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MIT Center for Energy and Environmental Policy Research

Newsletter

AUTUMN 2022

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Editorial.

Six months after our last newsletter, the global energy crisis remains the dominant theme in energy policy. Initially prompted by recovering demand after the COVID-19 pandemic and exacerbated by the supply shock following Russian aggression in Ukraine, this crisis has upended energy markets around the world. In Europe, in particular, it has accelerated efforts to diversify energy supplies, intensified discussions about energy market reforms, and seen wide-ranging market interventions to limit the costs facing consumers. Energy trade flows have shifted to reflect this evolving context, as market dynamics and geopolitical calculation enter into a new and uneasy equilibrium. What the armed conflict in Ukraine has also underscored is the vulnerability of energy infrastructure as a strategic target on the modern battlefield, with attacks on natural gas pipelines and electricity transmission lines causing extensive and costly disruptions.

Another source of recent disruption in the energy sector and beyond has been extreme weather. Natural disasters such as Hurricane Ian in the southeast United States and devastating floods in Pakistan have not only joined the list of the costliest events in human history, but their rising frequency and intensity is also increasingly attributed to climate change. While catastrophic events attract the greatest attention, more creeping developments such as record high surface water temperatures in France this summer – which forced curtailed output from parts of the nuclear power plant fleet – may be harbingers of a warming world, and signal the need for improved resilience and adaptation to climate change impacts. In such a world, the quantification and disclosure of climate risk will gain prominence, as exemplified by a recent proposal of the Securities and Exchange Commission to require that public companies provide climate-related data in public disclosure filings.

Recent assessments of global climate action suggest that humanity is still falling far short of tackling this unfolding crisis, however, and as this newsletter issue goes into print, negotiators from around the world will be converging in the Egyptian resort town of Sharm El-Sheikh for the annual climate summit to kick off a formal process – known as the 'Global Stocktake'– under the Paris Agreement that will predictably affirm the foregoing diagnosis. In some regions, the simultaneous energy crisis may have prompted a recalibration of near-term policy priorities, with Europe, for instance, reactivating conventional generating assets to improve energy security and affordability. Still, global investment in low-carbon energy technologies is expected to exceed US$1.4 trillion in 2022, marking a significant acceleration over recent years. With its passage of the 'Inflation Reduction Act of 2022' this past August, the United States is set to lead this surge as it injects unprecedented levels of public finance into the clean energy economy.

While change and volatility have become familiar hallmarks of the energy sector, the past six months have seen further acceleration of several disruptive trends. As public and private decision makers grapple with market turmoil, transformative technologies and evolving policy landscapes, MIT CEEPR will continue to rely on empirical data and proven methodologies to offer insights into the most pressing challenges we currently face. A global outlook – which has been a traditional feature of MIT CEEPR research and convening – is proving to be more important than ever. As always, this newsletter affords an accessible sampling of our latest research results, and also profiles of some members of our team. It is but a small snapshot of the diverse range of activities we are working on at CEEPR, and we invite you to learn more, engage with us, and explore ways to collaborate.

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MIT CEEPR Newsletter is published twice yearly by the MIT Center for Energy and Environmental Policy Research.

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Contents.

Research.

When "Low-Hanging Fruit" Are Beyond Reach: Management Practices and Firm Energy Efficiency

By: Valerie J. Karplus and Da Zhang

Industrial energy efficiency plays a central role in projections that achieve net zero greenhouse gas (GHG) emissions by mid-century. According to the IPCC, industry accounts for 33% of total emissions of the major global carbon dioxide (CO_2) due to its reliance on fossil fuels, especially coal, for electricity and process and building heating. China's industry accounts for 55% of the nation's primary energy use, or 12% of the global total.

Our experiment studies the relationship between management practices and electricity use outcomes in metal machining firms. While much of China's industrial energy use is concentrated in energy-intensive manufacturing (e.g., iron and steel, cement), high value-added manufacturing—which includes the metal machining firms in our study—accounts for fully 7% of the nation's energy use. Prior studies have found that firms with more developed structured practices are less energy intensive and less polluting. However, until now these interactions have never been studied in the context of a randomized intervention. Mechanisms are also poorly understood. Could management practices play a role in helping firms to deeply reduce CO_2 emissions?

Valerie J. Karplus and Da Zhang (2022), "When 'Low-Hanging Fruit' Are Beyond Reach: Management Practices and Firm Energy Efficiency", CEEPR WP-2022-009, MIT, June 2022.

We design a randomized experiment that provides small- and medium-sized metal machining firms with tailored recommendations to improve energy efficiency. The assessment of opportunities for each firm begins with the same menu of recommendations. We hypothesize two competing effects. On the one hand, the preexisting relationship between management practices and energy efficiency may limit the uptake and impact of our energy efficiency intervention, if management practices previously led firms to reap "low-hanging fruit," i.e., low cost energy saving opportunities. We call this the baseline effect. On the other hand, management disciplines may increase the intervention's impact, if it motivates or coordinates employees' efforts to realize energy savings from the intervention. We call this the cognition effect.

We test the net impact of these hypothesized competing effects and examine underlying mechanisms in a sample of 48 single-plant metal machining firms located in Jinan City, Shandong Province, China over six years. We measure generic management practices using the World Management Survey questionnaire and energy-centric management practices using a survey we developed. We report two main findings.

First, we find that the likelihood of recommendation adoption is positively and significantly associated with measures of structured management practices, consistent with a dominant role for the cognition effect. As shown in the figure below, a one standard deviation increase in management score increases the probability of adoption by 20-23 percentage points, statistically significant at the 5% level. We find a significantly higher probability of adopting recommendations that required the least customization. Among management disciplines, monitoring, targets, and incentives (human resource practices such as performance-based pay and promotion) are all positively correlated with adoption.

Second, we show that the intervention's main effect, a reduction in the unit cost of electricity, is larger in firms with less developed structured practices. Limiting the interaction to just the bottom quartile of low-scoring firms (see Figure), we find that this group is largely responsible for the unit cost effect, driving the overall unit cost reduction (significant at the 1% level): on average, firms in the bottom management quartile realized a unit cost reduction of 13% on average. We find that this effect can be traced to managers' suboptimal selection of transformer-related parameters at baseline, which resulted in higher electricity costs. The transformer-related recommendation alerted firms that they could reduce their energy costs by resizing their transformer or, in many cases, accurately reporting their maximum load to the grid company. Many firms' settings were found to deviate from the recommended optimum to various degrees. These deviations proved to be largest among the least well-managed firms, resulting in their paying higher electricity unit cost at baseline. As shown in the Figure, the effect size is larger when we condition on receiving the transformer adjustment recommendation. This effect is most strongly associated with low monitoring, target-setting, and incentive practice scores, providing evidence consistent with an "energy management gap" and thus spillovers from management to energy management. Our energy efficiency intervention had no net effect on the quantity of electricity use. Since the GHG intensity of the local electricity supply did not change during this period, our intervention also had no net effect on GHG emissions.

Based on our findings, we reach several conclusions. Our adoption results suggest that structured management practices may help firms absorb new ideas that are expected to reduce physical energy use and greenhouse gas emissions. At the same time, tailoring interventions to address management practice gaps in low-scoring firms may unlock opportunities to save energy cost, by closing the "energy management gap," but the result could be an increase rather than a decrease in energy use and GHG emissions if the recommendation mechanically reduces energy cost. Since many energy efficiency interventions incentivize firm participation by focusing on potential cost savings, these behavioral effects could offset the environmental benefits of these programs, especially in developing country firms where these behavioral effects could be stronger.

Interestingly, firms' pre-treatment adoption of the recommendations offered by our intervention did not vary with management practice scores, but unit-cost of electricity did. One potential reason is that managers of well-managed firms may have felt very limited to no external pressure to limit energy use for its own sake or for environmental reasons but were simply—and unknowingly—reaping spillovers from good management practices. Since firms in our setting were too small to be targeted by energy-saving policies during this period, firm responses and their interaction with management practices may well be very different in countries where firms face substantial policy or shareholder pressure. Understanding the interactions between external climate mitigation pressures and internal firm management disciplines in driving energy decisions represents an important frontier for future research.

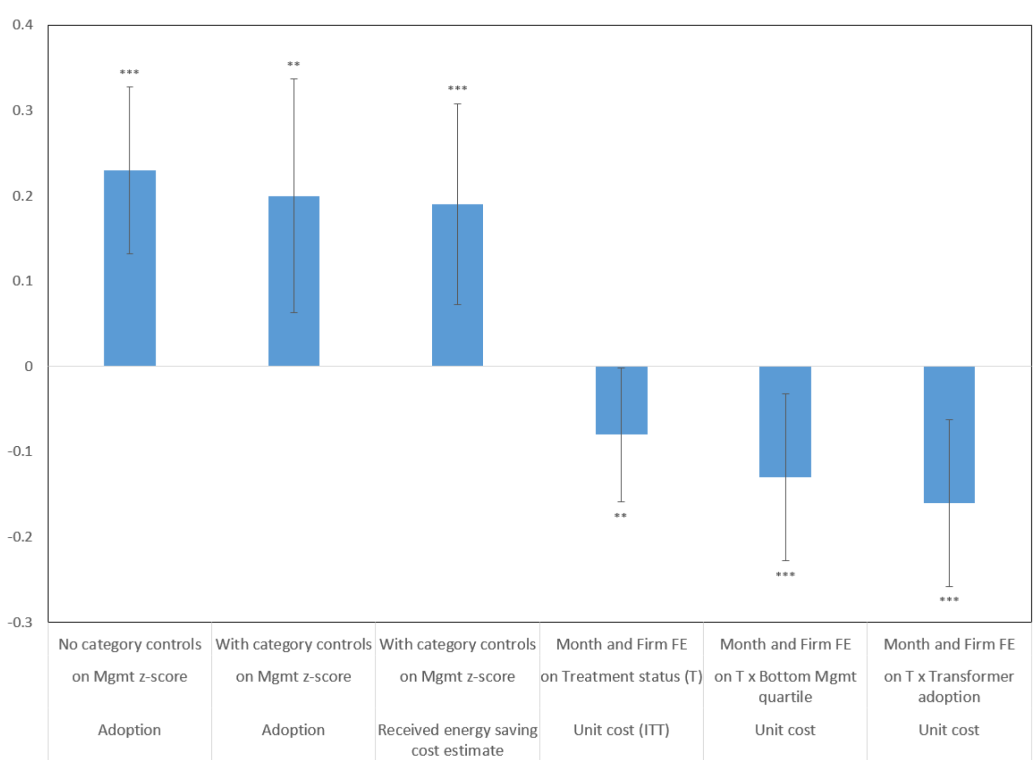

Figure 1. Relationship between management practice scores and the uptake and impact of an energy efficiency intervention.

