J.P. MORGAN CENTER FOR COMMODITIES
UNIVERSITY OF COLORADO DENVER BUSINESS SCHOOL

RESEARCH COUNCIL REPORT

December 4th , 2015 Meeting: Morning Panel Session on "The Transition to the Next Generation of Energy Sources"

Presentation by Professor Frank Wolak, Ph.D., Stanford University

Transcribed and Summarized by Hilary Till, Solich Scholar, J.P. Morgan Center for Commodities, University of Colorado Denver Business School; and Contributing Editor, *Global Commodities Applied Research Digest*

Business School
UNIVERSITY OF COLORADO DENVER

How to Incentivize the Siting of Wind-and-Solar Projects in California so that System-Wide Reliability is taken into Consideration

Report by Hilary Till
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At the December 2015 Research Council meeting, the J.P. Morgan Center for Commodities was delighted to host a presentation by Professor Frank Wolak of Stanford University, who provided a lecture on how to potentially improve California's wind-and-solar project development incentives. Professor Wolak's biography is at the end of this section, and his Research Council presentation is based on Wolak (2015a). This report will transcribe and summarize his presentation.

The morning panel of the Research Council's December 4th, 2015 meeting was on "The Transition to the Next Generation of Energy Sources." Professor Frank Wolak, Ph.D., Stanford University, was the first presenter and is standing at the podium. Seated on the far left are Professor Colin Carter, Ph.D., University of California, Davis (moderator and Chair of the Research Council); Ms. Amy Myers Jaffe, University of California, Davis (panelist); and Dr. David Mooney, Ph.D., National Renewable Energy Laboratory (panelist).

Introduction

In summarizing and excerpting from Professor Wolak's presentation, this report will draw from Wolak's working paper, slides, and remarks at the December Research Council meeting. This report will adopt the following conventions when referencing Professor Wolak. When quoting Wolak (2015a), this report will include in parentheses, the page number from which the citation is drawn. When quoting from Wolak's PowerPoint presentation, this report will include in parentheses, the slide number from which the citation is drawn. And when transcribing Wolak's remarks at the Research Council meeting, this report will include in parentheses, the timing of when the remarks were made during the morning session of the conference.

This summary has been written in a style that would enable Professor Wolak's research to be accessible to commodity industry practitioners and includes some further explanation of concepts and terminology that is not included in Wolak's working paper. Admittedly, and of necessity, this summary is quite brief in its coverage of wholesale electricity market design issues. In order to get an idea on the complexity of these issues, the interested reader is directed to, for example, Wolak (2004).

This report will cover the following points in summarizing Wolak's Research Council presentation:

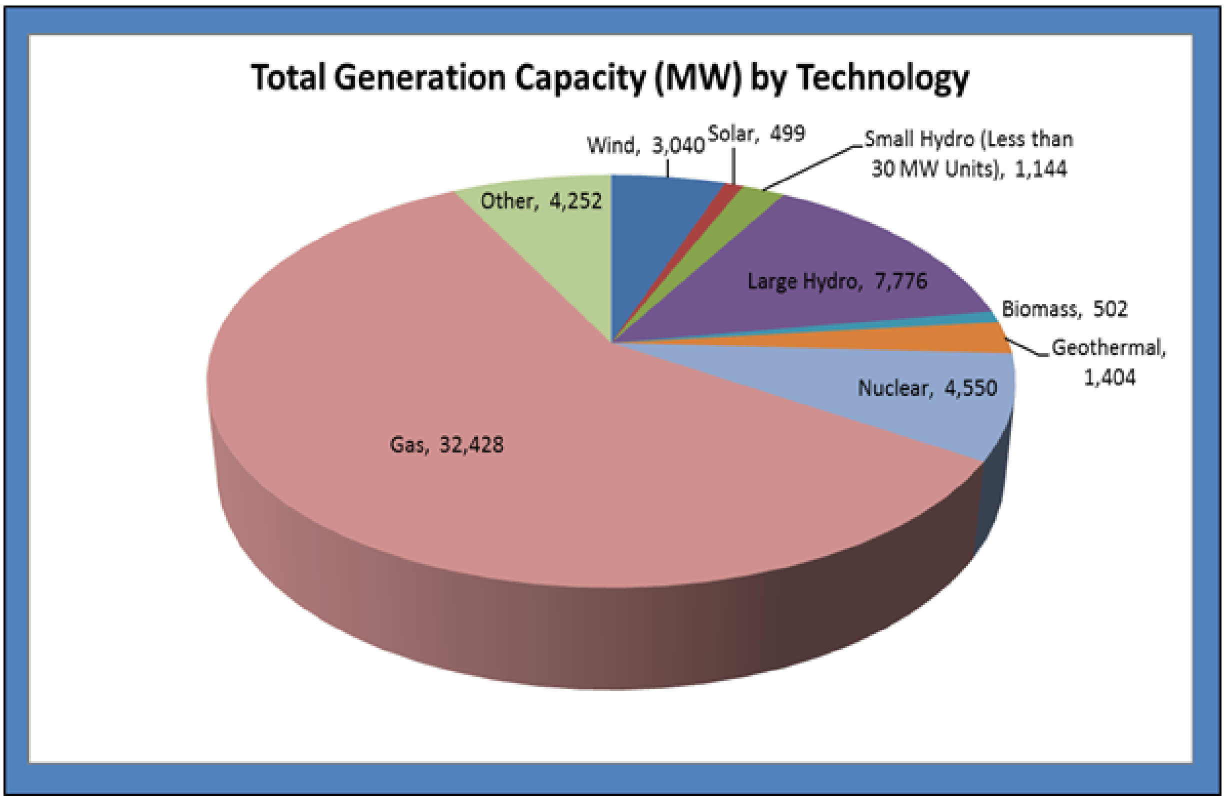
- The Context: Aggressive Renewable Energy Goals in California
- The Problem: A "Reliability Externality"
- The Research Questions
- The Study's Source of Data
- Data Description
- Methodology
- Empirical Results
- Public Policy Implications: The Market Design Challenge
- The Conclusion of Wolak's Presentation

The Context: Aggressive Renewable Energy Goals in California

"An increasing number of jurisdictions have substantial renewable energy goals for their electricity sectors (Slide 2)," noted Wolak. "For example, California's Renewable Portfolio Standard (RPS) proposes to increase the share of renewable energy in the state's electricity mix to 33 percent by 2020. The qualifying renewable energy technologies for California's program are wind, solar, geothermal, biomass and small hydroelectric facilities, with wind and solar resources expected to supply the vast majority of incremental renewable energy (p. 1)," explained Wolak in his working paper.

