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MIT CEEPR Newsletter

MIT Center for Energy and Environmental Policy Research

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Editorial

As we find ourselves in the midst of a global health pandemic, facing deep uncertainties about its long-term impact and the appropriate response, it is worth remembering that MIT CEEPR was born out of a crisis – the prolonged energy crisis of the 1970s, sparked by petroleum shortages that contributed to stagnant growth and price inflation around the world. A need to better understand the drivers and economic consequences of that crisis motivated the establishment of CEEPR, as did a desire to identify suitable policy options to avert or mitigate future crises.

Ever since, CEEPR has supported research and fostered debate on a variety of topics that entailed disruption and uncertainty for the energy sector. Whether on the restructuring of electricity markets, the acceleration of environmental policymaking, the emergence of unconventional oil and gas production, or rapid growth in the integration of renewable energy sources, CEEPR has consistently been able to offer guidance based on objective analysis by researchers and faculty affiliates across MIT.

Obtaining insights through robust methodologies and empirical data can be a slow process, and research outcomes will at times lag behind the pace of an unfolding emergency. But unlike the breathless commentary and the speculative or anecdotal advice that tend to fill the media channels during times of crisis, only prescriptions drawn from genuine research can deliver the reliable, unbiased foundation of effective decision making.

As the current health pandemic continues to unfold, CEEPR is already beginning to identify relevant questions and research designs to better understand the implications for the energy sector and, more importantly, to inform the policy response to this and future crises. We look forward to engaging with you, both remotely and at some point again in person, to share our discoveries, test our results, and brainstorm new research priorities. Until then, however, please stay well and safe.

—Michael Mehling

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Director's Message

Professor Christopher Knittel, at home preparing for remote teaching during the MIT campus-wide closure due to the COVID-19 pandemic.

When the last installment of this newsletter was published, it would have been impossible to predict the global health pandemic we currently face, or the magnitude of its economic and policy implications. Forced to make difficult choices under conditions of extreme uncertainty, MIT joined other institutions of higher education in an early and vigorous response to the threat posed by the novel coronavirus, cancelling classes and other campus activities well before the first state governors issued stay-at-home orders.

We are grateful to MIT for this leadership and foresight, and followed suit by cancelling all CEEPR events scheduled for spring and summer. Needless to say, the health and safety of our community are our foremost priority. But we did not take this step lightly, as we realize that our events are an important channel through which associates can engage with our work and the researchers behind it.

Likewise, the ability to obtain insights and feedback from external partners – including, in particular, those who experience the realities of daily practice – has been an invaluable source of data and means of testing the robustness of our research.

Fortunately, just as most of MIT's classroom activities have transitioned to online delivery, we can also revert to a virtual engagement format for CEEPR events. Over the course of the spring, we are hosting a series of webinars with MIT researchers and invited guests, featuring some of our latest research outputs as well as an informed discussion of topics of current concern. Our first webinar will address what has become perhaps the most visible impact of the pandemic on energy markets: the historical decline in crude oil prices, which has even seen U.S. crude futures close in negative territory.

It is safe to say that the novel coronavirus will have implications for energy and environmental policy that reach far beyond the shock to global fuel demand. Already, many commentators have outlined the opportunities offered by stimulus and bailout payments to engineer a green recovery of our economy. As governments weigh their options, factual, data-driven research of the kind CEEPR has always advanced will be essential to discern wishful thinking from possibility. At this point, we may not even fully understand all the ways in which the health crisis will affect energy markets and the environment, but we know the list is long.

For us at CEEPR, the last few months have served as a stark reminder of why our work matters in the real world. We count ourselves fortunate that our work can continue largely undiminished as vast segments of the economy have been forced to close down. With a renewed sense of urgency, we will therefore continue to dedicate our resources to better understand and prepare for the most pressing challenges faced in energy and environmental policy.

As we do so, we hope you can join us for our upcoming webinars, where we look forward to the stimulating and fruitful debates that have always been a hallmark of CEEPR events. Above all, however, we hope that you and those close to you stay healthy and safe during these challenging times.

Sincerely,

Christopher R. Knittel
Director, MIT CEEPR
George P. Shultz Professor of Applied Economics, MIT Sloan School of Management

Machine Learning for Solar Accessibility: Implications for Low-Income Solar Expansion and Profitability

by: Sruthi Davuluri, René García Franceschini, Christopher R. Knittel, Chikara Onda, and Kelly Roache

Most solar companies currently use credit scores to determine whom to approve for solar installations. Despite their widespread use, credit scores consider many aspects of a consumer's credit history that are not directly related to utility payment; therefore, the FICO score is an imperfect proxy for predicting utility payment performance. This implies that traditional credit score cutoffs exclude people with low credit scores and those with insufficient credit history, which disproportionately hurts low-to-moderate (LMI) income households.

The goal of this research[1] is: (1) to develop an alternative prediction model of default based on machine learning algorithms, specifically LASSO, SVM, and random forests; and (2) to compare its overall forecasting performance, as well as its implications for LMI consumers, to traditional credit metrics. We do so by developing a model that predicts the probability of non-delinquency of utility bill payments using a large data set of utility repayment and other financial data obtained from a credit reporting agency (CRA). We find that a traditional regression analysis using a small number of variables specific to utility repayment performance greatly increases accuracy and LMI inclusivity relative to FICO score, and that using machine learning techniques further enhances model performance.

A number of regression and machine learning techniques were used to predict utility bill delinquency. Among the variety of models that we explored, the random forest algorithm was clearly superior in terms of accuracy. Moreover, the random forest algorithm not only has better accuracy, but it also requires less data pre-processing. Finally, it is easier to interpret and runs more quickly. The alternative scoring methods developed with traditional regression analysis and machine learning techniques were compared to standard FICO cutoffs, with a number of different metrics, including accuracy, default rate, and LMI inclusion.

For example, the figure below displays the probabilities of non-delinquency using the random forest algorithm against the individual's FICO Score. There are many individuals who have a high probability of non-delinquency with the random forest algorithm, but do not have a very high FICO score, which demonstrates the amount of people that would have been rejected with the FICO cutoff, but accepted according to the random forest algorithm ("false negatives"). Additionally, there are quite a few data points with high FICO scores that do not have a very high probability with the random forest algorithm, who would be erroneously accepted ("false positives"). The figure suggests that there are high numbers of false negatives and false positives under traditional FICO scoring. Though the FICO Score is one variable used by the random forest algorithm, there are many other variables as well.

Importantly, the random forest algorithm, when tested with both 30 and 90 day definitions of delinquency, increase the number of LMI applicants approved. The random forest algorithm using a 30 day definition increases the number of LMI accounts approved by 11.4% to 14.0% depending on the stringency, while that using a 90 day definition increases LMI customers by 1.1% to 4.2%.

