Infrastructure Planning of the Western North American Electricity System with High Fractions of Wind and Solar Power

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SECTION I – RESEARCH SUMMARY

In research co-sponsored by the Link Foundation Energy Fellowship, we use a state-of-the-art planning model for the electric power system – the SWITCH model – to investigate the evolution of the power systems of California and western North America (specifically WECC, the Western Electricity Coordinating Council) from present-day to 2050 in the context of deep decarbonization of the economy. As the cost of electricity is an important factor for the economic welfare of society, cost-minimization framework is employed. We simulate how projected electricity demand, reliability requirements, and policy goals might be met at the lowest possible cost. The power system is constrained to reach 14 % of 1990 CO_2 emission levels by 2050 under a range of scenarios, each with specific assumptions about future demand profiles, costs, policy mandates, technological availably, and electric system flexibility.

The electricity system is of fundamental importance to the decarbonization of the entire energy system, as fuel switching away from oil and natural gas and towards electricity is a key decarbonization strategy. The scenarios presented here incorporate hourly electricity demand profiles resulting from the electrification of heating and vehicles, as well as from substantial energy efficiency. Even with aggressive efficiency measures, WECC-wide electricity demand is likely to increase by at least 75 % between present-day and 2050 due to population growth and additional demand from electric vehicles and electric heating.

The results presented here should be interpreted in the context of the economic optimization from which they are generated. They do not represent prescriptions or projections but rather they depict minimum-cost strategies for a range of possible scenarios that meet policy targets while also supplying reliable electricity. We find drastic power system carbon emission reductions to be feasible by 2050 under a wide range of possible futures. Assuming that carbon permit revenues are reinvested into the power system, the WECC-wide average cost of power in 2050 is found to range between $149/MWh and $232/MWh across scenarios. This power cost level represents a 21 to 88 % increase relative to a business-as-usual scenario in which emissions stay flat after 2020, and a 38 to 115 % increase (in real terms) relative to the present-day cost of power. As this study assumes little technological progress by default in many parts of the electricity system, these cost estimates may represent an upper bound. We demonstrate that breakthroughs in the cost of solar

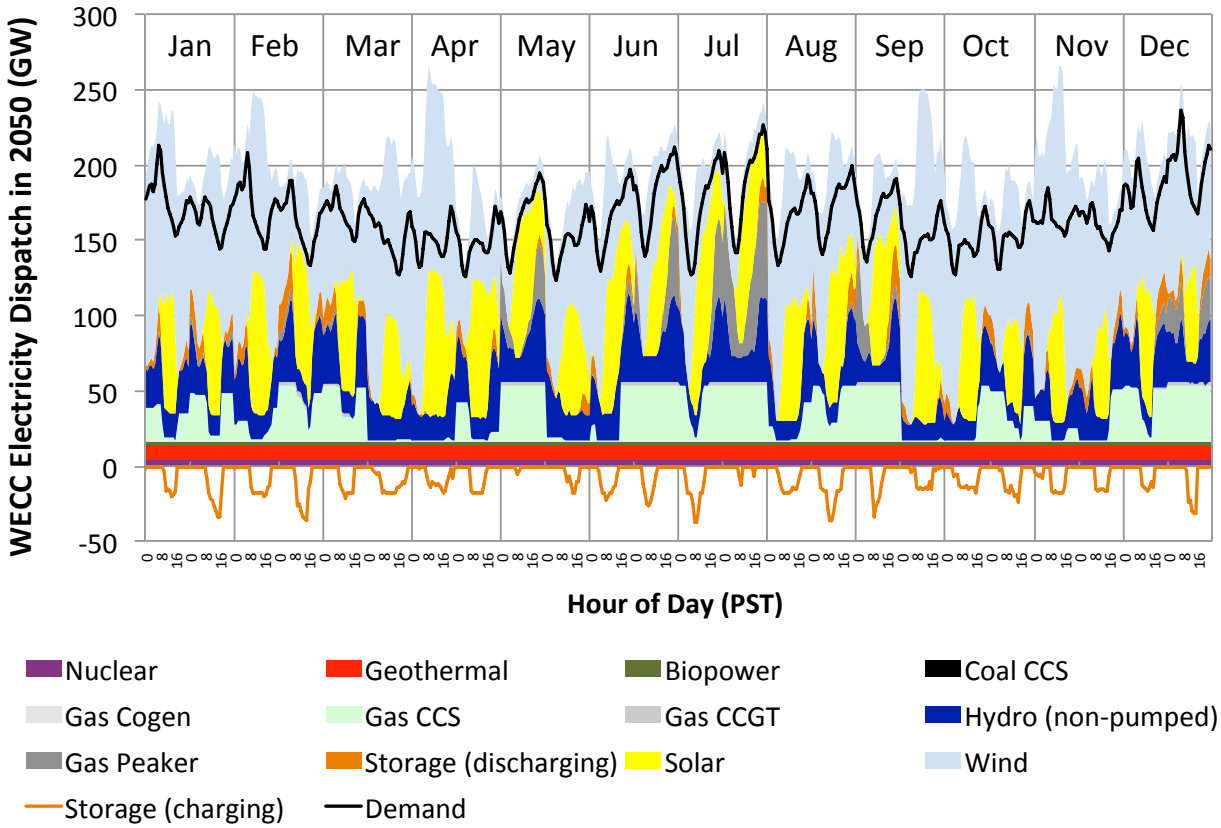
energy or the deployment of demand response could contribute greatly to containing the cost of electricity decarbonization.

