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MIT CEEPR Newsletter

MIT Center for Energy and Environmental Policy Research

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Notwithstanding political setbacks in some regions, the period since our last newsletter has underscored the growing earnestness of efforts around the world to decarbonize the energy system. International climate cooperation is part of that process, and two CEEPR research assistants report their impressions from attending the latest annual climate summit of the United Nations in this newsletter. But while the framework of rules and procedures negotiated by over 190 nations is important in setting overall parameters and an aspirational direction, the real action – as well as the attendant impacts – are mostly playing out at the national and local level. A number of recent CEEPR working papers featured in this newsletter address different aspects of the decarbonization challenge, looking at the costs and tradeoffs of different technology and policy solutions, and charting ways to continue delivering safe, affordable, and reliable energy services in a rapidly evolving policy context. To list some highlights from recent CEEPR research: Two working papers highlight , respectively, how extending the life of existing nuclear energy capacity and relying on flexible policy incentives can dramatically limit the cost of achieving a fully decarbonized electricity system. Transitioning to variable renewable energy sources at scale strains the ability of existing electricity market designs to meet their short- and long-run functions, and another recent working paper draws on theory and empirical data to identify the emerging challenges and suggest potential market reforms. Expanding seasonal storage capacity will be critical in such a system, and yet another working paper shows how power-to-gas applications can potentially satisfy this need at affordable cost. Other working papers look at the carbon footprint of bitcoin, the transportation preferences of millennials, and the distributional effects of electricity tariff design in evolving electricity markets. As always, these kinds of topics will continue to feature in CEEPR research on the major policy and economic challenges facing the energy sector, and we look forward to keeping you informed in future newsletters.

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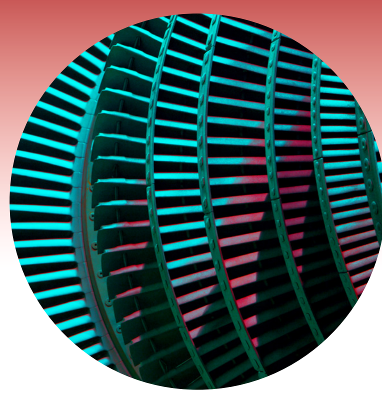

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The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Power Plants

by: Anthony Fratto Oyler and John E. Parsons

Nuclear power provides more than 20 percent of Spain's electricity. As each of the seven plants approaches its 40 year design life, a decision must be made whether to invest in a life extension. This decision must be made in light of Spain's goal of reducing GHG emissions. This research shows that life extensions are the least-cost alternative for further reducing GHG emissions.

The transformation of Spain's generation assets is a fundamental question facing industry and government leaders. Earlier this year the Spanish government released a "Commission of Experts" report analyzing a variety of installed capacity scenarios for 2030. Scenarios with and without nuclear life extensions were explored. More recently, the Prime Minister announced draft climate and energy legislation targeting 100 percent renewables by 2050 and an end to subsidies for fossil fuel generating plants. However, the announcement was silent on the role of the existing nuclear assets in the interim.

A new Working Paper[1] looks at the total system cost of supplying Spain's electricity needs in 2030 with and without nuclear life extensions. If the nuclear plants are retired, then Spain must select a replacement for the lost generation. In order to maintain the same level of GHG emissions, we examine the cost of replacement with additional solar PV, or with wind, or a combination of the two. Alternatively, it could include some incremental use of fossil-fueled generation such as NGCC units, which would produce incremental GHG emissions.

To calculate system cost, we model the least-cost dispatch to meet a 2030 scenario for hourly load given scenarios for hydro, solar and wind resources. Given the scale of solar PV and wind penetration anticipated by 2030, curtailment is likely to have a significant impact on system costs. The dispatch model optimizes the use of Spain's hydro reservoirs, pumped hydro, and future battery capacity in order to minimize curtailment of renewable generation. Our calculation of system cost captures the impact of curtailments after minimization using storage.

We utilized our dispatch model to determine portfolios of capacity that substitute different combinations of solar PV and wind capacity as a replacement for the nuclear life extensions. These substitute portfolios serve the same load and achieve the same level of total GHG emissions from generation, but have different costs.

Ultimately we show that investing in nuclear plant life extensions is the least-cost alternative for further reducing GHG emissions. Social cost savings on the extension of all seven plants are at least €8 billion relative to the next least-cost option.

Anthony Fratto Oyler

John Parsons

The research also examines the value of nuclear life extensions in comparison to natural gas-fired combined-cycle plants. We first do this without regard to any cost attributed to GHG emissions, and we again find nuclear plant life extensions are the most cost efficient option. Forecasted natural gas price would have to fall below €17/MWh before the avoided cost of combined-cycle generation fell below the incremental system cost of the nuclear generation and capacity. In addition, preserving the seven nuclear plants reduces GHG emissions by more than 16 million tons (CO_2eq).

As this working paper emphasizes, nuclear life extensions are an element of the least-cost path to decarbonization. An earlier CEEPR working paper, now published, had shown the same result for the U.S.—see Haratyk (2017). The importance of preserving the existing nuclear fleet is one of the conclusions of the recently released MIT study on the Future of Nuclear Energy in a Carbon-Constrained World (2018). Other colleagues here at MIT have also demonstrated the value of nuclear to decarbonization using a more complex and robust modeling framework—see Sepulveda et al. (2018).

[1] Anthony Fratto Oyler and John E. Parsons (2018), "The Climate and Economic Rationale for Investment in Life Cycle Extenstion of Spanish Nuclear Power Plants" *CEEPR WP-2018-016*, MIT, November 2018.

Governing Cooperative Approaches under the Paris Agreement

by: Michael A. Mehling

Article 6 of the Paris Agreement allows Parties to engage in voluntary cooperation as they implement the climate pledges contained in their nationally determined contributions (NDCs). One channel of cooperation – set out in Article 6.2 – involves the use of internationally transferred mitigation outcomes (ITMOs) towards achievement of NDCs. Although the provision omits explicit mention of markets, it harbors the promise of market-based approaches to lower the cost of achieving environmental policy objectives. Such cost reductions, in turn, offer an opportunity for greater climate ambition with given resources. By helping to achieve initial NDCs at lower cost, they can soften political resistance against more ambitious future pledges, and unlock resources that can be diverted towards additional abatement efforts.

Lower costs do not automatically translate into greater ambition, however. A growing body of research has examined the potential of cooperative approaches to weaken aggregate efforts if Parties transfer ITMOs with questionable integrity or are discouraged from progressively strengthening their NDCs over time.

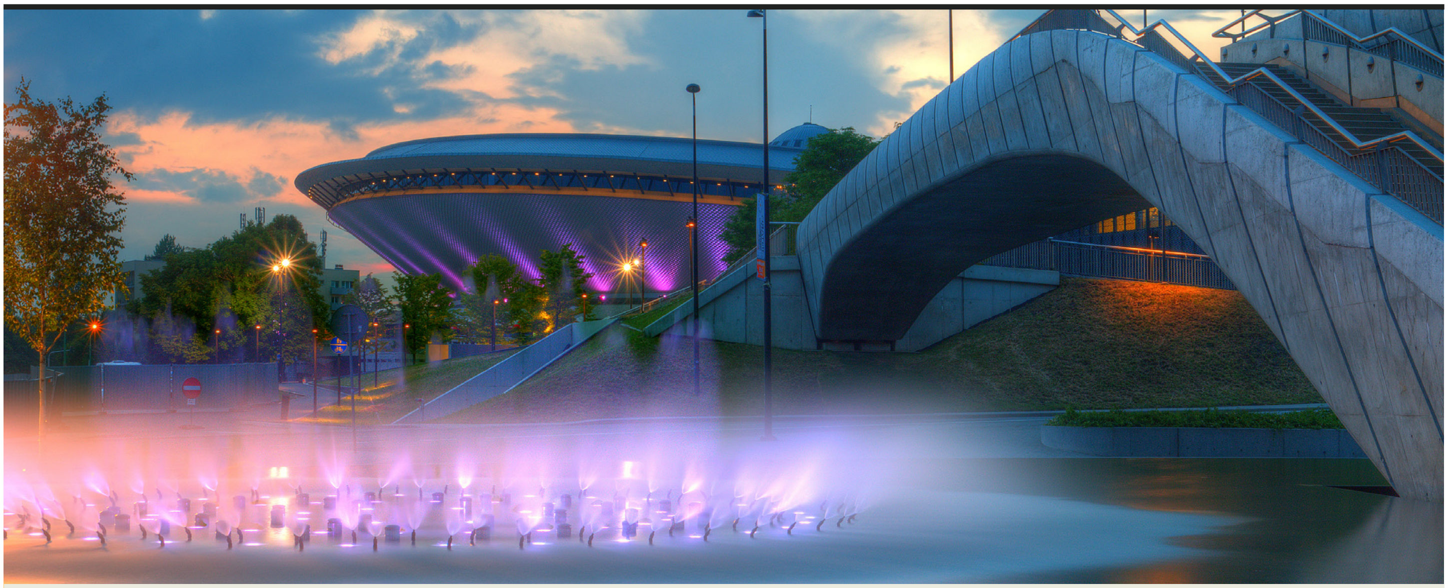
Unlike the Kyoto Protocol, the Paris Agreement requires all Parties to the Agreement to participate in mitigation, altering the incentive structure for countries as they consider their future climate pledges. As Parties negotiate guidance for the implementation of cooperative approaches under Article 6.2 of the Paris Agreement, they are therefore considering governance options to secure environmental integrity and address concerns about aggregate ambition.

