Roadmaps for Transitioning California and the Other 49 States to Wind, Water and Solar Power for All Purposes

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BAAQMD Advisory Council
San Francisco, California
February 13, 2014

J. G. Swanepoel/Dreamstime.com

Wind farm near Middelgrunden, Denmark
What’s the Problem? Why act Quickly?

Air pollution kills 2.5-4 million people worldwide each year.

Arctic sea ice may disappear in 10-30 years. Global temperatures are rising at a faster rate than any time in recorded history.

Increasing energy demand is increasing pollution, global warming, and energy prices.

Higher energy prices lead to economic, social, political instability

→ Drastic problems require immediate and definite solutions
Beijing, China, Jan 11-14, 2013
Sukinda, India

Lung of LA Teenage Nonsmoker in 1970s;

SCAQMD/CARB
# Electric Power

- **Recommended – Wind, Water, Sun (WWS)**
  - 1. Wind
  - 2. CSP
  - 3. Geothermal
  - 4. Tidal
  - 5. PV
  - 6. Wave
  - 7. Hydroelectricity

- **Not Recommended**
  - Nuclear
  - Coal-CCS
  - Natural gas, biomass

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# Vehicles

- **WWS-Battery-Electric**
- **WWS-Hydrogen Fuel Cell**
- Corn, cellulosic, sugarcane ethanol
- Soy, algae biodiesel
- Compressed natural gas

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*Energy & Env. Sci, 2, 148 (2009)*
Why Not Natural Gas?

50-70 times more CO$_2$ and air pollution per kWh than wind

Methane from natural gas a main contributor to Arctic ice loss.

Natural gas causes more global warming but less air pollution mortality than coal over 150 years due to less sulfate (a cooling agent) and more methane (a warming agent) from natural gas than coal. Coal causes higher mortality.

Hydrofracking causes land and water supply degradation and enhanced methane leaks.
Why Not Clean Coal (With Carbon Capture)?

50 times more CO$_2$ emissions per kWh than wind

150 times more air pollutant emissions per kWh than wind

Requires 25% more energy, thus 25% more coal mining and transport and traditional pollution than normal coal.
Why Not Nuclear?

9-25 times more pollution per kWh than wind from mining & refining uranium and using fossil fuels for electricity during the 10-19 years to permit (6-10 y) and construct (4-9 y) nuclear plant compared with 2-5 years for a wind or solar farm.

Risk of meltdown (1.5% of all nuclear reactors to date have melted)
Risk of nuclear weapons proliferation

Unresolved waste issues
Area to Power 100% of U.S. Onroad Vehicles

- **Wind-BEV**
  - Footprint: 1-2.8 km²
  - Turbine spacing: 0.35-0.7% of US

- **Cellulosic E85**
  - Footprint: 4.7-35.4% of US

- **Corn E85**
  - Footprint: 9.8-17.6% of US

- **Nuclear-BEV**
  - Footprint: 0.05-0.062%
  - Turbine spacing: 33% of total; the rest is buffer

- **Geoth BEV**
  - Footprint: 0.006-0.008%

- **Solar PV-BEV**
  - Footprint: 0.077-0.18%
# End-Use Power Demand For All Purposes

<table>
<thead>
<tr>
<th>Year and Fuel Type</th>
<th>World</th>
<th>U.S.</th>
<th>CA</th>
<th>NY</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010 (TW)</td>
<td>12.5</td>
<td>2.5</td>
<td>.21</td>
<td>.09</td>
</tr>
<tr>
<td>2030 with current fuels (TW)</td>
<td>16.9</td>
<td>2.83</td>
<td>.25</td>
<td>.10</td>
</tr>
<tr>
<td>2030 WWS (TW)</td>
<td>11.5</td>
<td>1.78</td>
<td>.14</td>
<td>.06</td>
</tr>
<tr>
<td>2030 Reduction w/ WWS (%)</td>
<td>32</td>
<td>37</td>
<td>44</td>
<td>37</td>
</tr>
</tbody>
</table>
Number of Plants or Devices to Power World