Finally, the impact of the alternative scoring methods on the profitability is estimated. The results shown in the Working Paper demonstrate that the random forest algorithm leads to an increase in profits for the firm, which is a very significant result from our study. The random forest algorithm both

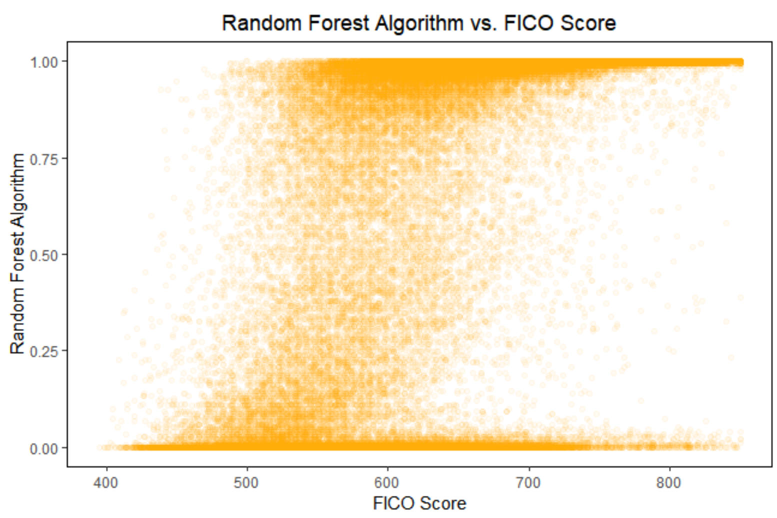


Figure: Random Forest Algorithm and FICO Score for 872,382 data points displaying the probabilities of non-deliquency behavior.

benefits the customers, by accepting more LMI customers, and benefits the firms, by increasing profits.

We can decompose the increase in profits from the random forest algorithm to two sources. The first is from the increase in profits due to accepting new customers who would have otherwise been denied under the FICO score cutoff, or a decrease in false negatives (π from New Customers). The second source stems from a reduction in losses from rejecting those who are accepted under the FICO Score cutoff but whom the random forest algorithm identifies as high-risk, or a decrease in false positives ("π from Less Delinquents").

Overall, the random forest algorithm improves accuracy when compared to the FICO Score, offers access to solar energy for more LMI customers, and leads to an increase in profits when compared to the FICO score cutoff, regardless of the stringency of the industry standard.

[1] Sruthi Davuluri, René García Franceschini, Christopher R. Knittel, Chikara Onda, and Kelly Roache (2019), "Machine Learning for Solar Accessibility: Implications for Low-Income Solar Expansion and Profitability", *CEEPR WP-2019-020*, MIT, December 2019.


Sruthi Davuluri


René Franceschini


Christopher Knittel


Chikara Onda


Kelly Roache

Social Comparison and Energy Conservation in a Collective Action Context: A Field Experiment

by: Serhiy Kandul, Ghislaine Lang, and Bruno Lanz

Social comparison feedback, which informs people about their behavior relative to the typical behavior of others, has been established as a cost-effective tool to promote resource conservation (e.g. Allcott, 2011; Ferraro et al., 2011; Costa and Kahn, 2013; Allcott and Rogers, 2014). Our field experiment[1] quantifies the effect of a social comparison feedback intervention on demand for indoor temperature in apartment buildings. Arguably, lowering indoor temperature during the heating season is associated with significant disutility, and the extent to which social comparison feedback can also incentivize behavior in a high-effort setting is an open question.

We design a simple letter informing treated subjects about how their average indoor temperature, measured over one month, compares to the corresponding average for "more than 200 comparable households" (i.e. the control group). The general layout of the letter closely follows Allcott and Rogers (2014), and includes a set of normative signals such as recommended temperature levels and smileys (injunctive norms, see Schultz et al., 2007). One implication of our design is that all the participants, including those performing better than the average, have a benchmark to improve.

Importantly, while all subjects in our field experiment are tenants and pay for their use of heating energy, a large majority rent their apartment in buildings that have no individual meters for heating energy use. For these tenants, building-level energy cost are shared across apartments in proportion to the volume of each property. It follows that the financial benefits of individual energy savings are only indirect, being conditioned on the behavior of other tenants in the same building. The implied collective action problem contrasts with previous studies in which energy savings imply either direct financial benefits (Allcott and Rogers, 2014) or no financial benefits at all (Myers and Souza, 2019).

In line with this, our intervention does not provide information on individual monetary savings, but rather considers the use of normative appeals referring to specific benefits of reduced energy demand (see Bicchieri and Dimant, 2019). These appeals are framed as a request for cooperation with the real estate agency to achieve corporate social responsibility objectives, financial savings for all the households in the building, or environmental benefits.

In this Working Paper, the researchers report results from a social comparison feedback experiment incentivizing a reduction of indoor temperatures during the heating season. Despite the fact that most participants in the experiment do not face direct financial benefits associated with lowering heating energy consumption, the authors estimate a statistically significant and non-trivial treatment effect of -0.54°F (-1.2%).

Our sample includes 45 apartment buildings, all located in a single Swiss canton and managed by a common real estate agency. All 855 apartments in these buildings are equipped with indoor temperature monitors — small devices without a display which record temperature every 15 minutes. 232 apartments in the control group did not receive any information over the observention period; while 623 households in the treatments were sent the information letters at the end of January 2019, referring to the average indoor temperatures measured in December 2018.

Based on difference-in-differences regressions on mean daily indoor temperature over the heating season (November 2018 - March 2019), we find that our intervention induces a -0.28°C (-0.54°F) reduction in average indoor temperature relative to control. This corresponds to a reduction of energy use by at least 2 percent (see Palmer et al., 2012), which is not trivial given the relatively low cost of the informational intervention. Moreover, the estimated treatment effect is stable with time, and very similar for subjects with pre-treatment temperature below-average and above-average.

We conclude that tenants in our sample are willing to sacrifice part of their comfort to reduce energy use, and that the presence of indirect monetary incentives is sufficient for social comparison feedback interventions to induce energy conservation behavior.

Table 2: Regression estimates for mean daily indoor temperature (°C)

	Model 1: Fixed-effect regression	Model 2: Fixed-effect quantile regressions				
		q=0.1	q=0.25	q=0.5	q=0.75	q=0.9
	(1)	(2)	(3)	(4)	(5)	(6)
Social comparison x post	-0.30***	-0.33***	-0.29***	-0.27***	-0.27***	-0.29***
	(0.07)	(0.07)	(0.05)	(0.05)	(0.06)	(0.09)
Corporate social responsibility x post	-0.25***	-0.27***	-0.24***	-0.23***	-0.25***	-0.23***
	(0.06)	(0.06)	(0.05)	(0.05)	(0.06)	(0.09)
Financial appeal x post	-0.31***	-0.36***	-0.33***	-0.30***	-0.28***	-0.27***
	(0.06)	(0.06)	(0.05)	(0.05)	(0.06)	(0.08)
Environmental appeal x post	-0.27***	-0.28***	-0.26***	-0.26***	-0.24***	-0.25***
	(0.07)	(0.06)	(0.05)	(0.05)	(0.06)	(0.09)
Apartments	821	821	821	821	821	821
Observations	120,441	120,441	120,441	120,441	120,441	120,441
(Pseudo)R^2	0.01	0.12	0.13	0.13	0.13	0.13

Notes: Column (1) reports linear fixed-effect regressions with robust standard-errors clustered at the apartment-level in parentheses. Columns (2) to (6) report fixed-effect quantile panel regressions (bootstrapped standard-errors). All regressions include apartment and day fixed effects. *, ** and *** denote statistical significance at 5% and 1% and 0.1% levels respectively.

In column (1), the researchers report a fixed-effect regression with average treatment effect estimated separately for each condition relative to control. Columns (2) to (6) report fixed effect quantile regression results to document heterogeneous effects. In all regressions, they control for apartment and day fixed effects, and report standard-errors clustered at the apartment level in parenthesis.

[1] Serhiy Kandul, Ghislaine Lang, and Bruno Lanz (2019), "Social Comparison and Energy Conservation in a Collective Action Context: A Field Experiment", *CEEPR WP-2019-021*, MIT, December 2019.