How to address such concerns has consistently proven to be one of the most contentious items in the negotiations on Article 6.2. Parties and other stakeholders have voiced widely divergent views on the need to include ambition and environmental integrity in governance of ITMO transfers, and successive textual proposals have featured long lists of options for potential inclusion in Article 6.2 guidance. Relevant options proposed by Parties and other actors fall along a continuum ranging from very prescriptive, with more centralized oversight, to very flexible, with considerable delegation to Parties engaged in an ITMO transfer.

A new Working Paper[1] maps stakeholder views and evaluates relevant options contained in the latest proposals for how guidance can balance necessary safeguards for climate ambition with flexibility to contain transaction costs and facilitate greater participation. In doing so, it draws on an analytical framework that incorporates economic theory, deliberative jurisprudence, practical case studies, and treaty interpretation. It concludes that neither over- nor under-regulation will lead to efficient outcomes, nor indeed be conducive to greater ambition.

Understood in light of the Paris Agreement's negotiating history – and its object and purpose – the wording of Article 6.2 allows Parties to consider ambition in operational guidance, but does not dictate a specific mitigation threshold or other material outcome. Parties thus retain significant discretion in how they choose to balance prescriptiveness and flexibility in guidance on Article 6.2.

A survey of the literature and case studies on market-based instruments lends support to specific recommendations for operational guidance on Article 6.2. Both theory and



Parties to the Paris Agreement can engage in voluntary cooperation and use internationally transferred mitigation outcomes towards their national climate pledges. As Parties negotiate guidance on the implementation of such cooperative approaches, they have to balance environmental safeguards with flexibility to contain transaction costs and increase participation.

experience highlight the importance of a governance framework that ensures transparency in cooperative approaches, and guarantees accurate accounting for ITMO transfers. Failure to include these essential features would threaten to repeat painful episodes in the history of carbon markets, during which these markets have incurred considerable reputational damage. Distinguishing such requisite elements from those that are needlessly restrictive is one of the central challenges facing policy makers in the operationalization of Article 6.2.

For that reason, the governance framework should avoid restrictions, such as a requirement for centralized approval of individual ITMOs, that incur high transaction costs, investor risk, and uncertain benefits. Experience with the Clean Development Mechanism (CDM), in particular, has shown how a lengthy and prescriptive approval process involving complex additionality tests can add transaction costs without guaranteeing desired environmental outcomes. This track record cautions against imposing quality criteria to regulate environmental integrity risks under Article 6.2; such criteria tend to suffer from their own regulatory failures, such as information asymmetries, capacity constraints, and regulatory capture.

Experience has also shown that mature and liquid markets rely on diversity of participation, arguing against an outright exclusion of non-Party stakeholder engagement in cooperative approaches. Other restrictions, such as quantity limits on transfers, can be effective in addressing environmental risks, but also curtail the economic benefits of cooperative approaches, and should therefore be used prudently, if at all. Empirical data suggest that some concerns may be misplaced, such as fears of a supposed perverse incentive under Article 6.2 to weaken future mitigation pledges. Research on the CDM has shown that the ability to engage in carbon trading has not meaningfully affected domestic climate policy choices, which are instead driven by other political priorities and institutional power structures. Conversely, uniform metrics for ITMOs can facilitate linkage by increasing fungibility, and should be considered.

Invariably, these options will require political choices among competing priorities, inviting tradeoffs and compromises that accommodate contingent preferences. Process may therefore acquire as much weight as substantive considerations in the elaboration of Article 6.2 guidance. Deliberations preceding such a compromise should be fair, inclusive, and transparent, and take place in appropriate forums. As such, technical guidance on Article 6.2 should not seek to supplant or correct political decisions on ambition and flexibility reached under the Paris Agreement.

Any viable compromise will likely reflect the delicate equilibrium struck in the Paris Agreement between pursuit of progressively greater climate ambition and a decentralized architecture that favors national determination by sovereign Parties. Whatever its final shape, the governance framework for Article 6.2 should avoid being too weak or too restrictive, as either outcome would diminish the very benefits that prompted introduction of compliance flexibility in the first place.

[1] Michael A. Mehling (2018) "Governing Cooperative Approaches under the Paris Agreement", *CEEPR WP-2018-017*, MIT, December 2018.

Michael Mehling

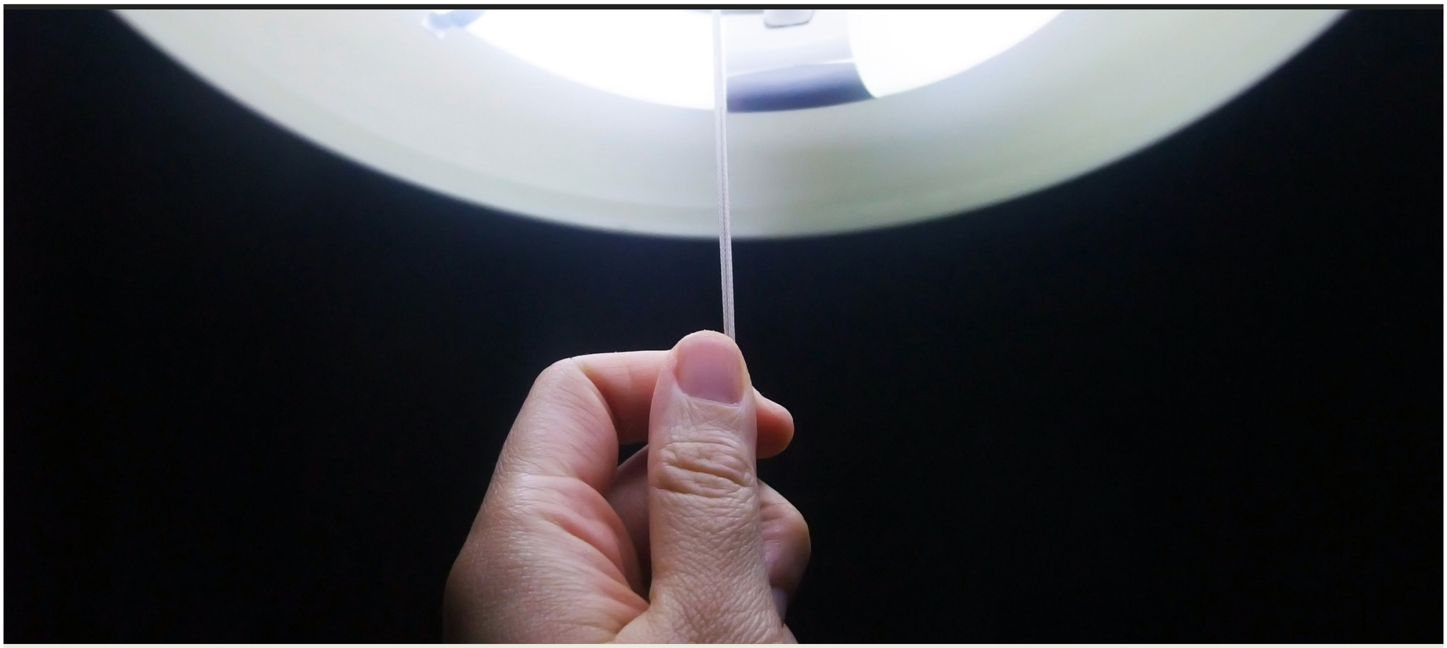
The Efficiency and Distributional Effects of Alternative Residential Electricity Rate Designs

by: Scott P. Burger, Christopher R. Knittel, Ignacio J. Pérez-Arriaga, Ian Schneider, and Frederik vom Scheidt

