U.S. commercial battery-based energy storage grew from nearly zero to 1.1GW over the past 16 years (U.S. Department of Energy, 2016). Looking forward, energy storage deployment is expected to accelerate in the near future, with annual capacity additions reaching 1.6GW by 2020, representing $2.5B in annual investment (GTM Research, 2017). This acceleration is driven by two factors. First, there is a rapid increase in the amount of renewable energy on the grid. This renewable energy is intermittent and must be paired either with storage or with highly responsive generation capacity (typically natural gas). Second, battery storage is a promising substitute for costly investments in peak-load generation assets. Thus, many states have adopted policies to promote energy storage, including energy assurance plans that call for energy storage as well as "multipliers" for energy storage under state Renewable Portfolio Standards (RPSs). Seven states have co-funded energy storage projects or mandate a minimum amount of grid-connected energy storage. California alone has mandated 1.325 GW of storage by 2020.

Energy storage (ES) is expected to lower nodal prices by lessening demand for high-cost, peak-load generation, lowering system marginal costs and creating a social welfare benefit for all ratepayers. But these effects remain largely unmeasured. The engineering literature includes estimates of these effects, but the estimates rely on parameterized models and simplistic assumptions about firm behavior. Moreover, these studies focus on internal, private benefits (e.g. Sioshansi, Madaeni, & Denholm, 2014) and disregard social welfare implications. My research will be the first to empirically estimate the effect of ES on hourly grid prices by employing data on nodal electricity prices and the locations of 450MW of grid-scale and behind-the meter ES capacity in California. These estimates answer two questions: First, ***do taxpayer subsidies for ES match the public benefit that ES generates by lowering average electricity prices?*** Second, addressing the role of ES in facilitating renewables, ***does ES increase revenue for intermittent renewables by increasing off-peak price during charging?***

Background & Literature

The distinguishing characteristic of electricity markets is that supply must instantaneously meet demand at all times and at all locations. This relationship has shaped electricity markets, yielding steeply-increasing short-run dispatch cost functions that match supply to inelastic short-run demand that varies considerably throughout a typical day. Load balancing requirements allow for the exercise of market power, particularly where transmission capacity is constrained, and hinder the integration of intermittent renewable capacity (Atkins, Chen, Kumar, Macauley, & Marathe, 2009; Borenstein, Bushnell, Kahn, & Stoft, 1995; Wolak, Nordhaus, & Shapiro, 2000). ES permits price arbitrage along the dispatch cost curve, facilitating use of intermittent renewables. It can address costly congestion between network nodes and decrease the effect of market power by offering a backstop during high demand periods that may alter the bidding strategies of imperfectly competitive suppliers. In a hypothetical world of extremely low-cost energy storage, the daily wholesale energy price profile is constant and equal to the average of the lowest-cost energy suppliers. Moreover, efficiency losses from market power would decline.

As stored energy is released during peak demand periods, the marginal wholesale price declines, and in markets with a uniform market-clearing price, the decline in price applies to all units of energy sold. This is a welfare transfer from infra-marginal generators to utilities (Walawalkar, Blumsack, Apt, & Fernands, 2008) and, assuming pass-through cost recovery, to consumers. Notably, this is the reverse of the so-called "solar subsidy problem," where the positive social welfare of distributed solar generation (cleaner air) is offset by negative effects on grid reliability and transmission costs which fall predominantly on those who do not adopt solar.

Methods

I estimate price and welfare effects by first regressing California Independent System Operator (CAISO) network pricing node (node) hourly day-ahead prices on a time-varying measure of energy storage capacity linked to the node, providing an estimate of the price effect associated with an increase in ES:

$$\log(P_{isht}) = \gamma_{sh} x_{isht} + \sum_{j \neq i} \gamma_{sh}^{ji} x_{jsht} + \delta_{ish} + \varepsilon_{isht} \quad (1)$$

where P_{isht} is the nodal price and x_{isht} is the capacity of ES present at node i, time t, during season s, and hour-of-day h; δ_{ish} are fixed effects. The coefficients of interest are the own-node effect of ES, γ_{sh}, and cross-node effects γ_{sh}^{ji}. Prices at each node reflect the overall cost of energy, including the local costs of congestion. Congestion costs change over each hour of the day based on grid topology and local patterns of demand. Fixed effects for each season, hour, and node account for this unobserved heterogeneity.