Estimates show effect sizes in log points, and error bars indicate 95% confidence intervals. FE - Fixed Effects. ITT - Intent to Treat. Statistical significance is indicated by the asterisks *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$.

Jonas Martin, Anne Neumann, and Anders Ødegård (2022), "Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model", CEEPR WP-2022-010, MIT, July 2022.

Research.

Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model

By: Jonas Martin, Anne Neumann, and Anders Ødegård

Achieving net zero emissions by 2050 represents a significant challenge for the global trucking, shipping and aviation sectors. Unlike the continuous improvements in battery storage technology for passenger and light-duty vehicles, only fossil fuels meet the considerable technical and economic requirements of most truck, ship and plane traffic as of today. Hence with the regulatory banishment of greenhouse gas emissions, there is widespread interest in using sustainable hydrogen fuels. Produced from renewable energy sources, water, and optionally carbon dioxide or nitrogen captured from the atmosphere, the respective fuels are hydrogen (eHydrogen), hydrocarbon fuels (eFuel) and ammonia (eAmmonia); where the "e" stands for renewable, electricity-based fuels. eFuel can be used in existing combustion engines, whereas eHydrogen and eAmmonia depend on electrochemical conversion in fuel cells or adjustments in combustion engines and fuel tanks. The most promising technical fuel pathways are eHydrogen and eFuel for long-haul trucking, eHydrogen, eFuel and eAmmonia for short-sea shipping and eHydrogen and eFuel for short-haul aviation.

Previous studies investigate the value chains with regard to the eHydrogen, eAmmonia and eFuel costs, costs of decarbonizing trucking, shipping and aviation, and the technical usability of alternative fuels in the transport sectors. While these studies rely on various sources of external fuel costs or focus on one mode, a reliable cost comparability of fuels and transport modes only occurs with uniform assumptions of the value chains' horizontal and vertical dimensions.

To understand the economic changes while decarbonizing long-haul trucking, short-sea shipping and short-haul aviation until 2050, this paper describes a new dynamic cost model. Its 140 parameters can be tailored to local conditions with reference to renewable electricity generation (onshore wind, offshore wind, hydropower), fuel production, fuel distribution and the use in the trucking, shipping and aviation sectors. We apply the model to Norway, which has excellent

renewable energy potential and is considered an early adopter of sustainable transport. The value chains are modelled for the alternative fuels, eHydrogen, eFuel and eAmmonia.

To compare fuel and transport alternatives, we apply the concept of levelized cost of energy, which conventionally assigns a power plant's total lifecycle cost to one unit of energy output. Total lifecycle cost includes capital costs, fuel costs, fixed and variable operations and maintenance costs, financing costs, and a utilization rate. We generalize the approach to calculate levelized cost of all process steps in the value chains, carrying out a detailed bottom-up analysis. Cost data and learning curves are compiled and evaluated in five-year increments from 2020 to 2050 based on publicly available data from articles in peer-reviewed scientific journals and frequently cited reports by consultants, agencies and industry experts, validated by practitioners. Several technologies face uncertainties in our cost estimations, so we implement a range of cost values to investigate the model's sensitivity in a best- and worst-case scenario. To adjust our model to freight transport, we collect further mode-specific cost data to deliver cargo via trucking, shipping and aviation. Taxes and subsidies for fossil and sustainable alternatives are neglected.

Considering onshore wind power as potentially low-cost, we find that the three transport modes will suffer cost disadvantages when using sustainable hydrogen fuels compared to fossil fuels (Figure 1). For decarbonization, the results reveal the most favorable fuel choices for the investigated transport applications: eHydrogen for long-haul trucking, eFuel in the early years and eAmmonia starting in 2030 for short-sea shipping, and eFuel for short-haul aviation. The existing cost rankings are maintained over the time period: shipping remains the cheapest, whereas aviation is the most expensive transport mode. Compared to current fossil-based transport without government intervention, shipping has the strongest transport cost sensitivity (+232%, 2020; +41%, 2050), followed by aviation (+138%, 2020; +36%, 2050) and trucking (+66%, 2020; +8%, 2050). Lower costs of electricity depending on the choice of renewable electricity generation (e.g. hydropower) significantly affects the levelized cost of transport. eFuel reacts most to lower electricity costs, due to the multiplicative effect of efficiency losses in production and consumption. Offshore wind creates the highest cost of transport.

We conclude that by betting on learning curves and substantial cost decreases of technologies needed along the value chain, heavy-duty transport decarbonization by 2050 cannot be achieved. Although the cost gaps to fossil-based transport decrease over time, we see that decarbonization pathways for heavy-duty transport are out of reach without government intervention. Future research is needed to identify optimal public and private support throughout the value chains. Evaluating asymmetric changes in transport costs and its implication on modal shift is another important research topic.

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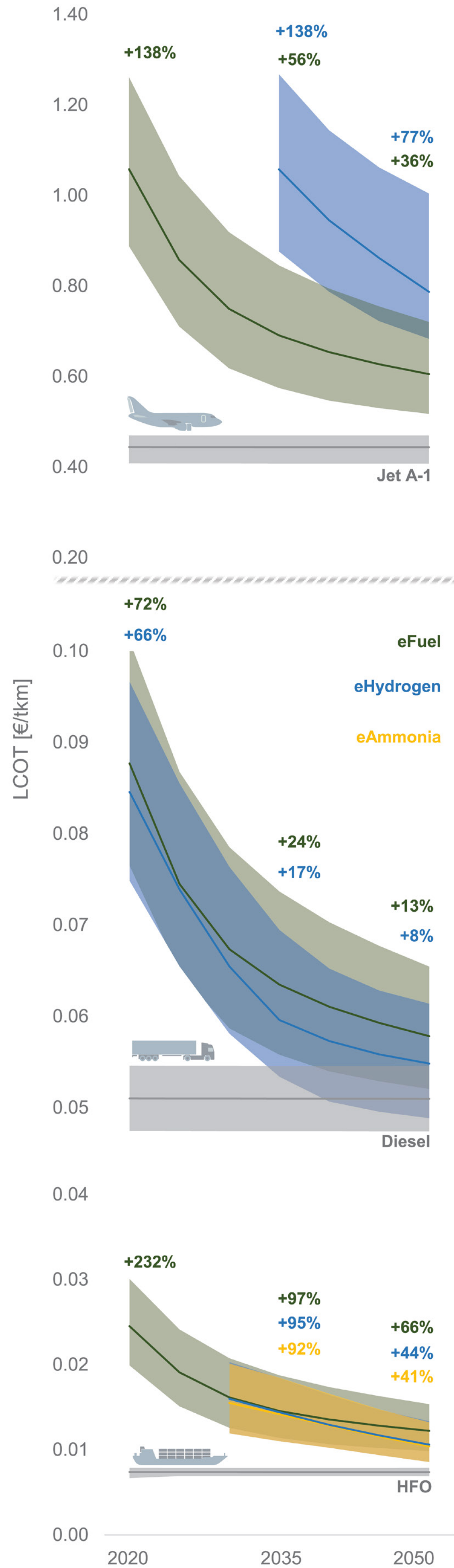

Figure 1. Change of levelized cost of transport in percentages for aviation, trucking and shipping (grouped from top) considering fuel options based on electricity from onshore wind.

Transport costs within and across modes change asymmetrically over time. Percentages show the cost gap of alternatives (base-case) benchmarked to the sector-specific fossil fuel case. Shadows show the maximum uncertainties of fuel costs and vehicle technologies (fossil fuel uncertainty represents the historical cost fluctuation). All shown costs without taxes and subsidies.

Research.

Long-term Equilibrium in Electricity Markets with Renewables and Energy Storage Only

By: Guillaume Tarel, Magnus Korpås, and Audun Botterud

In many regions of the world, the economic dispatch of electricity, and the corresponding financial arrangements, are organized using spot markets. This is for example the case in most European countries and in North America. In the simplest form of those markets, the wholesale price of electricity is determined at each time step, typically one hour, with the price equal to the variable cost of the marginal generation unit. The use of spot markets is often combined with other mechanisms to ensure revenue sufficiency for each generator. Existing or new power purchase agreements (PPAs), capacity and balancing remuneration mechanisms, and various environmental support mechanisms (such as zero emission credits) are other sources of revenue. It remains true, however, that one cornerstone of price formation in modern electricity markets is a variable cost or, to make it simple as in the traditional case, the product of the heat rate of generation technologies by their fuel costs, such as natural gas, coal, fuel-oil, uranium etc. Overall, spot markets have shown a high degree of efficiency in delivering large amounts of electricity, even though they exhibit limitations, such as the difficulty to adequately support peak generators and concerns regarding the market power of large generation owners. On top of that, their ability to function adequately in the presence of renewable energy sources (VRE) that have zero variable costs (e.g. wind, solar PV) is still a question of debate. To summarize this issue, VRE may reduce spot prices through the merit order effect, which in turn impacts other generators by increasing the "missing money problem".

VRE are undoubtedly a key element of future power systems: this is because they are deemed to answer three major concerns. Firstly, they support an economical generation system (since their per MWh generation costs have decreased rapidly in the past decades). Secondly, they provide security of supply for many countries by reducing the reliance of power systems on imports of primary energy, typically in the form of fossil fuels. And, finally, they contribute to meet climate targets since their greenhouse gas emissions are low, both in absolute and in life-cycle analysis terms. This overall attractivity explains why many regions of the world now plan for a very large increase of VRE capacities.

