Capturing Energy-Water-Land Interactions and Institutions in an Integrated Modeling Framework:

*The Economic Impacts of Water Shortages on the Western Power Grid*

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Project 1.2—Capturing governance, institutional, and system constraints in an integrated energy-water-land modeling framework

**Physical Systems**
- Crop Model: yearly; state/region
- Population, migration, demographics model: yearly; state/region
- Power System model: hourly; WECC
- Water Balance Model: daily; grid

**State-level CGE Model**
- Prices, Wages, Demand
  - Agriculture / Food
  - Primary energy
  - Electric power
  - Construction
  - Trade
  - Transportation
  - Services; e.g., health, tourism, insurance
  - Households

**Water Demand**
- Temperature, Precipitation, Extreme Events
- Water rights systems
- Water Supply

**Water Balance Model**
- Temporal scale: daily
- Spatial scale: grid

**Fine-scale Climate Drivers**
- Temperature, Precipitation, Extreme Events
- Temporal scale: daily
- Spatial scale: grid

**Extreme Events; Disaster declarations**

**Soft Coupling**
- Temperature, Precipitation, Extreme Events

**Hard Coupling**
- Population, labor, crop productivity, electric power supply/productivity

**Temporal scale:** yearly
**Spatial scale:** CA, rest of WECC, rest of US
Framing

• Overlapping and Interacting Networks of Natural and Human Systems
• Each System has Distinct Spatial and Temporal Variability
• “Impacts” occur when these patterns converge at specific locations/times

• Science Questions:
  1) What are the necessary spatial/temporal resolutions in each subsystem model and in coupled frameworks to characterize the impacts of interest?
  2) How does this inform resiliency and vulnerability?
Example of Interacting Networks: Atmosphere, Hydrology, Power, Economy

Atmosphere (diffuse network)

U.S. Drought Monitor

Drainage Basins (River network)

Electricity Power (Power network)

Regional Sectors (Economic network)

Industry Breakdown 2012
Motivating Questions

• What are the impacts of potential natural shocks to the coupled systems of land, water, energy, and economic activity?

• What infrastructure investments should be made to be resilient to the range of possible future stresses from natural systems?

• What effect do governance and institutional constraints have on a stressed system?
Convergence achieved when % Δ between iterations reaches a number close to zero
Hydrology-Electricity-Economy Coupling Methodology

Convergence achieved when % Δ between iterations reaches a number close to zero
University of New Hampshire Water Balance Model (WBM)

Water Balance Model
- Macro-scale process-based hydrology
- Daily time steps, 1 km² grid resolution

Inputs:
- Climate, river network, soil properties, crop maps, irrigated area, dam operations, populations
- Irrigation technology
- Cumulative water rights curves

Tracking System:
- Water is tracked from point of origin, through natural and irrigated processes. Each water stock is a mixture of the water sources

Aquifer Representation:
- Aquifers are represented as a spatially lumped pool, with outlet springs

Primary Model References:
- Grogan (2016)
- Wisser et al. (2010)
Hydrology-Electricity-Economy Coupling Methodology

Water Balance Model (WBM) \(\rightarrow\) Earth System Model

Downscaled temperature, precip

Water availability and levels

\% Δ in share of coal and gas generation

Power System Model

% Δ in electricity generation cost by region

% of unmet demand

Customer damage function

% Δ in sectoral output due to unmet demand

Regional Economic Model

% Δ in demand of electricity by region

% Δ in price of coal and gas

Convergence achieved when % Δ between iterations reaches a number close to zero
Power Systems Model

• Two Stage Model similar to what is used by Independent System Operators.

➢ PSM approximates typical two-settlement markets (day-ahead and real-time) by running the unit commitment first (day ahead) and then running the OPF model to account for transmission constraints (real time).

