Low Carbon Energy Scenario Insights for a Robust Electricity System
The Importance of Climate Change in Energy Planning and Scenario Analysis

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Outline

I Earlier work on decarbonization pathways and some key findings

II Current work
   — Path dependency of the electricity grid
   — Environmental justice-related work

III Climate change trends and energy system impacts
   — Modeling approach
   — Preliminary results
     • Hydro-power
     • Building modeling
   — Next steps
Earlier work for CEC – Deep Carbon Reductions for 80% reduction in 2050

- Decarbonization pathways: Aggressive Energy Efficiency, Low Carbon Electricity and Electrified End Uses, Low-GHG Biofuels, & Conservation
  - Electrification of transportation and building heating can sharply increase demand in 2050, but can be offset by aggressive energy efficiency

Earlier work for CEC – Impacts to System Load Shapes and DR Opportunities

- Combination of low carbon electricity and electrified end uses
  - Shift to Winter peaking system is predicted, similar to Northwest
  - Electrified end uses can expand the technology space/opportunities for demand shifting and grid support


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Key Objectives – LBNL/UCB project

“Building a Healthier and More Robust Future: 2050 Low Carbon Energy Scenarios for California”

• Path-dependency: what are implications of 2030 decisions on meeting 2050 GHG goals
• Health and environmental benefits of cleaner transportation
• Assessment of building greater energy system preparedness and resilience to climate change and other risks
• Deeper dive case studies on electrified heating and fuel cell vehicle costs
SWITCH WECC model

- Capacity expansion deterministic linear program

- Minimizes total cost of the power system:
  - Generation investment and operation
  - Transmission investment and operation

Geographic:
- Western Electricity Coordinating Council
- 50 load areas

Temporal:
- 72 distinct hours simulated per period
  - Dispatch simulated simultaneously with investment decisions
How to plan efficiently?
• Today until 2030 and then until 2050?
• Or today until 2050?

Carbon cap scenarios:
• 80% reduc. by 2050
• 1.5°C
• CA executive order (40% lower in 2030)
• Clean Power Plan

Preliminary Findings
Planning until 2030 results in:
• Later coal retirements
• Minor/no savings in periods 2020 and 2030
• More costly in 2040 and 2050
• CPP 9% more expensive in 2050
1. Transportation and vulnerable communities
   - Identify vulnerable communities: CalEnviroScreen
   - Air pollutants assessment using EMFAC model (ARB)
     - CO2, NOx, PM10, PM2.5
   - Utilize transportation electrification scenarios and spatially quantify pollutant changes
   - Calculate human health and environmental impacts from reduced order models such as APEEP and EASIUR
   - Impacts are reported in monetary terms, based on the Value of a Statistical Life (VSL) framework

2. Using the SWITCH model
   - For relevant policy scenarios, we compute air pollutants from electricity generation.
   - CO2, NOx, SOx, PM10, PM2.5

![Diagram showing the process of calculating external damages from all grid electricity pollutants by county (APEEP)]
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Warming Climate and Increase in Extreme Weather

**Annual Temp Anomaly to 2015 Global Land-Ocean Temperature Index**

- **Annual Mean**
- **5-year Mean**
- **Very Strong El Nino**

**California Temperature (F)**

**General trends for Southwest U.S. region, CA**

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Higher Frequency</th>
<th>Greater Intensity</th>
<th>Longer Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Waves</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Drought</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wildfires</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Extreme Rainfall</td>
<td>x</td>
<td>x</td>
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</tr>
</tbody>
</table>
“Probabilistic” Climate Scenarios

• Common set of “probabilistic” climate and sea level rise scenarios. The same scenarios that will be used for the California” Fourth Climate Change Assessment.

• The climate projections developed by Scripps suggests that from the present to 2050 the scenarios are independent of global emission scenarios (RCPs).

Data from Pierce et al., 2015. Scripps Institution of Oceanography
## Climate Change Impacts on Energy Systems

