Precourt Energy Efficiency Center

Funded Project Final Survey Report

Principal Investigator: Prof Mark Jacobson

Project Title: analyzing and Optimizing Supply and Demand of Intermittent Renewable Electricity Through Transmission Load Flow Modeling

1. *Project Description:*

Summary

The main focus of this project was to explore the feasibility and quantify the effects of combining solar, wind, geothermal, and hydroelectric power with remaining conventional power to meet the time-dependent electric power demand in California while also meeting an aggressive carbon emissions reduction target. Two aspects of the feasibility of expanded grid integration were studied. First, we examined the effects of injecting power from large renewable plants throughout California directly onto the high-voltage transmission lines already in place using power flow modeling of the California transmission system. In the second stage of the study, we assumed additional transmission infrastructure development in order to focus on the problem of planning a renewable and conventional portfolio for the state that best mitigates the intermittency of wind and solar while meeting an 80% reduction in carbon emissions from the California electric power sector. The project also involved mapping winds offshore of California and examining the feedback of wind turbines to energy in the atmosphere.

Research Activities:

In the first stage of the study, the goal was to combine a transmission load flow model with wind and solar radiation predictions from an atmospheric model to examine the ability of California to deliver a smooth supply of different future (c. 2020) penetrations of renewable energy, some of which is intermittent. The California grid with substantial expansion of wind and solar thermal power was modeled using power flow simulations of the Western Interconnect. Day-long profiles of the California grid were calculated by finding a series of hourly steady-state solutions to the power flow equations, based on initial solutions provided by the Western Electricity Coordinating Council (WECC 2007). The power flow solutions were obtained with an iterative Newton-Raphson technique in the Power-World Simulator (Power World Corporation, 2007).

We approximated hourly load fluctuations in the system for a given hour by scaling the baseline scenario load across California uniformly in such a way as to match power supply profiles from the California ISO OASIS database (CISO, 2007). We used average insolation data (Masters, 2004) and reported collector efficiencies (NREL, 1994) to give hourly solar generation inputs into the model at different locations. Wind generation was approximated using monthly-averaged windspeeds from a mesoscale meteorological model (Dvorak et al., 2009) and the power curve of the REPower 2MW turbine (REPower, 2004). All proposed renewable generation expansions were located at preexisting wind farms and planned solar thermal plants (CEC, 2009). Generation from natural gas plants was reduced at each hour to account for the additional wind and solar generation.

Steady-state power flow solutions were found for each hour over the course of a high-load summer day in 2016 and a typical winter day in 2007 to demonstrate the feasibility of meeting the load with large-scale renewables. This study found that in order to meet the load at each hour on a typical summer day, 31 transmission lines throughout the state would require additional capacity above the capacities projected by the WECC for 2016. While this study addressed some of the limitations of integrating intermittent generation that is located far from load centers and in areas of limited transmission infrastructure, the analysis of typical days, rather than extreme events, led to questions about the robustness of our conclusions. In response to this concern, an additional study was designed to include both typical days and extreme events in order to determine the effect on the acceptable levels of intermittent power generation on the grid from a system-wide load balance perspective.

In the system-wide load balance study, we developed a grid integration model that found the optimal installed capacity of wind and solar thermal plants at specific locations throughout the state in addition to distributed residential photovoltaics, geothermal plants, and spinning reserve natural gas plants in order to meet the fluctuating California ISO load. The system was required to meet an 80% reduction in electric power sector emissions from 2006 levels and the optimal solution was determined based on annualized capital costs, fixed and variable operations and maintenance costs, and fuel costs for each technology. Power balance (and an additional reserve capacity constraint) was required at each hour over 24 days throughout 2006 that represented both typical seasonal behavior as well as extreme meteorological and load events, as determined by a statistical analysis prior to the optimization. Power available from each wind farm site was calculated with simulated wind speed data and the power curve of a 2.5 MW turbine (REPower). Power from solar thermal plants was calculated using simulated insolation data at each site and a linear solar thermal (with storage) model based on experimental data from the SEGS systems and a tested thermocline tank storage system. The capacity of the storage tank was left as an optimization variable in order to determine the optimal storage tank size for future solar thermal systems. All simulated meteorological data was obtained from GATOR-GCMOM, a global-through-urban climate-weather-air pollution model (Jacobson 2001, Jacobson 2007), which was run for 2006 with a 21km SN by 14 km WE resolution over California and Nevada. Natural gas fuel use, emissions, and ramping constraints were modeled to match specifications for the Siemens-Westinghouse 501FD turbine. Hydroelectric power was constrained at each hour by an installed capacity constraint, assuming no additional development, and total annual generation was constrained in order to match the actual generation for 2006. Seasonal variation in the availability of hydroelectric power was not included in the simulations discussed here, but has been attempted in recent model development.