The fact that VRE will operate within spot markets, where prices traditionally were based on the variable costs of generators, is a sort of paradox that is the motivation for our research. More precisely, we address the question of price formation in power markets in which only VRE and electricity storage are present, that is in the absence of any variable costs except for load shedding represented using value-of-lost-load (in $/MWh). We use an analytical formulation developed in our previous work [CEEPR-WP-2020-005], i.e. we solve a simple optimization problem in which optimal capacities of wind and storage

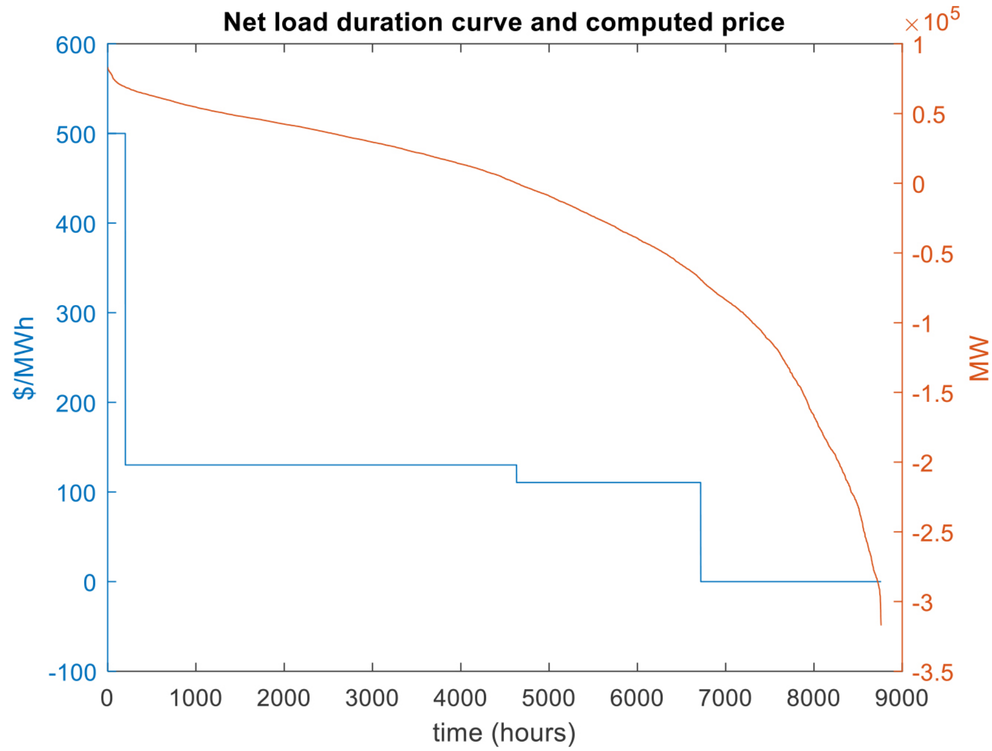

Figure 1. Results from a numerical optimization model used to validate the analytical findings. Net demand curve (red) and corresponding short-term prices (blue), which are computed from the dual value of the supply-demand equilibrium constraint, which coincides with prices found analytically.

As expected, the short-term price during load-shedding is vs (the VOLL), while it is 0 during VRE curtailment (wind surpluses). More interesting is that the price during other periods (when charge/discharge is at less than maximum capacity of storage), the short-term price is proportional to Λ. Λ is a value that depends on fixed costs of VRE and storage technologies. This structure is different to pricing electricity in a uniform way using either 0$/MWh or the average cost of electricity.

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technologies lead to the least cost of generation. We show that, under certain conditions, a price structure that is based, in part, on the fixed capital costs of generation sources (VRE and storage) is compatible with cost recovery for market players and overall cost minimization. This result is in contrast to earlier work with thermal generators as part of the resource mix, where prices in equilibrium depend on variable costs only.

Our results can be interpreted in various ways, keeping in mind that they are based on a simplified model. On the one hand, one could see the results as a proof that spot markets cannot work with VRE only, since market operators could not possibly ensure that all generators and storage operators are bidding their right price. However, on the other hand one can argue that the supervision and mitigation of market power in electricity markets already exists. For example, "economic withholding" is defined in NYISO tariffs as "submitting Bids for an Electric Facility that are unjustifiably high". In a case of economic withholding, NYISO "imposes a default bid on the Market Party". One could therefore see our result as a change to existing spot markets, in which additional supervision rules need to be created that allows market participants to reflect capital costs in their offers. Our result is therefore an additional element indicating that future VRE-based spot markets will likely be more complex to monitor and to operate. Overall, we do not claim to propose an actual market design based on our simplified model and case study. However, our results illustrate that more research is needed to better understand price formation in future low-carbon electricity markets, including studying the impact of having more markets participants, demand side management, capacity constraints, uncertainty, and more.

Guillaume Tarel, Magnus Korpås, and Audun Botterud (2022), "Long-term Equilibrium in Electricity Markets with Renewables and Energy Storage Only", CEEPR WP-2022-012, MIT, September 2022.

Robert S. Pindyck (2022), "Population, Productivity, and Sustainable Consumption", CEEPR WP-2022-011, MIT, August 2022.

Research.

Population, Productivity, and Sustainable Consumption

By: Robert S. Pindyck

Given current and projected future levels and growth rates of aggregate production and wealth, what level of consumption is sustainable? How does the sustainable level of consumption depend on the size and growth rate of the population? How does it compare to the optimal level of consumption that maximizes welfare? And how are the answers to these questions affected by uncertainty, over both the growth and productivity of the capital stock and the growth of population?

These questions presume a definition of "sustainable." A common definition is that future generations should be at least as well off as we are. But does "as well off" mean there is no reduction in per-capita consumption, or no reduction in the utility from consumption? And do we care about the number of people who are well off?

Much of the economics literature that addresses these questions defines a sustainable path for consumption as one for which social welfare is non-declining throughout the future. In turn, social welfare is usually defined as the present value of a flow of utility generated from consumption.

However, the definition of sustainability used in the existing economic literature creates two limitations. First, they are inherently deterministic in nature. They typically examine how sustainable trajectories for consumption depend on the (deterministic) growth rates of the capital stock, productivity, natural resources, and other factors that affect output and welfare. These studies yield insights into the relative importance of different factors that can limit future consumption, but they ignore the fact that the economy evolves stochastically, so it is impossible to ensure that welfare will never decline. The second limitation is that population is usually taken as incidental. Existing models do not account for social

utility (or disutility) from the very existence of people. This is at odds with a growing literature that examines how life itself might be valued. There are good reasons to believe that population growth will affect social welfare, and this can have profound implications for sustainable consumption.

To rectify these limitations, I propose to define sustainability in terms of expected value. A natural definition is that the expected value of social welfare is not expected to decline at any point in the future. This is the definition of sustainability I apply in my paper.

The next task is to define social welfare. The standard approach is to define social welfare as the expected discounted flow of CRRA utility from consumption. However, I broaden this definition to include population, and I allow both population and productive wealth to evolve stochastically.

My model rests on the following standard assumptions:

(1) I assume that all individuals are the same, i.e., there is no heterogeneity within the population.

(2) I assume that production and hence consumption requires productive wealth, which includes physical and human capital, as well as the technological know-how to make that capital productive.

(3) I measure sustainable consumption in terms of its relationship to wealth, i.e., I calculate a sustainable consumption-wealth ratio, and compare it to the optimal (unconstrained) ratio that maximizes welfare.

In addition, I assume production requires labor, and I take the labor force to be proportional to population. I assume that the relationship between population and output is isoelastic, and I examine how the elasticity affects the sustainable consumption-wealth ratio. Finally, I assume that population evolves as a continuous stochastic process. By introducing a more general social welfare function that explicitly includes population, I explore how sustainable consumption depends on the extent to which we value the existence of people, apart from their consumption and their contribution to aggregate output.

My model yields several important insights:

(1) As in earlier deterministic models, if the return on capital is low and/or population growth is high, a positive sustainable consumption-wealth ratio may not exist.

(2) An increase in the volatility of the return on capital always reduces the sustainable consumption-wealth ratio. However, an increase in the volatility of population growth can increase or decrease the ratio, depending on the parameters of the model.

(3) Sustainable consumption depends critically on the extent to which lives have intrinsic social value. For example, a positive intrinsic social value of lives raises the sustainable consumption-wealth ratio. The reason is that consumption and population become substitutes in terms of their contributions to social welfare.

(4) For plausible parameter values, the sustainable consumption-wealth ratio is well below the optimal ratio that maximizes social welfare. This implies that achieving sustainability can come at the cost of a substantial welfare loss.

These results raise questions about sustainability as a social objective. Notably, a high value of the discount rate means society wants utility, and hence consumption, now rather than later, possibly in conflict with the sustainability constraint. Should society be bound by that constraint and reduce its current consumption to benefit future generations, rather than consuming at the higher level that maximizes social welfare? Should we argue that the discount rate should be set close to zero on "ethical" grounds, which could put the sustainable level of consumption above the optimal level?

Another difficult problem raised by the model is how to decide whether human lives have intrinsic value, and what that value is relative to the value of consumption. We have shown that sustainable consumption can depend critically on the positive or negative value that society places on lives. There is probably no "correct" value for this parameter; instead, this parameter should be viewed as a vehicle for exploring how an intrinsic value of lives can affect sustainable consumption.

Perhaps most significantly, plausible parameter values put the sustainable consumption-wealth ratio below the optimal ratio that maximizes welfare. This result is reversed if society places a large positive value on lives, the elasticity of output with respect to population is close to or above one, and the volatility of the return on capital is low. But without these conditions, the goal of sustainability creates a policy dilemma. Should we reduce consumption to a sustainable level, even if this pushes social welfare below what it could be otherwise? Some may argue that sustainability is more important than maximizing welfare. However, we should be aware of the costs of sustainability, which this model shows, can be substantial.

