency

![Graph showing kWh/person from 1960 to 2010 with different sectors highlighted.](image)
California Energy Efficiency Strategies: Policy Drives Innovation

Residential New Construction

- All new residential construction in California will be zero net energy by 2020.
Commercial New Construction

• All new commercial construction in California will be zero net energy by 2030.

• Leverage opportunities from emerging technologies initiatives, incentive programs, and local initiatives targeting commercial building/property developers.
Signed into law, September 10, 2018

Even the title is inaccurate/misleading
GHG Emissions from LDV Use: Nations and Technologies

Propulsion Carbon Intensity (g CO$_2$-eq VKT$^{-1}$)

- 2016 CAFE w/ gasoline
- EU 2020 target
- EV w/ natural gas grid
- 100 mpg w/ cellulosic
- 1000 mpg w/ gasoline
- EV w/ low-C electricity

Per Capita Transport Use (VKT person$^{-1}$ yr$^{-1}$)

- 2050 Target: ~50-100 kg CO$_2$ person$^{-1}$ yr$^{-1}$
- 2004 Global Mean: ~500 kg CO$_2$ person$^{-1}$ yr$^{-1}$

Clean Energy Goals: Aggressive & Evolving

2013: 20%
2020: 33%
2030: 60%

California Senate Bill 100: 100% clean energy by 2045 and 2030 standard now 60% (without nuclear or large hydro)
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How to take a systems theoretic approach to all these assets and decisions?

The largest and most complex machine ever built: the grid

Coal / gas

Wind & solar

Transmission

Hi kWh EV

Future tech

Storage (molten salt)
SWITCH Electricity Model

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

- **Existing grid**
  - Locate existing generation, transmission, and loads
  - Explicit temporal and spatial representation

- **Demand growth**
  - Open Source/Flexible portfolio with specific connection/technology costs

- **Restrictions**
  - Operation: Spinning, quick-start, planning reserve margins; meet load
  - Policy: Carbon tax, carbon cap, RPS

- **Optimal cost grid**
  - Least cost investment and operational decisions
  - Joint generation, transmission, storage expansion; emissions

*Linear program that jointly minimizes Gx/Tx/Dx investment and operation costs over a period of 20-40 years with explicit temporal and spatial representation of all grid supplies, transmission, and loads (including electric vehicles).*

*All system demands are modeled as constraints: reliability; investment; risks, ...*
The SWITCH Modeling Framework

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

\[
\min_{(c_i)} \text{NPV} \sum_{i,k=1}^{n,m} TC_k(c_i)
\]

Total Cost \( TC_k = \text{Capital Cost}_i \cdot \text{Capacity} (c_i) + [\text{Variable Cost}_i \cdot \text{Capacity} (c_i) \cdot CF_i \cdot 8760] \)

\[
\sum_{i=1}^{n} \text{Capacity} (c_i) \cdot \text{Peak Contribution}_i \geq \text{Annual Peak Demand} \cdot [1 + \text{Reserve Margin}]
\]

\[
\sum_{i=1}^{n} [\text{Capacity} (c_i) \cdot CF_i \cdot 8760] \geq \text{Annual Load}
\]

Annual Load \( \cdot \) Spill Factor \( \geq \sum_{i=1}^{n} [\text{Capacity} (c_i) \cdot CF_i \cdot 8760] \)

Total Resource Potential\( _i \geq \sum_{k=1}^{m} \text{Capacity} (c_i) \)
RAEL’s "SWITCH" Power System Models to Plan the Clean Energy Transition

WECC (Western North America)

Chile

East African Power Pool (EAPP):
1. Kenya
2. Planned: Uganda & Tanzania

Mexico - in progress

Kosovo

Nicaragua:

China

Malaysian Borneo

India & Bangladesh in progress

Mexico - in progress

http://rael.berkeley.edu/edu/project/SWITCH
Pathways for Western North America
Dispatch in 2050:
Flexibility and variable renewables dominate

- Storage almost exclusively moves solar to the night
- Geothermal only remaining substantial baseload
Figure 1. Maps of average transmission and generation in the Reference scenario in 2020, 2030, 2040, and 2050.
RAEL partnerships on clean electricity in China with:

- Chongqing University
- North China Electricity University
- Sichuan University
- Tsinghua University
Why Housing Policy Is Climate Policy

In California, where home prices are pushing people farther from their jobs, rising traffic is creating more pollution.