To better capture cross-node effects, I employ a second specification that leverages the CAISO decomposition of prices into three "system lambdas" which represent the marginal value of energy (λ_e), congestion (λ_c) and line-loss, (λ_l). The ability of ES to lower generation costs is measured by its effect on λ_e, which is constant over all nodes, and can be estimated with time-series models. λ_c is specific to every node, and is generated from unobserved grid topology and constraints imposed by Kirchoff's Law, which determines how electrons "flow" over a network. Reducing net load at a single node will decrease the congestion cost at that node, but - counterintuitively - it may increase congestion cost elsewhere, depending on the grid topology and location of binding constraints (Blumsack, Lave, & Ilić, 2007). This topology is unobserved due to its designation as "critical infrastructure." I borrow from the peer effects literature and propose using the pooled LASSO estimator of Manresa (2016) to identify the cross-node effects of ES on congestion costs, the second term in (1). This estimator is appropriate when estimating spillover effects in sparse, unobserved networks. Estimation alternates between an own-effect regression stage with fixed effects and flexible cross-node effects using LASSO, which penalizes non-zero cross-node effects. The result is consistent with network theory and uncovers the observed effects of network constraints, even when the network itself is not observed. Welfare effects are then calculated from nodal price changes combined with nodal volumes.

Data

Energy storage capacity in the CAISO area between 2009 and 2017 is observed in two data sets (see Figure 1). Around 400MW of *added* capacity appears in the Department of Energy's Global Energy Storage (GS) Database[1], while another 50MW of behind-the-meter storage (e.g. Tesla Powerwall) appears in the California Self-Generation Incentive Program (SGIP) database[2]. Coordinates for the former are included in the DoE GS database, while the latter dataset includes the customer zip code.

[1] http://www.energystorageexchange.org/projects

[2] http://www.cpuc.ca.gov/sgip/

Locational Marginal Prices (LMP's) representing λ_e, λ_c and λ_l are obtained using CAISO's OASIS data portal from September 1, 2009 through August 31, 2017. The physical location of each node is derived from OASIS maps and each known ES location is merged to the nearest node. Nodes are clustered by name and proximity (N=771). To derive welfare effects, total volume of energy at each node and hour is necessary. I obtain this using the published load distribution factors (LDFs) associated with each of the three main load aggregation points (LAP) as weights on total LAP hourly demand.

Preliminary Results

Preliminary findings from a specification similar to (1) but restricting cross-node effects to zero indicate that the presence of ES at a pricing node in the CAISO network has an own-node negative effect of up to -1% on summertime peak prices, and a small, positive effect on overnight prices (Figure 2). These findings suggest that ES lowers average grid costs by marginally reducing daytime peak prices when storage is discharged. Estimating cross-node effects, calculating welfare changes, and comparing to federal and state ES subsidies remain proposed steps to be completed under the fellowship.

Deliverables

The proposed research is intended to be a dissertation chapter and a job market paper. Thus, the primary deliverable is a paper targeted at a top-tier general economics journal, along with the code and data necessary to share the spatial processes linking publicly-available ES data and publicly-available CAISO nodal pricing data. This paper would be completed by March 2019. A second paper focusing on the role of ES in facilitating renewables - specifically examining the effect of ES on prices during times correlated with high wind or solar production – would be completed by June 2019. Further work on siting location choices and energy market dynamics would be likely beyond the fellowship period.

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Figures

Figure 1: Energy Storage Capacity Added During Study Period by Type/Source. Totals do not include ES introduced before September 2009. Does not include 120MW of Pumped Hydro taken offline in 2012 due to unexpected fire.

