Last retreat...

- Observed seasonal, weekly, and daily variations in CA electricity grid
  - Peak / mean / min = 47 / 26 / 19 GW
- Scaled renewables and displaced fossil fuels to model a sustainable electricity grid
  - 60% renewables → wind + solar from 3.2 to 87 GW
- Examined changed assumptions in 60% grid
  - Critical period shifts from summer peaks in demand to winter lulls in renewables production
Data sources

- CA generation plant locations, type, and rated power (> 0.1 MW) [CEC]
- Hourly output from each type of CA generation source for > 1 year [CAISO]

A year in the present-day CA grid

* Seasonal, Weekly, Daily variations
* Many underlying factors

Peak: 47.1 GW
Min: 18.8 GW
Mean: 26.3 GW
The demand duration curve

<table>
<thead>
<tr>
<th>%Hrs</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>47.128</td>
</tr>
<tr>
<td>99.9</td>
<td>45.398</td>
</tr>
<tr>
<td>99.5</td>
<td>42.373</td>
</tr>
<tr>
<td>99.0</td>
<td>39.786</td>
</tr>
<tr>
<td>95.0</td>
<td>34.846</td>
</tr>
<tr>
<td>90.0</td>
<td>32.086</td>
</tr>
<tr>
<td>50.0</td>
<td>26.173</td>
</tr>
<tr>
<td>0.0</td>
<td>18.792</td>
</tr>
</tbody>
</table>

Total Power (GW)

% of Hours Exceeded

May 24, 2012
Caveats

- Captures dynamics as reflected in current design and deployment of these assets
  - Orientation, geographic diversity, weather, ...
- Does not reflect deeper constraints
  - Transmission capacity, ramping, ...
- Top level analysis of dynamics
  - Needs to be repeated at successively finer levels
A year in CA grid @ 60%

Peak: 87.6 GW
Min: 18.8 GW
Mean: 37.7 GW

Energy-agile industry?
A summer week @ 60%

May 24, 2012
A winter week @ 60%
What does this mean for Thermal?
What can we do to help the match?

- Load scheduling/shifting (continuous DR, virtual generation, supply-following loads, etc., etc., etc.)
  - Precooling, preheating, guardband adjustment
  - Deferral, acceleration, shaping
- Energy storage management
- Integrated Portfolio Management
  - Utilize resources in concert with non-dispatchables
An autumn day
Simple optimistic shift

- Find the best possible strategy for shifting fossil fuel demand to excess renewable generation

- Process:
  - Construct a list of possible shifting opportunities
    - Fossil fuel use within $k$ hours of excess
  - Move the load that must shift the furthest from fossil to renewables
  - Iterate until no more shifting is possible

- Optimistic in magnitude, conservative in targeting
The day with +/- 3 hours of shift
The same day
Storage algorithm

- Fill whenever there is excess generations and storage capacity
- Dispatch whenever storage is greater than zero and import or thermal energy is being used
  - Imports are first displaced, and then thermal is displaced
  - No restrictions on maximum dispatchable power, i.e. all storage can be dispatched in a single timestep (1 hour)
The day with 15 GWh of storage
The same day, again
Using hydro for firming

- Daily dispatchable energy is calculated as the integral over all hours in a day of hydro power minus the daily minimum.
- Then the dispatchable energy is distributed to minimize the peak import power of the day, with any excess used to minimize the peak thermal power of the day.
The day with hydro management

May 24, 2012
Technique discussion

- Idealistic utilization of the resources
- Simple mechanisms
  - Charge using fossil?
  - Less “greedy” - delay discharge?

- Is it enough to apply these strategies in concert?
Storage + Hydro + Shifting

![Graph showing Total Power (GW) vs % of Hours Exceeded with various lines representing different scenarios like Scaled to 60%, Hydro Dispatch, Shifting 6 hrs, Storage 15 GWh, Storage+Hydro+Shift.]

