Optimal Investment in Wind and Solar Power in California

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(based on Ph.D. research completed at U.C. Berkeley Energy and Resources Group)
Research Question

How much wind and solar power should California use by 2025?
METHODS
Research Approach

- Assign a cost to greenhouse gas emissions
- Build an optimization model to...
  - Choose
    - generator investments every 4 years
    - transmission investments every 4 years
    - hourly generator dispatch
    - hourly transmission dispatch
  - To satisfy hourly electricity loads, with a 15% reserve margin
  - At the lowest total cost (including carbon cost)
Wind Power Production

hourly data for 2002–04 from numerical weather model run by AWS Truewind

233 sites (23 GW), augmented with an equal number of fictitious lower-wind sites

site locations in this diagram are approximate
Solar Irradiance

Hourly irradiance for 2002-04 measured by California Irrigation Management Information System.

117 measurement sites nearby PV systems in the same evapotranspiration zone are assumed to have the same irradiance.
Interzonal Transfer Capability

[Map of California with interzonal transfer capability connections between various regions such as Humboldt, North Coast, Geyser, Sierra, Other PG&E, Other Bay Area, Fresno, Other SCE, LA-Orange, and San Diego.]
Projected Electricity Costs

Levelized Cost of Electricity (2007$/MWh)

- wind farms
- PV solar systems
- solar thermal troughs
- CC gas plants + carbon adder

Year:
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

Cost Range:
- $0 - $700
### Finance Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Real Rate (net of inflation)</th>
<th>Nominal Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finance Rate (to amortize capital costs)</td>
<td>6%</td>
<td>~9%</td>
</tr>
<tr>
<td>Finance Rate — distributed PV (home equity loan)</td>
<td>3%</td>
<td>~6%</td>
</tr>
<tr>
<td>Discount Rate (to convert to present-value)</td>
<td>3%</td>
<td>~6%</td>
</tr>
</tbody>
</table>
### Projected Fuel Costs (2007$/MBtu)

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural Gas</th>
<th>Nuclear</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>$5.34</td>
<td>$0.99</td>
<td>$1.61</td>
</tr>
<tr>
<td>2014</td>
<td>$6.56</td>
<td>$1.83</td>
<td>$1.71</td>
</tr>
<tr>
<td>2018</td>
<td>$7.56</td>
<td>$2.20</td>
<td>$1.83</td>
</tr>
<tr>
<td>2022</td>
<td>$8.12</td>
<td>$2.20</td>
<td>$1.94</td>
</tr>
</tbody>
</table>
### Projected Capital Costs (2007$/kW)

<table>
<thead>
<tr>
<th>Year</th>
<th>CCGT</th>
<th>DistPV</th>
<th>Trough</th>
<th>Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>$694</td>
<td>$7,549</td>
<td>$3,368</td>
<td>$1,648</td>
</tr>
<tr>
<td>2014</td>
<td>$650</td>
<td>$6,200</td>
<td>$2,909</td>
<td>$1,429</td>
</tr>
<tr>
<td>2018</td>
<td>$610</td>
<td>$5,093</td>
<td>$2,512</td>
<td>$1,239</td>
</tr>
<tr>
<td>2022</td>
<td>$572</td>
<td>$4,183</td>
<td>$2,169</td>
<td>$1,074</td>
</tr>
<tr>
<td>Inter-connect</td>
<td>+$64</td>
<td>+$0</td>
<td>+~$250</td>
<td>+~$330</td>
</tr>
</tbody>
</table>
RESULTS
Optimal Generator Portfolio
($30/tCO₂ Carbon Cost)
Hourly Generator Operation
SURPLUS ENERGY: At some times, additional wind power would not be useful.

CAPACITY SHORTFALL: More wind farms would not reduce the remaining peak load on gas plants.
Effect of Additional Wind Power on Gas Plant Construction and Operation

Marginal Reduction in Gas Plant Usage (%)

- **Fuel Savings** (% of wind MWh produced)
- **Capacity Savings** (% of wind nameplate MW)

Installed Wind Capacity (nameplate MW)
Marginal Cost and Benefits of Wind Power

- Avoided Carbon Costs @ $30/tCO2 (benefit)
- Avoided Fuel and Transmission Costs (benefit)
- Avoided Gas Plant Capital Costs (benefit)
- Total Marginal Benefit of Wind Power
- Marginal Cost of Wind Power
Effect of Solar Power on Gas Plant Usage

Marginal Reduction in Gas Plant Usage (%)

- **Fuel Savings** (% of solar MWh produced)
- **Capacity Savings** (% of solar nameplate MW)

Installed Solar Capacity (nameplate MW)

0% 10,000 20,000 30,000 40,000 50,000
Marginal Cost and Benefits of Solar Power

- Avoided Carbon Costs @ $30/tCO2 (benefit)
- Avoided Fuel and Transmission Costs (benefit)
- Avoided Gas Plant Capital Costs (benefit)
- Total Marginal Benefit of Solar Power
- Marginal Cost of Solar Power
Marginal Cost and Benefits of Solar Power

- Avoided Carbon Costs @ $150/tCO2 (benefit)
- Avoided Fuel and Transmission Costs (benefit)
- Avoided Gas Plant Capital Costs (benefit)
- Total Marginal Benefit of Solar Power
- Marginal Cost of Solar Power

Marginal Costs or Benefits of Solar Electricity (2007$/MWh)