In order to rapidly decarbonize, the power system undergoes sweeping change. Between present-day and 2030, the evolution of the WECC power system is dominated by the implementation of aggressive energy efficiency measures, the installation of renewable energy and gas-fired generation facilities, and the retirement of coal-fired generation. In the 2030 time frame, the flexibility provided by the existing transmission network, existing hydroelectric facilities, the geographic consolidation of balancing areas, and a large fleet of gas-fired generation units is largely sufficient to integrate 45 - 86 GW of wind and solar power capacity in WECC, representing 12 - 21 % of total electricity produced. Consequently, deployment of new storage or long-distance, high-voltage transmission capacity is shown not to be a dominant strategy through 2030. Transmission capacity into California, made available in part by the retirement of out-of-state coal generation, is dominated by renewable power in the form of bundled Renewable Energy Certificates (RECs) in the 2030 time frame. The cost of power stays almost constant until 2030 – despite demand growth and reduction in emissions – due to moderate gas prices, the expiration of existing generator sunk costs, and the development of high quality renewable resources.

Near- to mid-term renewable energy policy targets – either a 12 GW distributed generation mandate in California by 2020 or a California 50 % RPS by 2030 – can help to deploy renewable generation in California on an accelerated schedule. However, these policy targets have less effect on the generation mix in the 2040 to 2050 time frame, as the cap on carbon emissions is the dominant driver of renewable energy deployment post-2030.

Post-2030, the electricity system undergoes a radical transformation in order to eliminate almost all carbon emissions from the generation mix. In the 2040 time frame, deployment of wind, solar, and geothermal power reduce power system emissions by displacing gas-fired generation. In the 2050 time frame this deployment trend continues for wind and solar, but is accompanied by large amounts of new storage and long-distance, high-voltage transmission capacity. In stark contrast to present-day operation, electricity storage is used primarily to move solar energy from the daytime into the night in order to charge electric vehicles and meet demand from electrified heating (Figure 1). Low-cost solar power is found to increase the need for electricity storage. If demand response is deployed in large scale in this time frame, it substitutes for the functionality of storage, thereby strongly incentivizing the deployment of solar generation, especially in California.