➢ PSM models all 8760 hours in a year chronologically
Hydrology-Electricity-Economy Coupling Methodology

Convergence achieved when \( \Delta \) between iterations reaches a number close to zero
Regional Economic Model

- Static regional computable general equilibrium model based on the modeling framework of Rausch and Rutherford (2009)
- Calibrated to state-level data from the IMPLAN (IMpact analysis for PLANning) group, LLC.
- All four economic agents (producers, consumers, government, and foreign sector) represented.
- Captures inter-industry linkages across all 11 producing sectors—five energy sectors and six non-energy sectors.
- Aggregated to three regions: California, rest of WECC, and rest of US
- Intra- and international trade represented.
Hydrology-Electricity-Economy Coupling Methodology

Convergence achieved when % Δ between iterations reaches a number close to zero
Incorporating Unserved Electricity Impacts

• In addition to capturing impacts on the economy from changes in electricity prices, we can also capture productivity impacts from unserved energy.

• Based on survey data (~ 12,000 firms), Sullivan et al (2009) estimates customer damage functions that generate productivity impacts from unserved electricity demand by
  • Sector
  • Season
  • Day of week
  • Time of day

• Sullivan finds that multiple short duration outages are more costly than a few long duration outages

• The hourly detail and unserved electricity provided by the Unit Commitment component of PSM will allow us to capture differences in productivity impacts based on season, day of week, time of day.
Why Electricity-Economy Coupling?

<table>
<thead>
<tr>
<th>Model/Capabilities</th>
<th>Represents Ability to Substitute Across Sectors</th>
<th>Represents Physical and Engineering Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power System Model</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Economic Model</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Integrated Model</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Valid estimates of impacts and valuation of adaptive, resilient system design require the representation of both types of effects.
Existing Hybrid Models

- **Examples:**
  - Bohringer and Rutherford, 2009
  - USREP-ReEDS (MIT-NREL)
  - MRN-NEEM (CRA)

- **Limitations:**
  - Use a small number of “representative” demand hours
  - Neglect intertemporal constraints (unit commitment)
  - Neglect transmission constraints (optimal power flow)

- **Hypothesis:** Omitting these constraints will bias estimates of the impacts of extreme events

- **Our Contribution:** Couple regional CGE model to a power system model that captures intertemporal and spatial constraints
Extreme Events Scenarios

• What are the effects of extreme precipitation events in the Columbia and Colorado River basins on thermal generating plants that use water for cooling?

• Generator matching with 2 data sources
  • UNH Water Balance Model (WBM)
  • EIA and Egrid database

• We use the federal standard temperature threshold of 32 degrees C, above which generators at those locations are not available on that day.

• Ex: A total of 52 Coal, Nuclear and Gas generators, a total capacity of 21.5 GW, that use the Columbia or the Colorado basin for cooling were assumed offline.
Western Electricity Coordinating Council (WECC)

• Why WECC?
  • West has long history of water-stress
  • Important to economy of U.S.
  • Wide range of generation sources
  • Highly water dependent: 81% of generation in 2014 came from nuclear, coal, gas, and hydro power plants
  • May be reduced water availability in future due to climate change

Regional Entities. Source: NERC, 2015 Long – Term Reliability Assessment
# Effect of Coupling Power-Economy

**Shock case: shutting down of selected plants in WECC**  
(% change from base case)

<table>
<thead>
<tr>
<th>% Change in Electricity Cost (PSM)</th>
<th>Non-coupled system</th>
<th>Coupled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>9.3%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Rest of WECC</td>
<td>9.3%</td>
<td>6.1%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% Change in Electricity Demand (IMPLAN)</th>
<th>Non-coupled system</th>
<th>Coupled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>-7.3%</td>
<td>-5.1%</td>
</tr>
<tr>
<td>Rest of WECC</td>
<td>-6.6%</td>
<td>-4.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% Change in Unserved Electricity (PSM)</th>
<th>Non-coupled system</th>
<th>Coupled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>California (% of 1-hour in a year)</td>
<td>34.7%</td>
<td>10.9%</td>
</tr>
<tr>
<td>Rest of WECC (% of 1-hour in a year)</td>
<td>61.4%</td>
<td>16.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% Change in Total Generation (Mwh)</th>
<th>Non-coupled system</th>
<th>Coupled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>7.7%</td>
<td>-1.9%</td>
</tr>
<tr>
<td>Coal</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Gas</td>
<td>79.6%</td>
<td>-1.6%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Non-coupled system</th>
<th>Coupled system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest of WECC</td>
<td>-2.4%</td>
<td>-7.8%</td>
</tr>
<tr>
<td>Coal</td>
<td>-14.0%</td>
<td>-3.6%</td>
</tr>
<tr>
<td>Gas</td>
<td>120.8%</td>
<td>-1.0%</td>
</tr>
</tbody>
</table>
Effect of Temporal Resolution in Power