Installed Solar Capacity (nameplate MW)
Effect of Carbon Cost on Portfolio Design

Capacity Installed (MW, 2022–25)

Share of Electricity Supplied (2022–25)

- New Wind
- New DistPV
- New Trough
- Existing Geothermal
- Hydro
- Existing Nuclear
- New CCGT
- Existing Gas
- Existing Gas Cogen
- Existing Coal Cogen
- Existing Coal
“Supply Curve” for Emission Reductions

[Graph showing the cost of carbon emissions as a function of emission reductions from 1990 to 2025.]
Harmonizing Targets Across Sectors

Carbon Cost ($/tCO2)

Transport
- $150
- $100
- $50
  0
  50
  100
  80 M

Electricity
- $150
- $100
- $50
  0
  50
  25 M

Other Sectors
- $150
- $100
- $50
  0
  50
  60 M

All Sectors Combined
- $150
- $100
- $50
  0
  50
  150
  200
  250
  300
  175 M

Emission Reductions vs 1990 (10^6 tCO2)

Note: curves are hypothetical, for illustration only.
Effect of Emission Reductions on Power Bills

- Cost of electricity and carbon dioxide emissions
- Direct cost of electricity

Average Power Cost (2007$ / MWh)

- $0/tCO₂
- $200/tCO₂

Emission Reductions Relative to 1990
Combining Wind and Solar Reduces Emissions and Costs

CO₂ emission reductions, 2022 vs. 1990

Average Power Cost (2007$/MWh)

- solar, one mega-site
- solar, many sites
- wind, one mega-site
- wind, many sites
- wind + solar, many sites
SENSITIVITIES
Effect of Fuel Costs

Carbon cost (2007$/tCO2)

CO2 emission reductions, 2022 vs. 1990

- 50% of base case fuel cost
- 100% of base case fuel cost
- 150% of base case fuel cost

Avg. power cost in 2022 (2007$/MWh)

CO2 emission reductions, 2022 vs. 1990

- 50% of base case fuel cost
- 100% of base case fuel cost
- 150% of base case fuel cost
Effect of Equipment Costs

- **Carbon cost (2007$/tCO2)**
  - 0% of base case technological progress
  - 100% of base case technological progress
  - 200% of base case technological progress

- **Avg. power cost in 2022 (2007$/MWh)**
  - 0% of base case technological progress
  - 100% of base case technological progress
  - 200% of base case technological progress

**CO2 emission reductions, 2022 vs. 1990**
Effect of Conservation and Efficiency

![Graph showing the effect of conservation and efficiency on CO2 emissions and costs](image)

- **Top Graph:**
  - X-axis: CO2 emission reductions, 2022 vs. 1990
  - Y-axis: Carbon cost (2007$/tCO2)
  - Lines represent different scenarios:
    - Base case
    - 10% reduction in base-case demand by 2022
    - 20% reduction in base-case demand by 2022
    - 30% reduction in base-case demand by 2022

- **Bottom Graph:**
  - X-axis: CO2 emission reductions, 2022 vs. 1990
  - Y-axis: Avg. power cost in 2022 (2007$/MWh)
  - Lines represent different scenarios:
    - Base case
    - 10% reduction in base-case demand by 2022
    - 20% reduction in base-case demand by 2022
    - 30% reduction in base-case demand by 2022
HIGH RENEWABLE RESOURCE SCENARIO
Using Surplus Renewable Power for Vehicles

- Existing Coal
- Existing Coal Cogen
- Existing Gas Cogen
- Existing Nuclear
- Existing Geothermal
- New CCGT
- Existing Gas
- New DistPV
- New Trough
- New Wind
- Hydro
- System Load

Month and Hour (PST)
Improving the Cost–Emissions Tradeoff

Avg. power cost in 2022 (2007$/MWh)

CO2 emission reductions, 2022 vs. 1990
Improving the Cost–Emissions Tradeoff

![Graph showing the relationship between CO2 emission reductions and average power cost in 2022 (2007 $/MWh). The graph indicates that as CO2 emission reductions increase, the average power cost also increases. There is a label indicating “identify 2x more wind sites.”]
Improving the Cost–Emissions Tradeoff

- Identify 2x more wind sites
- Switch 50% of cars to electricity

**Avg. power cost in 2022 (2007$/MWh)**

**CO2 emission reductions, 2022 vs. 1990**
Improving the Cost–Emissions Tradeoff

- Identify 2x more wind sites
- Switch 50% of cars to electricity
- Charge electric cars during best hours
Improving the Cost–Emissions Tradeoff

- Identify 2x more wind sites
- Switch 50% of cars to electricity
- Charge electric cars during best hours
- Reduce electricity loads by 20%

Avg. power cost in 2022 (2007$/MWh)

CO2 emission reductions, 2022 vs. 1990
CONCLUSIONS
Conclusions

- There appears to be no sharp limit to the use of wind and solar power
  - costs rise smoothly and slowly as the system uses more intermittent renewable power

- Renewable power is worth developing to save fuel, even if its contribution to peak demand is low
  - Renewable power can become uneconomical when *too much* is produced at some times

- More renewable power can be used if diverse sites and technologies are developed

- Demand-side flexibility may allow wind and solar power to play a larger role at a lower cost
  - *e.g.*, well-timed charging of PHEVs, automatic adjustment of air conditioner and refrigerator setpoints
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