Major Results

The power flow study found that, with increased capacity in 31 transmission lines, renewable energy sources could provide at least 70% of California's electricity on a typical summer day in 2016. For reference, this same portfolio would have provided 50% of generation on a typical winter day in 2007 (See Figures 1 and 2). Additional transmission infrastructure upgrades would likely be necessary in order to maintain system stability during extreme meteorological and/or load events.

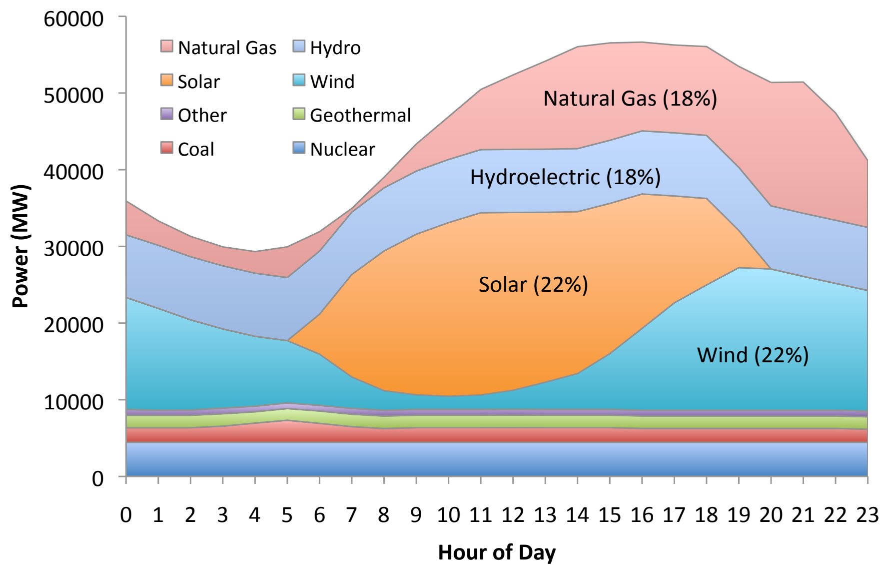

Figure 1. Generation mix for a projected peak load day in the summer of 2016. Each hour represents the generation mix in California associated with a power flow solution for the western interconnect.

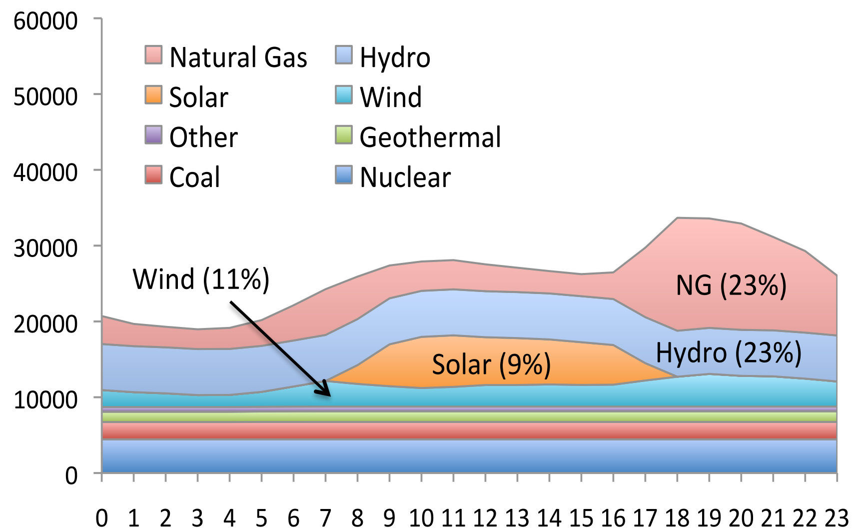

Figure 2. Generation mix for a low load day in the winter of 2007. Each hour represents the generation mix in California associated with a power flow solution for the western interconnect.