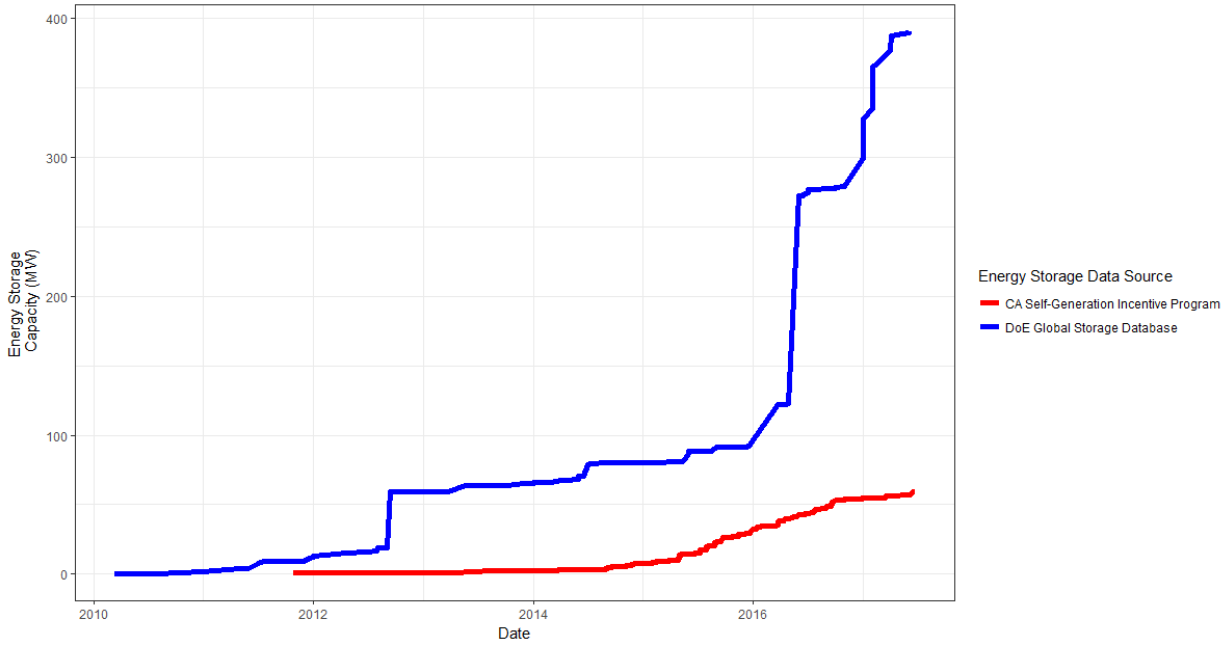
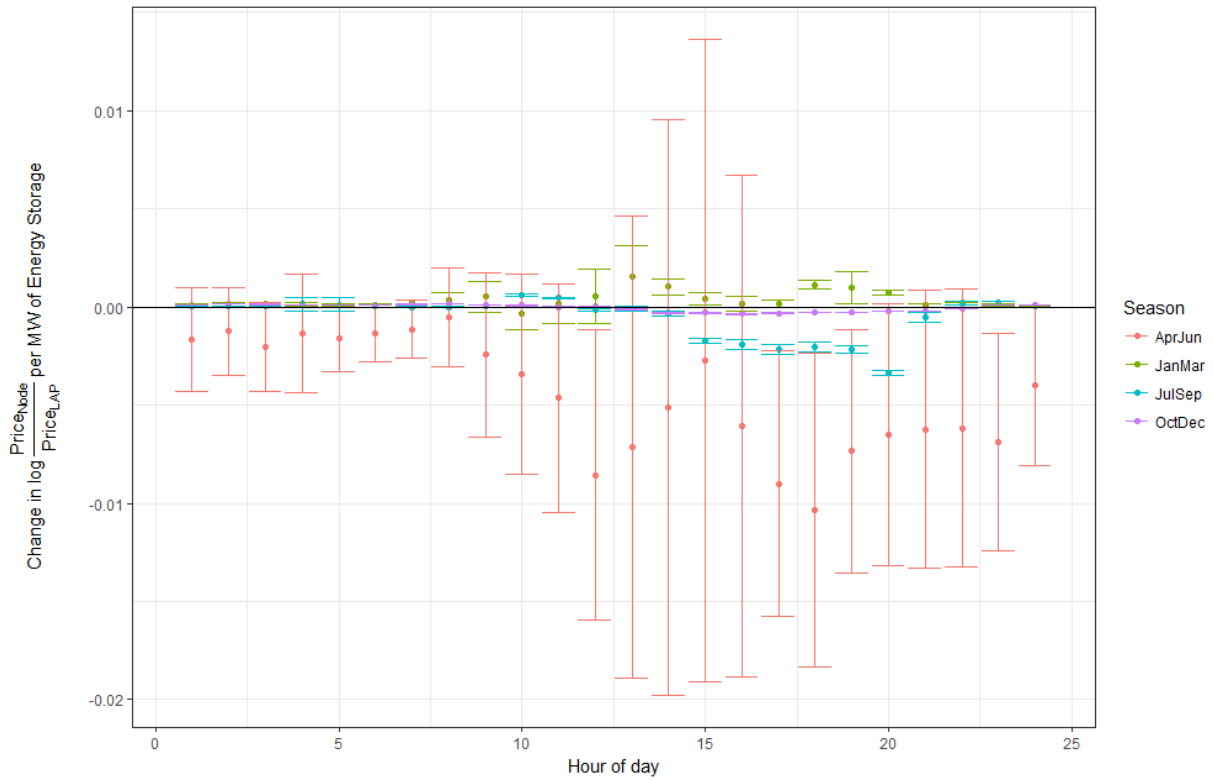