Serhiy Kandul

Ghislaine Lang

Bruno Lanz

Using Machine Learning to Target Treatment: The Case of Household Energy Use

by: Christopher R. Knittel and Samuel Stolper

The rising use of randomized controlled trials in economics has produced a wealth of evidence on the average causal effect of a great number of social and private-sector programs. Yet such programs quite often have widely divergent impacts across the treated population. Machine learning is fast becoming a powerful tool for estimating these kinds of heterogeneous treatment effects. One class of machine-learning algorithms – "tree-based methods" – has seen significant progress in recent years. It allows for causal estimation of conditional average treatment effects from regression trees, and has more recently been extended to estimate what are known as "causal forests."

A new MIT CEEPR Working Paper[1] applies such a causal forest algorithm to the evaluation of a large-scale behavioral intervention: a series of randomized experiments investigating the heterogeneous impacts of behavioral "nudges" towards energy efficiency in household energy use. The paper predicts treatment effects among more than 900,000 households and investigates the role of observed and unobserved household characteristics in determining outcomes. Its empirical setting is the retail electricity service territory of Eversource, the largest electric utility in New England. This context is especially ripe for estimation of heterogeneous treatment effects because of the large overall sample size, which provides greater statistical power than is normal in randomized controlled trials, and because Home Energy Reports tend to induce a wide variety of behavioral responses.

Eversource's flagship behavioral energy efficiency product is the Home Energy Report, a short, regular mailing that compares a customer's electricity (and natural gas) consumption to that of similar, nearby households and provides information on ways to save energy. Home Energy Reports have long been studied as an example of a successful "nudge" towards behavior that is both privately and socially beneficial. But despite consistent findings of reductions in electricity consumption, relatively little is known about the mechanisms that govern the household response to such reports. Through estimation of a causal forest, the new paper begins to shed light on these mechanisms.

Since 2011, Eversource has been experimentally rolling out Home Energy Reports across its service territory in consecutive waves. By leveraging data from 15 experimental waves covering 902,581 Eversource residential customers, the paper's authors, Christopher R. Knittel of the MIT Sloan School of Management and Samuel Stolper of the University of Michigan School for Environment and Sustainability, observe monthly household electricity consumption between the years 2013 and 2018 and cross-sectional characteristics pertaining to homes and their occupants. Their central estimate of the pooled average treatment effect across all program waves— estimated via panel regression—is a reduction in monthly electricity usage of 9 kilowatt-hours (kWh), or 1 percent.

What is more, the study shows a rise in

In a new paper on the use of machine learning methods to target energy efficiency measures, the authors use causal forests to evaluate the heterogeneous treatment effects of repeated behavioral nudges towards household energy conservation. They find that the average response is a monthly electricity reduction of 9 kilowatt-hours, but the full distribution of responses ranges from -30 to +10 kilowatt-hours.

the absolute treatment effect over the years, with no evidence of attenuation of program impacts; if anything, the reductions in electricity consumption continue to increase. For instance, the year-three pooled average treatment effect in the sample studied for this paper is -14 kWh, or -1.5 percent. However, the pooled average masks heterogeneity across waves and over time, because sample makeup varies across waves and the household response evolves with repetition, respectively: 81 percent of households reduce consumption by more than the monthly mean. The largest reductions are three times the mean, while some households actually increase their consumption.

What accounts for this sizable heterogeneity? Pre-treatment consumption and home value are the strongest predictors of individual responses, but several other characteristics have predictive power as well, and the relationship between treatment effect and these characteristics is non-linear. For instance, the authors find suggestive evidence that the social comparison embedded in Home Energy Reports induces a "boomerang effect": the households that are predicted to raise their consumption appear to be the ones that receive "positive" messaging about their own consumption relative to others by being told that they are consuming less than other, similar households.

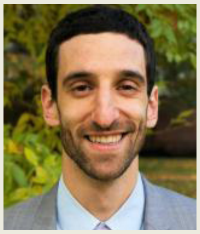
Application of the causal forest algorithm illustrates how machine learning might be used to improve the effectiveness of interventions. Understanding how different subgroups respond to a given treatment has the potential to unlock large increases in program effectiveness, by allowing for improved targeting of the existing treatment as well as improved design of the treatment itself. The authors find large potential welfare gains from targeting the treatment. To do so, they compare the monetized net benefits of the actual Home Energy Report distribution to the net benefits of sending reports only to those households for which benefits exceed the marginal cost of sending reports. That way, between $500 thousand and $1.2 million in deadweight loss can be hypothetically avoided each year.

As the authors concede, selective targeting may be difficult at the outset of an intervention, unless a previously-treated sample with similar characteristics is available. They find, however, that outcomes in the first year of the intervention provide valuable information for the targeting task: household- specific responses are persistent over time. In the studied context, at least 85 percent of available welfare gains from treatment in years 2 and 3 would have been achievable through the use of year-1 estimates. Among households that do respond in privately or socially beneficial ways, it may thus be possible to raise welfare through tailoring of treatment to include different information or rely on a different framing of the nudge.

—Summary by Michael Mehling

[1] Christopher R. Knittel and Samuel Stolper (2020), "Using Machine Learning to Target Treatment: The Case of Household Energy Use", *CEEPR WP-2020-001*, MIT, January 2020.

Christopher Knittel



Samuel Stolper

Climate Policy Without a Price Signal: Evidence on the Implicit Carbon Price of Energy Efficiency in Buildings

by: Ghislaine Lang and Bruno Lanz

In the absence of a global carbon price, individual countries often promote specific emissions abatement measures to reduce fossil fuel use. A prominent example is a widespread adoption of subsidized weatherization and energy efficiency programs in buildings. This approach to regulation implies that investment decisions determine the implicit price of carbon as the cost of reducing CO_2 emissions by one tonne (Gillingham and Stock, 2018).

In this paper[1], we provide empirical evidence on the implicit carbon price of alternative energy efficiency investments, namely insulation of exterior walls, roof or attic, replacement of windows, installation of smart thermostats that optimize heating operations using real-time information (e.g., weather forecasts), and replacement of the boiler, both with and without fuel switching from heating oil to natural gas. Intuitively, we construct a statistical counterpart to the often-cited "McKinsey curve" (McKinsey & Company, 2009), ranking energy efficiency interventions from the least to the most expensive. As current policies (e.g., subsidies for wall insulation or windows replacement) typically target interventions based on expected energy savings, we also document heterogeneous effects of alternative investments on energy use.

Our data comprise a portfolio of 548 apartment buildings (12,820 rental units) observed from 2001 to 2016. During the observation period, 240 buildings benefitted from a total of 402 energy efficiency improvements. We exploit observations for the 308 buildings that experienced no energy-related intervention to form a candidate control group and estimate a counterfactual trajectory for treated buildings in the absence of interventions. In particular, the staggered nature of investments across buildings allows us to provide evidence that treated and control buildings follow the same trend in the absence of energy efficiency investments.

In order to quantify energy savings associated with individual energy efficiency interventions, we employ a staggered difference-in-differences estimation strategy (Autor, 2003; Stevenson and Wolfers, 2006), controlling for year and buildings fixed effects, local weather shocks and fuel prices, as well as complementarity effects across interventions (Mulder et al., 2003). We then use detailed information about the financial cost of interventions to quantify the effect of a marginal investment in alternative energy efficiency improvements on building-level CO_2 emissions and heating expenditures. Together with standard engineering estimates on the lifetime of building elements and a discount rate (0% or 6%), this allows us to carry out inference on the implicit price of carbon associated with alternative investments.