Residential electricity tariffs typically distort — and thus do not allow consumers to respond to — the marginal cost of energy consumption. Rates are typically constant across time and location, despite the fact that short-run marginal costs can vary dramatically. As of the end of 2016, less than one quarter of one percent of residential customers in the U.S. faced electricity prices that reflected the real-time marginal cost of energy production. Furthermore, the bulk of system costs are recovered through volumetric charges — that is, charges per-unit of energy consumed — despite the fact that a substantial fraction of these costs are fixed in the short term. More economically efficient rate designs — enabled in part by the proliferation of smart metering infrastructure — could substantially improve market efficiency. However, the potential distributional impacts across customer types and incomes of transitioning from today's tariffs to more efficient designs have historically impeded progress.

A new Working Paper[1] examines the distributional and economical efficiency implications of residential electricity tariffs. Using interval metering data — measuring electricity consumption every 30 minutes — for more than 100,000 customers in the Chicago, Illinois area, we assess the economic benefits of efficient tariffs relative to alternative tariff designs. We then use census data to understand the demographics — i.e. income levels — of the customers in our sample. A regulator might seek to shift from the current tariff structure to a two-part tariff, because the two-part tariff has higher economic efficiency. If this two-part tariff has an equal fixed charge for all customers, we demonstrate that this shift is regressive; the change in monthly bills is larger, as a share of income, for lower income consumers. However, we show that a two-part tariff that bases the fixed charge on income or other measures that correlate strongly with income can improve distributional outcomes without substantially sacrificing economic efficiency.

The issues addressed in this paper are likely to increase in importance as distributed energy resources (DERs), such as rooftop solar, become more prevalent. When located and operated appropriately, DERs can deliver substantial benefits. However, if investment and operation decisions are not aligned with system objectives, DERs can substantially increase system costs. The lack of spatial variation in retail prices distorts where DERs are placed within a network and how they are operated. In addition, remunerating transmission and distribution costs through volumetric charges over-incentivizes solar adoption by driving a wedge between the private and social



Electricity tariffs typically charge residential users a volumetric rate that covers the bulk of energy, transmission, and distribution costs. The resulting prices, charged per unit of electricity consumed, do not reflect marginal costs and vary little across time and space. The emergence of distributed energy resources - such as solar photovoltaics and energy storage - has sparked interest among regulators and utilities in reforming electricity tariffs to enable more efficient utilization of these resources. The economic pressure to redesign electricity rates is countered by concerns of how more efficient rate structures might impact different socioeconomic groups.

returns to solar adoption. Adopters of some DERs, for example, rooftop solar, are able to reduce, or eliminate, their payments for transmission, distribution, and other regulated costs, despite the fact that these DER owners remain connected to and continue to use the network. Given utility revenue sufficiency constraints, this leads to increases in the transmission and distribution volumetric charges faced by other customers.

This can also have large distributional consequences. Because solar adoption tends to be positively correlated with income, high-income consumers are effectively passing on their contributions to transmission and distribution costs to lower-income consumers. Finally, widespread adoption of renewables can lead to larger diurnal price swings, exacerbating the difference between time invariant rates and the social marginal cost of consumption.

These converging challenges have led many regulators, policy makers, consumer advocates, and utilities to call for improved tariff designs. For example, the New York Department of Public Service recently called for "more precise price signals ... that will, over time, convey increasingly granular system value." New York is not an anomaly. In 2017, regulators in 45 of 50 U.S. states and the District of Columbia opened dockets related to tariff design or made changes to tariff design. Similarly, in November 2016, the European Commission issued a sweeping set of rulings, with tariff design as a centerpiece.

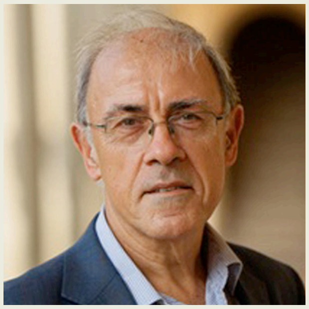
The economic pressure to redesign electricity rates is countered in part by concerns among policy makers and regulators of how more efficient rate structures might impact different socio-economic groups in terms of both average bills and bill volatility. For example, the Massachusetts Department of Public Utilities, the New York Department of Public Service, and the California Public Utilities Commission all list concerns about the distributional impacts of rates in their principles for rate design. Distributional concerns are not unfounded. For example, the U.S. Energy Information Administration recently found that 31% of U.S. households struggled to pay the costs of meeting energy needs. In practice, regulatory decisions highlight these concerns: in the U.S. in the second quarter of 2018, state electricity regulators rejected over 80% of utility requests to increase fixed charges, frequently citing the potential impacts on low-income customers.

Our work leads us to a number of novel findings. First, we find that, holding the proportion of fixed and volumetric charges in the tariff constant, annual electricity expenditures tend to decrease for low-income customers from movements towards more time-varying rates. However, increases in customer fixed charges tend to increase expenditures for low-income customers who, on average, consume less electricity than their more affluent counterparts. The net effect of a rate design with real-time energy prices and uniform fixed charges for residual cost recovery is a near monotonic negative relationship between income and changes in expenditures. Second, in our sample, the economic distortions of recovering residual network and policy costs through volumetric tariffs likely outweigh the distortions that emerge from charging an energy price that does not reflect the underlying time- and location-varying cost of energy. Finally, we find that changes to fixed charge designs can preserve the efficiency gains of transitioning to efficient residual cost recovery while mitigating undesirable distributional impacts. We highlight three methods for designing fixed-charges for residual cost recovery — based on customer demand characteristics, income, or geography — that mitigate the regressiveness of fixed charges.

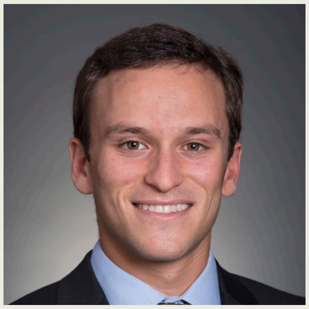
[1] Scott Burger, Christopher R. Knittel, Ignacio J. Pérez-Arriaga, Ian Schneider, and Frederik vom Scheidt (2019) "The Efficiency and Distributional Effects of Alternative Residential Electricity Rate Designs", *CEEPR WP-2019-002*, MIT, February 2019.

Scott P. Burger

Christopher R. Knittel



Ignacio Pérez-Arriaga



Ian Schneider

Frederik vom Scheidt

Imperative Sense of Urgency Reflected at COP24 Climate Negotiations

by: Sruthi Davuluri

In a 2°C scenario, 99% of coral reefs will be lost, with a concurrent loss of marine food webs, loss of fin fish and fisheries, and seagrass.

In December 2018, Sruthi Davuluri, a Research Assistant with MIT CEEPR, had the opportunity to attend the annual the annual summit of the Conference of Parties (COP) under the United Nations Framework Convention on Climate Change (UNFCCC), which convened in Katowice, Poland, along with 28,000 people including elected officials, policy makers, researchers, and scientists. In this contribution to our newsletter, she describes the context of the summit and some of its key proceedings.