Figure 2: Effect of Energy Storage on Own-Node Energy Price by Hour, γ_{sh}. Summer (Jul-Sep) months show tightly estimated negative effects during afternoon peaks. Results restrict cross-node effects (γ_{sh}^{ji}) to zero.



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Research Interests

Environmental economics, econometrics, industrial organization

Education

Ph.D., Environmental Economics, expected 2019
MA, Economics, expected 2017
Duke University
Advisor: Dr. Lori Bennear

MEM, Environmental Economics and Policy, 2012
Duke University, Nicholas School of the Environment
Advisor: Dr. Lori Bennear

BS, Environmental Policy Analysis and Planning, 2001
University of California, Davis
Advisor: Dr. Paul Sabatier

Publications

Martin D. Smith, Atle Oglend, **A. Justin Kirkpatrick**, Frank Asche, Lori S. Bennear, J. Craig, James Nance. "Seafood Prices Reveal Impacts of a Major Ecological Disturbance." *Proceedings of the National Academy of Sciences*, January 30, 2017. DOI: 10.1073/pnas.1617948114

Sills, Erin O., Diego Herrera, **A. Justin Kirkpatrick**, Amintas Brandão Jr, Rebecca Dickson, Simon Hall, Subhrendu Pattanayak et al. "Estimating the Impacts of Local Policy Innovation: The Synthetic Control Method Applied to Tropical Deforestation." *PLoS One* 10, no. 7 (2015).

Kirkpatrick, A. Justin, and Lori S. Bennear. "Promoting Clean Energy Investment: An Empirical Analysis of Property Assessed Clean Energy." *Journal of Environmental Economics and Management* 68, no. 2 (2014): 357-375.

Working Papers

Bryan Bollinger, Ken Gillingham, **A. Justin Kirkpatrick**, Steven Sexton. "Household Discount Rates and Net Energy Metering Incentives for Rooftop Solar Adoption" for *NBER Economics of Energy Markets 2017* (last updated June 2017)

Kirkpatrick, A. Justin, T. Robert Fetter. "Averting Expenditures and Desirable Goods: Consumer Demand for Bottled Water in the Presence of Fracking" (last updated July 2017)

Sexton, Steven E., **A. Justin Kirkpatrick**, Robert Harris, Nicholas Muller. "Siting Solar PV Capacity to Maximize Environmental Benefits" (last updated Dec. 2017)

Other Publications

National Oceanic and Atmospheric Administration. National Marine Fisheries Service, Northeast Fisheries Science Center. "Socio-economic Impact of Outer Continental Shelf Wind Energy

Development on Fishing in the U.S. Atlantic." By **A. Justin Kirkpatrick**, Sharon Benjamin, Geret DePiper, Tammy Murphy, Scott Steinback, and Chad Demarest. *OCS Study BOEM 2017-012*. Woods Hole, MA, 2017.