In contrast, Figure 1 shows the actual mix of California's existing generation technologies as of 2011, indicating just how ambitious its RPS goal is.

Figure 1
The Amount of Generation Capacity in the CAISO Control Area by Technology as of April 1, 2011



Source of Data: Wolak (2015a), Table 1.

Definition of Terms:
CAISO stands for "California Independent System Operator."
This ISO "manages the flow of electricity across the high-voltage, long-distance power lines that make up 80 percent of California's and a small part of Nevada's power grid," according to the California ISO website.

MW stands for Megawatt. It is a unit of electrical power equal to one million watts.

So how can one encourage investment in new wind and solar generation units to meet California's ambitious goals? At this time, new "wind and solar generation units are typically financed by long-term power purchase agreements (Slide 2)." Under these agreements, the renewable resource owners receive fixed prices for all the energy produced from their units, insulating them from "fluctuations in the short-term wholesale prices," which typically vary by time of day (p. 1).

As a result, the renewable resource owners locate new units in areas where they receive the most revenue. But is this an optimal solution? Should something else be optimized in choosing the location of renewable energy generation units (other than solely maximizing the revenue for resource owners)?

The Problem: A "Reliability Externality"

Yes, other factors should be considered, according to Wolak. One should also take into the consideration the increased cost of the electricity system's operation due to the increased volatility in renewable energy production.

The cost of system operation is increased because "more dispatchable generation units[1] (typically powered by fossil fuels) are required to provide operating reserves and quickly ramp up or down their production of energy in response to wind and solar energy production (p. 2)." In addition, given the variability of energy produced by wind and solar units, "more spending [is required] on storage and load-shifting technologies (Slide 3)."

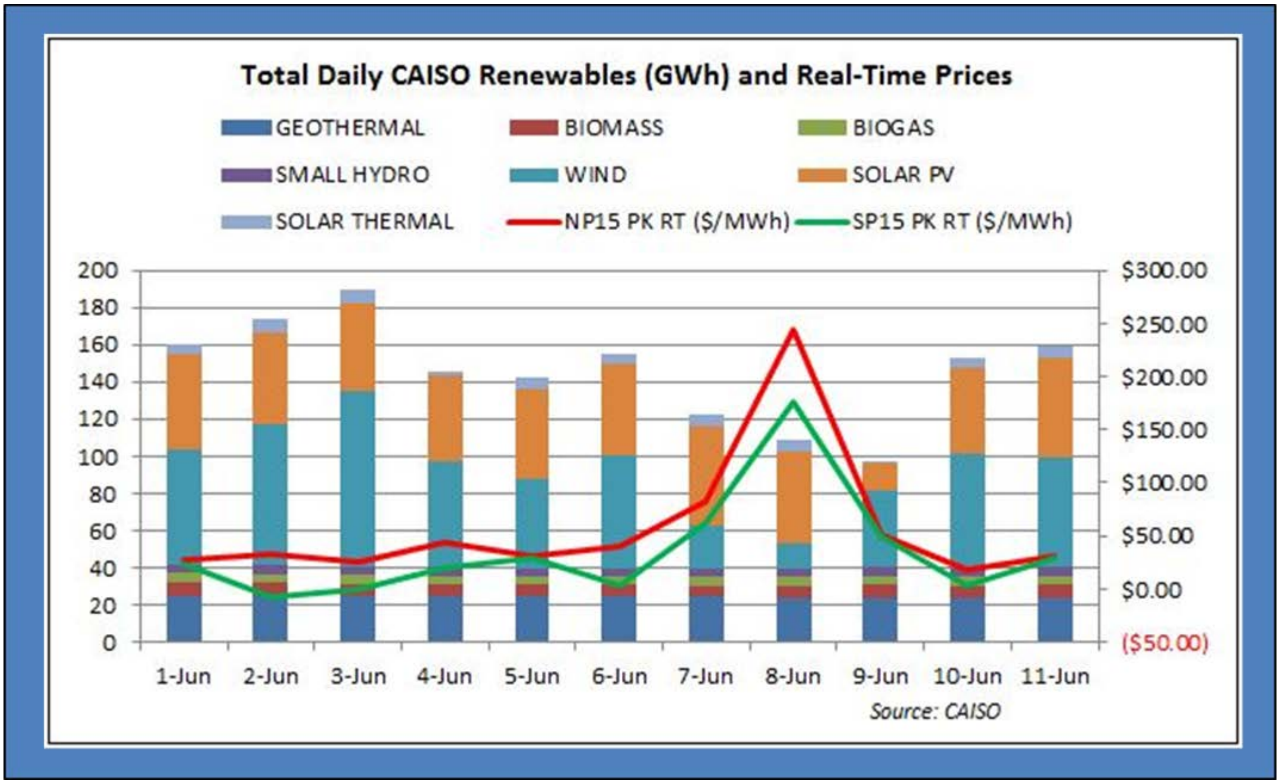
Under existing investment incentives and contracts, a "reliability externality" emerges, which is the "increased volatility in wind and solar energy production and the accompanying increased cost of system operation due to location decisions that do not account for the full system['s] reliability costs of these actions (Slide 3)," as summarized by Wolak.

[1] "A dispatchable source of electricity refers to an electrical power system, such as a power plant, that can be turned on or off; in other words they can adjust their power output supplied to the electrical grid on demand," according to the University of Calgary's "Energy Education" webpage.