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>PCT SUPPLY 2030</th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-MW wind turbines</td>
<td>50%</td>
<td>3.8 mill. (0.8% in place)</td>
</tr>
<tr>
<td>0.75-MW wave devices</td>
<td>1</td>
<td>720,000</td>
</tr>
<tr>
<td>100-MW geothermal plants</td>
<td>4</td>
<td>5350 (1.7% in place)</td>
</tr>
<tr>
<td>1300-MW hydro plants</td>
<td>4</td>
<td>900 (70% in place)</td>
</tr>
<tr>
<td>1-MW tidal turbines</td>
<td>1</td>
<td>490,000</td>
</tr>
<tr>
<td>3-kW Roof PV systems</td>
<td>6</td>
<td>1.7 billion</td>
</tr>
<tr>
<td>300-MW Solar PV plants</td>
<td>14</td>
<td>40,000</td>
</tr>
<tr>
<td>300-MW CSP plants</td>
<td>20</td>
<td>49,000</td>
</tr>
<tr>
<td><strong>100%</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Number New Plants or Devices to Power CA 2050

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>PCT SUPPLY 2050</th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-MW onshore wind turbines</td>
<td>25%</td>
<td>24,700</td>
</tr>
<tr>
<td>5-MW offshore wind turbines</td>
<td>10</td>
<td>7,800</td>
</tr>
<tr>
<td>5-kW Res. roof PV systems</td>
<td>10</td>
<td>19.1 million</td>
</tr>
<tr>
<td>100-kW com/gov roof PV systems</td>
<td>15</td>
<td>1.29 million</td>
</tr>
<tr>
<td>50-MW Solar PV plants</td>
<td>15</td>
<td>2140</td>
</tr>
<tr>
<td>100-MW CSP plants</td>
<td>15</td>
<td>1230</td>
</tr>
<tr>
<td>100-MW geothermal plants</td>
<td>5</td>
<td>72</td>
</tr>
<tr>
<td>1300-MW hydro plants</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>1-MW tidal turbines</td>
<td>0.5</td>
<td>3370</td>
</tr>
<tr>
<td>0.75-MW wave devices</td>
<td>0.5</td>
<td>4960</td>
</tr>
<tr>
<td></td>
<td><strong>100%</strong></td>
<td></td>
</tr>
</tbody>
</table>
Onshore wind:
spacing = 2.5% of CA
(green is open space)

Solar PV+CSP
power plants
0.68% of CA

Offshore wind:
spacing = 0.80% of CA
(blue is open space)

Geothermal
0.0069% of CA

Area to power
100% of CA for all purposes

All rooftop PV
(0.36% of CA)
Area to power 100% of NYS for all purposes with WWS

- Solar PV+CSP power plants: 0.85% of NYS
- All rooftop PV: 0.45% of NYS
- Geothermal: 0.01% of NYS
- Onshore wind: footprint = 0.05 km², spacing = 1.46% of NYS (blue is open space)
- Offshore wind: spacing = 4.62% of NYS (blue is open space)
New area to power 100% of Washington State for all purposes
NYS: 4-4.5 kWh/m²/day)
All wind over land in high-wind areas outside Antarctica ~ 70-80 TW
= 6-7 times world end-use WWS power demand 2030 of 11.5 TW
Hurricane Katrina
August 28, 22:00 GMT