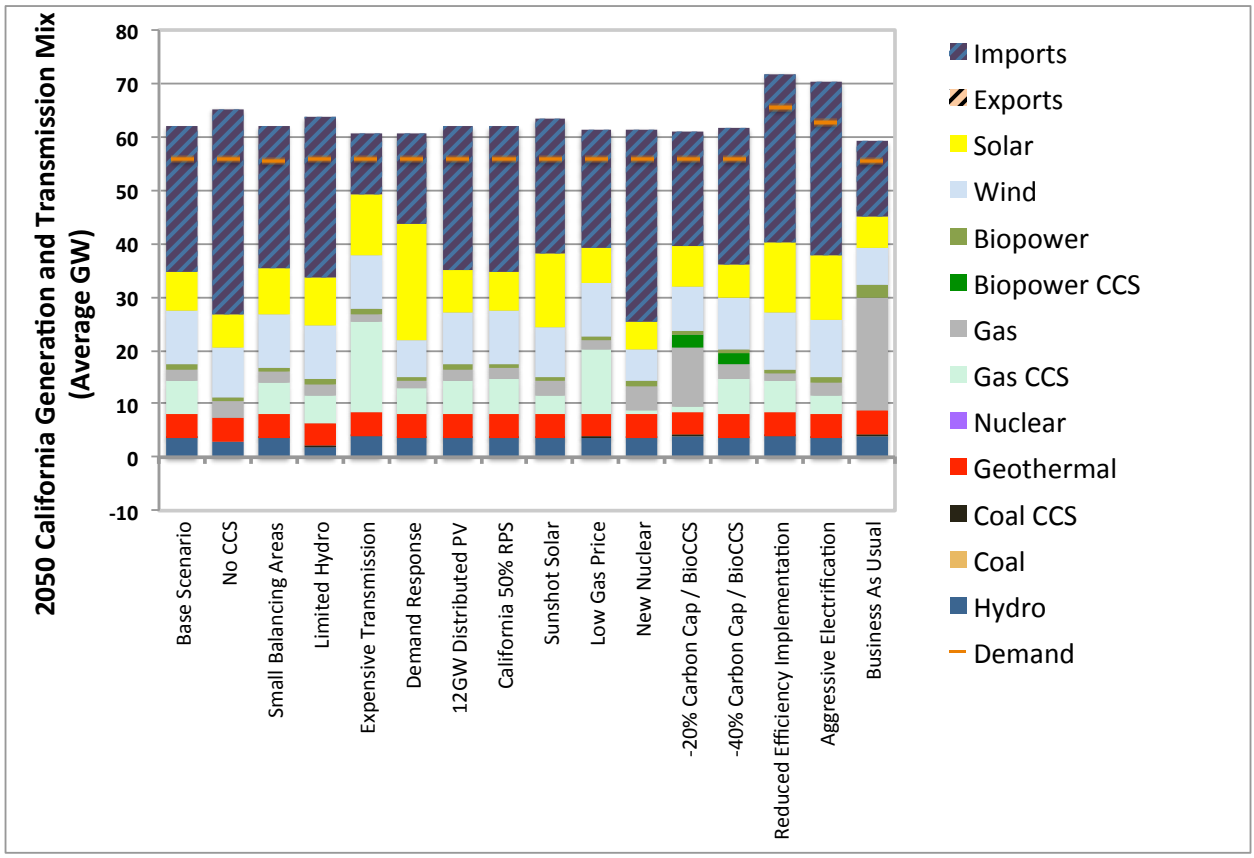
Figure 2: Base Scenario hourly power system dispatch across WECC in 2050



Two days per month are represented – the median demand day and the day on which the hour of peak demand occurs. Total generation exceeds demand due to distribution, transmission, and storage losses, as well as variable renewable energy curtailment.