Our results show substantial heterogeneity in energy savings across interventions. Widely subsidized investments such as exterior wall insulation and the replacement of windows are associated with energy savings of 18 and 5 percent, respectively. Further, point estimates for the implicit price of carbon associated with these interventions is around CHF 1,000 per tonne of CO_2, which is well above estimated benefits of avoided emissions (around USD 40/tCO_2, see Greenstone et al., 2013). By contrast, evidence suggests that the implicit price of carbon associated with the installation of smart thermostats is negative, and delivers energy savings of around 10 percent. This suggests that such investments are beneficial even in the absence of externalities associated with energy use.

Taken together, heterogeneity across interventions illustrates the difficulty for policy makers to select specific abatement measures instead of relying on a carbon price. In particular, we emphasize the need for transparent information about the cost of carbon abatement associated with different policy interventions. Moreover, while our estimates are consistent with evidence derived in other settings (e.g. Fowlie et al., 2018), evidence on the implicit price of carbon is by construction context-dependent (Gillingham and Stock, 2018), and further work on the impact of specific abatement measures is warranted.

[1] Ghislaine Lang and Bruno Lanz (2020), "Climate Policy Without a Price Signal: Evidence on the Implicit Carbon Price of Energy Efficiency in Buildings", *CEEPR WP-2020-004*, MIT, March, 2020.

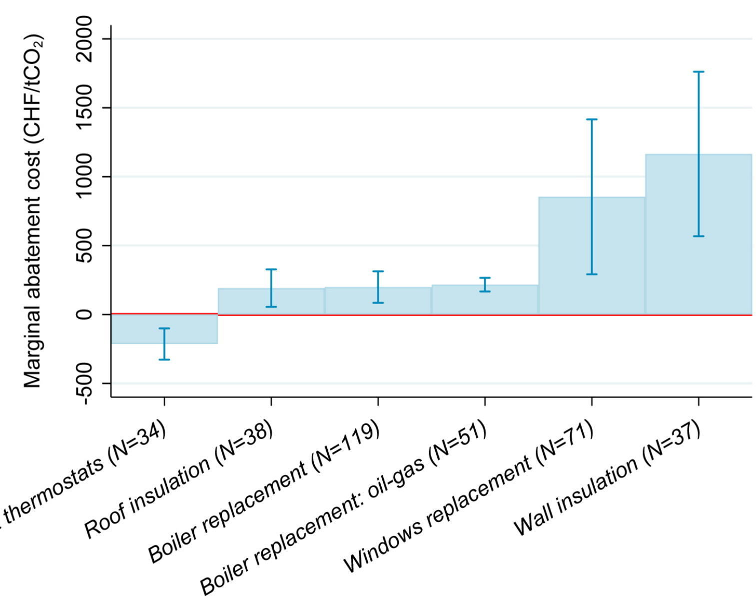


Figure: Ranking for the implicit price of carbon across interventions
The graph displays point estimates and 95% confidence intervals for estimates of the implicit price of carbon. Prices refer to a 2015 baseline; exchange rate approx. CHF 1 = USD 1

Ghislaine Lang

Bruno Lanz

Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern U.S. and the Role of Canadian Hydropower

by: Emil Dimanchev, Joshua Hodge, and John Parsons

Recent policy changes in the Northeast region of the U.S. commit several states to deep decarbonization of the electricity sector. New laws in New York and Maine mandate 100% clean electricity by 2040 and 2050 respectively. An executive order in Connecticut calls for 100% clean electricity by 2040. A recent bill in Massachusetts contained a goal of economy-wide net zero emissions by 2050. Meeting such climate policy objectives will require decisions about how to design a portfolio of low- or zero-carbon technologies that can meet future electricity demand.

Pathways toward zero-carbon electricity systems tend rely more or less heavily on wind and solar PV generation. An emerging question is what additional technologies are best suited to compensate for the high variability of wind and solar. Planners have to consider renewable intermittency at multiple scales: daily, synoptic (lasting multiple days), and seasonal. Solutions may include dispatchable low-carbon technologies, power-to-gas production of synthetic fuels such as hydrogen, thermal energy storage, or new technologies for long-term energy storage. For Northeastern U.S. states, a solution based on existing technology may be the use of hydropower reservoirs in neighboring Quebec.

This paper[1] addresses three main questions: 1) how the optimal technology mix and operation of the power systems of New England, New York, and Quebec, including the optimal trade between regions, change with deep decarbonization; 2) how transmission expansion impacts low-carbon power systems; and 3) how transmission expansion impacts power system costs. We explore each of these questions separately for New England and New York.

To address these questions, we use capacity expansion and dispatch modeling to simulate the planning and operation of a power system encompassing New England, New York, and Quebec. We model this power system in 2050 using projections for future demand, as well as costs and operational characteristics for electricity technologies. The power system is required to meet a range of decarbonization targets, reflecting CO_2 emission reductions between 80% and 100% relative to 1990 levels. Our model computes the cost-optimal mix of electricity technologies in 2050 by selecting among existing power plants that are expected to be operational in 2050 as well as possible new plants. Our model also estimates the least-cost operation of the power system needed to satisfy electricity demand for each of the 8,760 hours of the year. This includes choosing which type of power plant to turn on when, how to charge and discharge energy storage technologies, how to operate reservoir hydropower, and how electricity is to be traded between New England, New York, and Quebec. This work results in three main findings.

First, the optimal use of U.S.-Canadian transmission lines will change drastically as Northeastern states decarbonize their power systems. Today transmission capacity is used to deliver energy south, from Quebec to the Northeast (see the blue line in the figure below based on 2018 data). The role of Quebec hydro in Northeastern power systems is therefore as a generation resource. However, our results suggest that, in a future low-carbon grid, it is economically optimal to use the transmission to send energy in both directions (illustrated by the brown line in the figure below). In periods of renewable scarcity in the Northeast, Quebec exports energy (drawing down reservoir levels). In periods of relatively high renewable output in the Northeast, Quebec imports energy (leaving its reservoirs to recharge). This allows power system costs across New England and Quebec to be 5-6% lower than if we limited transmission flows to be north-to-south only. Two-way trading helps balance renewable intermittency at multiple time scales ranging from daily to seasonal. These results suggest that