May 24, 2012
Storage + Hydro + Shifting

May 24, 2012
A difficult week
Dealing with winter night time “lulls”

- Efficiency for shaping demand
  - Poor power proportionality of buildings and other loads, especially at night

- Curtailment
  - Demand response targeting “peaks”

- Long term storage

- Excellent opportunity for fuel
Opportunities

- Here, greedy techniques to minimize thermal and import energy — helps in spring and fall
- Optimize supply resources to benefit thermal production — target peaks, not average
- Create a “demand portfolio” — slack with a utility function
- Iterate to capture network constraints and finer time resolution
Conclusion

- The key challenges posed by a 60% grid differ from those concentrated on today
  - Peak summer cooling => winter night lulls
  - New energy-agile industries?
- Supply and demand management are far more important with deep penetration
  - Fundamentally limited by seasonal dynamics
  - Need to apply these and more in concert
- Peak shaving and ramp management return in a new and critical form
Questions? – Reading material

- Defining CPS Challenges in a Sustainable Electricity Grid, Jay Taneja, Randy Katz, and David Culler, ICCPS, April 2012
- The Future of the Electric Grid, Interdisciplinary MIT Study

Jay Taneja – taneja@cs.berkeley.edu
Electricity grids today

- Objective is to match supply and demand
- Constraints:
  - Transmission network
  - Generator ramp capabilities
  - Reserve requirements
  - Emissions limits

- Portfolio of generation
- Time-varying demand

Oblivious Loads
Grids are evolving

- Adding non-dispatchable, renewable sources
  - RPS standards and goals
  - Fewer knobs to turn

Goal of this study:
- Highlight and assess fundamental differences in future, more sustainable grids
- Improve management of sustainable grids to accommodate more renewable generation
### CA grid today - supplies

<table>
<thead>
<tr>
<th>Source</th>
<th>Rated (GW)</th>
<th>Capacity Factor(^1)</th>
<th>Total Energy (TWh)</th>
<th>% of Total Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geothermal</td>
<td>2.600</td>
<td>38.7%</td>
<td>8.68</td>
<td>3.8%</td>
</tr>
<tr>
<td>Biomass/Biogas</td>
<td>1.145</td>
<td>43.5%</td>
<td>4.30</td>
<td>1.9%</td>
</tr>
<tr>
<td>Small Hydro</td>
<td>1.380</td>
<td>31.7%</td>
<td>3.77</td>
<td>1.7%</td>
</tr>
<tr>
<td>Wind</td>
<td>2.812</td>
<td>29.1%</td>
<td>7.06</td>
<td>3.1%</td>
</tr>
<tr>
<td>Solar(^3)</td>
<td>0.403</td>
<td>28.7%</td>
<td>1.00</td>
<td>0.4%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.456</td>
<td>85.9%</td>
<td>33.00</td>
<td>14.6%</td>
</tr>
<tr>
<td>Hydro</td>
<td>12.574</td>
<td>27.7%</td>
<td>30.05</td>
<td>13.3%</td>
</tr>
<tr>
<td>Imports</td>
<td>11.055(^2)</td>
<td>66.6%</td>
<td>63.43</td>
<td>28.0%</td>
</tr>
<tr>
<td>Thermal</td>
<td>44.339</td>
<td>19.7%</td>
<td>75.43</td>
<td>33.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>80.764</strong></td>
<td><strong>32.6%</strong></td>
<td><strong>226.71</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>

---

1. Mean delivered power divided by rated power (excl. import)
2. For imports, rating is the maximum observed power
3. Residential net factored into demand
A mid-summer week
A mid-winter week
Scaling methodology

- Take current demand, current activity, current technology, current deployment
- At a crude top-level, scale (by category)
  - Represented by the time series
- Scale up the renewable portions (solar + wind)
  - Preserve the seasonal, weekly, daily, hourly effects of Mother Nature
- Scale back the fossil fuel-based supplies
- Maintain current demand as a reference
How much to scale solar and wind?

- Scaling of renewables depends on how availability interacts with demand
- At all timescales
- Find minimum combined capacity (cost?) that achieves a target penetration
  - Penetration == utilized energy with current demand
Joint scaling of wind and solar

<table>
<thead>
<tr>
<th>Source</th>
<th>Unscaled Rated (GW)</th>
<th>60% Scaled Rated (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>2.81</td>
<td>57.1</td>
</tr>
<tr>
<td>Solar</td>
<td>0.40</td>
<td>29.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>3.21</td>
<td>86.9</td>
</tr>
</tbody>
</table>
Sources and loads