Professor Frank Wolak, Ph.D., Stanford University, presenting at the Research Council's morning panel on December 4, 2015. Professor Gary Kochenberger, Ph.D., Interim Dean, University of Colorado Denver Business School, is on the right.

An example of Wolak's reliability concerns was provided by Ryser and Wieser (2015). In California, on June 8th and 9th, 2015, "demand for power rose and generation surged to meet it, [but] rain, widespread cloud cover and poor wind pushed down the amount of wind and solar generation available to help meet the demand. Because of the shortage of renewables, [spot power] prices surged." This is illustrated in Figure 2 on the next page.

Figure 2
An Illustration of a Spike in Power Prices in the CAISO Control Area in June 2015



Definition of Terms:
NP15 and SP15 are northern and southern zones in California respectively.

PK stands for Peak Hours.

RT stands for Real-Time.

MWh stands for Megawatt-Hour. It is a unit of electrical energy equal to one million watt hours.

GWh stands for Gigwatt-Hour. It is a unit of electrical energy equal to one billion watt hours.

PV stands for Photovoltaics.

Research Questions

Wolak essentially put forth the following two research questions:

- How imperfect is the present siting of wind and solar resources in California?
- How can contracts for renewable energy project developers be redesigned to incentivize the optimal siting of wind and solar units?

At the Research Council meeting, Wolak proposed a methodology for explicitly taking into consideration the reliability costs of intermittent power sources. He then suggested new market design initiatives, which take into consideration these reliability costs.

Wolak's data set, methodology, empirical results, and public policy advice are summarized below.

Source of Data

The source of Wolak's sample data is described in Figure 3.

Figure 3

Renewables Output and Revenues in California Electricity Market

Sample is CAISO fiscal year from April 1, 2011 to March 31, 2012. 40 wind generation locations and 13 utility-scale solar locations in the CAISO control area, 3,040 MW of wind capacity and 499 MW of solar capacity for a total of 3,539 MW of intermittent capacity.

Source: Wolak (2015b), Excerpted from Slide 11.

As noted, Wolak's study covers the CAISO control area. A graphical depiction of the CAISO Electricity Regions is provided in Figure 4 on the next page.

Figure 4
California (CAISO) Electric Regions

Source of Image: Federal Energy Regulatory Commission website.

By way of further background on CAISO, the Federal Energy Regulatory Commission's website explains that the "California Independent System Operator (CAISO) operates a competitive wholesale electricity market and manages the reliability of its transmission grid. … CAISO was founded in 1998 and became a fully functioning ISO in 2008." CAISO's website adds that the ISO "manages the flow of electricity across the high-voltage, long-distance power lines … for 30 million customers" in California and Nevada.

Data Description (and Explanation)

Wolak computes "hourly revenues for wind and solar resource locations" using "hourly generation unit-level output and locational marginal prices [LMPs] (Slide 4)." Locational Marginal Prices, in turn "essentially price congestion or other relevant operating constraints in the grid so … [one] can get potentially different prices at different locations for different hours of the day (6:09 to 6:30)." Therefore, LMPs are used as the location-specific *spot prices* for generation units. That said, one should note that LMPs are actually a mathematical construct.

For the interested reader, the following provides some further brief background on the LMP system.

Synapse Energy Economics (2006, p. 15) defines a LMP system as follows:
"The Locational Marginal Pricing system is a construct, based on operations research theory, which is designed to achieve two economic objectives simultaneously:

- Minimize the cost of generating enough electricity to meet load by using the least cost set of available generators possible given various constraints. This is known as 'least-cost, security-constrained dispatch;' and

- Produce the instantaneous price of electricity, at every point in the system, which reflects the instantaneous short-run marginal cost of serving one incremental unit of load at that location. This is what is referred to as the 'locational marginal price,' or LMP."

Schmalensee (2014, p. 6), in turn, defines LMPs as follows:

"Locational Marginal Prices (LMPs) [are the] … nodal prices for the network nodes at which each generator … is located. … LMPs are defined as the short-run marginal cost of meeting an additional MWh of demand at the node in the transmission system at which … [a] generator is located, taking into account transmission losses, transmission line capacity constraints, and the … costs of incremental generation."

Description of Methodology

Wolak essentially uses the following two quantitative tools to evaluate how imperfect existing wind-and-solar siting decisions have been: (1) Mean-Variance Analysis; and (2) Principal Component Analysis. The following provides very brief explanations of these well-known statistical tools.

<u>Mean-Variance Analysis</u>

Under Mean-Variance Analysis, one solves for the combination of "risky assets … [that] minimize[s] the variance of return (i.e., risk) at any desired mean return," as explained by Halliwell (1995). This mathematical technique was developed by Harry Markowitz in 1952, and for which he earned a Nobel Prize in 1990. As long as it is correct to assume that an investor's preferences are such that for a given level of expected return, that investor will choose the portfolio with the minimum variance from among the set of all possible portfolios, then mean-variance analysis is a useful tool. This is the key assumption of Markowitz's Modern Portfolio Theory (MPT). Once one has determined the set of portfolios that have the maximum return for a given level of risk, then one can graph each feasible mean-vs.-variance combination. This graph is called the "efficient frontier." Again, under MPT, we assume that investors are rational and will only consider portfolios that are represented by points along the efficient frontier. If in-sample data is used in this analysis, then care must be taken in making forward predictions based on the analysis' results.

Principal Component Analysis

Principal Component Analysis (PCA), in turn, is a commonly used statistical tool in the social sciences. According to Anderson (2013), PCA "is a multivariate procedure aimed at reducing the dimensionality of multivariate data while accounting for as much of the variation in the original data set as possible. This technique is especially useful when the variables within the data set are highly correlated … Principal components seek to transform the original variables to a new set of variables that are (1) linear combinations of the variables in the data set, (2) uncorrelated with each other, and (3) ordered according to the amount of variation of the original variables that they explain." After performing this procedure, an analyst attempts to attribute meaning to the new variables that explain the most amount of variation in the data. One caveat with this procedure is that it is necessarily performed on "in-sample data." There is no guarantee that the conclusions drawn from in-sample data will apply out-of-sample. (Or as a commodity futures trader might say, past performance is no guarantee of future success.)