2200 GMT 8/28/05 Wind speed 100 m AGL (m/s) no turbines (10.3; peak: 60.9)

2200 GMT 8/28/05 Wind speed 100 m AGL (m/s) New Orleans turbs (10.1; peak: 61.8)
Hurricane Katrina
August 29, 18:00 GMT

1800 GMT 8/29/05 Wind speed 15 m AGL (m/s) no turbines (7.78; peak: 30.6)

1800 GMT 8/29/05 Wind speed 15 m AGL (m/s) w/turbs A=28D²; c-a=50 (7.49; peak: 32.3)

No turbines

With turbines
Matching Power Demand With Solar, Wind, Geothermal, Hydro

California electricity was found to be obtainable from WWS for 99.8% of all hours in 2005, 2006 without over-sizing WWS capacity, using demand-response, or using much CSP storage.
## Costs of Energy, Including Transmission (¢/kWh)

<table>
<thead>
<tr>
<th>ENERGY TECHNOLOGY</th>
<th>2010-2013</th>
<th>2020-2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind onshore</td>
<td>4-10.5</td>
<td>≤4</td>
</tr>
<tr>
<td>Wind offshore</td>
<td>11.3-16.5</td>
<td>7-10.9</td>
</tr>
<tr>
<td>Wave</td>
<td>&gt;11</td>
<td>4-11</td>
</tr>
<tr>
<td>Geothermal</td>
<td>9.9-15.2</td>
<td>5.5-8.8</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>4-6</td>
<td>4</td>
</tr>
<tr>
<td>CSP</td>
<td>14.1-22.6</td>
<td>7-8</td>
</tr>
<tr>
<td>Solar PV (utility scale)</td>
<td>11.1-15.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Tidal</td>
<td>&gt;&gt;11</td>
<td>5-7</td>
</tr>
<tr>
<td>Conventional (+Externalities)</td>
<td>9.2 (+5.3)=14.5 14-19 (+5.7)=20-25</td>
<td></td>
</tr>
</tbody>
</table>

Jacobson et al. (2013)
10 states with highest % electric power from wind  \(+3 \, \text{¢/kWh}\)

Remaining 40 states  \(+4 \, \text{¢/kWh}\)

→ States with greatest increases in percent of electricity from wind experienced lowest electric power price increases.

http://www.eia.gov/electricity/sales_revenue_price/
Air pollution kills 60,000 (18,000-109,000) people per year in the U.S. prematurely, costing $534 (166-980) billion/year, or 3.3 (1-6.1) % of U.S. GDP.
WWS will generate 5.1 million 40-yr construction jobs and 2.6 million 40-yr operation jobs in the U.S. (these are gross, not net numbers).
Transition to WWS (Washington State Example)
Avoided Air Pollution Mortality and Morbidity Cost as % of State GDP
Summary – California Plan

Converting to WWS + electricity/H₂ reduces California power demand ~44%

→ Eliminates ~16,000 air pollution deaths/yr in state (~7% of GDP)
→ Eliminates $48 billion/year in global climate costs
→ 504,000 40-y construction jobs; 205,000 40-y operation jobs
→ Generates ~137,000 more operation jobs than destroys
→ Electricity cost savings: $1800/yr/person in 2050
→ Health +climate cost savings: $3700/yr/person in 2050
→ Mean footprint area of state: 0.78%; spacing area: 2.7%
Converting to WWS + electricity/H₂ reduces U.S. power demand ~37.3%

- Eliminates ~59,000 U.S. air pollution deaths/yr ($534 bil ~3.3% of GDP)
- Eliminates another $730 billion/year in global climate costs
- 5.1 million 40-y construction jobs; 2.6 million 40-y operation jobs
- Energy cost savings: $3400/yr/person in 2050
- Health+climate cost savings: $3100/yr/person in 2050
- Mean footprint area of states: 0.65%; spacing area: 1.8%

Multiple methods of addressing WWS variability.
Materials are not limits although recycling may be needed.
Barriers: up-front costs, transmission needs, lobbying, politics.
More Info and The Solutions Project

www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html

www.thesolutionsproject.org

@SolutionsProj (Twitter)
@mzjacobson
California's Transition to a Low Carbon Economy