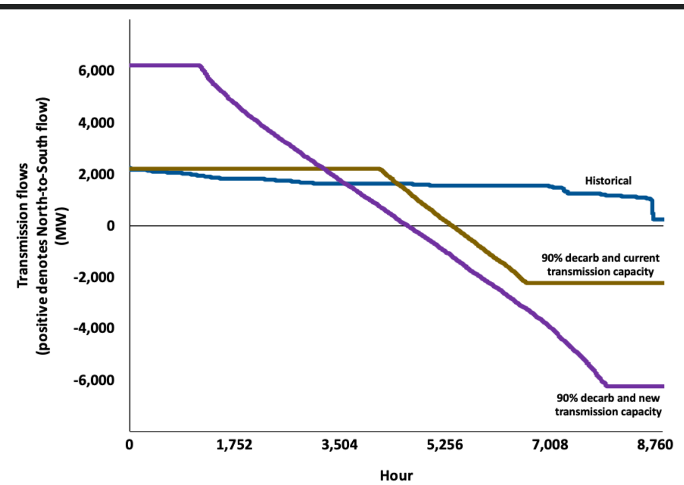
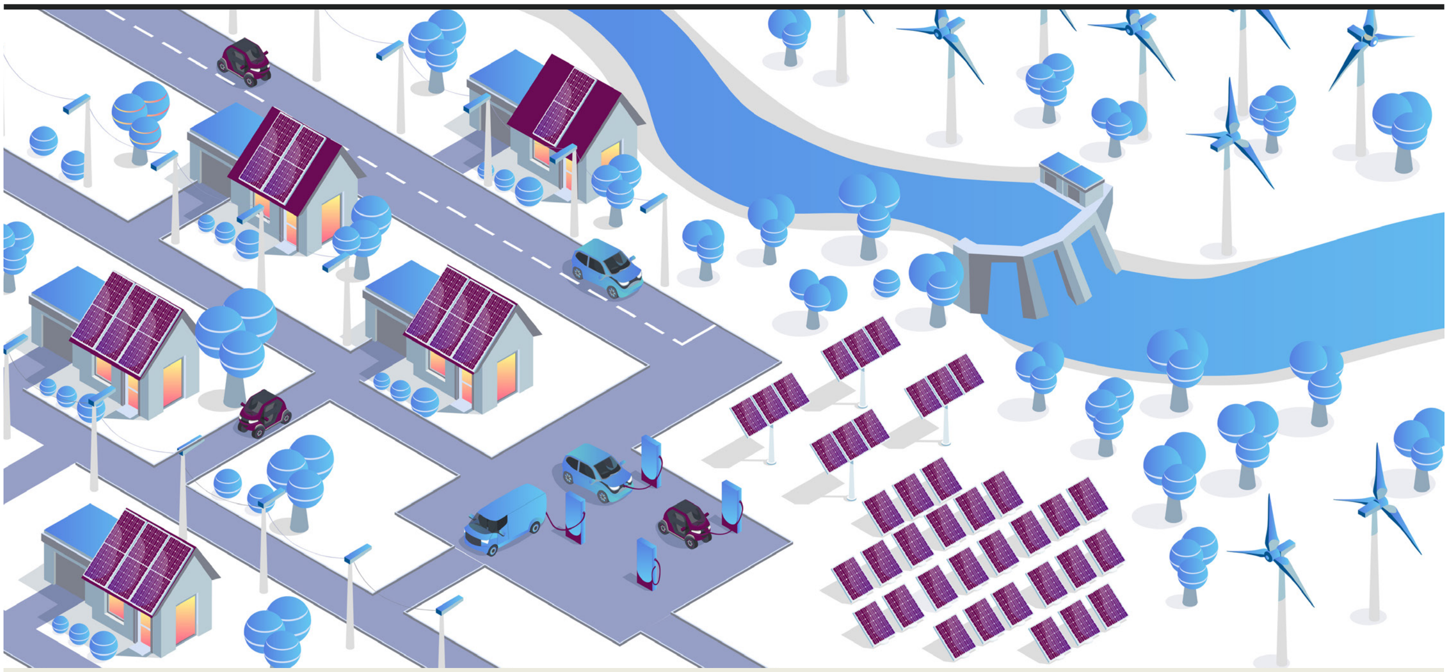


Figure: Changes in the optimal use of transmission infrastructure between New England and Quebec.



Meeting climate policy targets in the U.S. Northeast will likely require the nearly complete decarbonization of electricity generation. To that end, consideration is being given to expanding imports of hydropower from neighboring Quebec, Canada. We use a capacity expansion and dispatch optimization model to analyze the role Canadian hydro might play, and the economic trade-offs involved.

the optimal utilization of Quebec's hydro capacity in a low-carbon future is as a virtual energy storage resource for the Northeast, rather than as a generation resource.

Second, expanding transmission enables Quebec hydro to play a greater balancing role in future low-carbon power systems in the Northeast. We find that new transmission between Northeastern states and Quebec increases both imports from and exports to Quebec (shown by the purple line in the figure below for transmission expansion of 4 GW), allowing trading to further complement intermittent renewables. If we employ the analogy of Quebec's reservoirs as a battery for Northeastern power systems, more transmission to Quebec effectively increases the rate at which this battery can be charged and discharged. The additional balancing provided by new transmission would allow New England to reduce its reliance on gas-powered plants, reducing CO_2 emissions.

The role of Quebec hydro as a storage resource suggests that building additional transmission is a complement to deploying clean energy in the Northeast, rather than a substitute. This is in contrast to current plans by Massachusetts to use new transmission to import energy that substitutes for output from retiring nuclear plants. In the near term, new transmission will likely result in more imports. However, we show that, in the longer term, cost effective decarbonization entails that states build wind and solar PV plants and utilize transmission with Quebec to manage their intermittency.

Third, state goals for zero-emission electricity will be achieved at a lower cost if transmission with Quebec is expanded according to our results. We find that new transmission delivers net electricity cost savings (after accounting for the cost of new power lines) for decarbonization levels beyond 90%. For New England, we estimate that 4 GW of additional transmission reduces power system costs across New England and Quebec by \$3/MWh (13%) in a 99% decarbonized power system and by \$7/MWh (24%) in a 100% decarbonized power system in our central Base Case. For New York, we estimated savings across New York and Quebec of \$3/MWh (12%) and \$8/MWh (23%) respectively.

The magnitude of cost savings depend on additional assumptions such as whether states pursue a renewable-only approach to decarbonization, or whether states electrify other energy sectors such as transportation and heating. The full range of estimated cost savings from building 4 GW of additional New England-Quebec transmission is 11-26% for 99% decarbonization and 17-28% for 100% decarbonization.

[1] Emil Dimanchev, Joshua Hodge, and John Parsons (2020), "Two-Way Trade in Green Electrons: Deep Decarbonization of the Northeastern U.S. and the Role of Canadian Hydropower", *CEEPR WP-2020-003*, MIT, February 2020.

Emil Dimanchev

Joshua Hodge

John Parsons

Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage

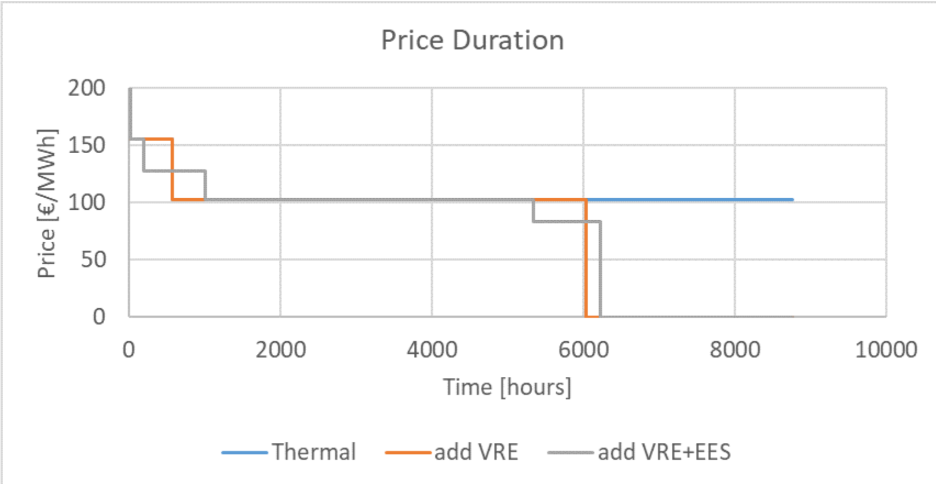
by: Magnus Korpås and Audun Botterud

This Working Paper investigates how variable renewable energy and energy storage impacts the formation of prices and optimal investments in electricity markets. The researchers use an analytical approach to derive the system-optimal conditions for installed capacity of all generators and storage devices. They show how all technologies recover their costs and maximize their profits in the system optimum, for an ideal short-term electricity market based on marginal cost and scarcity pricing without technology-specific support schemes. The researchers verify the analytical findings through a numerical example, which shows that the analytical approach gives identical results to a standard capacity expansion model.