—Summary by Diana Degnan

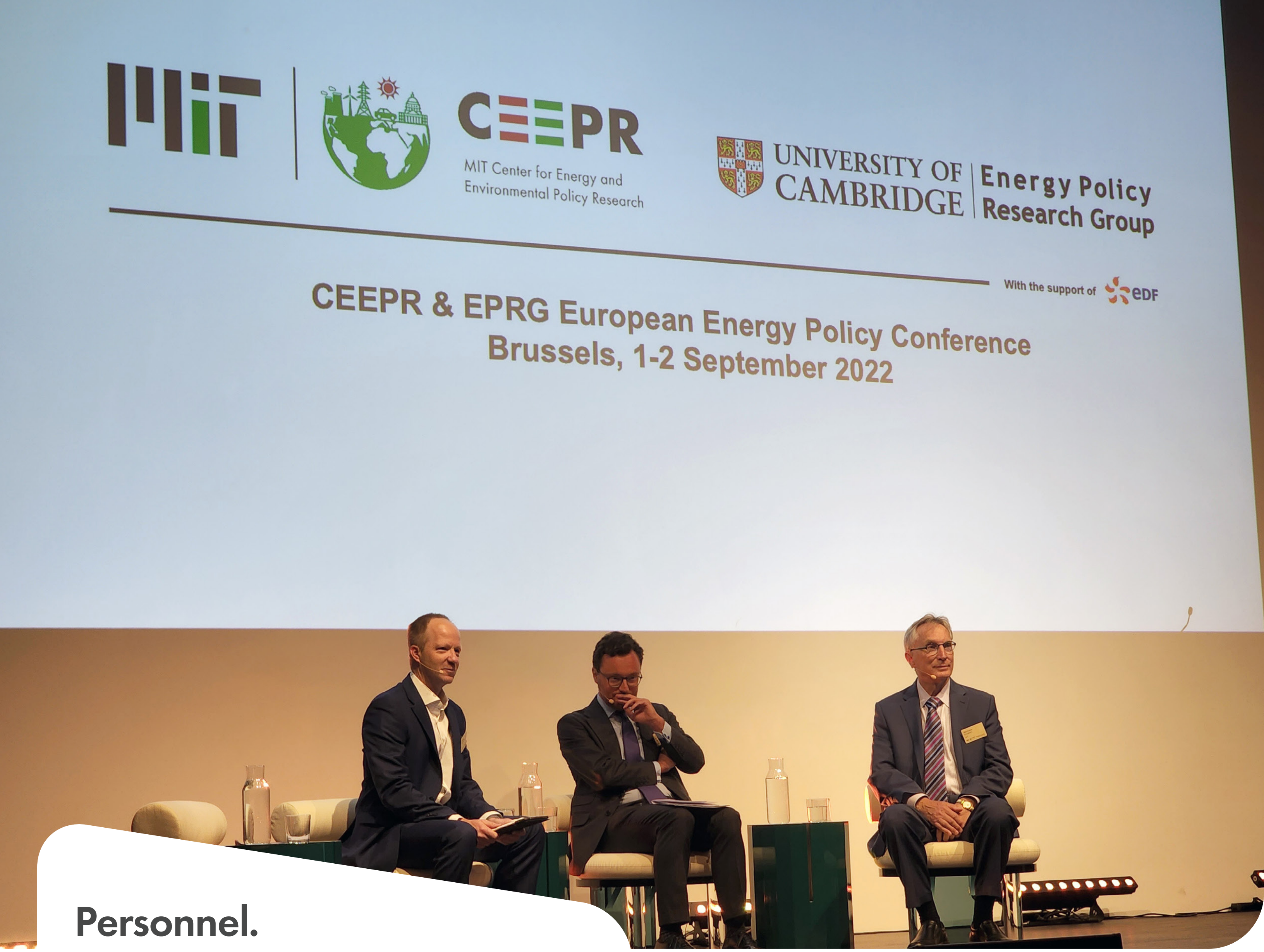

Photo: Professor Metcalf (right) participates in a session on "Pricing Carbon: Is It Useful?" alongside Dr. Robert Ritz from the University of Cambridge (center) and Professor Christopher Knittel from MIT (left) at the recent 2022 CEEPR & EPRG European Energy Policy Conference in Brussels, Belgium.

Personnel.

Gilbert E. Metcalf Joins MIT CEEPR as a Visiting Professor

By: Diana Degnan

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CEEPR is delighted to welcome Gilbert E. Metcalf as a Visiting Professor. Professor Metcalf is an economist who has made important contributions to academic scholarship and government policy making, with a focus on applied public finance and energy and environmental economics. He joins CEEPR from Tufts University, where he has been the John DiBiaggio Professor of Citizenship and Public Service and a professor of economics. Additionally, he continues to serve as a Research Associate at the National Bureau of Economic Research and a University Fellow at Resources for the Future. He holds an M.S. in Agricultural and Resource Economics from the University of Massachusetts Amherst and a Ph.D. in Economics from Harvard University.

Professor Metcalf has recently dedicated his work to climate finance and economic instruments for climate and energy policy, including carbon taxation, on which he has authored countless journal articles and several books. In addition, Professor Metcalf has devoted his academic expertise to public service, serving as Deputy Assistant Secretary for Environment and Energy at the U.S. Department of Treasury from 2011 to 2012, where he was also the founding U.S.

Board Member for the United Nations Green Climate Fund.

Despite his sizeable accomplishments in these fields, Metcalf was not interested in environmental economics and public finance in college. "I didn't really have any interest in environmental issues when I was in college. I didn't have any interest in economics either." As a math major, Metcalf recalls, "I loved the math. I loved the theory. But I felt like it was devoid of any practical use. I wanted some policy engagement with it. When I discovered economics, I realized this is exactly what I should have been doing since day one."

Metcalf first got involved in energy and environmental policy after college when he took part in anti-nuclear demonstrations at planned nuclear power projects in Montague, Massachusetts and Seabrook, New Hampshire. His interest in environmental economics deepened when he entered an Agriculture and Resource Economics Master's program at the University of Massachusetts-Amherst. Metcalf says, "that was when I really learned a lot of the theory and got to see more broadly all of the interesting issues in this field."

Metcalf's interest in tax policy and public finance developed during his Ph.D. at Harvard University. He spent several years working on projects in the area of state and local public finance, particularly the interaction between the federal tax system and state and local budgets. While working as a graduate student at the National Bureau for Economic Research, Metcalf met a fellow researcher and Ph.D. student, Kevin Hassett. "Kevin and I started talking, and we realized there were some really interesting questions to tackle around how the federal tax code affects energy policy. We wrote a number of papers in that field, and I've stayed in this field ever since," says Metcalf.

Bridging the gap between academia and policy, Metcalf wrote a book on carbon taxation – "Paying for Pollution: Why a Carbon Tax is Good for America" – that he intended for wider audiences. Metcalf recalls, "I'd spent a fair amount of time talking with policy members in DC, either with members of Congress directly or with their staff. I envisioned the reader of my book as a Congressional Aide. His or her boss would come in and say, 'Hey what is this thing about a carbon tax? What do I need to know?' The aide would go and pull my book off the shelf. It was a new challenge and I enjoyed doing it."

Metcalf recognized the value of providing policymakers with clear, factual assessments to ground their environmental policies. "Policymakers, whether in the Administration or on the Hill, have always been interested in engaging with academics to get new ideas, see if their ideas have problems, or find hidden pitfalls they might not be aware of. There's any number of lobbyists working for particular interest groups that are happy to meet with members of Congress, their staffs, members of the White House, or the Treasury. But these people have a particular point of view based on who their employer is. Academics have a more arms-length relationship with the issues and can be a little more objective. This is often very helpful for policymakers," Metcalf says.

While at the Treasury in 2011 and 2012, Metcalf oversaw the U.S. government's involvement in all multilateral environment, climate, and energy funds. He led the Treasury team at annual international climate negotiation meetings, including at the United Nation's annual

Conference of the Parties (COP). "Part of what is going on in international climate change committees is you're talking about making commitments to reduce emissions, but you're also talking about providing finance for developing countries to help them do that mitigation. Anything involving finance fell under the purview of the Treasury," Metcalf says.

Metcalf was integral in developing a framework for the Green Climate Fund at COP 17. Looking back, Metcalf remembers, "that was a really difficult negotiation. You have developing countries that want as much money as possible to go into the fund with as few strings attached as possible. Some of that is understandable; they don't want to be micromanaged by developed countries. But on the other hand, you have developed countries that want to make sure we get the biggest bang for our buck and make sure their money isn't being wasted. I also would have to be able to go back to Congress and make sure Congress would give us the funding to put in the fund. It was a real challenge to thread the needle there."

Despite his extensive experiences in academia and policy making, Metcalf remembers his time as a professor most fondly: "The most impactful role has been being a teacher. In particular, I've loved teaching graduate microeconomics. It's an incredible delight when you see [students] get that 'Aha!' moment." Looking forward to his work at CEEPR, Professor Metcalf is excited to conduct research with his new MIT colleagues on how climate policies are likely to affect the broader economy. "I think where CEEPR is heading now is quite exciting. If I can contribute to that, that's great," he anticipates.

Gilbert E. Metcalf (2022), "Five Myths About Carbon Pricing", CEEPR WP-2022-016, MIT, October 2022.

Research.

Five Myths About Carbon Pricing

By: Gilbert E. Metcalf

Among economists, there is near unanimous consensus that a necessary component of any portfolio of policies to address climate change includes carbon pricing. However, this sentiment is not shared nearly as widely among policymakers and the general public. Much of the political opposition to carbon pricing and carbon taxes in particular is driven by vested interests in fossil fuel production and the obfuscation of scientific facts. However, some of the opposition is driven by confusion or misunderstanding of the policy impacts. This paper addresses those misunderstandings and focuses in on five myths: 1) that a carbon price will hurt economic growth; 2) that carbon pricing will kill jobs; 3) that a carbon tax and cap and trade program have the same economic impacts; 4) that we can't achieve carbon reduction targets with a carbon tax; and 5) that carbon pricing is regressive. I find that all five of these statements are false.