<table>
<thead>
<tr>
<th>Hydro-meteorological and/or climate parameter</th>
<th>Energy supply</th>
<th>Energy demands</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air temperature</strong></td>
<td>Turbine production efficiency, air source generation potential and output, solar PV panel efficiency, T&amp;D capacity</td>
<td>Cooling/heating demand; Demand simulation/modeling</td>
</tr>
<tr>
<td><strong>Rainfall</strong></td>
<td>Hydro-generation potential and efficiency, biomass production</td>
<td>Demand, simulation/modeling</td>
</tr>
<tr>
<td><strong>River flow</strong></td>
<td>Hydro-generation and potential, hydro-generation modeling (including dam control)</td>
<td>Power station cooling water demands</td>
</tr>
<tr>
<td><strong>Wind speed and/or direction</strong></td>
<td>Wind generation potential and efficiency</td>
<td>Demand, simulation/modeling</td>
</tr>
<tr>
<td><strong>Sea level</strong></td>
<td>Offshore operations, coastal energy infrastructure</td>
<td></td>
</tr>
<tr>
<td><strong>Cloudiness</strong></td>
<td>Solar generation potential</td>
<td>Demand, simulation/modeling</td>
</tr>
<tr>
<td><strong>Drought statistics</strong></td>
<td>Hydro-generation output</td>
<td>Demand</td>
</tr>
<tr>
<td><strong>Humidity</strong></td>
<td></td>
<td>Demand, simulation/modeling</td>
</tr>
<tr>
<td><strong>Short-wave radiation</strong></td>
<td>Solar generation potential and output, output modeling</td>
<td>Demand, simulation/modeling</td>
</tr>
<tr>
<td><strong>Coastal wave height and frequency, and statistics</strong></td>
<td>Wave generation potential and output, generation modeling, off-shore infrastructure protection and design</td>
<td></td>
</tr>
<tr>
<td><strong>Flood statistics</strong></td>
<td>Raw material production and delivery, infrastructure protection and design</td>
<td>Cooling water demands</td>
</tr>
<tr>
<td><strong>Storm statistics (includes strong winds, heavy rain, hail, lightning)</strong></td>
<td>Infrastructure protection and design</td>
<td>Demand Surges</td>
</tr>
</tbody>
</table>

Ref: Ebinger, Vergara, World Bank 2011
Example impact to CA energy and GHG: Residential Heating Sector

- Heating Degree Days: California
- 16% drop in 2014 (ARB data)
- 25-30% drop in 2014 (my est.)
Future demand impact: “extrinsic” AC demand (more equipment adoption)

**Shifts in CDD by climate zone from 2015 to 2050**

Central California coast (Division 4) ➔ present-day Southern California (Division 6), Southern California CDD ➔ will exceed current day Central Valley (Division 5).
Climate change is important to factor into energy planning and scenario analysis

- Impacts to Energy demand (cooling, heating)
- Impacts to Energy infrastructure (e.g. generation, T&D)
- Impacts to Electricity Load Shapes and resource planning (e.g. peak demands)
- Impact to Energy system resiliency (e.g. summer heat waves)
- Impact to Policy focus areas
  - E.g. if heating demand is decreasing, then perhaps focusing on building retrofitting is not as important
  - If peaks are increasing, DR even more important
  - Code Requirements for heating vs. cooling
Approach: Model Structure and Key Outputs

Assumptions:
Building Stock
Pop. Growth
Climate Change Scenarios + Decarb. Scenarios

Resiliency Scenario Modeling to 2050

Hydrological Availability and Variability
Building Stock Load Shapes vs. Climate Change Scenario
Other shocks e.g. fuel prices, earthquake (wildfires)

SWITCH Electricity supply model for WECC (“Quasi-stochastic” version)

Key Outputs:
Impact on electricity generation portfolio, overall costs, reserve margin, etc.
"Quasi-stochastic" SWITCH Model

**Goal:** Identify electricity system requirements under a wider range of future uncertainties

What if there is prolonged drought (hydro variability); fuel price swings; load uncertainty?

**Plan:**
- Enable probabilistic inputs, more scenario runs
- Migration of SWITCH to Python PYOMO platform in progress
- Robust optimization: minimize total cost subject to constraints for different weather scenarios (wind, hydro, load)
Impacts on Hydropower (Preliminary)

Reservoir Behavior

- Increased reservoir inflow variability under climate change across all major water reservoirs
- Average annual generation is similar to current, but individual years will vary over a larger range, and increased extremes cause more spillage.
Impacts on Hydropower (Preliminary)

- Hydropower Impacts – Inflow and Generation

- Despite similar inflow and average annual generation:
  - LCOE, fuel use, GHG emissions, and Balancing Capacity requirements still increase!

- Increased hydropower variability and extreme events decreases balancing power plant efficiency

- Part load effects, increased reliance on inefficient peaker plants during extended drought events → Increased GHG emissions

- Inability to make use of all inflow for hydropower during flood events

- Bulk water availability not the only driving factor

Impacts on Ren. Potential (Preliminary)

- Water Constrained Solar Thermal Potential
  - Preliminary results – Precipitation impact only
    - Water availability can potentially constrain solar thermal potential
    - Heavily dependent on climate model
      - Different predictions for spatially resolved precipitation
    - Dry cooling important for maximum usable potential capacity
    - Analogous results for geothermal
Impacts on Electric Demand (Preliminary)

• Building modeling
  o Representative building models:
    ✓ Residential – Multi-Family and Single-Family (PNNL)
    ✓ Commercial – Multiple Types (NREL, LBNL)
  o Developing weather data for CEC building climate zones for use in EnergyPlus
  o Determining projections of building stock changes in residential and commercial sectors (in collaboration with LBNL)

• Bottom-up composition of electric load changes
  o Develop hourly resolved representative year load profiles for climate change-impacted buildings.