How does Wolak specifically use Mean-Variance analysis and Principal Component Analysis? This will now be covered.

Required Assumptions

In order to use the two quantitative tools in the study's particular domain, we need to make two assumptions. The first assumption is that one can appropriately ascribe real-time spot prices to the wind and solar energy output from CAISO's existing generating units, and that the appropriate prices to use are Locational Marginal Prices, which, in turn, are mathematical constructs. The second assumption is that "the best measure of the marginal social value of the output of any particular generator is given by the location-specific spot prices [which] that generator faces," quoting from Schmalensee (2014, p. 5). In other words, we are assuming that we are choosing the appropriate variables to optimize from a social welfare point-of-view.

Application of Quantitative Techniques to a Wholesale Electricity Market

Given these two assumptions, one could choose to maximize the system-wide revenue that would have been generated for renewable resource owners, if they had been paid the location-specific spot prices (rather than their contracted fixed prices) for the intermittent energy produced by their wind and solar resources.

But then we are still left with the "reliability externality." Let us assume that an appropriate way to measure the reliability cost of using intermittent energy sources is to calculate the volatility of their hourly (hypothetical) revenue system-wide, assuming the resource owners had been paid spot prices for the renewable energy output. In an optimization, one would minimize this volatility in order to eliminate this "reliability externality."

As touched upon above, Wolak's empirical study employs the well-known mean-variance-optimization (MVO) technique familiar to investment managers, who use Markowitz's 1952 technique for optimal portfolio construction. In Wolak's novel application of Markowitz's optimization technique, one wants to discover the configuration of existing wind and solar resources that provides the highest (hypothetical) revenue relative to how volatile these (hypothetical) revenue streams are. Wolak employs the following two constraints in his optimization: (1) the existing locations of wind and solar resources are maintained; and (2) the same total megawatts of renewable energy investments, as in the existing configuration, are also maintained. An implicit assumption is that one can alter how much energy capacity each location can have. A quantitative investor would recognize an analogy to portfolio construction: one assumes one can alter the weights of each constituent asset but with the usual constraint that no leverage (and no short sales) are permissible.

Wolak can then calculate an "efficient frontier" that provides different configurations of existing capacity that would have produced the highest total revenues per different levels of risk (or standard deviation) over the study's timeframe. Lastly, he can isolate the reconfiguration of existing resources that would have maximized the total-revenue-per-risk ratio.

Wolak next compares the "actual capacity shares of wind and solar resources … to the wind and solar capacity shares of these resource locations on the efficient frontier (Slide 4)." This enables him to quantify what the potential improvement to system operation would have been using investment incentives that took into consideration reliability costs. (The term, "capacity share," refers to the amount of generation capacity of a renewable energy generation unit relative to the system's total renewable energy generation capacity.)

Wolak's presentation also describes further refinements, both in terms of what to optimize and in terms of drilling down further into the data. He also calculates efficient frontiers for the mean and standard deviation of hourly *output*; the previously described efficient frontiers were for *revenues.* In addition to examining both wind-and-solar units in the CAISO control area, he also examines portfolios of solely wind units and portfolios of solely solar units. And he also calculates the efficient frontiers system-wide at each hour of the day in the CAISO system. These further refinements do not alter the qualitative conclusions that one would have drawn from exclusively examining the maximization of total revenue relative to revenue-volatility.

An overall goal of the paper is to understand how to take into consideration (and reduce) the reliability costs of renewable energy sources. To that end, Wolak uses one of the methods for performing Principal Component Analysis to attempt to understand what the key factors are in driving the volatility of both revenues and output from wind and solar units.

Empirical Results

Preview of Main Results

Wolak finds that the actual capacity shares of wind and solar resources are suboptimal within a mean-variance framework. Figures 5 and 6 summarize his results.

During his presentation, Wolak also drew particular attention to the following surprising result: "The efficient frontier … of the wind units effectively gives … [one] most of the diversification benefits [at least for his data sample.] The addition of solar surprising[ly] ... doesn't add too much to [the] … diversification benefit. … There is often this idea that wind and solar tend to complement each other, but ... at least for the case of California, this doesn't appear to be the case for the [study's] sample period (8:00 to 8:34)."

Figure 5
Summary of Main Results

- Hourly output efficient frontier implies that 48 percent increase in the expected hourly output of solar and wind generation is possible relative to expected hourly output with existing capacity shares
  - No increase in the standard deviation in hourly output
  - Only change the capacity shares of the wind and solar investment at the locations in the CAISO control area (with no change in aggregate wind and solar shares)
- Hourly revenues efficient frontier implies a 28 percent increase in the expected hourly revenues to wind and solar generation units relative to expected hourly revenues with existing capacity shares
  - No increase in the standard deviation of hourly total revenues
  - Only change the capacity shares of the wind and solar investments

Source: Wolak (2015b), Excerpted from Slide 5.

Figure 6
Optimal Siting Solution for Wind and Solar Investments

- The capacity shares for wind and solar investments on both output and revenues efficient frontiers concentrate the same total capacity of wind and solar investments on a substantially smaller number of locations than the actual wind and solar capacity investments.

Source: Wolak (2015b), Excerpted from Slide 6.