Bay Area Air Quality Management District
San Francisco, CA
February 13, 2014

Dr. Jim Williams
Chief Scientist, E3
Pathways Team

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  – Dr. Elaine Hart
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  – Amber Mahone
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  – Dr. Jeff Greenblatt
  – Dr. Bill Morrow
  – Dr. Margaret Torn
  – Grace Wu

• Advisory Board
  – Dr. John Weyant, Stanford
  – Dr. Jae Edmonds, PNNL
  – Dr. John Reilly, MIT
California Climate Policy Goals

- 2020 requirement set by Assembly Bill 32 (AB 32)
  - Reduce statewide GHGs to 1990 levels by 2020

- 2050 target set by Executive Order S-3-05
  - Reduce statewide GHGs 80% below 1990 levels by 2050
AB32 and Beyond

- Business as usual projection
- 2020 Goal under AB32
- 2050 Goal
- Executive order

Today

- Transportation
- Electricity
- Industry

Million metric tonnes CO2e

2007 analysis of AB32 options and costs in electricity and natural gas sectors

Tool and documentation at http://www.ethree.com/CPUC_GHG_Model.html
From global scale “wedges” to physically realistic, location-specific strategies

Pacala and Socolow, 2004
2050 Model Block Diagram

- Macroeconomic drivers
- Infrastructure stock rollover model
- Electricity system model

Outputs
- GHGs
- Costs

Scenarios
- Baseline (BAU)
- Mitigation

Economic Activity & Population Growth

Sector Stock rollover model
- Additions
- Stock In Use
- Retirements

Output: Energy Demand (by Time and Fuel Type)

Electricity System Dispatch & Grid Operability Model
- Gen Capacity Additions by Type
- Current Gen Capacity
- System Balancing
- Transmission
- Storage
- Import / Export
- Capacity Retirements

Output: Electric Energy Production by Type

GHG Emissions

Mitigation Measures
- Measures added according to scenario rules, until mitigation target achieved.
- Individual measures constrained by feasibility.
Stock Rollover Example: Housing Vintages

Williams et al, 2012, SOM
The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity

James H. Williams, Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price, Margaret S. Torn

Several states and countries have adopted targets for deep reductions in greenhouse gas emissions by 2050, but there has been little physically realistic modeling of the energy and economic transformations required. We analyzed the infrastructure and technology path required to meet California’s goal of an 80% reduction below 1990 levels, using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability. We found that technically feasible levels of energy efficiency and decarbonized energy supply alone are not sufficient; widespread electrification of transportation and other sectors is required. Decarbonized electricity would become the dominant form of energy supply, posing challenges and opportunities for economic growth and climate policy. This transformation demands technologies that are not yet commercialized, as well as coordination of investment, technology development, and infrastructure deployment.

In 2004, Pacala and Socolow (1) proposed a way to stabilize climate using existing greenhouse gas (GHG) mitigation technologies, consistent with an Intergovernmental Panel on Climate Change (IPCC) emissions trajectory that would stabilize atmospheric GHG concentrations.
2050 Mitigation Scenario Results

Reductions from:
- Energy Efficiency
- Electricity Decarbonization
- Smart Growth
- PV Roofs
- Biofuels
- Non-Energy, Non-CO₂
- Electrification

Baseline Emissions

1990 Emissions Level

Remaining Emissions

80% below 1990 Level (90% below 2050 Baseline)
**ENERGY EFFICIENCY**

End Use Energy Consumption (Quads)

- Mitigation Baseline

**GENERATION DECARBONIZATION**

Electric Generation GHG Intensity (Mt CO$_2$e/GWh)

- Mitigation Baseline

**ELECTRIFICATION**

Electricity Share of Total End Use Energy (%)

- Mitigation Baseline

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**Key Metric in 2050**

**Constraints**

- Max feasible rate of improvement: $1.3\%$ y$^{-1}$
- Fundamental changes in the built environment
- Limitations on changes in human behavior
- Grid operability requires some natural gas usage
- Large infrastructure investment required
- Facility and transmission siting challenges
- Smart charging
- Battery technology and cost
- Low-carbon source of electricity