Dispatchable Sources

Non-Dispatchable Sources

Oblivious Loads

Aware Loads

LoCal
A year... daily averages

- IMPORTS: 28.0%
- THERMAL: 33.3%
- WIND: 3.1%
- SOLAR: 0.4%
- BIOMASS/BIOGAS: 1.9%
- GEOTHERMAL: 3.8%
- HYDRO: 13.3%
- SMALL HYDRO: 1.7%
- NUCLEAR: 14.5%

Total CA Power (GW)

LoCal

May 24, 2012
Example: Solar
Example: Solar - Scaled
Example: Wind
Example: Wind - Scaled
Mean daily patterns

![Graph showing mean daily patterns for different energy sources normalized to daily minimum.](image)

- **SOLAR**: 17%
- **WIND**: 30%
- **DEMAND**: 11%
Daily Demand Pattern

May 24, 2012
Daily Solar Pattern

Hour of Day

Power Normalized to Daily Minimum (%)
Daily Wind Pattern

Power Normalized to Daily Minimum (%) vs. Hour of Day

May 24, 2012
CA grid @ 60%

<table>
<thead>
<tr>
<th>Generation Type</th>
<th>Current Grid</th>
<th>Scaled Scenario - 60% Renewables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity/Peak (GW)</td>
<td>Total Energy (%)</td>
</tr>
<tr>
<td><strong>Renewables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geothermal</td>
<td>2.600 / 1.095</td>
<td>3.8%</td>
</tr>
<tr>
<td>Biomass/Biogas</td>
<td>1.145 / 0.616</td>
<td>1.9%</td>
</tr>
<tr>
<td>Small Hydro</td>
<td>1.380 / 0.646</td>
<td>1.7%</td>
</tr>
<tr>
<td>Wind</td>
<td>2.812 / 2.470</td>
<td>3.1%</td>
</tr>
<tr>
<td>Solar</td>
<td>0.403 / 0.457</td>
<td>0.4%</td>
</tr>
<tr>
<td><strong>Non-Renewables</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nuclear</td>
<td>4.456 / 4.581</td>
<td>14.6%</td>
</tr>
<tr>
<td>Hydro</td>
<td>12.574 / 6.286</td>
<td>13.3%</td>
</tr>
<tr>
<td>Imports</td>
<td>N/A / 11.055</td>
<td>28.0%</td>
</tr>
<tr>
<td>Thermal</td>
<td>44.339 / 27.014</td>
<td>33.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>80.764 / 47.128</td>
<td>100.0%</td>
</tr>
</tbody>
</table>
Effects of demand shifting

- 20% Renewables (Capacity: 11.5 GW)
- 30% Renewables (Capacity: 20.6 GW)
- 40% Renewables (Capacity: 31.0 GW)
- 50% Renewables (Capacity: 47.1 GW)
- 60% Renewables (Capacity: 86.9 GW)
- 70% Renewables (Capacity: 460.1 GW)

Proportion of Fossil Fuels Eliminated (%)

Hours of Shifting

May 24, 2012
Load shifting algorithm

- Optimistic
  - Any amount of load at any time

- Conservative
  - Simplistic greedy algorithm
How much does storage help?
How much does shifting help?
How much does hydro mgmt help?
Hourly changes

Cumulative Distribution Function of Hours (%)

Hourly Change (GW)
Shifting
Thermal with Shifting

![Graph showing total power (GW) versus percentage of hours exceeded. The graph includes two lines: one for 'THERMAL - Scaled' and another for 'THERMAL - Shifted 6 hrs.' There is also a table showing energy values at different percentages of hours exceeded.]
Storage

May 24, 2012
Thermal with Storage
Hydro scheduling

![Graph showing total power vs. % of hours exceeded]

<table>
<thead>
<tr>
<th>% Hrs</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max</td>
<td>4.111</td>
</tr>
<tr>
<td>99.9</td>
<td>4.111</td>
</tr>
<tr>
<td>99.5</td>
<td>4.097</td>
</tr>
<tr>
<td>99.0</td>
<td>4.017</td>
</tr>
<tr>
<td>95.0</td>
<td>3.517</td>
</tr>
<tr>
<td>90.0</td>
<td>2.768</td>
</tr>
<tr>
<td>50.0</td>
<td>0.000</td>
</tr>
<tr>
<td>0.0</td>
<td>0.000</td>
</tr>
</tbody>
</table>
Thermal with Hydro scheduling

May 24, 2012
Storage + Hydro + Shifting

[Nov-Apr]

[May-Oct]