IPBES 2019: The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on Global Assessment of Biodiversity and Ecosystem Services. (Contributing Author)

Industry Experience

Freelance Consultant, TerraCarbon, Peoria, IL. (2014-2017)

Economist, NOAA Fisheries, Northeast Fisheries Science Center, Social Sciences Branch, Woods Hole, MA. (2012-2014)

Freelance Consultant, Rhodium Group, New York, NY. (2012)

Teaching

Instructor of Record, PUBPOL800K: Statistics Boot Camp (at Duke Kunshan University, Summer 2017)

Teaching Assistant, ENV850: Program Evaluation (Graduate Professional, Spring 2017)

Instructor of Record, ENV710: Applied Data Analysis for Environmental Science (Graduate Professional, Fall 2016)

Teaching Assistant, ENV520: Environmental Econ (Graduate Professional, Fall I 2015)

Teaching Assistant, ENV521: Resource Econ (Graduate Professional, Fall II 2015)

Teaching Assistant, EOS201: Environmental Science and Policy (Undergraduate, Spring 2016)

Conference and Workshop Presentations

Research Presentations

2018 American Economic Association (AEA) Allied Social Sciences Associations Annual Meeting - *Siting Solar PV Capacity to Maximize Environmental Benefits* (with Steve Sexton, Robert Harris, and Nicholas Muller)

2017 UC Santa Barbara Occasional Workshop - *Siting Solar PV Capacity to Maximize Environmental Benefits* (with Steve Sexton, Robert Harris, and Nicholas Muller)

2017 Heartland Environmental and Resource Economics Workshop at Illinois (UIUC) - *Energy Insecurity and Red-lined America* (solo author)

2017 Association of Environmental and Resource Economists (AERE) Annual Summer Conference - *Visibility and Peer Effects in Residential Solar Photovoltaics* (with Steve Sexton, Bryan Bollinger, and Ken Gillingham)

2017 Association of Environmental and Resource Economists (AERE) Annual Summer Conference - *Averting Expenditures and Desirable Goods: Consumer Demand for Bottled Water in the Presence of Fracking* (with T. Rob Fetter)

2017 Gulf of Mexico Alliance All Hands Meeting - *Seafood Prices Reveal Impacts of Gulf Hypoxia* (with Martin Smith, A. Oglund, F. Asche, L. Bennear, K. Craig, J. Nance)

2017 American Economic Association (AEA) Allied Social Sciences Associations Annual Meeting - *Averting Expenditures and Desirable Goods: Consumer Demand for Bottled Water in the Presence of Fracking* (with T. Rob Fetter)

2016 Center for Environmental and Resource Economic Policy (CEnREP) Camp Resources - *Averting Expenditures and Desirable Goods: Consumer Demand for Bottled Water in the Presence of Fracking* (with T. Rob Fetter)

2016 National Bureau of Economic Research (NBER) Economics of Energy Markets Conference - *Household Demand for Solar PV and Price Discriminating Subsidies* (with Steve Sexton, Bryan Bollinger, and Ken Gillingham)

2014 International Institute of Fisheries Economics and Trade (IIFET) Biennial Conference - *The Economic Impact of Offshore Wind Development in the NW (US) Atlantic Fisheries*

2014 Mid-Atlantic Fisheries Management Council - *Who Fishes There? A baseline of fishing to inform offshore wind siting.*

2012 APPAM Fall Research Conference - *Closing the "Energy-Efficiency Gap": An Empirical Analysis of Property Assessed Clean Energy*

2012 AABPA Conference (poster presentation)

Panel Chair
2014 IIFET Conference, Panel title: *Management: Regulation and Allocation*

Awards

Duke Environmental Economics Doctoral Scholars Fellowship (DEEDS) (2017-2018)

Duke University Energy Initiative Fellow (2016-2019)

Mary Katherine Kubat Award Finalist (2012), AABPA

Professional Service

Referee and Grant Reviews
Journal of the Association of Environmental and Resource Economists (JAERE); *Journal of Environmental Economics and Management* (JEEM)
NOAA Saltonstall-Kennedy Marine Resource Economics Grant Program

Associations
Association of Environmental and Resource Economists (AERE)
International Institute of Fisheries Economics and Trade (IIFET)
North American Association of Fisheries Economics (NAAFE)