I begin by addressing the first myth, that carbon pricing will hurt economic growth. Undeniably, any program to reduce pollution will have economic costs. But how large are the costs? One way to assess this is to look at the impact of existing carbon taxes on economic growth. I analyze the results of a forthcoming paper I wrote with Harvard economist James Stock in which we examine carbon taxes employed in 15 European countries. We estimate the dynamic effect on GDP growth of the unexpected component of the carbon tax using a local projection method. Our study produces impulse response functions (IRF's) for a counterfactual of a one-time permanent increase in the carbon tax by $40, for a tax that covers 30% of the country's emissions. We find no significant impact on GDP growth, either in a positive or a negative direction (see Figures 1-3 on the following page), which is consistent with existing theory that long run GDP growth rates are driven more by fundamentals than by policy variables such as tax rates. I conclude that, based on the burgeoning literature on the economic impact of carbon taxes, there is little evidence that carbon taxation has a significant adverse effect on economic growth.

I turn next to the second carbon pricing myth - that carbon pricing is a job killer. Once one accepts the view that carbon pricing does not hurt economic growth, it is not surprising to learn that it doesn't adversely impact overall employment either. The results I referenced while refuting the previous myth support this view. Similarly, an analysis of the employment effects of the British Columbia carbon tax by a Canadian

researcher found modest positive impacts on employment. While aggregate impacts were small, that paper found significant job shifting from carbon intensive to non-carbon intensive sectors. A fall in carbon intensive sector employment is not surprising. That the tax does this without affecting overall employment is encouraging, though the analyses to date have not addressed the transitional costs of making the shift.

A third myth is that carbon taxes and cap and trade programs are equivalent. Carbon pricing entails raising the marginal cost of producing goods that burn fossil fuels in their production, therefore aligning private and social costs. Cap and trade programs and carbon taxes are dual instruments. However, important differences between the two carbon pricing systems remain. The two systems differ in three important ways. First, since a cap and trade system fixes emissions, prices fluctuate with economic conditions. These fluctuations complicate life for businesses focused on long-lived capital-intensive project investments. A carbon tax provides price certainty that provides some reassurance for project planning. Second, most countries have well-functioning tax collection systems and already impose fuel excise taxes. Thus, imposing a carbon tax involves little incremental investment in administrative systems. In contrast, cap and trade systems generally requires an entirely new administrative agency to create and track allowances, hold auctions, and develop rules to prevent fraud and abuse. The third and by far the most important difference is in how the two carbon pricing systems interact with other carbon reduction policies. Complementary policies tend to relax binding caps. Therefore, depressed allowance prices in emission trading systems may help explain why cap and trade system tend to have lower prices than the tax rates of carbon tax systems.

I also refute myth 4: that carbon taxes are incompatible with emissions reduction targets. In a 2009 paper, I sketched out an initial way to construct a carbon tax to achieve emission reduction goals. I followed that up in a 2020 paper with a more detailed proposal for a U.S. Emissions Assurance Mechanism (EAM) to include as part of carbon tax legislation. The EAM proposal creates a target emission reduction focusing on cumulative emission reductions relative to the baseline over the fifteen-year period. This reflects the fact that greenhouse gas emissions are a stock rather than a flow pollutant. Having a target based on a particular future year means many different emission pathways with different cumulative emissions could be consistent with that target. While this approach does not guarantee that emission reduction targets are hit, it provides some assurance that targets will be met. Just as one can add carbon tax elements to a cap and trade program to control prices, one can add cap and trade elements to a carbon tax to provide greater assurance of hitting desired emission reduction targets. Therefore, a carbon tax can clearly be made to support political commitments to emission reduction goals.

I conclude by challenging the fifth myth: that carbon pricing is regressive. Carbon pricing is, to a large extent, a tax on energy consumption. It has long been understood that household spending on energy is a larger fraction of income for lower income households than for higher income households. Thus, the logic goes, carbon pricing is regressive since it raises the cost of energy which is a higher share of household budgets for low-income households. What this ignores is the fact that taxes have impacts on household income sources (wages, transfers, and capital income). Economists refer to the former as "uses side impacts" and the latter as "sources side impacts." We can decompose the distributional impacts of a tax reform into source and use side influences. I provide a theoretical framework to motivate a decompsition analysis I did in a 2011 paper with colleagues at MIT. Our paper provides an example of such a decomposition by analyzing a carbon pricing policy where the revenue from the policy is distributed in a way that does not enter household utility. Our results suggest that the conventional view of a carbon tax as regressive must be re-examined, given the importance of source-side impacts. In fact, analyses focusing on a U.S. carbon tax suggest the tax would be progressive even before considering how to rebate the revenue.

—Summary by Diana Degnan

(note that all referenced prior work can be found in the full paper on the CEEPR website)

Figure 1. Real Carbon Tax Rates Over Time.

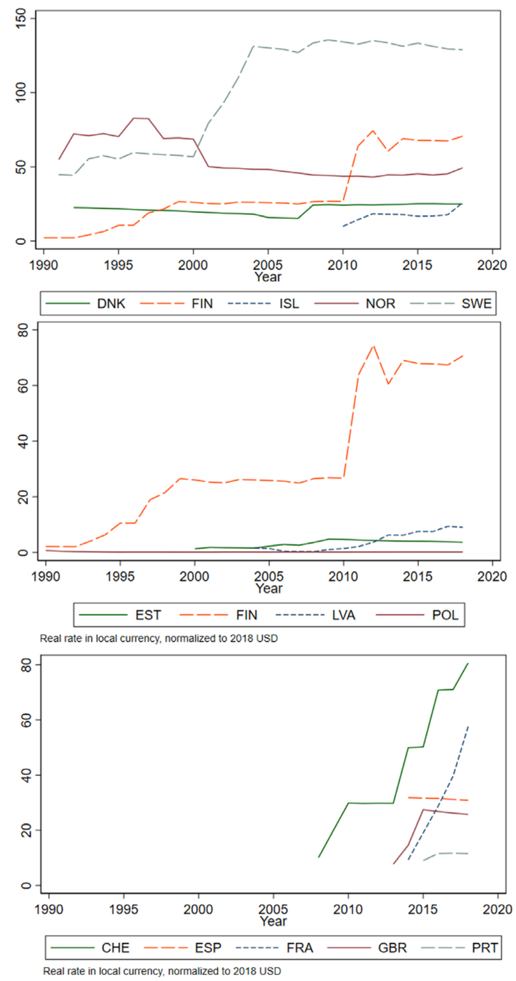


Figure 2. Carbon Tax Impact on GDP Growth.

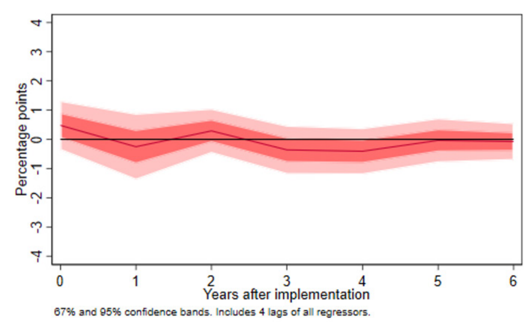
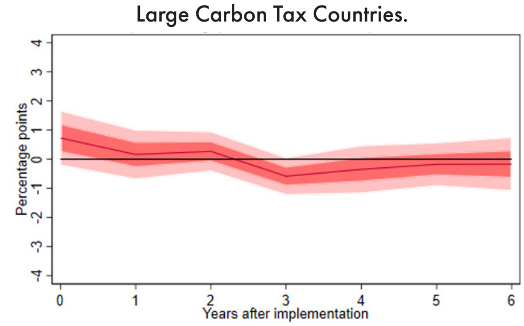


Figure 3. Carbon Tax Impact on GDP Growth for Large Carbon Tax Countries.



Research.

The Macroeconomic Effects of a Carbon Tax to Meet the U.S. Paris Agreement Target: The Role of Firm Creation and Technology Adoption

By: Alan Finkelstein-Shapiro and Gilbert E. Metcalf

The potential adverse effects of taxing carbon emissions on firms, job creation, employment, and aggregate economic activity are a central theme in current discussions of environmental policy. This topic has taken on greater importance with the Biden Administration's April 2021 Paris Agreement commitment to reduce greenhouse gas pollution by roughly 50% from 2005 levels by 2030 – an ambitious target. Given emission reductions between 2005 and today, a 35% reduction from current levels is needed to achieve the Biden Administration's target.

We analyze the effects of a carbon tax in a general equilibrium framework with labor search frictions, an endogenous production structure, and pollution externalities. We extend existing analyses by introducing pollution externalities and a focus on how firms' decisions over entry and technology adoption are influenced by the carbon tax. Our model incorporates two margins of adjustment that have been jointly absent in existing quantitative analyses of carbon taxes: (1) firm entry and (2) firms' choices over (polluting vs. green) production technologies.

These margins are important for a comprehensive assessment of the aggregate impact of carbon taxation for at least two reasons. First, the regulatory costs associated with the environmental policy not only affect the labor and capital decisions of existing firms—an intensive margin of adjustment to a carbon tax—but also the incentive of potential firms to enter the market in the first place. In turn, firm entry and exit has direct implications for job creation and aggregate economic activity. Second, a carbon tax shapes firms' relative costs of production and, in doing so, influences the relative merits of adopting green technologies - an extensive margin of adjustment to this tax.

Our model uses a carbon tax scheme designed to reduce long-run emissions by 35% and rebate carbon-tax revenue lump-sum to households. We find that this policy can generate mild, positive, long-run effects on consumption, output, employment, and labor force participation; negligible long-run adverse effects on unemployment; and a long-run increase in both the number and the share of firms that adopt green technologies. In our simulations, the 35% reduction is achieved in five years, making the Biden Administration's 2030 target feasible. Moreover, the transition path to an economy with lower emissions need not entail short-term reductions in consumption, output, or labor force participation. Since some of the output increase is used for fixed costs of adopting green technologies, increases in consumption or output does not necessarily imply welfare increases.