Variable Renewable Energy (VRE) technologies are now deployed at an accelerated phase in electricity markets all over the world. Up to now, investments in these resources have been driven, to a large extent, by different subsidy schemes. However, in the last few years, the cost for field-ready VRE installations has declined so fast that in more and more areas, onshore wind and utility-scale solar have become competitive with conventional generation without any form of subsidy. In a future where VRE is the cheapest technology, calculated in terms of lifetime costs of kWh delivered, current electricity markets are challenged if no changes to their design take place. First and foremost, this is due to the well-known merit-order effect which expresses that conventional generators with higher marginal costs are dispatched less and potentially pushed out of the market as more low or zero marginal cost VRE enters the system and reduce the average short-term price in the electricity market. Moreover, the merit-order effect will also impact the deployment of VRE as long as they receive no subsidies and must rely on short-term electricity prices in the electricity market to cover their expenses.

In this research[1], we derive simple but generally valid cost recovery conditions for VRE and thermal generators in energy-only markets with scarcity pricing. Under a set of assumptions, we show that all generators, including VRE, recover their costs by traditional marginal cost pricing and that this results in an optimal generation capacity portfolio for the system. This implies that the merit-order effect of VRE may not be a problem for efficient development and operation of the power market as such, but it will have an impact on the amount of thermal generation capacity that is needed in the system. We further investigate the implications of introducing energy storage systems (ESS) in the market since in particular batteries have experienced tremendous cost reductions in the last years and are expected to be cost-competitive for different grid applications in the near future.

We take an analytical approach to study market equilibrium in competitive low-carbon electricity markets. We first derive analytical expressions for the optimality conditions for thermal generators, VRE and EES where the objective is to minimize the total cost of



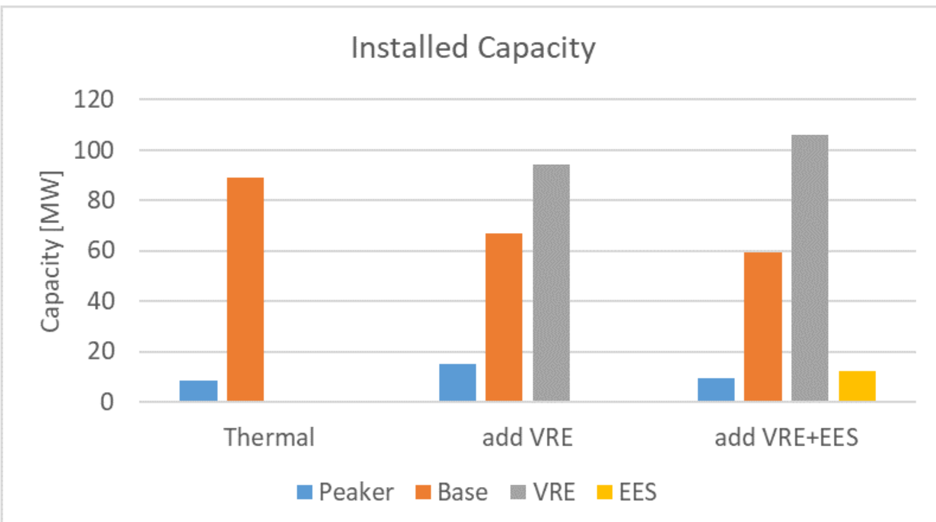


Figure: Example of price segments and optimal plant capacities derived from the analytical model.

Optimal investment in VRE gives many hours with zero price, and pushes thermal baseload capacity out of the market. Adding competitive EES creates new price segments based on the value of stored energy, and therefore triggers more VRE capacity in optimum. All technologies recover their costs in all three cases, with average costs of 115 €/MWh (Thermal), 81.6 €/MWh (add VRE), and 81.4 €/MWh (add VRE+EES).

meeting a hourly demands over a year. We then show how profit maximization of each generation and storage resource in a market based on marginal cost pricing and administrative scarcity pricing can give the same results as the optimal investment portfolio under system cost minimization. This result also applies to cases where surplus VRE gives periods with zero prices, and cases where EES sets the price either based on the marginal cost of charging or the marginal value of discharge, depending on the instantaneous power balance.

Our analytical results show that when EES is used for charging excess VRE that otherwise would have been curtailed, it triggers more VRE capacity in the long run. This is because the EES creates a new price segment based on the marginal value of storage, where the VRE gains additional profits. This result has important implications for the electricity market: 1) EES pushes more thermal capacity out of the market, both because of its balancing ability and because it triggers more investments in VRE, 2) EES leads to lower total amounts of curtailed VRE in equilibrium, although it triggers more VRE investments.

We verify the analytical findings through a numerical example, which shows that the analytic model gives identical results to a standard capacity expansion model with sequential operation of the generation and ESS units. The numerical example is based on data and scenarios for the European power system in 2050. Our case study results indicate that EES can trigger substantial new VRE investments, and thus have an important role in lowering the CO_2-emissions from power systems operated under a competitive market regime. The results also indicate that the impact of EES on average system costs are much less prominent than on CO_2-emissions, even with high carbon prices in line with low-carbon scenarios for Europe in 2050. How a marginal economic benefit will impact the willingness to invest in merchant EES in electricity markets is an important topic for further analyses.

[1] Magnus Korpås and Audun Botterud (2020), "Optimality Conditions and Cost Recovery in Electricity Markets with Variable Renewable Energy and Energy Storage", *CEEPR WP-2020-005*, MIT, March 2020.

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Zeroing in on Decarbonization

by: Leda Zimmerman, Department of Nuclear Science and Engineering

To avoid the most destructive consequences of climate change, the world's electric energy systems must stop producing carbon by 2050. It seems like an overwhelming technological, political, and economic challenge — but not to Nestor Sepulveda.

"My work has shown me that we do have the means to tackle the problem, and we can start now," he says. "I am optimistic."

Sepulveda's research, first as a master's student and now as a doctoral candidate in the MIT Department of Nuclear Science and Engineering (NSE), involves complex simulations that describe potential pathways to decarbonization. In work published last year in the journal Joule, Sepulveda and his co-authors made a powerful case for using a mix of renewable and "firm" electricity sources, such as nuclear energy, as the least costly, and most likely, route to a low- or no-carbon grid.

These insights, which flow from a unique computational framework blending optimization and data science, operations research, and policy methodologies, have attracted interest from The New York Times and The Economist, as well as from such notable players in the energy arena as Bill Gates. For Sepulveda, the attention could not come at a more vital moment.

"Right now, people are at extremes: on the one hand worrying that steps to address climate change might weaken the economy, and on the other advocating a Green New Deal to transform the economy that depends solely on solar, wind, and battery storage," he says. "I think my data-based work can help bridge the gap and enable people to find a middle point where they can have a conversation."

An optimization tool

The computational model Sepulveda is developing to generate this data, the centerpiece of his dissertation research, was sparked by classroom experiences at the start of his NSE master's degree.