"When you start a journey on foot but then realize that your destination is very far away, you wouldn't continue walking - you would jump on a bike. Similarly, we need to display the same sense of urgency." This is how a representative from Belgium aptly summarized the strong and urgent action required by all countries to address the global challenge of climate change.

COP24 followed soon after the publication of the Special Report on Global Warming of 1.5°, released by the Intergovernmental Panel on Climate Change (IPCC) in October 2018, based on a UNFCCC mandate to produce such a report issued during COP21 in Paris in 2015. The Special Report (SR15) clearly states that that Earth has already reached a 1° Celsius increase in average global surface temperatures above pre-industrial levels. One of the main takeaways claims that in the case that future emissions are limited to those pledged by each country in their Nationally Determined Contributions (NDCs), global surface temperatures will most likely surpass 1.5° by about 2030 and 2° by about 2050.

Although parts per million (ppm) of CO_2 in the atmosphere or inches of sea level rise are difficult to relate to, SR15 painted a dire picture about the impacts on different regions of the world under various 1.5° and 2° scenarios. For instance, once the 1.5° threshold is reached, between 128 and 143 million people who live in coastal areas will be exposed to sea level rise and more extreme storms, a figure that increases to 141–151 million people for 2°. With a change of precipitation, increased snowmelt, and rising sea levels, the impact on runoff and water systems will be severe across all continents, leading to natural disasters and severe droughts. Tropical regions, which include parts of

West Africa, Southeast Asia, and South America, are predicted to have more heatwaves, producing increased heat stress on both crop yields and livestock while reducing the biodiversity of rainforests.

Even if global average temperatures are stabilized at 1.5°, local average temperatures will actually be much higher in regions such a Sub-Saharan Africa, where temperature increases are projected to lead to higher stress on water supply and increase of climate-change hotspots, severely impacting agricultural production and water supply. Predicted outcomes are particularly dire for small island nations, which face high risks of coastal flooding until complete inundation, increased stress of fresh water supply, and a persistent heat stress affecting agriculture and human health. Tens of thousands of people are at risk of displacement with a 1.5° increase in global temperatures, which also would likely result in 70-90% of coral reefs being lost. In a 2°C scenario, 99% of coral reefs will be lost, with a concurrent loss of marine food webs, loss of fin fish and fisheries, and seagrass.

SR15 identifies pathways to limit and stabilize temperature increases to 1.5° or 2°, but both require serious and urgent action at a pace and scale without precedent in human history. They would require aggressive and adaptive policies, comprehensive economic transitions, and far-reaching changes in consumption behavior. Elements of this transition include increased electrification, decarbonization of the power sector, a drastic shift in future investments, sweeping changes in land use, and emission reductions across all sectors. Both temperature scenarios also require net zero CO_2 emissions worldwide by 2050, along with serious reduction of other greenhouse gas emissions.

The concept of a "carbon budget" for 1.5° and 2°, respectively, has been introduced to determine the amount of carbon emissions that will most likely lead to these temperature increases. The IPCC states that a carbon budget of 580 $GtCO_2$ would lead to a 50% probability of stabilizing temperature levels to 1.5 degrees. However, there are high levels of uncertainty with the various calculations of the carbon budget due to the assumptions underlying the assessment models referenced in the report, and the question of how to allocate said carbon budget is even more complex. Nevertheless, the concept of a carbon budget helps characterizes the limited flexibility with which we can move forward.

"It's not something we can solve during this conference alone, we need to see climate change mainstreamed into all agendas moving forward."
— Patricia Espinosa, Executive Secretary of UN Climate Change

The relevant climate science including the capacity and limitations of certain technologies, climate change models, and the aforementioned pathways forward must be communicated clearly to policy-makers so they can move forward appropriately. However, some of the language, presentation, and visuals used in the summary for policy-makers were not assembled in a very comprehensible way, which may have caused policy-makers to misconstrue some key points. Upon asking delegates, some of them confided in me that they understood that the 1.5° and 2° scenarios both present considerable dangers, and that there are ways to prevent them, but they failed to understand how.

Beyond the IPCC Report, the climate negotiations themselves led to large announcements and the passing of important agreements. One of the main purposes of COP24 was to formulate a rulebook, eventually known as the "Katowice Climate Package," which established guidelines on how different nations will reach the commitments made in Paris during COP21. The rulebook covers many areas including how to ensure transparency when accounting for each country's progress towards its NDC, the controversial topic of expecting developed countries to contribute to climate financing to support the mitigation and adaptation in developing countries, and establishing a procedure for how to conduct the "Global Stocktake" every five years to quantify collective progress. One of the sections that proved most difficult to resolve was Article 6, regarding the provisions for voluntary market mechanisms, the negotiations of which will be continued at COP25 in Chile. Other key outcomes of COP24 include the increased commitments by the World Bank and individual countries to the Green Climate Fund, and the end of the Talanoa Dialogue which resulted in the Talanoa Call For Action, asking all countries and stakeholders to respond with a much-needed sense of urgency.

While the international agreements themselves were a very significant outcome of the conference, I realized that the more substantial consequences were the international connections formed, the distribution of valuable research, and most importantly – the display of local efforts across the world, which encourages other to act in their local community despite the slow-moving pace of national governments.


Sruthi Davuluri

Impressions from COP24: 3Qs with Sruthi Davuluri

Sruthi Davuluri is currently pursuing a M.S. in the Technology and Policy Program at MIT, and is a Research Assistant working with Professor Christopher Knittel. Over the past two years, Sruthi has worked with solar startups, a demand response project, and research on how electric distribution systems may adapt to heightened DER penetration.

Did you find anything surprising or unexpected at COP24?

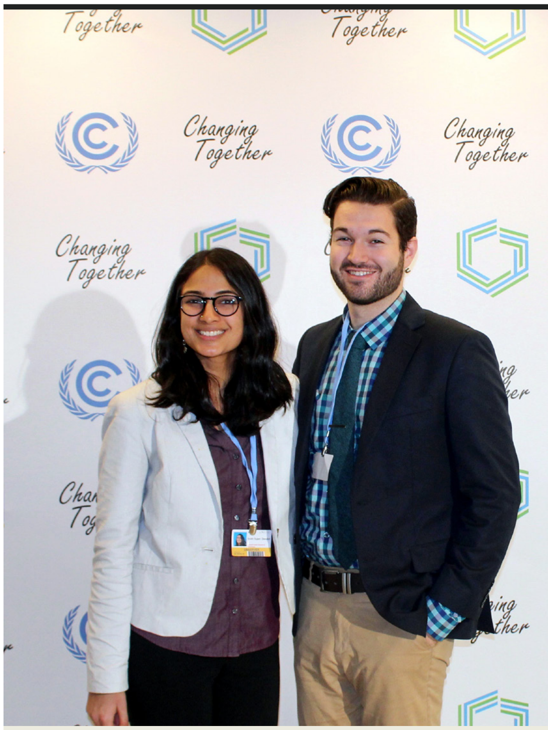
I was surprised that a lot of the rhetoric at COP24 revolved around the transition from ICE to electric vehicles (EVs). However, the claim that increased demand for EVs alone will cut emissions and improve air quality fails to recognize a few important factors.

The misnomer Zero Emission Vehicle (ZEV) has the danger of assuring consumers that their driving habits will not lead to carbon emissions. However, 80% of Poland's electricity currently comes from coal; therefore their EV initiatives could actually be doing more harm and releasing more emissions rather than creating a positive influence. Therefore, an informed consumer should think critically of where their energy is being supplied from before investing in an EV. The policymakers should critically consider alternatives including public transportation, ride-sharing, or bicycle options.

Furthermore, current lithium-ion battery technology requires valuable natural resources such as lithium and cobalt, which are primarily being mined in South America and the Democratic Republic of Congo (DRC) respectively. Therefore, policymakers must look at the full life cycle of these technologies, and assess the level of dependence we want on these minerals, before advocating for them so strongly and publicly. It is imperative to remain aware of the political situation in these natural-resource-rich countries and to assess how future partnerships could help or hurt the local populations.

Is there a particular focus that you think nations should work on improving before this year's COP?