The absence of significant adverse aggregate effects from a carbon tax are at odds with those documented in existing quantitative studies on the macroeconomic effects of carbon taxes in literature. Indeed, these studies, which abstract from firms' ability to adopt different technologies in response to policy, find that for similar carbon tax-induced reductions in emissions, a carbon tax has non-trivial negative effects on labor, labor income, consumption, and output. Our analysis

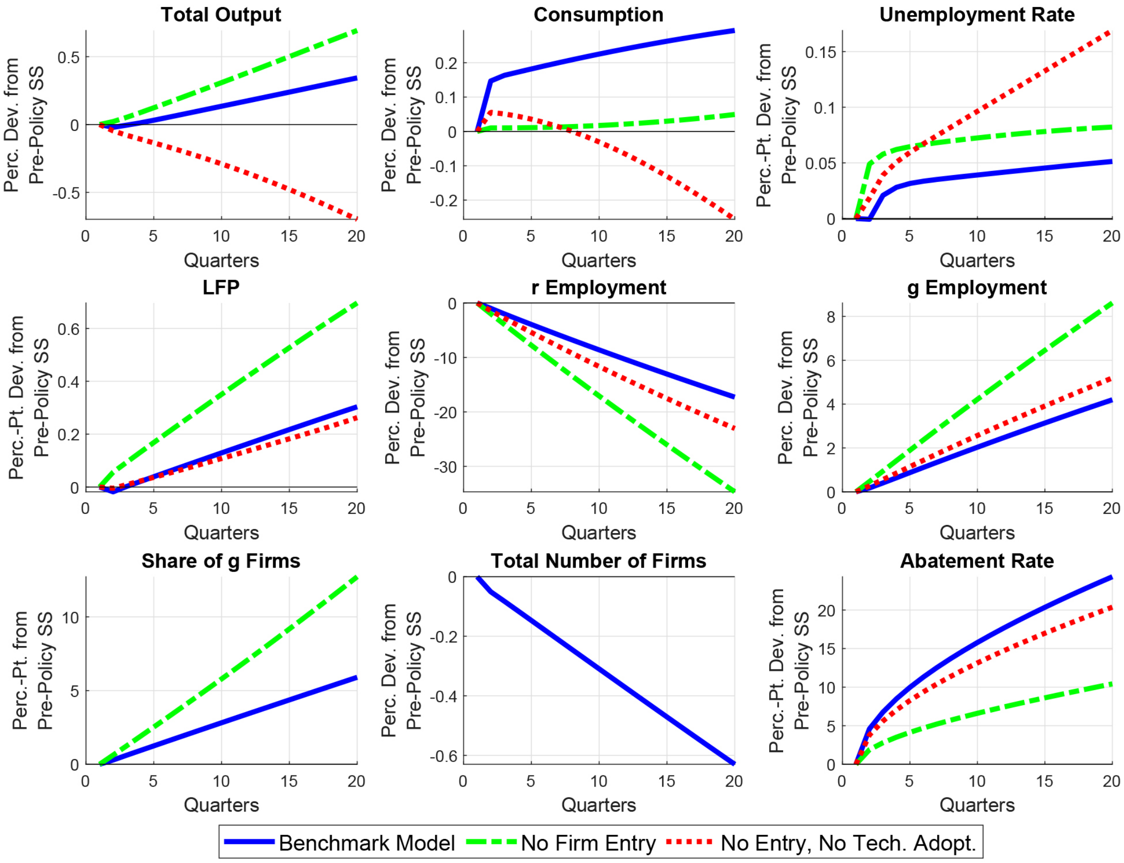


Figure 1. Transitional Dynamics in Benchmark Model and Model Variants (Gradual Reduction in Emissions via Carbon Tax)

In the presence of search and matching frictions, costly firm creation, and costly technology adoption, the transition path to the new steady state may take time and could potentially entail short-term employment, consumption, and output costs. We model the carbon tax to rise linearly from zero to its steady-state value at the end of 20 quarters (5 yrs). We show the transition path of (1) the benchmark model (solid blue line), (2) the benchmark model variant without firm entry (dashed-dotted green line), and (3) the benchmark model variant with neither firm entry nor technology adoption (dotted red line).

Note: Perc. Dev. denotes percent deviations and Perc.-Pt. Dev. denotes percentage-point deviations.

differs by stressing the role of firm entry and green technology adoption decisions in shaping the net positive effects of a carbon tax on aggregate outcomes and the limited adverse effects on unemployment. Specifically, firms' ability to choose green production technologies leads to policy-induced endogenous changes in the economy's technological (regular vs. green) composition of aggregate production—an effect that is absent in models that abstract from green technology adoption. This technological composition effect is the central mechanism behind the positive effects of a carbon tax on consumption and output.

In our model with endogenous technology adoption decisions, along with firm entry and exit, a carbon tax triggers endogenous changes in both the market structure and in the economy's technological composition of production—that is, the prevalence of polluting versus green production technologies in the aggregate production process. These policy-induced endogenous changes improve the economy's average firm productivity and cost profile and, in doing so, lead to improved labor market and macroeconomic outcomes. The heart of our model, and a key finding of our analysis, is that endogenous changes in the economy's dirty-clean technological composition of production that arise as an indirect result of taxing emissions, can play a decisive role in shaping labor-market and macroeconomic outcomes in response to a carbon tax. These changes can potentially generate positive (albeit small) macroeconomic and welfare effects.

—Summary by Diana Degnan

Alan Finkelstein-Shapiro and Gilbert E. Metcalf (2022), "The Macroeconomic Effects of a Carbon Tax to Meet the U.S. Paris Agreement Target: The Role of Firm Creation and Technology Adoption", CEEPR WP-2022-013, MIT, September 2022.

Reyer Gerlagh, Matti Liski, and Iivo Vehviläinen (2022), "Rational Rationing: A Price-Control Mechanism for a Persistent Supply Shock", CEEPR WP-2022-014, MIT, October 2022.



Research.

Rational Rationing: A Price-Control Mechanism for a Persistent Supply Shock

By: Reyer Gerlagh, Matti Liski, and Iivo Vehviläinen

Administratively set price caps are part of the standard design in electricity (wholesale) markets, with the purpose of restoring the equilibrium through rationing in rare situations in which the supply fails to meet the demand. Such caps are typically high, $9,000/MWh during the Texas power crisis, and intended to bind only in short-lasting events such as production or transmission outages. Once the glitch is resolved, the market is expected to return to the status quo ante. For example, both private and industrial consumers' technology choices or longer-term contracts based on the prevailing spot price can remain unaltered.

The shock due to the conflict in Ukraine is different: Supplies are not expected to return back to normal soon, the shock is persistent. In contrast to a one-time anomaly, the demand is expected to adjust but with a delay as not all consumers respond to prices in real time – the short-term demand is sticky in electricity markets. Due to the stickiness, there is a misallocation in the market that cannot be immediately resolved. We show that the efficient intervention corrects for the misallocation by introducing an aggregate "demand response" through rationing not only when the market fails to clear but whenever the market price exceeds the social value of consumption. In our quantification, the efficient policy implements a temporary price cap well below the administrative price caps currently in place.

A persistent shock means persistent over-consumption by the sticky consumers. The optimal policy regulates the price of consumption at a level that trades off the surplus from non-sticky (i.e., price-responsive) vs.

sticky parts of the demand, together with a rationing protocol to implement the price cap. This non-market mechanism has the same general motivation as, e.g., in Joskow & Tirole (2007), i.e., a market imperfection, but there is an important difference: We introduce the price-control mechanism for all parties in the market. The approach seems unavoidable, e.g., in exchanges where trading takes place with a uniform price without powers to ration consumers individually. In such a situation, we find that the optimal price cap needs to be time-varying, responding to changes in market demand. In particular, the cap starts binding in response to a persistent supply shock, rises to a higher level as the demand adjusts to the shock, and finally stops binding when the demand has adjusted. In this sense, the cap is temporary.

We calculate the social value of rationing using basic price theory. We illustrate it in a specific context, the Nordic market for wholesale electricity (see Figure below). The supply and demand bids to the exchange contain information on the social value of rationing, and they form the basis for calculating the optimal price cap, hour by hour. The bids indicate how the demand changes in response to the shock which is essential for the optimal adjustment of the price cap. In any given hour, if the clearing price rises above the optimal price cap, the mechanism implements the cap by an elimination procedure for the demand bids to obtain the required rationing. We quantify the mechanism using the actual bids in 2019-2022 as data.

We find a number of strong predictions for the optimal intervention. First, in persistent supply crises, the optimal price cap is only a fraction of the actual harmonized EU price cap. The rudimentary reason for the difference is that the harmonized price cap pays no attention to the welfare gains from a demand response achieved through rationing. The mechanism has no bearing on market clearing in normal times; it gains traction only after the onset of the supply crises in winter 2021-2022. Second, the rationed quantities are minuscule in relation to total volumes in the market suggesting that executing the physical rationing in regions that participate in trading should not be a major hurdle. Third, the intervention has strong distributional implications; a small demand reduction leads to a large price drop. In our stress tests, the policy leads to transfers from producers to consumers measured in billions of euros over a short period of time, although it should be borne in mind that our theory is justified by efficiency and not by redistribution objectives. Finally, the mechanism can be adopted without reforming the market clearing rules in place.

Cited reference: Joskow, P. and Tirole, J. (2007). Reliability and Competitive Electricity Markets. The RAND Journal of Economics 38(1): 60-84.