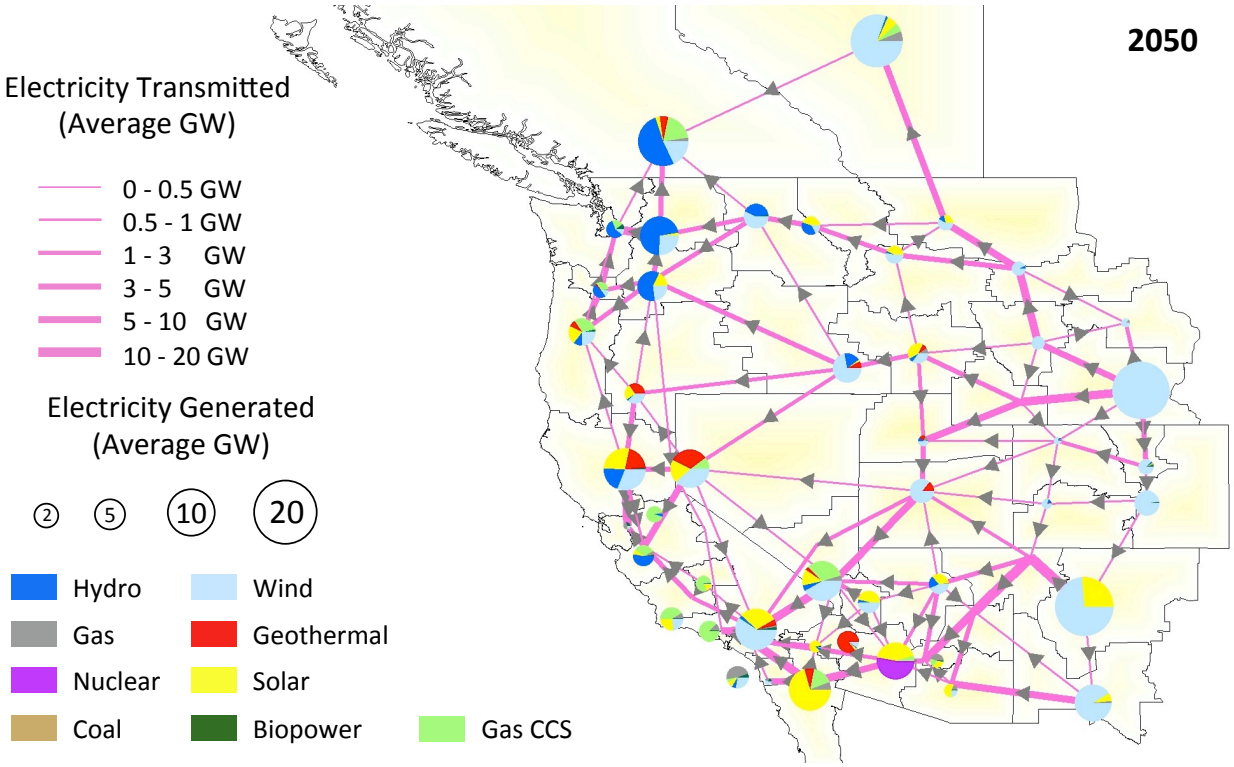
Through 2050, transmission lines that exist today are found to be mostly sufficient to move power between Pacific Coast states. New transmission capacity is built primarily to move power over hundreds of miles from the inside of the continent towards demand centers on the coast. High-voltage DC transmission may be well suited to provide much of this new transmission capacity. Transmission capacity over the California border is increased by 40 - 220 %, implying that transmission siting, permitting, and regional cooperation will become increasingly important over time. California remains a net electricity importer in all scenarios investigated. The percent of electricity imported into California ranges from 22 % to 60 %, with most scenarios resulting in imports of about 40 %. The implementation of demand response programs could reduce the necessary import/export capacity into California. The deployment of out-of-state nuclear power or a lack of availability of Carbon Capture and Sequestration (CCS) technology would require high levels of California transmission import/export capacity.