Hourly:
- Hourly model solved for the entire year (8736 hours)
  - Operational constraints of generators present.
  - Temporal and spatial constraints present
  - Solution time is approximately 20 minutes

Time Slice:
- 17 representative hours of a year are solved
  - Operational constraints of generators not present.
  - Spatial constraints present
  - Solution time is less than 1 minute
## Impacts on Sectoral Output

<table>
<thead>
<tr>
<th>Sector</th>
<th>Without Unserved Elect Impacts</th>
<th>With Unserved Elect Impacts (Hourly model)</th>
<th>With Unserved Elect Impacts (Time averaging model)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>California</td>
<td>ROWECC</td>
<td>Rest of US</td>
</tr>
<tr>
<td>Agriculture</td>
<td>-0.200%</td>
<td>-0.300%</td>
<td>0.047%</td>
</tr>
<tr>
<td>Mining</td>
<td>0.200%</td>
<td>0.200%</td>
<td>-0.022%</td>
</tr>
<tr>
<td>Construction</td>
<td>0.001%</td>
<td>0.038%</td>
<td>-0.002%</td>
</tr>
<tr>
<td>Manufacture</td>
<td>-0.018%</td>
<td>-0.200%</td>
<td>-0.009%</td>
</tr>
<tr>
<td>Electricity</td>
<td>-5.100%</td>
<td>-4.300%</td>
<td>0.700%</td>
</tr>
<tr>
<td>Telecomm</td>
<td>0.001%</td>
<td>0.063%</td>
<td>-0.043%</td>
</tr>
<tr>
<td>Retail Trade</td>
<td>-0.016%</td>
<td>-0.008%</td>
<td>-0.020%</td>
</tr>
<tr>
<td>Finance</td>
<td>-0.029%</td>
<td>-0.012%</td>
<td>-0.024%</td>
</tr>
<tr>
<td>Services</td>
<td>-0.021%</td>
<td>0.000%</td>
<td>-0.020%</td>
</tr>
<tr>
<td>Public</td>
<td>-0.017%</td>
<td>-0.034%</td>
<td>-0.007%</td>
</tr>
</tbody>
</table>
Hydrology-Electricity-Economy Coupling Methodology

Convergence achieved when % Δ between iterations reaches a number close to zero
## Regional Economic Impacts

(Fully coupled model with unserved energy impacts)

<table>
<thead>
<tr>
<th></th>
<th>Household demand</th>
<th>Gross State Product</th>
<th>Foreign exports</th>
<th>Foreign imports</th>
<th>Domestic exports</th>
<th>Domestic imports</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>-0.30%</td>
<td>-0.30%</td>
<td>-0.20%</td>
<td>-0.07%</td>
<td>-0.10%</td>
<td>0.00%</td>
</tr>
<tr>
<td>Rest of WECC</td>
<td>-0.80%</td>
<td>-0.60%</td>
<td>-1.40%</td>
<td>-0.80%</td>
<td>-1.10%</td>
<td>-0.80%</td>
</tr>
<tr>
<td>Rest of US</td>
<td>0.01%</td>
<td>-0.01%</td>
<td>0.10%</td>
<td>0.20%</td>
<td>0.10%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Total US</td>
<td>-0.10%</td>
<td>-0.09%</td>
<td>-0.06%</td>
<td>0.03%</td>
<td>-0.02%</td>
<td>-0.02%</td>
</tr>
</tbody>
</table>
Future work: Improving the Representation of Renewables

- Current power system models assume generation from renewables (including hydro generation) is exogenous, based on “average historical year.”

- Therefore, optimization of generating units only applies to thermal units. Our goal is to include renewables (especially hydro generation) in this optimization.

- Bring in detailed models of hydroelectric generation and small systems with hydro that resolve the water flow and constraints endogenously.

- Research question: what are the implications of using an exogenous vs an endogenous representation of hydro in our model to estimate the impacts from water shocks?

- Method: Variant of PSM with explicit modeling of 7 cascaded reservoirs/generators in Columbia River basin.
Thank you!!