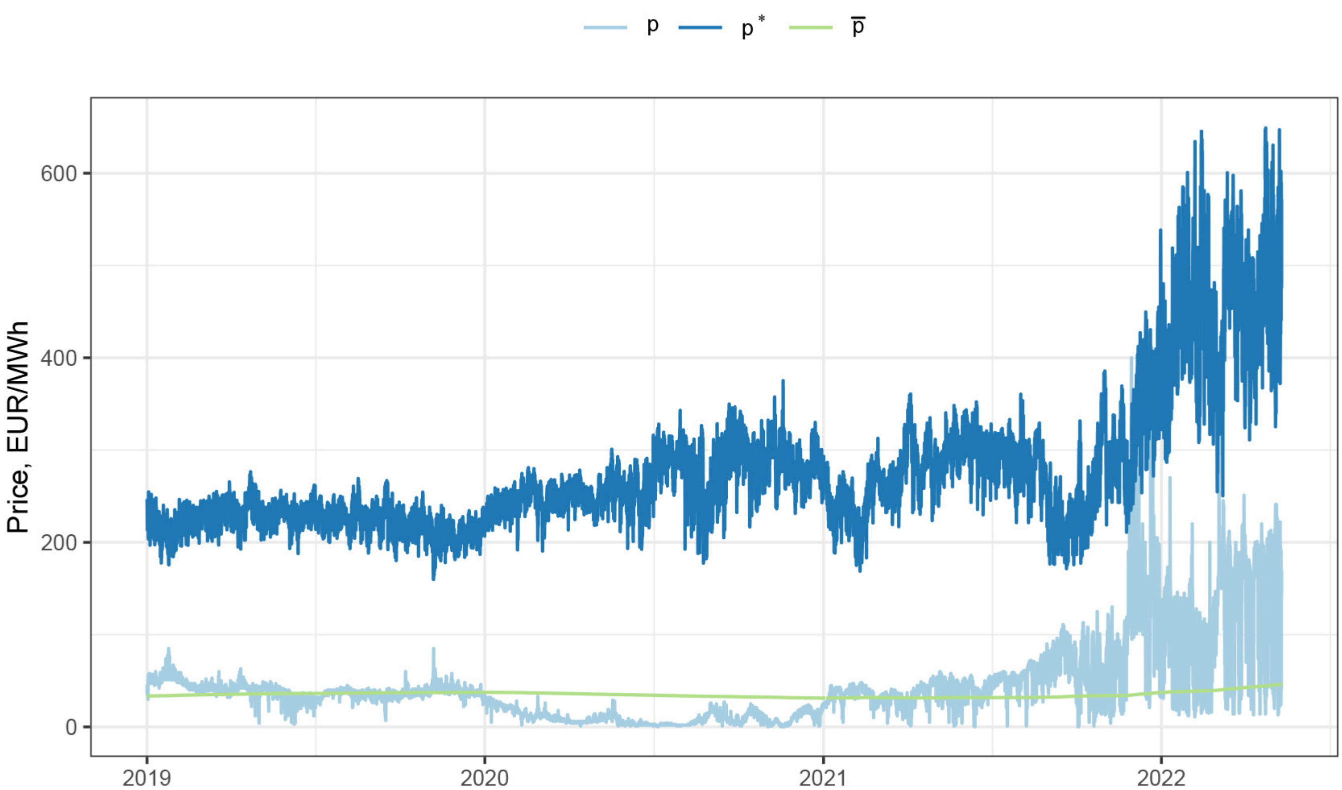


Figure 1. Nordic Market Price, Price Cap, and the Reference Price

Note: Optimal price cap (dark blue), market price (light blue), and reference price (green) from Jan. 1, 2019 to May 10, 2022. The reference price is a rolling three-year average of the historical market prices.

Research.

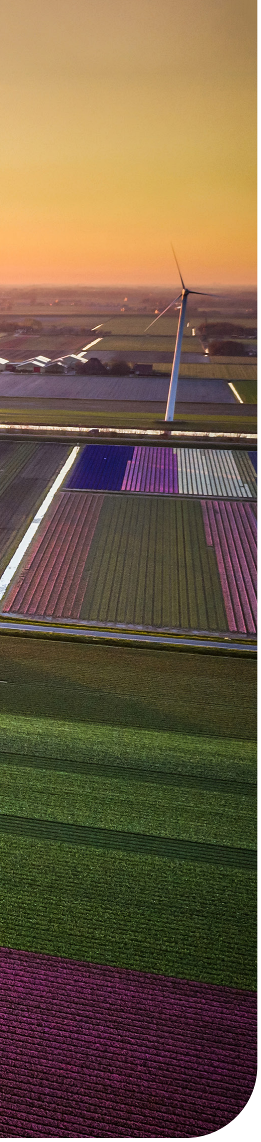
Electricity Retail Rate Design in a Decarbonizing Economy: An Analysis of Time-of-Use and Critical Peak Pricing

By: Tim Schittekatte, Dharik Mallapragada, Paul L. Joskow, and Richard Schmalensee

Currently, U.S. residential and small commercial electricity consumers are typically billed based on nearly flat rates, i.e., a constant price per kWh of electricity consumed accounts for most of their bills. Ongoing developments in the power system, both on the supply and demand sides, increase the efficiency loss of not transmitting time-varying prices and "scarcity" conditions in wholesale markets to end users. However, the adoption of retail rates that vary with spot wholesale prices has lagged far behind the deployment of smart meters with the necessary capabilities in the U.S. In practice, the pass-through of widely varying hourly spot prices is not popular among consumers; consumers highly value price predictability and sudden increases in bills often becomes a political problem. In this work, we investigate the question of how to better reflect the time-varying conditions in the wholesale electricity markets in residential and small commercial retail rates while balancing consumer preference for price predictability and bill stability.

We focus on two popular "second-best" rate designs: time-of-use rates (TOU) and critical peak pricing (CPP). TOU rates are predefined, e.g., at least a year ahead, and calibrated on historical price data. Typically, the TOU rate coefficients differ by season, type of day (workdays or weekends), and/or time of the day (e.g., peak, shoulder, or off-peak). Under TOU rates consumers are given predictable incentives to shift or reduce their demands and are protected from unexpected price shocks. Faruqui et al. (2020) report that nearly 400 TOU rates have been tested in pilots globally, but that in 2018 only 4% of residential customers were on TOU rates in the U.S. CPP is designed to induce reductions in consumption, either through demand shifting or conservation during hours with the highest wholesale prices, often associated with the highest net demand days of the year. During a critical peak pricing event, announced on short notice, a consumer enrolled in a CPP plan is then exposed to a significantly increased price for the duration of the event (typically not more than a few hours). An alternative or additional feature is for consumers to allow for overridable remote load control during critical peak pricing events. In exchange for their consent, consumers receive a discount on their electricity bill.

The existing literature has been skeptical about the value of TOU rates, typically finding that they capture only about one-fifth of the efficiency gains of dynamic retail pricing that passes along wholesale spot price. We introduce alternative criteria to assess the performance of TOU rates, complemented or not with CPP. The proposed criteria are tailored



Tim Schittekatte, Dharik Mallapragada, Paul L. Joskow, and Richard Schmalensee (2022), "Electricity Retail Rate Design in a Decarbonizing Economy: An Analysis of Time-of-Use and Critical Peak Pricing", CEEPR WP-2022-015, MIT, October 2022.

to a context with increasing penetration of both intermittent generation and easily shiftable loads within a day such as the charging of electric vehicles and the cycling of heat pumps, air conditioners, and electric water heaters. The criteria can be split up in two groups: time series analysis and simulation models.

With regards to the time series analysis, in addition to the computation of the annual (standard) Pearson correlation between spot prices and the alternative rates, as relied upon in the previous literature, we introduce the use of the daily Spearman rank correlation between spot pricing and the alternative rates to better reflect incentives to shift consumption between hours of the day. The Pearson correlations reflect absolute wholesale price variations over time while the Spearman rank correlations reflect relative wholesale price variations between hours within a day. For the simulation models, in addition to representing load with independent hourly demand functions, as in the prior literature, we model load shifting with a cost-minimizing optimization model.

We compute results for each criterion using data from three US power systems for a period between 2011-2020: CAISO, ERCOT and ISO-NE. CAISO has a high penetration of grid-based solar PV, ERCOT has a high wind penetration, and ISO-NE is a gas-dominated system without significant penetration of grid-base intermittent renewables. We can think of ISO-NE as a control representing the thermal-dominated systems upon which many of the previous papers relied. Different TOU rate designs are tested, complemented or not by CPP. The TOU rates for a particular year are calibrated based on the preceding three years of wholesale prices. CPP is proxied by the replacement of the TOU rates by the observed wholesale price for a limited number of the highest priced hours per year. In that sense, we assume full consumer response to these high prices, which would likely require load control in practice.

The results from the time series analysis for CAISO SP15 and ERCOT Houston Hub confirm that the out-of-sample annual Pearson correlations between TOU rates and spot prices are low (averaging 0.3-0.5) but show that these significantly improve when passing through a limited number of high-priced "scarcity" hours replacing the respective TOU rate in those hours (averaging 0.6-0.8). This reinforces the usefulness of CPP to deal with scarcity events. An important finding is that out-of-sample daily Spearman rank correlations of TOU rates and spot prices are relatively high (averaging 0.7-0.8) and that rank correlations are especially high during summer when load is highest for all three systems (up to 0.9). This implies that, conditional upon power system characteristics and their specific design, TOU tariffs can provide a high proportion of socially efficient load-shifting incentives.

The simulations confirm that well-designed TOU rates can reasonably replicate the load-shifting incentives of spot pricing (up to 60-70% of the potential). These results hold especially true for CAISO SP15 and ERCOT Houston Hub, systems with relatively high penetrations of wind and solar. The results for ISO-NE, acting as a control, indicate that these findings are to a certain extent conditional upon changes in the supply mix. However, we find that the relative performance of TOU rates compared to spot pricing is stronger impacted by how flexible electricity consumption is characterized.

Important peak pricing events often occur within TOU periods of relative high prices. Accordingly, TOU rates alone give flexible load good incentives to respond by reducing load during scarcity price events. In any case, there is significant value in mobilizing additional demand reduction during those moments; complementing TOU rates with a CPP program as well further increases efficiency. With regards to the implementation of a CPP program, we recommend promoting load control programs where, e.g., at the reward of a discount on the bill, a third party (LSE or other) can regulate an appliance for a limited period. We tend to think that load control with an option to opt out (e.g., overriding load control and possibly giving up the price discount) will perform better than having consumers react to an unexpected increased rate during scarcity events.

We conclude that well-designed TOU rates, especially when accompanied with a CPP program involving load control during infrequent scarcity price events, are more attractive from an efficiency perspective than the existing literature suggests. As a result, TOU rates accompanied by CPP offer a valuable intermediate step towards improved electricity retail rates that balance efficiency considerations with consumer/political pressures for price predictability and bill stability. An important question, which we plan to investigate, is whether the presented results still hold in systems with significantly higher penetration of intermittent wind and solar generation and storage.

Jonas Martin, Emil Dimanchev, and Anne Neumann (2022), "Carbon Abatement Costs for Hydrogen Fuels in Hard-to-Abate Transport Sectors and Potential Climate Policy Mixes", CEEPR WP-2022-017, MIT, November 2022.

Research.