• Preliminary results for 2050 vs 2010
Impacts on Electric Demand (Preliminary)

- Impacts on Residential Buildings (climate impacts only)
  - Increased temperatures cause increased cooling needs
  - Increased overall electricity demand
    - 0.8% to 4.3% increase over historical demand
  - Increased typical peak electric demands
    - Representative typical increases of 2.0% to 4.2% over historical
  - Electric demands increase, overall energy demand at the building level actually decreases
    - Lower space heating demand
  - Electrification of residential heating through heat pumps:
    - Reduced overall energy consumption – space heating and water heating
Next steps and timeline

• Estimation of extrinsic cooling demand (Dec/Jan’17)
• Perform analogous modeling for the commercial building sector with UC-Irvine (Dec/Jan ’17)
• First runs of Python-version of SWITCH, Jan’17
• Incorporation of building load shapes in SWITCH and resiliency scenarios (Jan-June’17)
Conclusions/ Summary

- Long Term Energy Scenarios teams are building upon previous work to quantify the impacts of climate change on energy supply and demand in California to 2050 and to investigate energy system resiliency

- Preliminary conclusions:
  - 2030 vs. 2050 planning can have path dependency favoring longer term planning
  - Water availability can potentially limit solar thermal / geothermal supply, and increase hydropower variability and GHG emissions
  - Shifts in climate will lead to increased cooling demand and lower heating demand and need to plan for increased electricity demand and peak demands

- Follow up work to focus on:
  - Health and environmental benefits of cleaner transportation
  - Assessment of building greater energy system preparedness and resilience to climate change and other risks, using more probabilistic electricity supply modeling (quasi-stochastic SWITCH model)
Acknowledgments

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Thank you

mwei@lbl.gov
Back-Up Slides
Current Work: Three Teams working on 2050 Long Term Energy Scenarios

Lawrence Berkeley National Lab  
*Sustainable Energy Systems*

University of California, Berkeley  
*Renewable & Appropriate Energy Laboratory*

University of California, Irvine  
*Advanced Power and Energy Program*

Energy + Environmental Economics (E3)

*Approximate CEC project duration:  Sept 2015 – Sept 2017*
Historical (1981–2010) and future (2080–2099) US CDD and HDD, calculated from CMIP5 RCP8.5 climate model
### Energy Demand Bottom-Up Modeling – recent studies and this work’s goals

<table>
<thead>
<tr>
<th>REF.</th>
<th>Inst.</th>
<th>Geo.</th>
<th>Time Scale</th>
<th>Intrinsic Demand</th>
<th>Extrinsic Demand</th>
<th>Load Shapes/Peak Demand</th>
<th>Grid Impacts</th>
<th>Cost Impacts</th>
</tr>
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<tbody>
<tr>
<td>Xu 2012 LBNL</td>
<td>LBNL</td>
<td>CA</td>
<td>2100</td>
<td>X</td>
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<tr>
<td>Davis, Gertler, PNAS 2015</td>
<td>UC-Berkeley</td>
<td>Mex.</td>
<td>2100</td>
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<tr>
<td>Dirks et al. 2015</td>
<td>PNNL</td>
<td>U.S.</td>
<td>2100</td>
<td>X</td>
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<td>X</td>
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<tr>
<td>Huang, Gurney 2016</td>
<td>ASU</td>
<td>U.S.</td>
<td>2100</td>
<td>X</td>
<td>X</td>
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<tr>
<td><strong>This Project’s Goals</strong></td>
<td><strong>LBNL UC-Berk./UC-Irvine/E3</strong></td>
<td>CA</td>
<td>2050</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Impacts on Electric Demand (Preliminary)

• **Next Steps**
  - Perform analogous modeling for the commercial building sector
  - Capture non-temperature climate impacts (to extent possible)
  - Take into account changes in building stock and heating type distribution
  - Take into account different vintages of buildings to the extent possible
    ✓ Depends on availability of prototype building models

• **Lessons for Long-Term Planning**
  - Plan for increased electricity demand and peak demands over and above population growth
  - Focus on decarbonization of electricity resources and electrifying end uses
Impacts on Hydropower (Preliminary)

• Methodology Overview

- Climate Scenario
  - Atmospheric Data
  - Hydrologic Downscaling
    - Runoff / Streamflow
    - Min Fill, Max Fill
    - Release Constraints
    - Fill Profile, Outflow Constraint

- Water Reservoir Fill Operational Model
  - Reservoir Demand Profile
  - Powerhouse Parameters
  - Reservoir Parameters
  - Grid Conditions
  - Net Load
  - Ancillary Service Needs
  - Cost Signals