Figure 2: California average hourly generation mix by fuel, imports and exports, and demand in 2050



Wind and solar power are key elements in power system decarbonization, providing 37 – 56 % and 17 – 32 % of energy generated respectively across WECC in 2050 if no new nuclear capacity is built. At these penetration levels of variable renewable energy, the least cost strategy for meeting policy, reliability, and demand targets includes the curtailment of wind, and to a lesser extent solar facilities at hours of high renewable output and/or low electricity demand (Figure 2). In this study, transmission and storage are installed to capture energy from variable renewable facilities, but there is an economic trade-off between building additional storage and transmission facilities or slightly over-sizing renewable power facilities such that there is ample energy from these facilities in hours of great need. Curtailment of some variable renewable power becomes the lowest-cost strategy under the aggressive carbon targets investigated in this study. Demand response can help to reduce curtailment, but does not entirely eliminate curtailment. Consequently, determining how the cost of variable renewable curtailment is compensated will become increasingly important over time.

Figure 3: Base Scenario average hourly generation mix by fuel within each SWITCH load area, and average hourly transmission flow between load areas in 2050



In an effort to integrate wind and solar resources into the power system, the amount of installed gas capacity remains relatively constant between present-day and 2050, though CCS is installed on some gas plants by 2050. The fleet-wide average capacity factor of non-CCS gas generation drops steeply between 2030 and 2050, reaching only 5 % to 16 % in 2050 for scenarios that meet the 86 % emission reduction target, indicating that gas plants are only operated for a handful of hours each year but are of extremely high value during those few hours. This result suggests the difficulty of supporting gas generation through energy and ancillary service market revenues, and implies the need for other revenue streams such as a capacity market. As there is little space in the carbon cap for fossil fuel emissions by 2050, sub-hourly spinning reserves are almost exclusively provided by hydroelectric and storage facilities.

Both gas-fired CCS and nuclear power are found to be economical in the context of deep emission reductions, but neither is found to be essential to meeting 2050 emission targets. Both technologies are subject to large political and/or technical uncertainty and therefore economics may not be the driving force for installation. The deployment of moderate amounts of flexible gas CCS to balance variable renewable generation is found to be one of the most effective ways to contain the costs of reducing carbon emissions, especially in California. Gas CCS is not found to be economical to run in baseload mode due to the prevalence of inexpensive wind and solar power, as well as incomplete emissions capture by the CCS system. Coal-

fired CCS is not deployed at scale in any scenario investigated due to unfavorable economics and incomplete emissions capture. The finding that baseload fossil fueled CCS is not economical at deep carbon reduction levels is counter to the prevailing thinking about CCS and follows directly from using a detailed modeling platform such as SWITCH.

Biomass CCS can be effective at reducing power sector emissions far below zero by 2050, and can therefore be thought of as a hedge against incomplete decarbonization of other sectors (notably the transportation sector). The cost to make the power system net carbon negative is moderate if biomass is made available to the electric power system instead of to the production of biofuels.

SECTION II – SCHOLAR CONTRIBUTIONS

Dr. Nelson has made a number of contributions to the science and policy community as a Link Foundation Energy Fellow. In these contributions, the fellowship is acknowledged where possible.

JOURNAL PAPERS:

4. **Nelson, J. H.**; Mileva, A.; Johnston, J.; Kammen, D. M. "Long-term Planning for Carbon Emission Reductions Reveals Paradigm Shifts in the Electricity Sector." *In Preparation.*
3. Mileva, A.; **Nelson, J. H.**; Johnston, J.; Kammen, D. M. "SunShot Solar Power Reduces Costs and Uncertainty in Future Low-Carbon Electricity Systems." *Environ. Sci. Technol.,* 47 (16), pp. 9053-9060 (2013).
2. Wei, M.; **Nelson, J. H.**; Greenblatt, J. B.; Mileva, A.; Johnston, J.; Ting, M.; Yang, C.; Jones, C.; McMahon, J. E.; Kammen, D. M. "Deep Carbon Reductions in California Require Electrification and Integration Across Economic Sectors." *Environ. Res. Lett., 8,* 014038*,* (2013).
1. **Nelson, J.**; Johnston, J.; Mileva, A.; Fripp, M.; Hoffman, I.; Petros-Good, A.; Blanco, C.; Kammen, D. M. "High-Resolution Modeling of the Western North American Power System Demonstrates Low-Cost and Low-Carbon Futures." *Energy Policy*, 43, pp. 436-447 (2012).