The system-wide load balance study has further found, to date, that the optimal generation portfolio to achieve an 80% reduction in carbon emissions from 2006 levels includes 36 GW of installed wind power at 25 sites; 3.6 GW of installed solar thermal power at 10 sites; over 10 GW of installed residential photovoltaic systems distributed throughout the state; 4.7 GW of installed geothermal power; 17 GW of available installed hydroelectric power (7 GW of which is installed in the Pacific Northwest); and 14GW of combined-cycle natural gas plants that operate as spinning reserves when not producing power. The generation mix over the course of a spring day and a peak load summer day are shown in Figures 3 and 4. In a brief study of suboptimal wind generation schemes, we also found that the cost- and emissions-benefits of aggregating distant wind farms leveled off above approximately 20 wind farm sites. The initial optimal portfolio is expected change after additional model development has been undertaken, including the addition of a day-ahead scheduled natural gas generator fleet, a seasonal hydroelectric availability constraint, and the implementation of a full stochastic optimization problem that accounts for meteorological and load forecast uncertainties. Additional model development will also treat forced outage rates in order to calculate the loss-of-load expectation for a given generation portfolio.

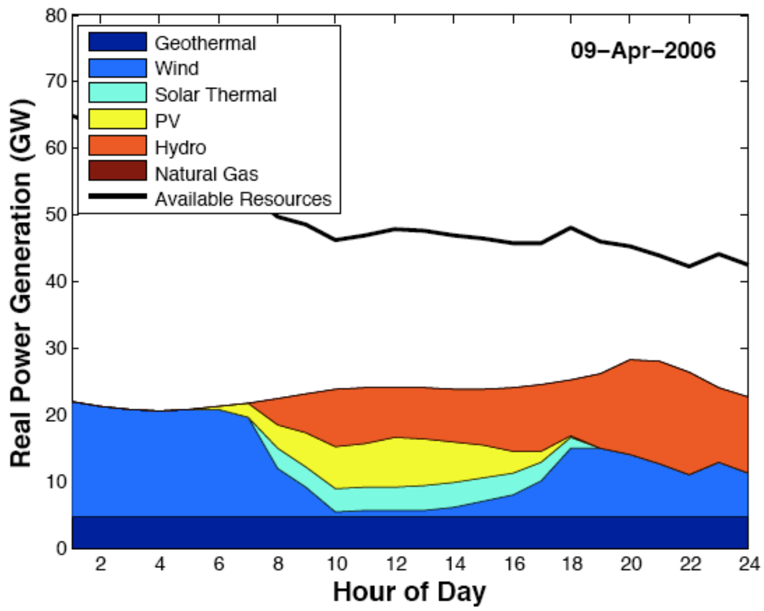

Figure 3. Theoretical generation mix throughout the day on April 9, 2006 based on the optimal generation portfolio obtained with the grid integration model.

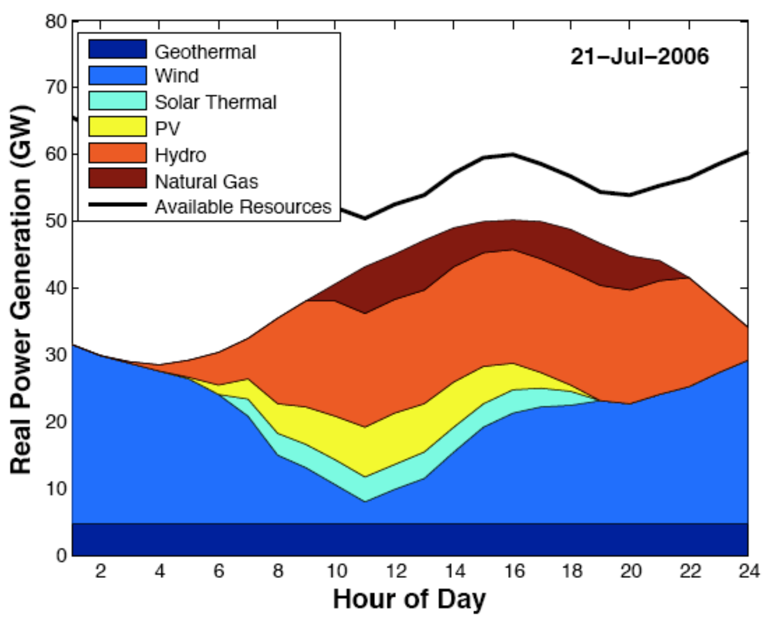

Figure 4. Theoretical generation mix throughout the day on July 21, 2006 (peak load conditions) based on the optimal generation portfolio obtained with the grid integration model.