The question of inequity is one of the most important and most sensitive topics of conversation at the international climate change conference. At one table, delegates from small island countries, which are at risk of disappearing underwater, are negotiating with large superpowers that depend upon fossil fuels to stimulate their economies. It would be helpful to focus more efforts on collaboration with neighbors, because climate change does not respect any borders drawn by humans, and will invariably hurt the marginalized communities and lower-income populations first. It is difficult to expect developing countries to view climate change mitigation in the same light as the developed countries that benefited from the industrial revolution and already used so much of the total carbon budget.



As they prepare to graduate from MIT this year and p
Anthony Fratto Oyler take time to give us some persona
CEEPR and their recent trip to Katowice as part of MIT's C

From what you've learned, how can we minimize our individual climate impacts?

There are many ways we could reduce our carbon footprint during the average day, such as a shift in our diet. Given the fact that agricultural and pastural lands are such a large contribution to greenhouse gas emissions, one clear way we can make a big impact is through our food consumption. This does not necessarily mean we need to stop eating meat tomorrow, but eating more local foods, less red meat, produce during the appropriate season, or even going one day a week as a vegetarian, could go a long way in reducing our carbon footprint.

"Despite the slow-moving pace of national governments, I felt inspired by the display of local efforts across the world, which encourages others to act in their own local community."

— Sruthi Davuluri

Impressions from COP24: 3Qs with Anthony Fratto Oyler

ursue careers in the energy space, Sruthi Davuluri and l insights into what they've learned during their time at OP24 delegation.

As a first-time attendee of COP, what was going through your mind?

The first day I was just overwhelmed and in awe of the entire conference itself which is a massive sprawling of connected venues. During the week, I was struck by the severity of what we are facing, feeling honestly very small. We were constantly reminded of the short amount of time we have to drastically decarbonize our society.

Sitting in on negotiations, it was difficult to imagine countries coming together to find a solution when they couldn't even agree on a single sentence for a guidance document. I sat through multiple talks where Saudi Arabia (joined either silently or vocally by Russia and the U.S.) would backpedal on numerous phrasing agreements. This came out in front of everyone at the end of the first week. The U.S., Saudi Arabia, Russia, and Kuwait delayed the conclusion of the technical plenary session by refusing to include the word "welcome" in describing the IPCC special report on the impacts of 1.5°C.

After seeing the negotiations take place upfront, did you develop other concerns regarding the process?

I think it's important to communicate the realities and difficulties of such a conference of the UN. I am a complete supporter of international agreements but I would be remiss to say if I wasn't slightly naïve about the efficiency of the process prior to COP.

One of the primary goals of COP24 was to finalize an "operating manual" for how to implement the Paris Accords. It was tackling questions like GHG reporting, climate finance, and carbon trading. It was incredibly clear that these questions would not be easily answered. First, you have to decide to what flexibility in the rules you will give countries and more so who pays for all the investment needed.

By the time I left COP at the end of week one, technical talks were still going on despite having "officially closed." By the conclusion of COP24 the parties had not reached an agreement on all parts of the rulebook, passing some of it to COP25 in Chile this year.

What did you ultimately take away from COP24?

Ultimately, I felt hopeful. There were tens of thousands of individuals from all over the world working through research, policy, and leadership to address climate change in their own communities even without national government support. I was most impressed during the times spent engaging with other attendees in between the Country Pavilions or listening to the side talks of organizations taking on the mantle of mitigating and adapting to the very real repercussions of climate change occurring now in communities across the world. Rather than feeling burdened by the amount of effort needed to decarbonize our society, I felt empowered by my ability to at least try and build a better future for myself. I may have been given a world facing its potentially biggest environmental, economic, social, and moral issue but that doesn't mean I resign myself to accepting a world I did not choose.

Anthony is a Technology and Policy Master's Candidate ('19) at MIT. His research focuses on the valuation of technology that will play a role in the decarbonization of electricity sector and the policy that will support such shifts. His collegiate career has been spent between research labs, private industry, and fellowships with the U.S. Bureau of Land Management, the Utah Governor's Office of Energy Development, and Iberdrola's Global Regulation Department. Upon graduation Anthony will be a consultant at E3.

"I may have been given a world facing its potentially biggest environmental, economic, social, and moral issue but that doesn't mean I resign myself to accepting a world I did not choose."

— Anthony Fratto Oyler

Challenges for Wholesale Electricity Markets with Intermittent Renewable Generation at Scale

One of the most consequential trends in the energy sector in recent years has been the rapid growth in electricity generation from intermittent renewable energy sources, notably wind and solar photovoltaic. Due to their intrinsic variability and a unique cost structure – with high up-front capital costs, but almost no marginal operating costs – these energy sources fundamentally challenge traditional models of electricity market design and regulation. In a recent Working Paper[1] published by the MIT Center for Energy and Environmental Policy Research (CEEPR), Paul Joskow, Professor of Economics, Emeritus at MIT and a former CEEPR faculty director, draws on the theoretical literature and empirical data from the California Independent System Operator (CAISO) to diagnose the impacts of variable renewable energy generation at scale on electricity markets.

As the cost of these renewable energy technologies continues to fall and the number of states with ambitious renewable energy penetration goals and support policies continues to expand, such impacts stand to further amplify, providing the starting point for Joskow's timely analysis. A pioneer of modern electricity market design, Joskow sets out by recalling the short- and long-run resource allocation functions of current wholesale electricity markets in the United States, and shows how both functions are affected by the variability and low marginal operating costs of renewable energy resources such as wind and solar power.

In the short run, electricity markets should secure the efficient real-time operation of existing generating capacity, clear supply and demand at efficient wholesale prices that reflect the marginal cost of supply at any given moment, and do so while maintaining the reliability of the system. A growing share of renewable energy in the electricity mix affects the level, hourly distribution, and volatility of wholesale prices, however, impacting the profitability of dispatchable generators and requiring new products and services to safeguard system reliability. Likewise, direct and indirect subsidies for renewable energy generation distort efficient spot price formation, and long term contracts and other out-of-market revenues tend to selectively favor renewable resources. Taken together, these factors impact the ability of electricity markets to meet their short-run function of ensuring an efficient and reliable electricity supply.

What is more, such short-run effects also have dynamic long-run implications. Current electricity markets meet their long-run function by creating profit expectations and incentives that support efficient decentralized investments in new generating capacity as well as efficient retirements of existing generating capacity. That function is undermined when short-run price signals fail to reflect the scarcity value of generation due to price caps, limited demand-side participation in the wholesale market, and out-of-market actions by system operators during network security emergencies. As expanding renewable energy generation alters the merit order of generation, spot market prices for electricity decline, and net revenues from energy prices provide falling quasi-rents to support unsubsidized investment. In the absence of adequate short-run price signals, policy makers have resorted to other mechanisms aimed at securing resource adequacy, such as capacity obligations, capacity pricing, and scarcity pricing, but these, in turn, have imperfections that can lead both to short-run operating inefficiencies and distorted investment incentives for market entry and exit decisions.

Over time, Joskow observes, these factors threaten an outcome that is unstable and inefficient. As renewable generation with zero short-run marginal costs expands, wholesale market prices will fall. An energy-only market with price caps will therefore not yield adequate revenue to deter premature exit of dispatchable generating capacity or attract efficient entry of new dispatchable generating capacity or substitutes, such as storage, that offer ramping and ancillary services matched to the operating attributes of a system with intermittent generation at scale. Revenues from capacity and scarcity pricing will have to grow accordingly, creating a slippery slope where technologies increasingly vie to benefit from subsidies, long term contracts, and other out-of-market revenues to recover their capital costs. Looking to the future, Joskow predicts that these developments will lead to profound changes in the design of competitive wholesale markets in the United States, or otherwise threaten an outcome where out-of-market revenue streams, government intervention, and centralized resource planning will

> *"These developments raise profound questions about whether current market designs can be adapted to provide good long-term price signals to support investment in an efficient portfolio of generating capacity and storage consistent with public policy goals."*
>
> **— Paul L. Joskow**

Intermittent renewable energy sources like wind raise new challenges for electricity market design.

increasingly replace decentralized market incentives.