"In courses like Nuclear Technology and Society [22.16], which covered the benefits and risks of nuclear energy, I saw that some people believed the solution for climate change was definitely nuclear, while others said it was wind or solar," he says. "I began wondering how to determine the value of different technologies."

Recognizing that "absolutes exist in people's minds, but not in reality," Sepulveda sought to develop a tool that might yield an optimal solution to the decarbonization question. His inaugural effort in modeling focused on weighing the advantages of utilizing advanced nuclear reactor designs against exclusive use of existing light-water reactor technology in the decarbonization effort.

"I showed that in spite of their increased costs, advanced reactors proved more valuable to achieving the low-carbon transition than conventional reactor technology alone," he says. This research formed the basis of Sepulveda's master's thesis in 2016, for a degree spanning NSE and the Technology and Policy Program. It also informed the MIT Energy Initiative's report, "The Future of Nuclear Energy in a Carbon-Constrained World."

The right stuff

Sepulveda comes to the climate challenge armed with a lifelong commitment to service, an appetite for problem-solving, and grit. Born in Santiago, he enlisted in the Chilean navy, completing his high school and college education at the national naval academy.

"Chile has natural disasters every year, and the defense forces are the ones that jump in to help people, which I found really attractive," he says. He opted for the most difficult academic specialty, electrical engineering, over combat and weaponry. Early in his career, the climate change issue struck him, he says, and for his senior project, he designed a ship powered by hydrogen fuel cells.

After he graduated, the Chilean navy rewarded his performance with major responsibilities in the fleet, including outfitting a $100 million amphibious ship intended for moving marines and for providing emergency relief services. But Sepulveda was anxious to focus fully on sustainable energy, and petitioned the navy to allow him to pursue a master's at MIT in 2014.

It was while conducting research for this degree that Sepulveda confronted a life-altering health crisis: a heart defect that led to open-heart surgery. "People told me to take time off and wait another year to finish my degree," he recalls. Instead, he decided to press on: "I was deep into ideas about decarbonization, which I found really fulfilling."

After graduating in 2016, he returned to naval life in Chile, but "couldn't stop thinking about the potential of informing energy policy around the world and making a long-lasting impact," he says. "Every day, looking in the mirror, I saw the big scar on my chest that reminded me to do something bigger with my life, or at least try."

Convinced that he could play a significant role in addressing the critical carbon problem if he continued his MIT education, Sepulveda successfully petitioned naval superiors to sanction his return to Cambridge, Massachusetts.

Simulating the energy transition

Since resuming studies here in 2018, Sepulveda has wasted little time. He is

Wielding complex algorithms, nuclear science and engineering doctoral candidate Nestor Sepulveda spins out scenarios for combating climate change. *Photo credit: Gretchen Ertl*

focused on refining his modeling tool to play out the potential impacts and costs of increasingly complex energy technology scenarios on achieving deep decarbonization. This has meant rapidly acquiring knowledge in fields such as economics, math, and law.

"The navy gave me discipline, and MIT gave me flexibility of mind — how to look at problems from different angles," he says.

With mentors and collaborators such as Associate Provost and Japan Steel Industry Professor Richard Lester and MIT Sloan School of Management professors Juan Pablo Vielma and Christopher Knittel, Sepulveda has been tweaking his models. His simulations, which can involve more than 1,000 scenarios, factor in existing and emerging technologies, uncertainties such as the possible emergence of fusion energy, and different regional constraints, to identify optimal investment strategies for low-carbon systems and to determine what pathways generate the most cost-effective solutions.

"The idea isn't to say we need this many solar farms or nuclear plants, but to look at the trends and value the future impact of technologies for climate change, so we can focus money on those with the highest impact, and generate policies that push harder on those," he says.

Sepulveda hopes his models won't just lead the way to decarbonization, but do so in a way that minimizes social costs. "I come from a developing nation, where there are other problems like health care and education, so my goal is to achieve a pathway that leaves resources to address these other issues."

As he refines his computations with the help of MIT's massive computing clusters, Sepulveda has been building a life in the United States. He has found a vibrant Chilean community at MIT and discovered local opportunities for venturing out on the water, such as summer sailing on the Charles.

After graduation, he plans to leverage his modeling tool for the public benefit, through direct interactions with policy makers (U.S. congressional staffers have already begun to reach out to him), and with businesses looking to bend their strategies toward a zero-carbon future.

It is a future that weighs even more heavily on him these days: Sepulveda is expecting his first child. "Right now, we're buying stuff for the baby, but my mind keeps going into algorithmic mode," he says. "I'm so immersed in decarbonization that I sometimes dream about it."

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Energy Economics Class Inspires Students to Pursue Clean Energy Careers

by: Kathryn Luu, MIT Energy Initiative

Jing Li, an assistant professor of applied economics, engages with her students during the Electricity Strategy Game debrief. *Photo credit: Kelley Travers*

Jing Li, an assistant professor of applied economics in the MIT Sloan School of Management, stands at the front of the classroom and encourages her undergraduate students to dig deeper. "Why was this a good idea?" she prompts. "How did people come up with these numbers?"

It's the second-to-last day of class, and the students in 15.0201/14.43 (Economics of Energy, Innovation, and Sustainability) are discussing their teams' results and the logic behind the decisions they made in the Electricity Strategy Game — a main feature of this elective.

"[With] so much magic," a student quips in response to Li's question, to a chorus of laughter.

The real magic, they all know, is in Li's approach to teaching: She holds her students accountable for their conclusions and throws them head-first into challenging problems to help them confidently engage with the complexities of energy economics. "She didn't baby us with tiny data sets. She gave us the real deal," says Wilbur Li, a senior computer science major and mechanical engineering minor (no relation to Jing Li). He initially took the class to round out his fall semester schedule, unsure if he would keep it due to a rigorous class load. However, just a couple of weeks into the semester, he was sold on the class.

"It's one of those classes at MIT that isn't really a requirement for anyone, but it's a class that only draws people who are genuinely interested in the subject area," he says. "That made for really good discussions. You could tell that people were interested beyond an academic sense."
15.0201/14.43, a part of MITEI's interdisciplinary Energy Studies minor, is a relatively new course. The class, which is also offered as graduate-level course 15.020, made its debut in the spring 2019 semester and was developed to expand the energy economics offerings at MIT. Part of the motivation for creating 15.0201/14.43 stemmed from the fact that Professor Christopher Knittel's course, 15.037/15.038 (Energy Economics and Policy), is consistently in high demand, without enough supply to accommodate interested students.

"Professor Knittel and I have positioned our two courses so that someone who wants to get a taste of energy economics could take either one and come away with a good mental map of the field, but also that someone who is very serious about a future career in energy would find it useful to take both," says Li.

Li's class focuses on innovation and employs environmental economics principles and business cases to explore the development and adoption of new technology, and business strategies related to sustainability.

"The class has been particularly attractive to students who are interested in the energy landscape, such as how energy markets impact and relate to local environmental issues and how to provide energy to parts of the globe that currently lack access to affordable or reliable energy," she says. "It has also appealed to students interested in applied microeconomics."

In addition to crunching large data sets and bringing in guest speakers, such as Paul Joskow, the Elizabeth and James Killian Professor of Economics Emeritus and chair of MIT's Department of Economics, a major element of the class — and a runaway favorite of many of the students — is the Electricity Strategy Game. The game was created by professors Severin Borenstein and James Bushnell for the University of California at Berkeley's Haas School of Business.