Finally, the project also involved mapping winds offshore of California and examining the effect of wind turbines on energy in the atmosphere. These latter studies resulted in papers that are now published (Dvorak et al., 2010; Sta. Maria et al., 2010).

The first paper combined multi-year mesoscale modeling results, validated using offshore buoys with high resolution bathymetry, to create a wind energy resource assessment for offshore California (CA). The siting of an offshore wind farm is limited by water depth, with shallow water being generally preferable economically. Acceptable depths for offshore wind farms were divided into three categories: 20 m depth for monopile turbine foundations, 50 m depth for multi-leg turbine foundations, and 200 m depth for deep water floating turbines. The CA coast was further divided into three logical areas for analysis: Northern, Central, and Southern CA. A mesoscale meteorological model was then used at high horizontal resolution (5 and 1.67 km) to calculate annual 80 m wind speeds (turbine hub height) for each area, based on the average of the seasonal months January, April, July, and October of 2005/2006 and the entirety of 2007 (12 months). A 5MW offshore wind turbine was used to create a preliminary resource assessment for offshore CA. Each geographical region was then characterized by its coastal transmission access, water depth, wind turbine development potential, and average 80 m wind speed. Initial estimates showed that 1.4–2.3 GW, 4.4–8.3 GW, and 52.8–64.9 GW of deliverable power could be harnessed from offshore CA using monopile, multi-leg, and floating turbine foundations, respectively. A single proposed wind farm near Cape Mendocino could deliver an average 800 MWof gross renewable power and reduce CA's current carbon emitting electricity generation 4% on an energy basis. Unlike most of California's land based wind farms which peak at night, the offshore winds near Cape Mendocino are consistently fast throughout the day and night during all four seasons.

The second paper presented a parameterization of the interaction between wind turbines and the atmosphere and estimated the global and regional atmospheric energy losses due to such interactions. The parameterization was based on the Blade Element Momentum theory, which calculates forces on turbine blades. Should wind supply the world's energy needs, this parameterization estimated energy loss in the lowest 1 km of the atmosphere to be ~0.007%. This is an order of magnitude smaller than atmospheric energy loss from aerosol pollution and urbanization, and orders of magnitude less than the energy added to the atmosphere from doubling CO2. Also, the net heat added to the environment due to wind dissipation was found to be much less than that added by thermal plants that the turbines displace.

California Energy Commission (CEC) (2009) Large Solar Energy Projects, www.energy.ca.gov/siting/solar/index.html.

California Independent System Operator (CISO) (2007) Oasis: system load reports, http://oasis.caiso.com.

Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, Renewable Energy, 35, 1244-1254, doi:10.1016/j.renene.2009.11.022, 2010, www.stanford.edu/group/efmh/winds/.

Jacobson, M. Z. (2001), GATOR-GCMM: 2. A study of day- and nighttime ozone layers aloft, ozone in national parks, and weather during the SARMAP Field Campaign, J. Geophys. Res., 106, 5403-5420.

Jacobson, M.Z., Y.J. Kaufman, and Y. Rudich (2007), Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions, J. Geophys. Res., 112, D24205, doi:10.1029/2007JD008922.

Katzenstein, W. and J. Apt, 2009: Air Emissions Due to Wind and Solar Power. *Environ. Sci. Technol.* 43(2), 253-8.

Masters, G.M. (2004) Renewable and Efficient Electric Power Systems: Appendix C: Hourly clear-sky insolation tables, John Wiley & Sons, Hoboken, New Jersey, 654 pp.

National Renewable Energy Laboratory (NREL) (1994) Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.

Power World Corporation (2007), www.powerworld.com/products/simulator.asp.