In his paper, Joskow traces the growth in wind and solar generation and the federal and state policies that have promoted it, and describes the wholesale electricity market designs that have been adopted by Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) with support from the Federal Energy Regulatory Commission (FERC) to highlight the performance attributes of these markets. He then draws on the rich data available for the wholesale market managed by CAISO to show how the advanced penetration of renewable energy in California – spurred by a broad portfolio of support policies and mandates – has resulted in discernible impacts on generation supply, spot energy pricing, as well as entry and exit patterns associated with intermittent generation at scale. In particular, the Californian example affirms the impacts of growing renewable energy penetration on the profitability of different generating technologies, as reflected in the fact that net revenues currently accruing to a hypothetical new gas turbine in CAISO are far from sufficient to cover its capital costs. Ultimately, thus, the Californian case study raises serious questions about the ability of CAISO and current electricity market designs in the other U.S. regional markets and outside the U.S. – for instance in Europe – to support an efficient long-run equilibrium of intermittent and dispatchable generating technologies.

In the final sections of his paper, Joskow brings together the theoretical and empirical evidence to highlight challenges to prevailing wholesale market designs and potential responses to these challenges. He focuses on long-term investment incentives, storage, and dynamic pricing, and concludes with some observations about more fundamental changes taking place in the U.S. in response to growing state intervention in electricity markets. As the example of California shows, an electric power system with deployment of intermittent generation at scale will need some combination of highly flexible generating capacity, storage, and demand-side responses with the ability to respond rapidly to dispatch instructions. Flexible resources with relatively low capital costs will be favored, as these may be dispatched for relatively short durations when they can earn market revenues from sales of energy. As such a system progresses towards full decarbonization, moreover, fossil-fueled dispatchable generation will be increasingly limited, necessitating new products and technologies that can respond not only to the intra-day variability, but also to the seasonal variability of renewable resources.

If current organized wholesale markets are to support aggressive decarbonization through wind and solar generation, more effective scarcity pricing or capacity pricing mechanisms will thus likely be required to provide net revenues that can deter inefficient exit and attract efficient entry. Capacity markets have been redesigned frequently as their imperfections have been revealed, however, and efficient scarcity pricing will not be feasible without reforms of retail pricing. Technological advances certainly create new opportunities: the wider diffusion of smart meters, for instance, makes some variation of real time retail pricing, including critical peak pricing, much more feasible than was once the case. Still, the philosophy of free entry and exit driven by market forces will likely continue to give way to extensive government intervention through decarbonization goals and renewable energy mandates. For Joskow, the resulting transition will proceed more efficiently if we prepare sooner rather than later by adjusting the procurement process and developing a separate market for long-term contracts – a market that is compatible with attracting investments consistent with the integrated resource portfolios that are increasingly being defined by government policy makers rather than market incentives.

[1] Paul L. Joskow (2019), "Challenges for Wholesale Electricity Markets with Intermittent Renewable Generation at Scale: The U.S. Experience." *CEEPR WP-2019-001*, MIT, January 2019.

Paul Joskow

The Carbon Footprint of Bitcoin

by: Christian Stoll, Lena Klaaßen, and Ulrich Gallersdörfer

Blockchain has its roots in the cryptocurrency Bitcoin, which was the first successful attempt to validate transactions via a decentralized data protocol. Participation in its validation process requires specialized hardware and vast amounts of electricity, which translate into a significant carbon footprint.

In 2008, Satoshi, the pseudonymous founder of Bitcoin, published a vision of a digital currency, which only a decade later reached a peak market capitalization of over $800 billion (CoinMarketCap, 2018; Nakamoto, 2008). The revolutionary element of Bitcoin was not the idea of a digital currency in and of itself, but the underlying blockchain technology. Instead of a trusted third party, incentivized network participants validate transactions and ensure the integrity of the network via the decentralized administration of a data protocol. The distributed ledger protocol created by Satoshi has since been referred to as the 'first blockchain' (Yaga, Mell, Roby, & Scarfone, 2018).

During 2018, the computing power required to solve a Bitcoin puzzle increased more than threefold, and heightened electricity consumption accordingly (Blockchain.com, 2018; de Vries, 2018). Speculations about the Bitcoin network's source of fuel have suggested, among other things, Chinese coal, Icelandic geothermal power, and Venezuelan subsidies (The Economist, 2018). In order to keep global warming below 2°C – as internationally agreed in Paris at COP21 – net-zero carbon emissions during the second half of the century are crucial (UNFCCC, 2015). To take the right measures, policy makers need to understand the carbon footprint of cryptocurrencies.

In a new Working Paper, we present a techno-economic model for determining electricity consumption in order to provide an accurate estimate of the carbon footprint of Bitcoin.[1]
Firstly, we narrow down the power consumption, based on mining hardware, facilities, and pools. Secondly, we develop three scenarios representing the geographic footprint of Bitcoin mining, based on pool server IP, miners' IP, and device IP addresses. Thirdly, we calculate the carbon footprint, based on the regional carbon intensity of electricity consumption. In comparison to previous work, our analysis is based on empirical insights. We use hardware data derived from recent IPO filings, which are key to a reliable estimate of power consumption as the efficiency of the hardware in use is an essential parameter in this calculation. Furthermore, we include assumptions about auxiliary factors which determine the power usage effectiveness (PUE). Losses from cooling and IT-equipment have a significant impact, but have been largely neglected in prior studies.

Besides estimating the total power consumption, we determine the geographical footprint of mining activity based on IP addresses. This geographical footprint allows for more accurate estimation of carbon emissions compared to earlier work.

We show that, as of November 2018, the annual electricity consumption of Bitcoin ranges between 35.0 TWh and 72.7 TWh, with a realistic magnitude of 48.2 TWh. We further calculate that the resulting annual carbon emissions range between 21.5 and 53.6 $MtCO_2$; a ratio which sits between the levels produced by Bolivia and Portugal.
The magnitude of these carbon emissions, combined with the risk of collusion and concerns about control over the monetary system, might justify regulatory intervention to protect individuals from themselves and others from their actions.

[1]Christian Stoll, Lena Klaaßen, and Ulrich Gallersdörfer (2018) "The Carbon Footprint of Bitcoin", *CEEPR WP-2018-018*, MIT, December 2018.

Christian Stoll

Lena Klaaßen

Ulrich Gallersdörfer

Fuel-switching and Deep Decarbonization

by: Christian Stoll

Humanity has used up two thirds of the carbon emission budget compatible with the goal of limiting global warming to 2°C. Global mean temperature has increased by 0.9°C, and out of the last twenty years, eighteen were among the warmest since 1880. As emissions continue to rise, limiting global warming below 2°C is widely considered to require substantial policy intervention. As a result, 195 countries agreed to take respective actions in 2015 in Paris.

To reduce carbon emissions, economic theory suggests use of carbon pricing as the most cost-efficient policy instrument. From a welfare perspective, carbon pricing, in the form of a carbon tax or cap-and-trade mechanism, reduces emissions at the lowest cost. However, in practice, policy makers increasingly resort to phase-out mandates to achieve committed emission reductions. As climate policy research focuses on carbon pricing as the first-best option, research into the effects and design of phase-out mandates has lagged behind.

To decarbonize the power sector, the public debate has increasingly focused on phasing out coal power plants. Promoters of coal phase-outs highlight the expected climate benefits of fuel-switching from coal to gas. For every year of coal displacement, fuel-switching to gas adds 1.4 to 2.4 years until depletion of the carbon budget, as gas combustion emits less than half the CO_2 of coal. Therefore, gas may act as a bridge-fuel until zero-emission technologies are available at scale.

Research has suggested that phase-outs are politically more feasible than carbon pricing at sufficiently high levels, and highlighted their ability to destroy existing structures while creating space for innovation. Phase-out policies are touted as transparent, simple, and influential in creating anti-fossil norms. An example is the nuclear phase-out in Germany, which has been credited with triggering more R&D spending on renewable resources than the Renewable Energy Act (EEG).