By Scott Wiener and Daniel Kammen
Senator Wiener is the chairman of the California Senate's Housing Committee. Dr. Kammen is a professor of energy at the University of California, Berkeley.

March 25, 2019
Electric versus Petroleum Mobility (is cheaper than gasoline)

Electric 3.5 miles/kWh:

\[
\frac{3.50 \text{ / gal}}{25 \text{ miles/gal}} = 14\text{¢ / mile}
\]

Hybrid 45 mpg:

\[
\frac{3.50 \text{ / gal}}{45 \text{ miles/gal}} = 7.8\text{¢ / mile}
\]

Electric 4 miles/kWh:

\[
\frac{0.12 \text{ / kWh}}{4 \text{ miles / kWh}} = 0.03 \text{ / mile}
\]

Photovoltaics:

\[
\frac{0.05 \text{ / kWh}}{4 \text{ miles / kWh}} = 1.25 \text{¢ / mile}
\]

And just announced solar @ 1.7/kWh

off peak it’s ≈ 6¢
Overview

• Introduction to RAEL

• The current (global) decarbonization agenda

• **Sustainable energy systems across scales**

• Data science for behavioral change (emerging)
Perhaps the Busiest Plot We Should All Love

Best Research-Cell Efficiencies

https://www.nrel.gov/pv/assets/images/efficiency-chart.png
Technological learning

- One-factor experience curves typically used to explain decreased costs with increases in production volume (e.g. economies of scale)
- May underestimate surges of innovation or breakthrough discoveries (especially for high-tech products)
- Simultaneously, could overestimate the cost of deployment measures
- Challenge: data (e.g. for innovation) is lacking and proxy information often necessary
Solar cost decreases 10% per year

Cumulative production GigaWp

Source: Professor Emanuel Sachs, Massachusetts Institute of Technology.
* Assumes annual production growth of 35% and an 18% learning curve. PV costs based on 18% capacity factor and 7% discount rate.
June 2, 2016: Saeed Mohammed Al Tayer CEO of Dubai Electricity and Water Authority (DEWA)

800 MW of solar at 2.99 cents/kWh

Location: Mohammed bin Rashid Al Maktoum Solar Park

Dubai's goal: lowest carbon footprint of any city in the world
Low cost solar powered home energy products are transforming rural energy access in developing nations.
Off-grid Electricity Enabled by Storage and Efficient Lights, but ...

Impossible without secure mobile money
All SHS with data (n=1025) marked on a map with satellite-derived estimates of solar potential during operations period.
Information Technology Enables Transformative Energy Access Technologies
Led to a Next Wave of Off-grid and Mini-grid products

UGP-470L1
Unique 16.6 cu/ft Solar Powered DC Fridge

The Unique 470L1 DC powered fridge/freezer is the largest upright solar fridge in North America (16.6 cu/ft of total storage). Equipped with the world’s most reliable compact DC cooling system (Danfoss/Secop compressor), the UGP-470L1 is super efficient, only drawing 865 Wh/24hrs in a +25°C/77°F ambient, set at -14°C/+5°F in the freezer and +4°C/39°F in the refrigerator. Its cabinet construction features 4” (10 cm) of insulation in the freezer and 2.5” (6 cm) of insulation in the fridge. It’s spacious interior layout includes heavy duty wire shelves and storage basket along with an integrated vertical can holder.

Matchup with one of Unique’s propane ranges or cooktops for big savings – please see our “Matched Pair” promotion.

Operation: 24V

Features:
- Largest upright solar DC fridge in North America
- Outstanding performance - can dial down the thermostat to +1°C performance in fridge in high ambient
- Highly efficient construction features 4” (10 cm) of insulation in the freezer and 2.5” (6 cm) in the fridge - very low DC power drain
- Danfoss/Secop compressor – the world’s leading DC compressor (2 year warranty)
- In-line fuse for protection
- Thermostat
- Adjustable heavy-duty wire shelves
- Vertical can holder
Storage experience curves