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December 16, 2017

Ms. Elisa Pepe
NBER Pre-doctoral Fellowship Program on Energy Economics

Dear Ms. Pepe and Selection Committee:

It is my privilege to write this letter offering my **highest possible recommendation** for A. Justin Kirpatrick for the NBER Pre-doctoral Fellowship Program on Energy Economics. **Justin is the best Ph.D. student I have worked with in my 13 years at Duke.**

I have known Justin since the fall semester of 2010 when he began the Master's in Environmental Management (MEM) program at the Nicholas School of the Environment at Duke. I supervised his Master's Project, hired him (together with Dr. Martin Smith also of the Nicholas School) as an Associate in Research after his graduation, and then persuaded him to come back to Duke to get his Ph.D.

Justin's inquisitive nature and ability to tackle hard analytic problems with limited oversight were evident during his master's project. He wanted to evaluate an innovative renewable energy-financing scheme, called Property Assessed Clean Energy (PACE), adopted in a few California cities from 2008-2010. PACE programs provide municipal loans to households for residential solar installations and payments on these are collected through property tax assessments rather than through traditional loan payments. When a house is sold, both the solar infrastructure and the payments (through the property tax assessment) transfer to the new owner. Justin used a synthetic control matching method to estimate the impacts of the PACE program in three cities/counties in California. His was one of the first (if not the first) use of synthetic control methods in Energy Economics and he had to address several methodological issues including determining the proper form for bootstrapping standard errors for such estimators. In this paper he finds evidence that PACE financing did have a significant and positive impact on residential solar PV adoption relative to what we would have expected absent such programs. This paper, which is so much superior to any other master's project I have ever supervised, was published in JEEM *before* Justin returned to get his Ph.D.!

Justin currently has several project underway in the Energy Economics field that are nearing completion. One project is estimating the impact of the visibility of solar panels using LIDAR data on subsequent adoptions of solar panels by neighbors. One is examining the impact of fracking locations in PA on bottled water purchases. Both are in final stages before being submitted for peer-review.

The project he proposed for this fellowship, which will be his job market paper, examines the impact of energy storage on electricity prices and the welfare effects of any price changes. The basic idea behind the impact of storage on prices is that storage should be used to buy power when prices are low and discharge power when prices are high. The steady-state solution is one in which electricity prices are flat, as all price differentials have been arbitraged away through electricity storage. During the transition to this steady state, one should observe decreases in peak prices and increases in off-peak prices in areas with more storage relative to areas with less

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storage. Justin has compiled a unique dataset of nodal prices, storage levels, and congestion and electricity nodes in California. He can use these data to test the price hypothesis. In preliminary results, he has found that nodes with higher levels of installed storage have lower peak prices relative to nodes with less storage, controlling for a variety of other determinants of nodal prices. The particular shift in prices favors wind generation which is highest at night when prices are lowest and storage units are likely to buy electricity. This clean wind generation is then dispatched during the day when it might offset solar (another clean source of electricity) or fossil fuel generation. To the extent that wind offsets fossil fuel generation, there are welfare gains from pollution reduction.

In addition to examining the impact of storage on prices, Justin is also examining the impacts of storage on social welfare. I have already purported a potential positive impact on social welfare from shifts in generation created by energy storage opportunities. But who bears the cost of that gain? The so-called "solar subsidy problem" results from the fact that subsidies for solar result in decreases in grid reliability and increases in grid access costs that are mostly born by those not installing solar? Is there a similar distributional concern with energy storage? So far, the results suggest that the answer no. The decrease in the market clearing price of electricity in peak periods results in lowered costs for the utility, which should be passed on to all consumers.

With significant amounts of energy storage set to come online over the next decade, this is important and timely work and Justin is the right person to do it. Justin is a brilliant and highly productive guy. The proposed research builds on his prior research in energy economics and he is well-trained and well-equipped to carry it out over the next year. His empirical skills and overall potential as a scholar are better than any graduate student I have ever worked with at Duke. I give him my highest possible recommendation.

Sincerely,



Lori Snyder Bennear
Juli Plant Grainger Associate Professor of Energy Economics and Policy
Associate Director, Duke University Energy Initiative