And yet, a view that focuses on coal and gas appears too narrow-minded, as it ignores central factors required for answering the question of which fuel-switching strategy is cost-optimal in order to remain on a politically agreed decarbonization pathway. In particular, zero-carbon resources inevitably become necessary at a certain point to remain on the decarbonization pathway, yet existing infrastructure carries the risk of long-term lock-in of high-carbon technologies. This potential lock-in has its roots in power plants that continue operations as they become stranded.

In a new Working Paper,[1] I present a simple model to find the least-cost resource mix, which is consistent with the committed climate targets. Firstly, I explain the intuition and logic of the model. This includes an explanation of how a capacity planner can determine the resource mix in order to cover load demand at least-cost, how climate targets constrain the task, and how carbon constraints switch the roles of fuel types. Secondly, I mathematically formulate the problem so as to numerically determine the least-cost resource mixes which satisfy distinct targets along the decarbonization pathway. Lastly, I solve the model, drawing on the example of Germany.

The case-study, based on the example of Germany, reveals counter-intuitive results that go against conventional opinions on the role of coal. The findings suggest that, when considering stranded assets, a decarbonization pathway that involves the expansion of renewables and includes a continued, but gradually declining role for coal, turns out to be less expensive than a strict coal phase-out.

Committed decarbonization targets can still be achieved by adding only minimal new gas capacity. It is more cost-effective to initially keep existing coal resources in the market, and expand zero-carbon technologies. The costs in a scenario with a politically forced coal phase-out are significantly higher, as additional gas resources have to fill the supply gap.

A case-study reveals results that go against conventional assumptions about the role of coal.

[1] Christian Stoll (2019) "Fuel-switching and Deep Decarbonization", *CEEPR WP-2019-005*, MIT, March 2019.

Christian Stoll

Actually, Millennials Don't Own Fewer Cars

by: Meredith Somers, MIT Sloan News Writer

Millennials get blamed for ruining a lot of things, but the auto industry shouldn't be one of them, according to a new CEEPR working paper.

Avocado sales, craft beer, cable television — what hasn't the millennial generation impacted? According to a new Working Paper[1] from CEEPR Director Christopher Knittel: the auto industry.

In his paper "Generational Trends in Vehicle Ownership and Use: Are Millennials Any Different?," Knittel finds that no, millennials are not different, at least when it comes to owning as many cars as baby boomers. They do, however, put more miles on their cars compared to the older generation.

"While we find that millennials are altering life-choices that affect vehicle ownership, the net effect of these endogenous choices is to reduce vehicle ownership by less than 1%," Knittel and his co-author, Elizabeth Murphy of Genser Energy, write.

Knittel and Murphy used data from the U.S. Department of Transportation's National Household Transportation Survey, the U.S. Census, and the American Community Survey for their research on household vehicle ownership, and vehicle usage (measured in annual vehicle miles traveled, or VMT). The various data sets range from 1990 to as recently as 2017. While there's disagreement on the official age range for millennials — the Pew Research Center deems anyone born between 1981 and 1996 a millennial — for this study, "millennial" was assigned to heads of households born between 1980 and 1994. The only generation the U.S. Census Bureau defines is baby boomers; people born between 1946 and 1964.

The authors note they are not the first to research millennials and their life choices compared to earlier generations. But as with things like millennials' food preferences and investments — which are viewed as disruptive to established industries — claims about their decisions on transportation "have not been explored rigorously, and limited data have been used to support these

"These results underline the importance of policy in addressing climate change. The low vehicle ownership statistics we've been quietly hoping will solve climate change are an artifact of the economic conditions and general life cycles millennials have faced and do not represent some fundamental difference in their demand for cars."

— Christopher R. Knittel, Director, MIT CEEPR

1 *The percent reduction in the number of cars owned by millennial households, compared to baby boomers.*

hypotheses."

The idea that millennials are afraid of risk, stay in one place, and don't make large investments like buying houses or cars, grew out of "a discussion that is dominated by anecdotal evidence," the authors write.

According to the research — which factors in variables like income, living in a city versus a rural area, and marital status — millennials drive 2,234 more miles per year than comparable baby boomers.

The researchers also found that millennials were more likely to live in urban areas, and less likely to marry before 35. Millennial families are also slightly larger (by about 2 percent) than those of baby boomers.

"Together, the results suggest that while millennial vehicle ownership and use may be lower early on in life, these differences are only temporary and, in fact, lifetime vehicle use is likely to be greater," the paper states.

So what does this mean for global emissions? Knittel and Murphy write that developing countries like China and India — and their growing emissions levels — will play a bigger role in the environmental discussion, and note that their data is only for the U.S. But the U.S. is "still an important driver of global emissions" they write, and the research suggests U.S. leadership in reducing emissions "may be more difficult than often thought."

[1]Christopher R. Knittel and Elizabeth Murphy (2019) "Generational Trends in Vehicle Ownership and Use: Are Millennials Any Different?", *CEEPR WP-2019-006*, MIT, April 2019.

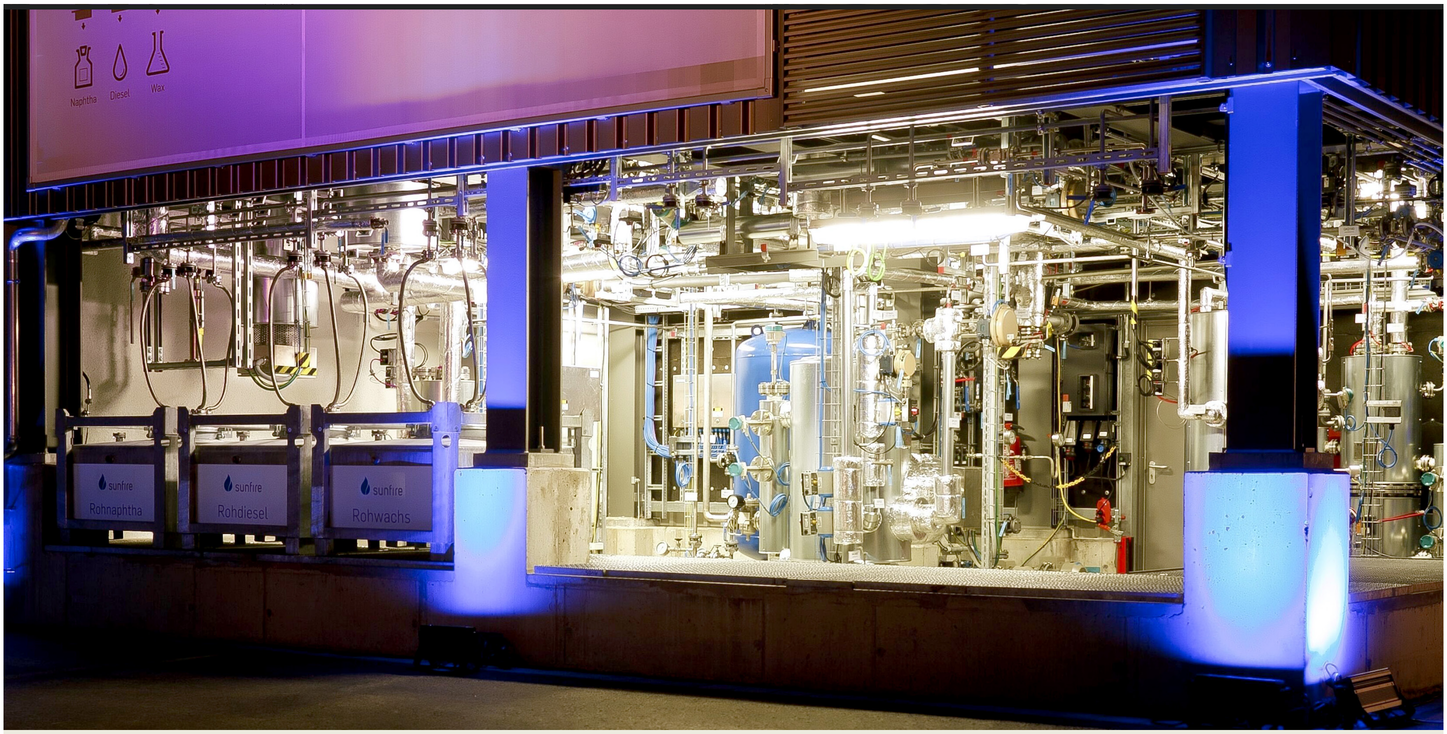
Christopher Knittel **Elizabeth Murphy**