REPORTS AND BOOK CHAPTERS:

3. **Nelson, J. H.**; Mileva, A.; Johnston, J.; Kammen, D. M.; Wei, M.; Greenblatt, J. B. "Scenarios for Deep Carbon Emission Reductions by 2050 in Western North America using the SWITCH Electric Power Sector Planning Model." CEC-500-2010-047, California Energy Commission, Forthcoming (2014).
2. Wei, M.; **Nelson, J. H.**; Ting, M.; Yang, C., Kammen, D. M.; Jones, C.; Mileva, A.; Johnston, J.; Bharvirkar, R.; Greenblatt, J. B.; McMahon, J. E. "California's Carbon Challenge: Scenarios for Achieving 80% Emissions Reduction in 2050." Tech. Rep. LBNL-5448E, Lawrence Berkeley National Laboratory (2012).
1. Tidwell, V.; Dale, L.; Franco, G.; Averyt, K.; Wei, M.; Kammen, D.; **Nelson, J. H.** "Energy Impacts." Chapter 12 in: Assessment of Climate Change in the Southwest United States. Technical Report, U.S. National Climate Assessment, [Garfin, G., Jardine, A., Merideth, R., Black M., Overpeck, J. (eds.)]. Tucson, AZ: Southwest Climate Alliance (2012).

INVITED TALKS AND PRESENTATIONS:

7. California Climate Policy Modeling Dialogue and Workshop, "Planning Power Systems with Deep Emission Reductions by 2050 Using the SWITCH Model," Davis, CA (12/16/2013).
6. Webinar, National Renewable Energy Laboratory, "Quantifying the Cost of Decarbonizing the Western North American Electric Power System Through 2050," (10/29/2013).
5. Energy and Resources Group Colloquium, "Quantifying the Cost of Decarbonizing the Western North American Electric Power System Through 2050," Berkeley, CA (09/25/2013).
4. Lead Commissioner Workshop on Evaluating Electricity Sector Needs in 2030, California Energy Commission, "Simultaneous Planning of Generation, Transmission, and Storage Capacity for 2030 and Beyond Using the SWITCH Model," Sacramento, CA (08/19/2013).
3. Energy and Environmental Economics (E3), "Planning Pathways to 90% Carbon Emission Reductions in WECC by 2050 Using the SWITCH Model," San Francisco, CA (06/21/2013).
2. 9th International Summer Academy on Energy and the Environment, "Integrated Generation, Transmission, and Storage Planning With Large Fractions of Renewable Energy," Berlin, Germany (07/26/2012).
1. Panelist, California Energy Commission, "Capturing Benefits of Renewable Energy for California," Sacramento, CA (04/12/2012).

SECTION III – FINANCIAL STATEMENT

Discretionary funds from Link Foundation Energy Fellowship were used:

- to defray the cost of publication in the journal *Energy Policy*
- for computing equipment
- to attend a conference on the integration of renewable energy in Berlin, Germany

SECTION IV – IMPACT OF FELLOWSHIP

Dr. Nelson greatly appreciates the opportunities brought through the award of his Link Fellowship. Link Fellowship funds contributed not only to Dr. Nelson's immediate research, but also added to the ability of his research group to perform state-of-the-art work on the topic of renewable energy integration into the electricity system. In addition, it is likely that Dr. Nelson received the Kendall Science Postdoctoral Fellowship at the Union of Concerned Scientists in part due to prior fellowship experience.