REPower (2004) www.repower.de/fileadmin/download/produkte/PP_MM92_uk.pdf.

Sta. Maria, M.R.V., and M.Z. Jacobson, Investigating the effect of large wind farms on energy in the atmosphere, *Energies*, 2, 816-836, doi:10.3390/en20400816, 2009, www.mdpi.com/1996-1073/2/4/816/pdf.

Western Electricity Coordinating Council (2007), www.wecc.biz.

2. **How have the results from this project contributed to the solution of energy efficiency challenges? How is it likely to contribute to solutions in the future?**

The wind energy mapping work has helped to reduce a barrier to the implementation of cleaner and more sustainable electric power into California by identifying specific locations where wind farms can be placed.

The work on matching hourly power demand with a combination of renewables has motivated others to explore this method of using variable-supplied renewable energy sources without the need (or with a lesser need) for storage. The implementation of this method has the potential for significantly reducing a barrier to intermittent renewable energy supplies.

The work on examining the effect of wind turbines on energy in the atmosphere has helped to reduce a misconception that a large number of turbines will change large-scale wind circulation patterns and slow down the winds noticeably in the global average.

3. **What undergraduate or graduate students, as well as Post-Doctoral fellows, were involved this project. How were they involved?** ***Please list their name, classification and a short description of their involvement.***

Hoste, Graeme, undergraduate/M.S. student. He received VPUE grants so was not funded by the project, but he worked on an aspect of the project, namely combining different renewables to match hourly power demand in California.

Dvorak, Mike, PhD student. Mapping and analyzing winds for wind energy.

Hart, Elaine, PhD student. Examining the effect on matching hourly power demand by combining different renewables through the transmission system in California.

Sta. Maria, Eena. PhD student. Examining the effects of wind turbines on local and global energy in the atmosphere.

4. **Will you be continuing work on this project? How and with whom? Please include any comments.**

Yes. The three PhD students on the project will continue toward their PhD degrees on the same topics. Their funding now is from a combination of fellowships and parts of related projects rather than a centralized project.

5. **Are you seeking or have you received additional funding as a result of this project, or for continued work on this project?** ***Please list the amount you are seeking/have received, source of the additional funding and a short description.***

We wrote a proposal for a renewal grant last year from Precourt (PEEC) but were not funded. We did not write a proposal to the new Precourt Center this year, but may do so the next round.

6. **Has this project generated any other projects?** ***Please describe.***

This project has helped tremendously in pushing forward the study of combining renewable energy systems together.

7. **What patents, if any, have you received or applied for?**

None

8. **Please list all academic and non-academic (Op-Eds, news magazines, etc) publications and conference presentations as well as articles in progress that came about as a result of this project. May we post these on the PEEC website?** ***If so, please list the URL or provide a pdf version.***

Peer-Reviewed Published Papers

Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, *Renewable Energy*, doi:10.1016/j.renene.2009.11.022, 2009, www.stanford.edu/group/efmh/winds/.

Jacobson, M.Z., and M.A. Delucchi, Powering the planet, *Scientific American (Cover Story)*, November 2009

Jiang, Q., J.D. Doyle, T. Haack, M.J. Dvorak, C.L. Archer, and M.Z. Jacobson, Exploring wind energy potential off the California coast, *Geophys. Res. Lett.*, 35, L20819, doi:10.1029/2008GL034674, 2008.

Sta. Maria, M.R.V., and M.Z. Jacobson, Investigating the effect of large wind farms on energy in the atmosphere, *Energies*, 2, 816-836, doi:10.3390/en20400816, 2009, www.mdpi.com/1996-1073/2/4/816/pdf.

Conference Papers

Dvorak, M.J., M.Z. Jacobson, and C.L. Archer, California offshore wind energy potential, Proc. AWEA Wind Power 2007, Los Angeles, California, June 3-6, 2007, CD-ROM.

Sta. Maria, M.R.V., and M.Z. Jacobson, Examining the effects of wind farms on array efficiency and regional meteorology, Proc. AWEA Wind Power 2007, Los Angeles, California, CD-ROM.

Sta. Maria, M., and M.Z. Jacobson, New parameterization for wind farm effects on the atmosphere. Proc. AWEA Wind Power 2008 Conference, Houston, Texas, June 1-4, 2008, CD-ROM.