Two-factor learning curves: manufacturing and R&D Deployment as a function of cost and R&D ... a better fit

\[
\frac{C_2}{C_1} = \left(\frac{V_2}{V_1}\right)^{-b} \left(\frac{[R&D]_2}{[R&D]_1}\right)^{-a}
\]

Two-factor learning curves: manufacturing and R&D Deployment as a function of cost and R&D … a better fit
EnerVault Iron-Chromium Technology
1 MW-hr capacity at 250 kW (4 hour duration)
Turlock, CA
California Advancing Energy Efficiency

Figure 2: The duck curve shows steep ramping needs and overgeneration risk

Net load - March 31

- Ramp need
  - ~13,000 MW in three hours

- Overgeneration risk
Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity

Deborah A. Sunter1,2,3,* , Sergio Castellanos1,3,4,5,6* and Daniel M. Kammen1,3,4,7

The rooftop solar industry in the United States has experienced dramatic growth—roughly 50% per year since 2012, along with steadily falling prices. Although the opportunities this affords for clean, reliable power are transformative, the benefits might not accrue to all individuals and communities. Combining the location of existing and potential sites for rooftop photovoltaics (PV) from Google’s Project Sunroof and demographic information from the American Community Survey, the relative adoption of rooftop PV is compared across census tracts grouped by racial and ethnic majority. Black- and Hispanic-majority census tracts show on average significantly less rooftop PV installed. This disparity is often attributed to racial and ethnic differences in household income and home ownership. In this study, significant racial disparity remains even after we account for these differences. For the same median household income, black- and Hispanic-majority census tracts have installed less rooftop PV compared with no majority tracts by 69 and 30%, respectively, while white-majority census tracts have installed 21% more. When correcting for home ownership, black- and Hispanic-majority census tracts have installed less rooftop PV compared with no majority tracts by 61 and 45%, respectively, while white-majority census tracts have installed 37% more. The social dispersion effect is also considered. This Analysis reveals the racial and ethnic injustice in rooftop solar participation.
Solar Is Not

THE WALL STREET JOURNAL.

Solar Subsidies Take Money From the Poor to Help the Rich
Sunroof's Data

- Millions of oblique images acquired, processed, and refined.

Sun location

Attenuate light

Blocked by tree?

Cloudy?

Images: Joel Conkling – Philomathia Forum presentation on Google Sunroof
Racial disparity – even at same income

A

State Normalized Solar Deployment

B

Solar Deployment Advantage Relative to Non-Segregated Census Tracts

Median Household Income, 2013 USD
A significant amount of tracts lack PV installations.

**Percentage of Census Tracts with installed PV on Buildings**

<table>
<thead>
<tr>
<th></th>
<th>Existing Installations</th>
<th>No Installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black</td>
<td>53%</td>
<td>47%</td>
</tr>
<tr>
<td>Hispanic</td>
<td>76%</td>
<td>24%</td>
</tr>
<tr>
<td>Asian</td>
<td>83%</td>
<td>17%</td>
</tr>
<tr>
<td>White</td>
<td>79%</td>
<td>21%</td>
</tr>
</tbody>
</table>
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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

http://coolclimate.berkeley.edu/maps
Household GHG emissions in New York Metro Region

Energy

Transportation

Consumption

Total
Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities

Christopher M. Jones 1, *, Stephen M. Wheeler 2 and Daniel M. Kammen 1,3,4

Figure 2. Carbon footprint of S.F. Bay Area households by Census block group.

http://coolclimate.berkeley.edu
Article

Carbon Footprint Planning: Quantifying Local and State Mitigation Opportunities for 700 California Cities

Christopher M. Jones ¹, *, Stephen M. Wheeler ² and Daniel M. Kammen ¹,³,⁴

http://coolclimate.berkeley.edu

Figure 6. Average household carbon footprints of San Diego County neighborhoods under CA climate targets.
The Oakland EcoBlock
The Under2MOU Coalition

Co-chairs 2017: Edmund G. Brown Jr., Governor of California Philippe Couillard, Premier of Québec Winfried Kretschmann, Minister-President of Baden-Württemberg Willies Mchunu, Premier of KwaZulu-Natal Aristóteles Sandoval, Governor of Jalisco Jay Weatherill, Premier of South Australia
Thank you for touring a vital physics playground

- Twitter: @dan_kammen
- URL: http://rael.berkeley.edu