*Williams et al, 2012*
- California receives proportional share of US low carbon biofuel feedstock (no biofuel imports)
- Biofuels become resource-limited premium transportation fuel
- 2050: 4.6 Bgge cellulosic ethanol, 1.8 Bgge algal biodiesel

Williams et al, 2012, SOM
## Low Carbon Generation

### Renewable vs. Carbon capture and storage vs. Nuclear

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Renewable Energy</th>
<th>Nuclear Energy</th>
<th>Generation w/ CCS</th>
<th>Other</th>
<th>Energy Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>6%</td>
<td>8%</td>
<td>-</td>
<td>86%</td>
<td>--</td>
</tr>
<tr>
<td>High Renewables</td>
<td>74%</td>
<td>6%</td>
<td>-</td>
<td>20%</td>
<td>12,000 MW</td>
</tr>
<tr>
<td>High Nuclear</td>
<td>35%</td>
<td>55%</td>
<td>-</td>
<td>10%</td>
<td>4,000 MW</td>
</tr>
<tr>
<td>High CCS</td>
<td>36%</td>
<td>7%</td>
<td>47%</td>
<td>10%</td>
<td>8,000 MW</td>
</tr>
<tr>
<td>Mixed</td>
<td>34%</td>
<td>19%</td>
<td>39%</td>
<td>8%</td>
<td>6,000 MW</td>
</tr>
</tbody>
</table>
All Low-C Electricity Scenarios have high investment costs: but options similar

Cumulative Capital Investment, 2009-2050 (Billion, 2008 US$)

Williams et al, 2012, SOM
Non-Cost Factors Likely to Affect Low Carbon Generation Choice

**Non-GHG Environmental Impact**
- Nuclear fuel cycle
- Land use
- Water use
- Fossil fuel extraction for CCS
- CO$_2$ storage

**System Operability and Reliability**
- Need low carbon balancing resources
- Regional integration
- Resource diversity
- Energy storage
- Flexible load/enhanced demand response
- Curtailment
Net Cost of Mitigation

- Other
- Biofuels
- Energy Efficiency
- Electrification
- Electricity Decarbonization
- Gasoline Savings
- Diesel Savings
- Other Fuel Savings
- Net Mitigation Cost

Mitigation Cost and Savings Relative to Baseline (Billion 2008$)

- Cost
- Savings
- Net Cost

2020

2035

2050

Williams et al, 2012
Our current energy system is about as sensitive to oil price volatility as our mitigation case is to uncertainty about new technology costs.
What’s so pivotal about the role of electricity?

- Electricity in 2050 goes from 15% to 55% of end-use energy, changing places with oil.
- Energy economy changes from one dominated by variable (fuel) costs to fixed (capital) costs.
- Pegs economy to price-stable, domestically sourced energy – green kWh – instead of price-unstable, global commodity – barrel of oil.
- Scale of up-front investment in low carbon generation very large – same order of magnitude for renewable, nuclear, CCS scenarios.
- Puts premium on lowering the capital cost of low-carbon generation and electrified transportation before we have to buy in bulk.
Key Findings

- Net cost estimate comparable to those in other 2050 studies ~ 1.3% of GDP, with large uncertainty in both technology cost and fuel cost

- Requires energy transformation: very low carbon electricity, very high EE, very high electrification

- Technical challenges: EE retrofits, HDVs, electricity balancing, biofuels, industry, non-energy/non-\(\text{CO}_2\) GHGs

- Planning challenges: technology R&D, infrastructure deployment, land use, transportation

- Coordination challenges: across sectors; between levels of government; public-private

- Policy challenges: getting neighbors to join; adaptability; planning under uncertainty; cost containment; equity
Next Steps in Pathway Modeling