- Hydropower Generation Profile
Impacts on Ren. Potential (Preliminary)

Methodology Overview – Solar Thermal

1. GIS Data
   - Land Cover
   - DNI
   - Urban Areas
   - Protected Areas
   - Slope Maps
   - etc...

2. California Land Area

3. Land Exclusions

4. Available Insolation

5. Usable Land Area


7. ST Plant Parameters
   - Solar-to-Elec Efficiency
   - Aperture Area
   - Total Area
   - Capacity Factors
   - Collector Type

8. Calculate Water Consumption

9. Water Cons. Factors

10. Hydrologic Region

11. Demand

12. Apply to Hydrologic Region Water Balance


*For Geothermal, potential is already known, so process starts from water consumption step
Climate Impacts on Building Loads

• Modeling Structure

- Climate Scenario
  - Atmospheric Data
- Zoning and Data Extraction
  - Weather Data Input for Building Modeling
  - Building Load Modeling
    - EnergyPlus Platform
    - Commercial Prototypes
    - Residential Prototypes
  - Loads for Individual Building Types
- Bottom-Up Composition of Load Profile
- Building Load Profile and Magnitude Perturbations

- Heating System Scenarios
- Building Stock Projections

Representative Building Prototypes
Impacts on Electric Demand (Preliminary)

- Impacts on Residential Buildings (climate impacts only)
  - Increased temperatures cause increased cooling needs

- Increased overall electricity demand
  - 0.8% to 4.3% increase over historical demand

- Increased typical peak electric demands
  - Representative typical increases of 2.0% to 4.2% over historical

- Specific events can have higher peak demand increases

- Extents depend on climate model

- Need to plan for increased electricity demand and peak demands over and above population growth
Impacts on Electric Demand (Preliminary)

- Impacts on Residential Buildings
  - Electric demands increase, overall energy demand at the building level actually decreases
  - Increased cooling demand, but also decreased space heating demand
  - Meeting a given increment of cooling demand is typically more efficient than the same for heating demand
    - Natural gas boiler vs. refrigeration cycle (COP > 3)
  - Electrification of residential heating through heat pumps:
    - Reduced overall energy consumption – space heating and water heating
Impacts on Electric Demand (Preliminary)

- Impacts on Residential Buildings (climate impacts only)
  - Spatially resolved impacts by CEC building climate zone
    - Largest increases in populated climate zones in Southern California
    - Certain regions show decreases in electricity use, but are relatively unpopulated / have initially low demands.
Impacts on Ren. Potential (Preliminary)

- **Water Constraints on Solar Thermal and Geothermal Deployment**

  - Translate capacity potential to water consumption in each hydrologic region, determine how demand impacts regional water balance under climate change

  - **Cooling types considered:**
    - Wet cooling (tower)
    - Dry air cooling (blower)
    - Hybrid wet/dry cooling

  - **Final metrics – Water Impact Indicators**
    - Net Usable Water Supply [TAF]
      - Water available for power plant use after water balance
    - Deployable potential capacity
      - Absolute [GW]
      - Relative [%]
Impacts on Ren. Potential (Preliminary)

• Water Constraints on Solar Thermal and Geothermal Deployment

  • Deployable Solar Thermal Potential: **199.6 GW**
    - Land Exclusions:
      - US and CA Protected Lands
      - Lakes, Rivers, Open Water, Wetlands
      - Land Cover: Developed Land, Forests, Agriculture Lands
      - DNI < 7.0 kWh/m²/day
      - Contiguous Area < 1 km²
      - Land Slope > 3.5%
    - Focused in South Lahontan and Colorado River regions

  • Additional Geothermal Potential (USGS)
    - Identified Hydrothermal (Likely): **3.64 GW**
    - Undiscovered Hydrothermal: **14.99 GW**

  • Both potentials are spatially resolved by hydrologic region
    - Spatial component important to consider
Impacts on Ren. Potential (Preliminary)

• Water Constrained Geothermal Potential
  
  o Preliminary results – Precipitation impact only
  
  o Dry cooling necessary to ensure maximum energy potential utilization

  o Cooling system isn’t the only determining factor
    ✓ Enough water may be available in areas with low energy potential
    ✓ Spatial component important to consider
Impacts on Ren. Potential (Preliminary)

• Next Steps
  o Include the climate impacts on evapotranspiration due to temperature changes in the water balance
  o Include scenarios for future water demand change in agriculture and urban sectors into the water balance

• Lessons for Long-Term Planning
  o Must consider scenarios with and without solar thermal and geothermal capacity in the future renewable portfolio
    ✓ Investigate how these constraints change the future optimized renewable portfolio and introduces risks for planning.
Impacts on Hydropower (Preliminary)

• Hydropower Impacts – Inflow and Generation

- Overall inflow volume is similar or greater, but increased extremes cause more spillage.