Conference Talks

Dvorak, M.J., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, AWEA Offshore Wind Power Workshop, Wilmington, Delaware, Sept. 9-10, 2008.

Dvorak, M.J., a. Boucher, and M.Z. Jacobson, Method to improve offshore wind energy resource assessments using cokriging, International Association for Mathematical Geology Conference 2009, Aug. 23-29, 2009, Stanford University.

Jacobson, M.Z., M. Dvorak, C.L. Archer, and G. Hoste, Energy solutions to air pollution and climate change in California. Fourth Annual California Climate Change Conference, California Energy Commission, Sacramento, California, Sept. 10-13, 2007.

Conference Posters

Dvorak, M., M.Z. Jacobson, and C.L. Archer, California offshore wind energy potential, Wind Power 2007 conference, Los Angeles, CA, June 3-6, 2007.

Dvorak, M., M.Z. Jacobson, and C.L. Archer, Prospects for California offshore wind energy development, 4th annual California Climate Change Conference, Sacramento, CA, Sept. 10-13, 2007.

Dvorak, M., and M.Z. Jacobson, Development potential for California's offshore wind energy resource, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 10-14, 2007.

Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, American Wind Energy Association Offshore Wind Power workshop, Wilmington, Delaware, Sept. 9-10, 2008.

Dvorak, M.J., and M.Z. Jacobson, Offshore wind resource assessment based on mesoscale modeling, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 15-19, 2008.

Dvorak, M.J., A. Boucher, and M.Z. Jacobson, Method to improve offshore wind energy resource assessments using cokgriging, American Wind Energy Association Offshore Wind Project Workshop, Boston, Mass., Dec. 2-3, 2009.

Dvorak, M.J., A. Boucher, and M.Z. Jacobson, Method to improve offshore wind energy resource assessments using cokgriging, American Geophysical Union, Fall Meeting, San Francisco, California, Dec. 14-18, 2009.

Dvorak, M.J., A. Boucher, and M.Z. Jacobson, Method to improve offshore wind energy resource assessments using cokgriging, American Meteorological Society 90th Annual Meeting, 20th Conference on Probability and Statistics in the Atmospheric Science, Atlanta, Georgia, January 17-20, 2010.

Hart, E.K., M.J. Dvorak, and M.Z. Jacobson, Power flow simulations of a more renewable California grid utilizing wind and solar insolation forecasting, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 15-19, 2008.

Hart, E.K., M.J. Dvorak, and M.Z. Jacobson, Power flow simulations of a more renewable California grid utilizing wind and solar insolation forecasting, Windpower 2009, Chicago, Illinois, May 4-7, 2009.

Hart, E.K., and M.Z. Jacobson, Planning a target renewable portfolio using atmospheric modeling and stochastic optimization, American Geophysical Union, Fall Meeting, San Francisco, California, Dec. 14-18, 2009.

Sta. Maria, E., and M.Z. Jacobson, Examining the effects of wind farms on array efficiency and regional meteorology, Wind Power 2007 conference, Los Angeles, CA, June 3-6, 2007.

Sta. Maria, E., and M.Z. Jacobson, Investigating the feedbacks of large wind farms on the local weather and climate, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 10-14, 2007.

Sta. Maria, E., and M.Z. Jacobson, New parameterization for wind farm effects on the atmosphere, Wind Power 2008 conference, Houston, Texas, June 1-4, 2008.

Sta. Maria, M., and M.Z. Jacobson, Investigating interactions between wind turbines and the atmosphere, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 15-19, 2008.

Sta. Maria, M.R.V., and M.Z. Jacobson, New parameterization for the interaction between wind turbines and the atmosphere, The Fifth International Symposium on Computational Wind Engineering (CWE2010), Chapel Hill, North Carolina, May 23-27, 2010.

Conference Abstracts

Dvorak, M., and M.Z. Jacobson, Development potential for California's offshore wind energy resource, *EOS Transactions, AGU, 88*(52), Fall Meet. Suppl., 2007.

Dvorak, M.J., and M.Z. Jacobson, Offshore wind resource assessment based on mesoscale modeling, *EOS Transactions, AGU, 89*, Fall Meet. Suppl., 2008.