The game is designed to replicate the world of deregulated wholesale electricity markets. Players are divided into firms and utilize electricity generation portfolios, based on actual portfolios of the largest generation firms in the California market, to compete in a sequence of daily electricity spot markets, in which commodities are traded for immediate delivery. Each portfolio contains differing generation technologies (thermal, nuclear, and hydro), with varying operating costs. Spot market conditions vary from hour to hour and day to day. Players must develop strategies to deploy their assets over a sequence of spot markets while accounting for the cost structure of their portfolio, varying levels of hourly electricity demand, and strategies of other players. The game is conducted in six rounds, with the second half of the game taking into account carbon permits. Winners are determined by the financial performance of their firm and an evaluation of the logic of the firm's actions, which the teams describe in a series of memos to Li.

"I loved the Electricity Strategy Game! It was really fun to have to figure out how to predict demand and then how to price supply accordingly," says Anupama Phatak, a junior mechanical engineering major and economics minor. "The bid for portfolios was also a really cool process. I put a lot of time and effort into understanding the game and developing a strategy, so it made the process all the more rewarding when my team won."

Wilbur Li echoed Phatak's enthusiasm. "My favorite part of the game was definitely the auction — it was the most exciting part," he says. "Every single group did research on their own to figure out what sort of bidding prices they wanted for each piece of property [power plants] — and when we showed up, every single group had wildly different final prices for what we bid on the plants."

For Isaac Perper, a senior mechanical engineering and computer science double major and economics minor, the value of the game was in getting a glimpse of how energy portfolios would play out in real-life auctions. "We all had different portfolios, so I think that was the most interesting part. We got to see differences between coal, hydro, and gas plants and the different price points at which they are profitable. I think the auction mirrored what you would expect in a real market," he says.

Many of the students who took 14.43 (Economics of Energy, Innovation, and Sustainability) are making it their mission to apply the lessons learned from the class to their career goals. The class helped inspire Wilbur Li to pursue a career in cleantech product development, such as working on smart meters or more efficient transportation for wind turbine blades.

"A class like 14.43 definitely helps with understanding how the products that are being worked on can be scaled in terms of figuring out which players in the economy would want to pick up and utilize a product," he says. "It has given me a deeper understanding of how technology scales on a market level, as well as how to understand and account for the target impact of those technologies."

Phatak says that the class has made her more conscious of the adverse environmental consequences of products such as palm oil. "I now understand that even the smallest ingredient in our everyday products can have negative impacts around the world that I might not even see," she says. Because of the topics covered in Li's course, Phatak is now actively pursuing internships in sustainability.

Perper shared that the class opened his eyes to a lot of inefficiencies that exist in the energy market today. Indeed, he says that his life's goal is to help to solve some of those inefficiencies. "Going into this class, I had kind of thought that we have our different electricity producers and some pollute more than others, but in terms of the actual market structure and how electricity is distributed, paid for, and expanded into developing areas, all of those things were more complicated and inefficient than I had expected," he says. When he returns to MIT in the fall to pursue his master's degree in computer science and electrical engineering, Perper will be thinking more about the bigger questions in terms of energy policy and technology.

Li says she hopes that students come away from 14.43 with "more questions than answers," as well as a honed sense of which questions are worth spending time to answer. She also aims for her students to leave with the knowledge that sustainability and energy touch every organization in some way.

"Whatever kind of organization you are a part of and the role you take in that organization — investor, manager, employee, customer, voter — you can contribute to the sustainability goals of your organization with your ideas, voice, and actions," she says.

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Designing Effective Auctions for Renewable Energy Support

by: David Matthäus

This Working Paper assesses the effect of prevalent auction design elements on effectiveness, using a unique dataset with results of auctions for renewable energy support from 1990 to 2017.

Current strategies to mitigate climate change rely on policy instruments providing incentives for investment in clean energies. Over 90 countries, among them some of the largest economies, e.g., Brazil, California, China, Germany, or India, have shifted support instruments towards auctions for renewable energy support. The main challenge in auction design is the trade-off between cost-efficiency and post-auction realization (i.e., effectiveness). My empirical analysis provides empirical evidence for and against prevailing theoretical findings on auction design.

The climate crisis urges policymakers to accelerate decarbonization. A first step in climate strategies is to decarbonize power markets, as two-thirds of global greenhouse gas emissions originate from the energy sector. Emissions reduction typically requires a shift of production from fossil fuels towards nuclear and renewable generation.

Although the cost of renewable energy production has dropped drastically in the last decades, new capacities still depend on subsidies—worldwide transfer payments for renewables amounted to US$ 170 billion in 2018.

Governments have used different support schemes, such as feed-in-tariffs, feed-in premiums, and tax reductions, to foster investment in renewable technologies. For many years, regulators have mainly determined subsidy rates based on cost estimates. Recently, governments started to allocate subsidies with auctions for renewable energy capacity. In renewable auctions, governments auction off contracts that guarantee subsidized remuneration for producers of renewable energies. Regulators try thereby to exploit competition in order to discover relevant needs for subsidies.

Price discovery and competition have dropped auction prices far below expectations. But amid enthusiasm about cost-efficiency in renewable auctions, authorities started to realize that winning bidders might have bid below cost, consequently not realizing their projects. In view of the climate crisis and the state of renewable generation in many countries, effectiveness (i.e., how much capacity is deployed) is just as important as efficiency (i.e., at what subsidy rate it is

David Matthäus

deployed). Obviously, the choice of the policy instrument is as important as its design. In a recent strand of literature, researchers have discussed auction design and its impact on the trade-off between efficiency and effectiveness.

In this CEEPR Working Paper[1], I empirically analyze the effect of prevalent auction design elements on the effectiveness of renewable auctions. I use a unique hand-collected dataset comprising auction results from 1990 until 2017. Particularly, I find that pre-qualifications and penalties can act as powerful enforcement mechanisms to drive effectiveness. This is intuitive and confirms results from recent literature. However, I do not find evidence for effects of technological banding or pricing rule on effectiveness. This sheds new light on findings from auction models and case studies, which argue in favor of specific configurations of technological banding or pricing rule to steer effectiveness

The study is the first to present a global dataset of renewable auction results over a multi-year period. Therefore, it is also the first to provide policymakers with empirical evidence for and against prevailing theoretical findings and anecdotal evidence on the design of renewable auctions.

My study provides policy makers with two major implications on the design for renewable auctions. First, regulators should include pre-qualifications or penalties if they aim to boost realization rates. Both reduce the real-option value inherent in non-realization drastically and might impede highly aggressive market entry strategies, attracting more serious bids through both channels. Second, policymakers can use other design criteria to adapt the auction design to the regulatory scheme, social norms, or non-monetary goals without deteriorating effectiveness. Regulators can, for example, indiscriminately choose between technological banding or technology-neutral auctions. The former can help to ensure a reliable mix of generation technologies and foster small scale, immature technologies. The latter has the potential to maximize efficiency.

[1] David Matthäus (2020), "Designing Effective Auctions for Renewable Energy Support", *CEEPR WP-2020-002*, MIT, February 2020.

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Snapshots from the Fall 2019 CEEPR Workshop on November 21, 2019:

Left: **Patrick Landais**, High Commissioner at the French Alternative Energies and Atomic Energy Commission (CEA) and advisor to French President Macron, with CEEPR Director Christopher Knittel. Dr. Landais gave the dinner keynote address.

Right: **Adnan Z. Amin**, outgoing Director General of the International Renewable Energy Agency (IRENA), gave a talk about global energy transformation in the workshop's opening session on "Envisioning the Future of Energy."