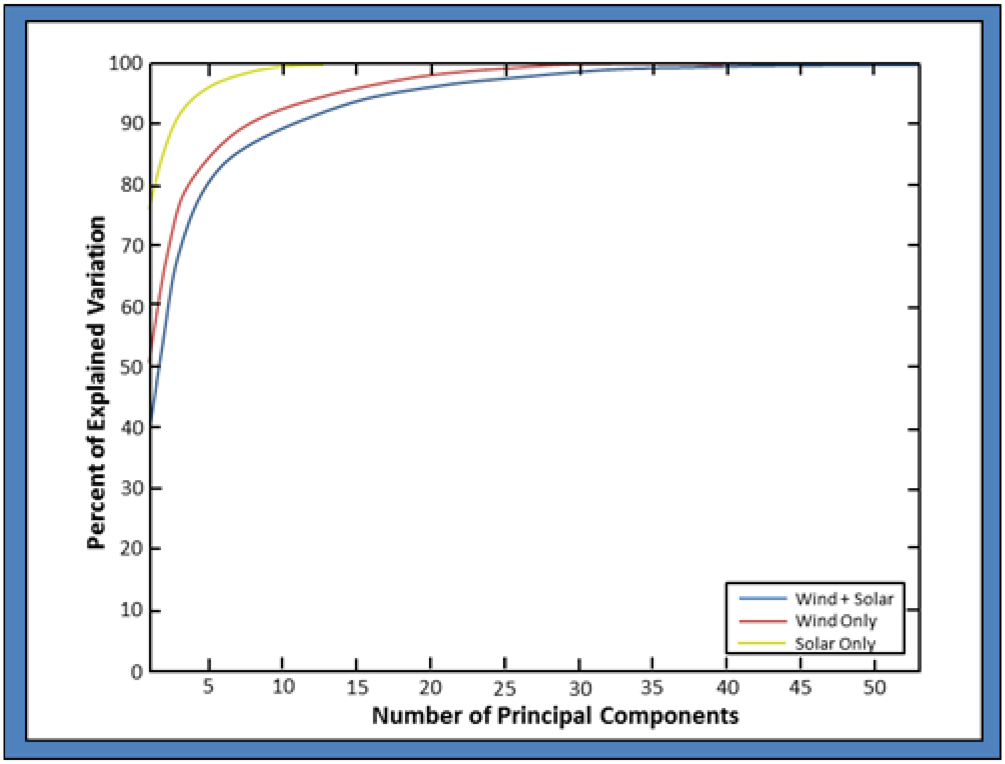
As summarized above, Wolak found that one could potentially improve output-relative-to-variability and revenue-relative-to-variability by "reconfiguring the same total megawatts (MWs) of wind and solar investments across existing wind and solar resource locations in the CAISO control area (p. 3)," which are encouraging results. In addition, Wolak also examined the possibility of solely minimizing two variability metrics, but did <u>not</u> find as encouraging results.

<u>Principal Component Analysis</u>

Wolak uses a principal-components-analysis (PCA) procedure to assess "the extent [to] which [it] is possible to construct a portfolio of wind and solar generation units that significantly reduces the standard deviation of the *hourly capacity factor* … and the standard deviation of the hourly revenue per MW of capacity … relative to the values of these variables using the actual capacity share (p. 15)." (Italics added.) The term, "hourly capacity factor," is the ratio of wind or solar energy actually produced divided by what could be potentially produced by these resources. Can only a handful of variables meaningfully explain the variability in both the hourly capacity factor and the hourly revenue in Wolak's CAISO sample? The answer to this question is yes. Can we ascribe meaning to these variables? Again, the answer is yes. Does this mean that a number of the existing wind and solar resources are essentially superfluous since they do nothing to tamp down on system variability? Once again, the answer is yes.

Wolak's results in Figure 7 on the next page show that "a single common factor is responsible for … [roughly] 80% of the hourly variation in the 13 solar generation units and more than … [50%] of the hourly variation in the 40 wind units. Even for the case of the 53 wind and solar units, one factor is responsible for more than … [40%] of the hourly variation (p. 16)."

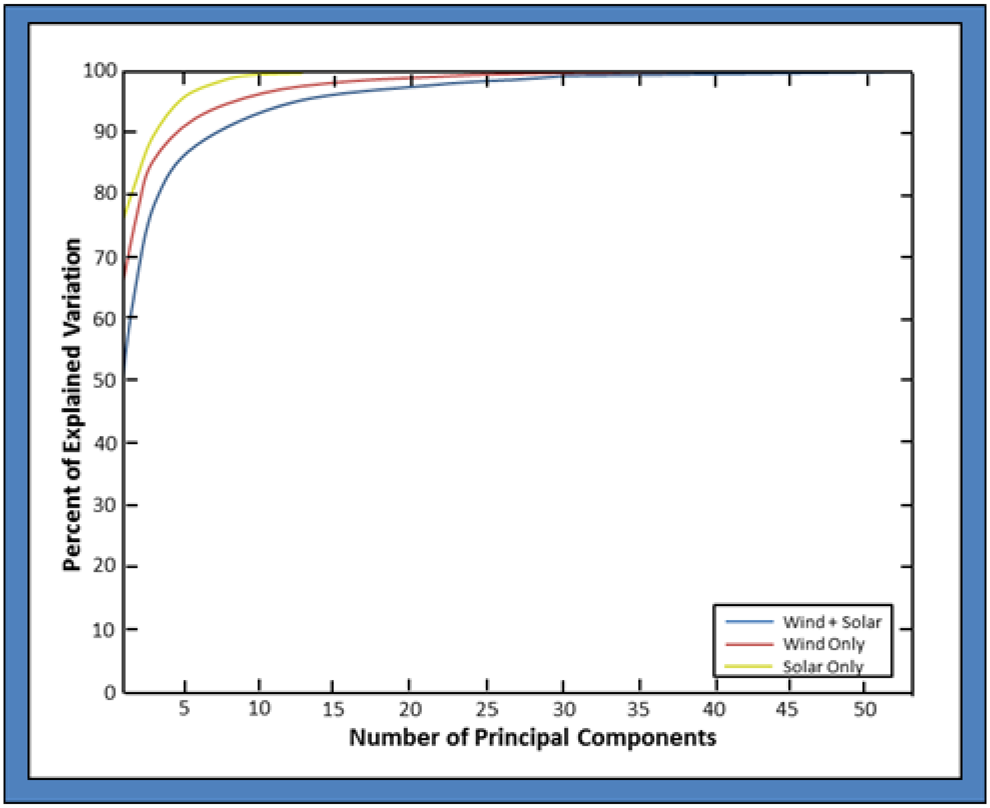
Figure 7
An Application of Principal Component Analysis for Understanding the Drivers of Variation in Hourly Location-Specific Capacity Factors



Source: Wolak (2015b), Slide 14.