Hart, E.K., M.J. Dvorak, and M.Z. Jacobson, Power flow simulations of a more renewable California grid utilizing wind and solar insolation forecasting, EOS Transactions, AGU, 89, Fall Meet. Suppl., 2008.

Sta. Maria, E., and M.Z. Jacobson, Investigating the feedbacks of large wind farms on the local weather and climate, *EOS Transactions, AGU, 88*(52), Fall Meet. Suppl., 2007.

Sta. Maria, M., and M.Z. Jacobson, Investigating interactions between wind turbines and the atmosphere, *EOS Transactions, AGU, 89*, Fall Meet. Suppl., 2008.

Awards

Abstract selected as one of six out of 20 papers to compete for International Association for Mathematical Geology Conference Student Paper Award, August, 2009, Stanford, California, Dvorak, M.J A. Boucher, and M.Z. Jacobson, Method to improve offshore wind energy resource assessments using cokriging, International Association for Mathematical Geology Conference 2009, Aug. 23-29, 2009, Stanford University.

9. Provide a URL address for any websites that provide more information for interested parties on your research project, including photos and videos. We will add this information to your project summary on the PEEC website.

Paper on "A plan for a sustainable future" (Scientific American)
http://www.stanford.edu/group/efmh/jacobson/susenergy2030.html

Paper on California wind energy potential (Renewable Energy)
www.stanford.edu/group/efmh/winds/.

Paper on the effects of large wind farms on energy in the atmosphere (Energies)
www.mdpi.com/1996-1073/2/4/816/pdf

Poster on combining different renewables to match hourly power demand
http://www.stanford.edu/~ehart/AGU09_Poster_Hart.pdf

10. Have you developed any specific products, (such as databases, physical collections, educational aids, software, etc), as a result of this project? *If so, please list along with a short description.*

Maps of offshore California wind energy resources.

http://www.stanford.edu/group/efmh/jacobson/PDF%20files/dvorak-archer-jacobson-2009.pdf

11. Were any undergraduate or graduate courses generated as a result of this project? *If so, please list the course title and a short description.*

No, but some material was used in CEE 063/263C, "Weather and Storms"

12. Have you provided any information regarding your research to any public or private institutions (e.g., legislative briefing, government panel, congressional testimony, corporate presentation) or any public or private institution asked you for information regarding your research? *If so, please list the organization, date and a short description.*

We have had press coverage of some of the studies performed, including those on combining renewables, California's wind energy resources, and the Scientific American article. As a result, we have had requests from several individuals or representatives of organizations for information on this work.

We have also taken part in some documentaries where some of the work was discussed. These include:

Documentary on Renewable Energy, Future Earth/MSNBC, Helen Lambourne, Interviewed, Boulder City, Nevada, July 13, 2009 (Coming out March, 2010).

Documentary on Climate change and air pollution, PBS, Joy Leighton and Bob Gliner, Stanford, California, June 26, 2009.

Documentary segment on alternative fuels and renewable energy, Discovery Channel Canada, Frances Mackinnon, Producer, March 8, 2007; aired March 29, 2007.

13. Have you partnered or worked with businesses, governmental agencies, NGOs, or other public or private organizations in connection with your project? If so, what role have they played? Please list the institutional name, type of institution and a short description of the partnership.

Worked with the Naval Research Lab (NRL) in Monterey on wind mapping and analysis.

Worked with Faculty at the University of Delaware (Willet Kempton) on wind energy resources.

A student (M. Dvorak) visited NOAA and NREL and discussed work.

Below is a list of three seminars from each of these collaborations.

Dvorak, M., C.L. Archer, W.M. Kempton, a. Dhanju, R.W. Garvine, and M.Z. Jacobson, Offshore wind energy potential near California and the mid-Atlantic bight, Naval Research Laboratory, Monterey, California, July 19, 2007.

Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential. Earth System Research Laboratory Physical Sciences Division, National Oceanic and Atmospheric Administration, Boulder, Colorado, Aug. 27, 2007.

Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, Gerard J. Mangone Center for Marine Policy, University of Delaware, Sept. 13, 2007.

14. What public education activities have you undertaken in conjunction with this project?

Presentation, “Review of energy solutions to global warming, air pollution, and energy security,” Los Altos High School, Science and Technology Week Series, November 2, 2009.