- California 2030 GHG target
- US 80% decarbonization pathways for UN DDPP
- California-China climate cooperation
- Pathways v2 – new, improved tool
  - electricity sector, uncertainty analysis, co-benefits analysis
Deep Decarbonization Pathways Project for 12 Major Emitting Nations

E3/LBNL Team is Developing US Model for DDPP consistent with <2°C warming

Using two modeling platforms: Pathways v2 and GCAM

Pathways will model US at regional level based on electricity system (NERC regions)

- Sponsored by UN SDSN, led by Columbia Univ. Earth Institute
- Goal is to encourage nations to make deep commitments at COP-21
- Preliminary results report at UN General Assembly Fall 2014
Regulation and Local Action
AB32 is *Not* Primarily Cap and Trade

- Scoping Plan for 2020 has >80% of GHG reductions from “complementary” measures
- 33% renewable portfolio standard
- California solar initiative
- Vehicle fuel efficiency standards
- SB375 VMT reductions
- Building and appliance efficiency standards
- Water efficiency

Will post-2020 GHG policy continue similar approach?
What does low C transition look like?

+ 10 years: all new homes “zero net energy”

+ 20 years: 60% of existing homes deep retrofits
What does low C transition look like?

Example: water heaters

- Over next 20 years, 75% of gas water heaters need to be replaced with heat pump electric
What does low C transition look like?

+ Example: light-duty vehicles

- Over next 20 years, 70% of gasoline and diesel LDVs need to be replaced with EVs or PHEVs
Relevant Cost Metrics

$/$Household for water heating
- Includes efficiency measure costs as well as energy costs
- Can be reported by subsector and service area (*water heating shown below under an electrification scenario for PG&E*)

$/$Commercial sq. foot for space heating
- Space heating commercial subsector shown at right for PG&E under a high electrification scenario

Many possible metrics
- cost per person or hh
- changes in electric rates
- improvement in air quality
- changes in cost of driving & transport
Some areas where local regulators & government can play leading role

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Regulation &amp; Local Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>- Improve codes and standards</td>
</tr>
<tr>
<td></td>
<td>- Innovative finance for EE retrofits</td>
</tr>
<tr>
<td></td>
<td>- Targeting of poorly performing buildings</td>
</tr>
<tr>
<td>Low carbon electricity</td>
<td>- Community solar</td>
</tr>
<tr>
<td></td>
<td>- Flexible customer loads</td>
</tr>
<tr>
<td></td>
<td>- Low impact renewables/transmission siting</td>
</tr>
<tr>
<td>Transportation</td>
<td>- Zoning, density, urban infill</td>
</tr>
<tr>
<td></td>
<td>- Transit, mode shift, bike friendly</td>
</tr>
<tr>
<td></td>
<td>- Electric charging infrastructure</td>
</tr>
<tr>
<td>Industry</td>
<td>- Fuel switching and efficiency options</td>
</tr>
<tr>
<td></td>
<td>- Refinery emissions, heavy crude</td>
</tr>
<tr>
<td></td>
<td>- On site renewable generation or CCS</td>
</tr>
<tr>
<td>Non-energy/non-CO2 GHGs</td>
<td>- Waste management, landfill gases</td>
</tr>
<tr>
<td></td>
<td>- Animal feedlots, agricultural tillage</td>
</tr>
<tr>
<td></td>
<td>- Reduce HFCs, SF6, other high GWP</td>
</tr>
</tbody>
</table>
A few thoughts on regulation & the low carbon transition

+ Transformation of energy system required
  - Goes beyond incremental tailpipe/smokestack regulation
  - Active, broad-based, enduring public support essential

+ All state agencies need a carbon mandate
  - Example: CPUC has separate electricity programs, lacks GHG organizing principle

+ Regulatory and sectoral boundaries will get blurred
  - Example: Electrified transportation
  - New cooperation across silos will be required

+ AQMDs play special role
  - Understanding of multi-pollutant control & tradeoffs
  - Electrification moves all emissions toward stationary sources
Thank You

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