Wolak also decomposed the factors largely responsible for the variation in hourly revenue amongst renewable energy generation units. The results in Figure 8 on the next page show that "[t]he first factor accounts for … [about] 80% of hourly variation in the revenues earned by the 13 solar units. The first [three] factors account for more than 70% of the hourly variation in the revenues earned by the 40 wind units. For the 53 wind and solar units, … [more than] 50% of the hourly variation in revenues is accounted for by the first factor (pp. 16-17)."

Figure 8
An Application of Principal Component Analysis for Understanding the Drivers of Variation in Hourly Location-Specific Revenues per MW



Source: Wolak (2015b), Slide 15.

Wolak provides an intuitive explanation of these PCA results. "Sunny days in California are typically sunny at all locations in California and the same is largely true for cloudy days. … Windy days in California tend to be more localized but there are still significant contemporaneous correlations in wind output (Slide 16)." Given how correlated "the output and revenue of solar and wind resources are within each hour of the day (p. 17)," the combination of wind and solar generation units yields limited output variability reduction benefits (relative to the case if these variables had been independent (Slide 16) and (16:13 to 16:31).

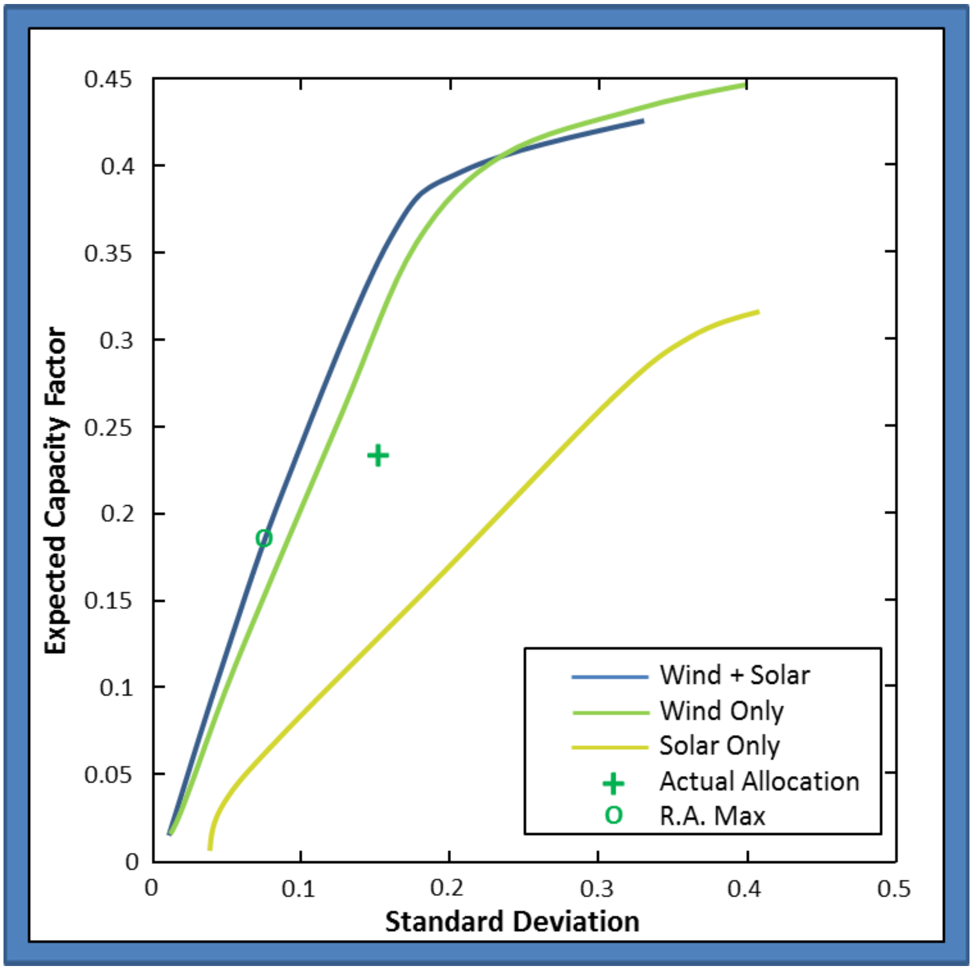
Efficient Frontier Computation

As referred to above, Wolak computed the efficient frontier for wind and solar output and revenue. Please see Figure 9 on the next page. "Each point along the efficient frontier computes the capacity shares for each wind and solar location that minimize the standard deviation of hourly output … subject to achieving a given level of expected hourly output … (p. 20)." Figure 9 also includes the "actual allocation," which is "the actual capacity-weighted hourly mean output and standard deviation of hourly output … to illustrate how far from … [the] efficient frontier the actual capacity-weighted share portfolio of wind and solar resources is from this frontier." Figure 9 illustrates the efficient frontiers for (a) just solar units; (b) just wind units; and for (c) both wind and solar units. Regarding the latter efficient frontier, "the same total capacity shares for wind and solar capacity as actually exists" is maintained (p. 20). Lastly, Figure 9 includes "R.A. Max," which is the "adjusted portfolio maximum output portfolio [for the solar-and-wind frontier;] …[t]his is the point on the wind and solar efficient frontier that has the largest value of the ratio of the expected hourly output divided by the standard deviation of hourly output (p. 20)." Wolak did the same computations for hourly revenues; please see Figure 10, which is on page 18.

In addition to the results reported in Figure 5 above, one can see from Figure 9 that "[t]he risk-adjusted expected hourly output per MW of capacity maximizing portfolio selects a 15 percent lower expected hourly output per MW of capacity but a 50% lower standard deviation of the hourly expected output per MW of capacity relative to the actual capacity-weighted-share portfolio (p. 24)."