Shared Capacity and Levelized Cost with Application to Power-to-Gas Technology

by: Gunther Glenk

While wind and solar power sources have outpaced early projections in terms of cost reductions and share of power generation (Comello et al., 2018; Kök et al., 2018), two challenges remain unsolved in the transition to a decarbonized economy. First, the production of electricity depends on intermittent weather conditions and, second, decarbonization measures must include other sectors, especially, transportation and industrial processes. A promising solution could be new Power-to-Gas (PtG) technology. By converting and reconverting electricity to hydrogen (Buttler and Spliethoff, 2018), reversible PtG can effectively store electricity at large scale and provide a clean energy carrier (hydrogen) to processes that are otherwise difficult to decarbonize (Davis et al., 2018). One objective of this paper[1] is to assess when a reversible PtG facility would be economically viable and both electricity and hydrogen competitive with fossil-based alternatives in the market.

For its economic viability, I find that a reversible PtG facility breaks-even if and only if the average contribution margin of operation exceeds a full cost measure per unit of capacity, which I term the levelized fixed cost (LFC). The measure accounts for the upfront investment, fixed operating expenses and any tax-related cashflows. As a technology that can store electricity over time, the break-even point of reversible PtG is widely thought to rely on the volatility in power prices and the continuous switch between conversion and reconversion. While my analysis confirms this tie, it shows that the ability to trade the storage medium (hydrogen) is even more important. Through access to the market, reversible PtG receives a price for hydrogen and the possibility to generate value from its conversion without the need to reconvert after prices have changed sufficiently. As a consequence, I find that for conditions frequently observed in current markets, reversible PtG will break-even when it largely produces the one output that has



Power-to-Gas could become a central enabler of the transition towards a sustainable economy by reversibly converting electricity to hydrogen. Contrary to the common belief that fossil fuels are indispensible, this analysis shows that reversible PtG will be sufficiently competitive with fossil-based energy sources so as to solve the challenges of intermittent renewable electricity generation and widespread industrial decarbonization. *Photo credit: Electrolysis facility. Sunfire GmbH, Dresden / renedeutscher.de*

the higher average price.

For the facility's competitiveness, an investor would make use of the concept of levelized product cost, which provides a useful metric. Since levelized cost identifies the lowest price required to break-even, the concept is widely used in the energy sector to find the cheapest power generation technology to serve a particular load that results from, say, insufficient renewable production (MIT, 2007). Measuring the competitiveness of electricity and hydrogen generated with reversible PtG requires an investor to allocate joint costs cross-sectionally and to find the allocation at the break-even point of the facility. Here my analysis shows that the cost allocation emerges as a main driver of competitiveness as the economics of reversible PtG divide the sizable joint costs into a large and a small share. With the shift to renewable energy, I find that the small share will be allocated to electricity which enables a competitive levelized cost despite the high cost for the new technology and using hydrogen as a fuel.

The empirical part of the paper seeks to assess the economic prospects for reversible PtG in Germany and Texas, two jurisdictions that have exhibited a rapid growth of renewables (IEA, 2017). Given the current market environment, the numerical evaluations yield that reversible PtG breaks-even only if the average price of hydrogen is above that of the price of electricity and the facility largely produces hydrogen. To break-even on electricity production, the price of hydrogen would have to be negative to generate a contribution margin at the current electricity price that exceeds the high cost of capacity. With regard to competitiveness, the calculations show that electricity and hydrogen are, in both jurisdictions, only competitive in niche applications. Hydrogen, for instance, is competitive at small- and medium-scale but not with the lower prices paid for large-scale supply of industrial hydrogen produced from fossil fuels.

Incorporating recent market trends, the calculations line out a trajectory for reversible PtG that corroborates its promising potential for solving the challenges of intermittency and decarbonization. These trends include sustained cost reductions, efficiency improvements, and that reversible PtG is integrated vertically with a co-located wind energy source to benefit from operational synergies. Due to these synergies, hydrogen produced with reversible PtG becomes competitive with large-scale industrial hydrogen supply already in the current market. Electricity production remains presently more expensive but is likely to become cheaper than conventional power generators over the coming decade.

[1]Gunther Glenk (2019) "Shared Capacity and Levelized Cost with Application to Power-to-Gas Technology", *CEEPR WP-2019-007*, MIT, April 2019.

Gunther Glenk

Notable Changes

This semester, CEEPR welcomed three experts to Cambridge as Visiting Scholars, who will collaborate with faculty and other MIT researchers on new projects.

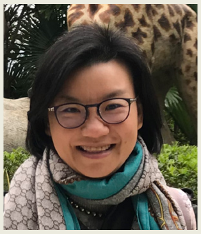
In January, **Professor Mathias Reynaert** arrived at CEEPR. He is an Assistant Professor at the Toulouse School of Economics in France. Mathias' research focuses on environmental and energy economics, industrial organization, political economy and empirical methods. During his time at MIT, he will be looking into three projects related to European actions to reduce carbon emissions from automobiles and the behavior of firms and consumers in response to European Union emissions standards.

In February, **Dr. Bjarne Steffen**, a Senior Researcher in the Energy Politics Group at ETH Zurich, began his visit at MIT. His research addresses the role of financial actors (e.g., investors and banks) in the ongoing sustainable energy transition. Working closely with CEEPR faculty member Professor Valerie Karplus of the MIT Sloan School of Management, Bjarne will focus on a project assessing power generation investments by state and investor-owned utilities.

Finally, in April, CEEPR welcomed **Professor Jacqueline Lam** to MIT. She is an Associate Professor at the University of Hong Kong and previously a Visiting Senior Research Fellow with our colleagues at EPRG at the University of Cambridge. Jacqueline will focus her work on the study of human migration due to air pollution and its social cost.


Mathias Reynaert


Bjarne Steffen


Jacqueline Lam

Recent Working Papers

WP-2019-007
Shared Capacity and Levelized Cost with Application to Power-to-Gas Technology
Gunther Glenk, April 2019

WP-2019-006
Generational Trends in Vehicle Ownership and Use: Are Millennials Any Different?
Christopher R. Knittel and Elizabeth Murphy, April 2019

WP-2019-005
Fuel-switching and Deep Decarbonization
Christian Stoll, March 2019

WP-2019-004
Competition for Electric Transmission Projects in the U.S.: FERC Order 1000
Paul L. Joskow, March 2019

WP-2019-003
Machine Learning from Schools about Energy Efficiency
Fiona Burlig, Christopher R. Knittel, David Rapson, Mar Reguant, and Catherine Wolfram, February 2019

WP-2019-002
The Efficiency and Distributional Effects of Alternative Residential Electricity Rate Designs
Scott P. Burger, Christopher R. Knittel, Ignacio J. Pérez-Arriaga, Ian Schneider, and Frederik vom Scheidt, February 2019

WP-2019-001
Challenges for Wholesale Electricity Markets with Intermittent Renewable Generation at Scale: The U.S. Experience
Paul L. Joskow, January 2019

WP-2018-018
The Carbon Footprint of Bitcoin
Christian Stoll, Lena Klaaßen, and Ulrich Gallersdörfer, December 2018

WP-2018-017
Governing Cooperative Approaches Under the Paris Agreement
Michael A. Mehling, December 2018

WP-2018-016
The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Power Plants
Anthony Fratto Oyler and John E. Parsons, November 2018

All listed and referenced working papers in this newsletter are available on our website at ceepr.mit.edu/publications/working-papers

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2018-2019 cohort of MIT CEEPR Research Assistants at the 2018 Fall Workshop.
Pictured from left to right: Andrés Inzunza, Bora Ozaltun, Sruthi Davuluri, Benny Ng, Paula Meloni, Anthony Fratto Oyler, and Tomas Wesley Green