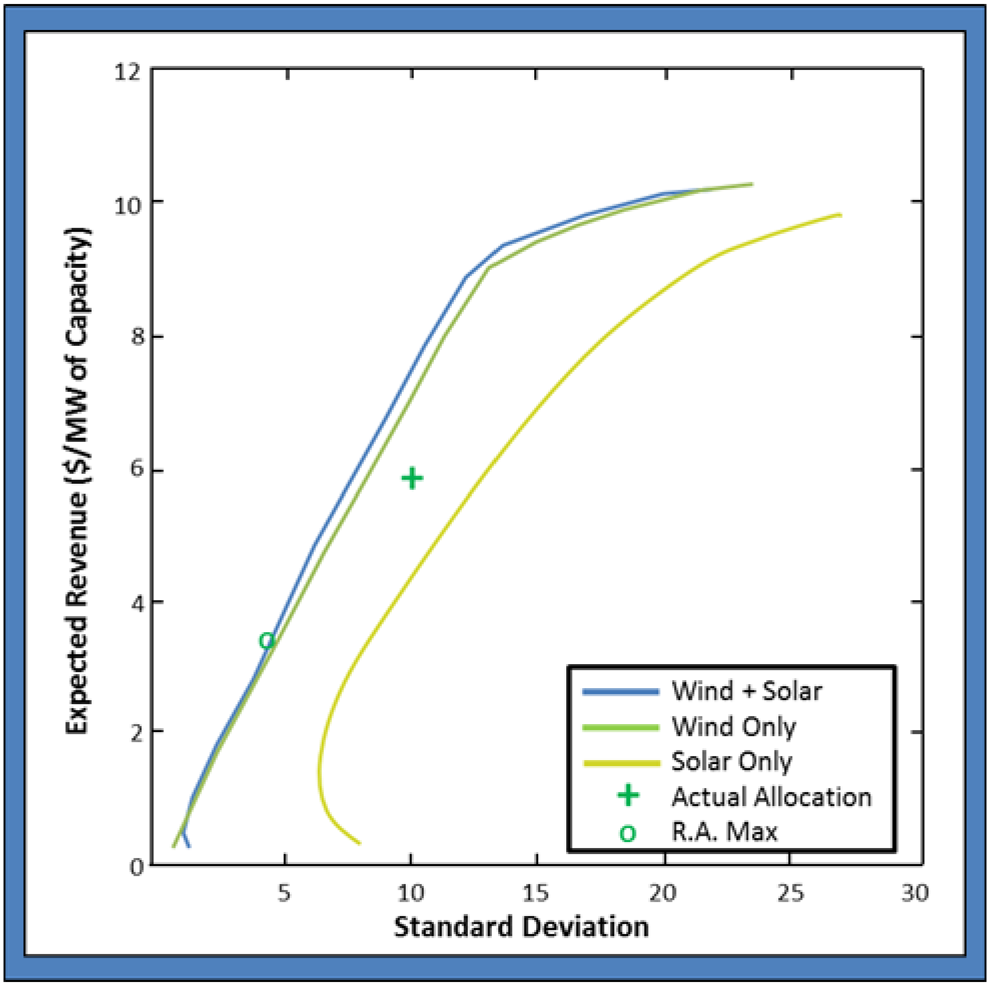
Wolak also computed both "[t]he risk-adjusted maximum expected hourly output portfolio on the efficient hourly output … and the risk-adjusted maximum expected hourly revenue maximizing portfolio on the efficient hourly revenue frontier ... In both cases, weights for these portfolios focused on a small number of wind and solar locations, with the vast majority of existing locations having a zero portfolio weight (p. 36)." Therefore, one implication of Wolak's efficient-frontier computations is that "California's wind and solar investments should be concentrated at fewer locations in order to achieve a capacity mix that is closer to both the hourly output and hourly revenues frontiers (p. 29)."

Figure 9
Expected Hourly Output per MW and Standard Deviation of Hourly Output per MW Efficient Frontier



Source: Wolak (2015b), Slide 22.

Figure 10
Expected Hourly Revenue per MW and Standard Deviation of Hourly Revenues per MW Efficient Frontier



Source: Wolak (2015b), Slide 25.

Public Policy Implications: The Market Design Challenge

Wolak then discussed the public policy implications of his empirical results. Please see Figure 11, which draws from his slides.

Figure 11

Empirical results are consistent with the existence of a substantial "reliability externality" associated with the current mix of wind and solar investments California.

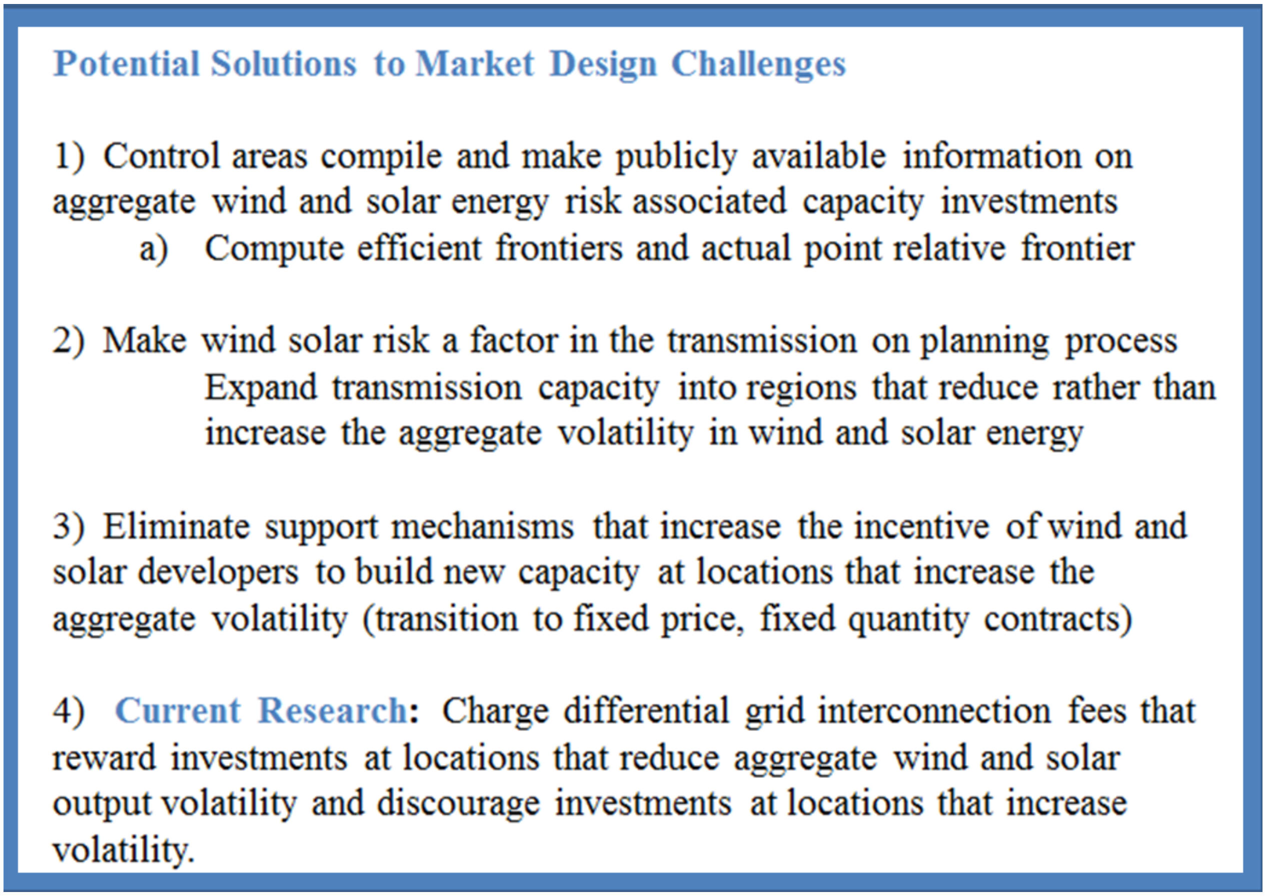
> Possible to increase significantly expected hourly output and expected hourly revenues from changing the capacity shares of wind and solar locations without increasing the standard deviations

Market Design Challenge: How to provide incentives for wind and solar project developers to internalize the reliability costs of their future investments to lower system-wide cost of achieving a given renewables energy goal.

Source: Wolak (2015b), Excerpted from Slide 29.

Wolak next enumerated possible future public policy solutions to the externality that he had identified. He stated, "The big issue is that there certainly appears to be this reliability externality. The question is: what do you do? So one of the things is just making sure that people understand what locations are going to enhance reliability. So [the] first [priority] … is just information provision, providing this kind of information to the various ISOs. The other [conclusion] is [to] incorporate … [these insights] into the transmission planning process, to essentially say, look this is a location that really is not going to help contribute to reliability. And then finally, [we should] eliminate the sort of support mechanisms that increase the incentive for … build[ing] at these locations [that are not optimal, when taking reliability into consideration] (21:50 to 22:24)." Figure 12 summarizes these market design solutions.

Figure 12



Source: Wolak (2015b), Slide 30.

Conclusion of Presentation

Wolak concluded his presentation by summarizing his study's main empirical results, which are shown in Figures 14 and 15.

Figure 14

Conclusions

Hourly output and hourly revenues efficient frontiers for all wind and solar resource locations in the California ISO control areas aids in assessing output mean and variance and revenue mean and variance impacts of potential wind and solar capacity investments

Economically meaningful differences between portfolios on the efficient frontier and the actual wind and solar capacity mix are found.

In California, risk-reducing benefits of diversification were captured by a mix of wind resources, with the addition of solar resources only slightly increasing the set of feasible portfolio mean and variance combinations

California has added over 4,000 MW of new wind and mostly solar since the end of the sample period

Source: Wolak (2015b), Slide 32.

Figure 15

Risk-adjusted maximum expected hourly output portfolio on the efficient hourly output frontier and the risk-adjusted maximum expected hourly revenue maximizing portfolio on the efficient hourly revenue frontier focused on a small number of wind and solar locations, with the vast majority of existing locations having a zero portfolio weight.

Source: Wolak (2015b), Excerpted from Slide 33.

Endnotes

As noted by Professor Ajeyo Banerjee, the executive and faculty director of the J.P. Morgan Center for Commodities, the Center is grateful to the three Research Council members who organized the highly successful morning panel of the JPMCC's December 4th Research Council meeting. The panel organizers were Professor Colin Carter, University of California, Davis (and Chair of the Research Council); Professor (Emeritus) Margaret Slade, Vancouver School of Economics, University of British Columbia (and Co-Chair of the Research Council); and Dr. Benjamin Lee, Research Scientist, National Renewable Energy Laboratory.

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Matthew Fleming, the Program Coordinator for the JPMCC, created the audiovisual record of the December Research Council meeting. Katherine Farren, the Editorial Assistant for the JPMCC's *Global Commodities Applied Research Digest*, produced the graphics for this report. Their assistance in preparing this report is gratefully acknowledged by its author.

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Professor Wolak's fields of specialization are Industrial Organization and Econometric Theory. His recent work studies methods for introducing competition into infrastructure industries — telecommunications, electricity, water delivery and postal delivery services — and on assessing the impacts of these competition policies on consumer and producer welfare. From January 1, 1998 to March 31, 2011, Professor Wolak was the Chair of the Market Surveillance Committee of the California Independent System Operator for electricity supply industry in California. He is a visiting scholar at University of California Energy Institute and a Research Associate of the National Bureau of Economic Research (NBER). He currently directs the Program on Energy and Sustainable Development (PESD) in the Freeman-Spogli Institute (FSI) for International Studies. From January 2012 to December 2013, Professor Wolak was also a member of the Emissions Market Advisory Committee (EMAC) for California's Market for Greenhouse Gas Emissions allowances. This committee advised the California Air Resources Board on the design and monitoring of the state's cap-and-trade market for Greenhouse Gas Emissions allowances. Professor Wolak received his Ph.D. and M.S. from Harvard University and his B.A. from Rice University.

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