Carbon Abatement Costs for Hydrogen Fuels in Hard-to-Abate Transport Sectors and Potential Climate Policy Mixes

By: Jonas Martin, Emil Dimanchev, and Anne Neumann

Additional climate policy efforts are needed for "hard-to-abate" sectors such as heavy-duty trucking, shipping, and aviation, in order for governments to deliver on net zero emission targets and limit global warming within 1.5°C. While electrification plays a primary role in 1.5°C and 2°C decarbonization pathways for light vehicles, other sectors – aviation, parts of heavy-duty road transport, and maritime transport – may be impractical or very difficult to electrify, even in the long term. One abatement strategy in these sectors is the replacement of fossil fuels with renewable hydrogen fuels.

To design climate policy, governments rely on estimates for the costs of alternative abatement options. Abatement costs allow decision makers to understand how alternative solutions compare, how much a policy will cost, or what options can be implemented within a given budget. However, it is currently unclear how economically feasible different hydrogen fuels are as abatement options in the trucking, shipping, and aviation sectors. Martin, Neumann, and Ødegård (2022, see page 6) showed that the hydrogen fuels are far from cost competitive on a total cost of ownership basis.

This paper estimates the abatement costs of replacing fossil fuel use in freight trucking, shipping, and aviation with renewable hydrogen fuels. Specifically, this work focuses on long-haul trucking, short-sea shipping and short-haul aviation. We use a detailed bottom-up technoeconomic cost model. The model's high level of detail allows us to compare

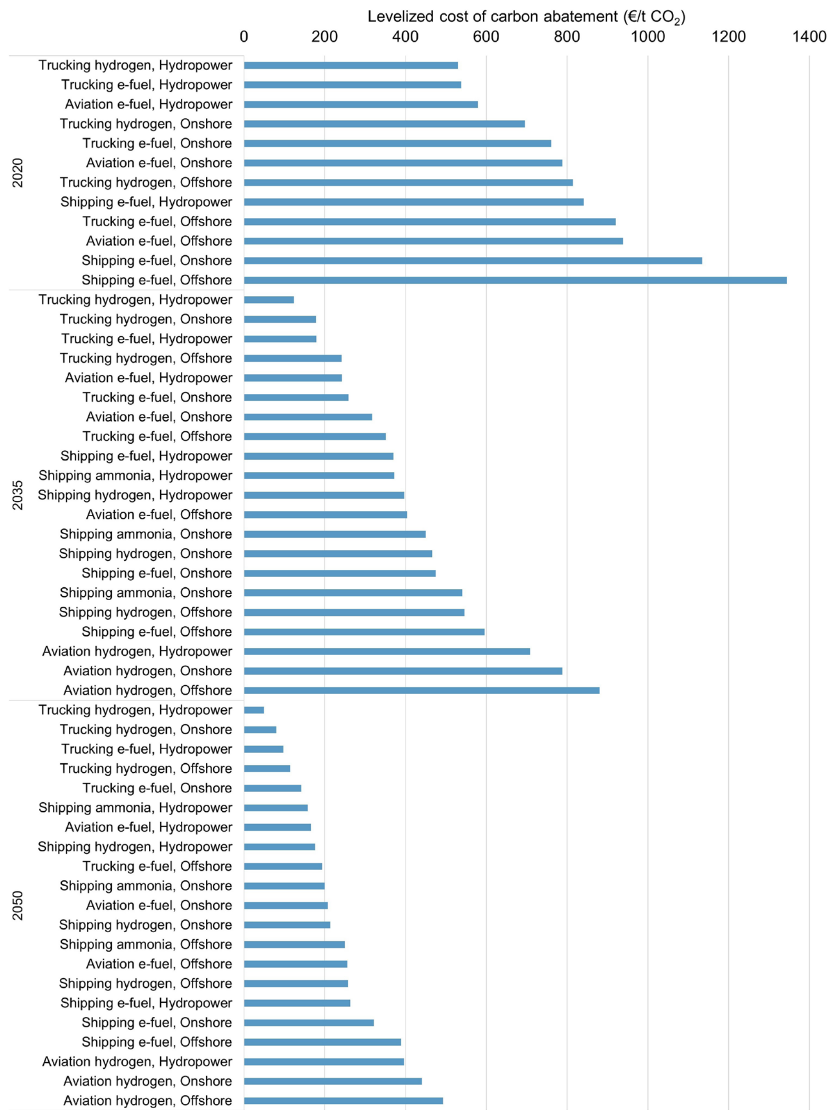


Figure 1. Abatement cost in ascending order for the renewable hydrogen fuels produced by onshore wind, hydropower and offshore wind and used in three transport modes for 2020, 2035 and 2050.

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abatement across sectors (trucking, shipping, and aviation), fuels (hydrogen, ammonia and e-fuels), and across time (2020, 2035, 2050). Our estimates across these dimensions are internally consistent and allow inter-sector and inter-fuel comparisons.

We quantify abatement costs by calculating the Levelized Cost of Carbon Abatement (LCCA) across sectors and fuels. Our LCCA estimates can be interpreted as long-run marginal abatement costs (covering a horizon long enough to allow changes in the capital stock). From a policy perspective, our LCCAs represent the carbon price required for an abatement action to break even, or the carbon price at which an abatement action may be assumed to be taken. This paper also explores how subsidies on different parts of the hydrogen value chain can contribute to reducing clean transport costs. Finally, we estimate how different combinations of carbon pricing and hydrogen subsidies may impact the competitiveness of clean transport.

We estimate abatement costs for hydrogen fuels of €530-1,345/tCO_2 in 2020. Comparing across sectors and electricity sources, we find the lowest abatement costs in 2020 in the trucking sector, equal to €530/tCO_2 for hydrogen and €760/tCO_2 for e-fuel, both produced from hydropower. Trucking remains the lowest cost abatement out of the options we studied also in the following years until 2050 (if electricity comes from hydro or onshore wind). This is due to the fact that the trucking sector exhibits the lowest cost premium on a €/tkm basis and the relative emission intensity of diesel-powered trucks. This implies that trucking could serve as an early niche market for the development of hydrogen technologies that could drive cost reductions in electrolysis, having in mind the fast developments in battery truck technology.

Turning to technological differences within sectors, abatement cost for e-fuels in trucking are higher than for hydrogen because a comparably low vehicle Capex cannot offset higher fuel cost and a lower engine efficiency. In shipping, from 2030 and beyond, ammonia exhibits the lowest abatement cost, starting with €538/tCO_2 in 2030 and reaching €200/tCO_2 in 2050. In aviation, e-fuel use, which costs €788/tCO_2 and reaching €208/tCO_2 in 2020, is a cheaper abatement option compared to hydrogen all the way to 2050.

For policy, this analysis suggests that if carbon prices remain at current levels (€84/tCO_2 in Europe in the first half of 2022 and generally lower in other jurisdictions), renewable hydrogen fuels will require additional governmental incentives. Based on our results, such incentives appear necessary at multiple points on the value chain. We show that subsidizing the €/kg cost of hydrogen has a relatively large impact out of the interventions we tested, which suggests that innovation policy targeting hydrogen costs could be seen as a focal point of future hydrogen policy.

In 2021, the U.S. House of Representatives proposed a tax credit for hydrogen fuel equivalent to a subsidy of $3/kg. Our results show that with current costs, hydrogen use in trucking would still require a high carbon price or other incentives to be cost-competitive. However, potential cost declines of components and processes across the value chains alleviate the need for subsidies. By 2035, the cost model we use estimates a potential hydrogen cost of €3/kg. At that point, either a carbon price of €200/tCO_2, or a lower carbon price paired with a hydrogen subsidy could be enough to incentivize hydrogen adoption.

E-fuel costs are more sensitive than other hydrogen fuels to fuel production subsidies.

In Memoriam.

Professor Emeritus Richard "Dick" Eckaus, who specialized in development economics, dies at 96

By: Danna Lorch | Department of Economics

Richard "Dick" Eckaus, Ford Foundation International Professor of Economics, Emeritus, in the Department of Economics, died on Sept. 11 in Boston. He was 96 years old.

Eckaus was born in Kansas City, Missouri on April 30, 1926, the youngest of three children to parents who had emigrated from Lithuania. His father, Julius Eckaus, was a tailor, and his mother, Bessie (Finkelstein) Eckaus helped run the business. The family struggled to make ends meet financially but academic success offered Eckaus a way forward.

He graduated from Westport High School, joined the United States Navy, and was awarded a college scholarship via the V-12 Navy College Training Program during World War II to study electrical engineering at Iowa State University. After graduating in 1944, Eckaus served on a base in New York State until he was discharged in 1946 as lieutenant junior grade.

He attended Washington University in St. Louis, Missouri, on the GI Bill, graduating in 1948 with a master's degree in economics, before relocating to Boston and serving as instructor of economics at Babson Institute, and then assistant and associate professor of economics at Brandeis University from 1951 to 1962. He concurrently earned a PhD in economics from MIT in 1954.

The following year, the American Economic Review published "The Factor Proportions Problem in Economic Development," a paper written by Eckaus that remained part of the macroeconomics canon for decades. He returned to MIT in 1962 and went on to teach development economics to generations of MIT students, serving as head of the department from 1986 to 1990 and continuing to work there for the remainder of his career.

The development economist Paul Rosenstein-Rodan (1902-85), Eckaus' mentor at MIT, took him to live and work first in Italy in 1954 and then in India in 1961. These stints helping governments abroad solidified Eckaus' commitment to not only excelling in the field, but also creating opportunities for colleagues and students to contribute as well — occasionally in conjunction with the World Bank.

Longtime colleague Abhijit Banerjee, a Nobel laureate, Ford Foundation International Professor of Economics, and director of the Abdul Latif Jameel Poverty Action Lab at MIT, recalls reading a reprint of Eckaus' 1955 paper as an undergraduate in India. When he subsequently arrived at MIT as a doctoral candidate, he remembers "trying to tread lightly and not to take up too much space," around the senior economist. "In fact, he made me feel so welcome," Banerjee says. "He was both an outstanding scholar and someone who had the modesty and generosity to make younger scholars feel valued and heard."

The field of development economics provided Eckaus with a broad, powerful platform to work with governments in developing countries — including India, Egypt, Bhutan, Mexico, and Portugal — to set up economic systems. His development planning models helped governments to forecast where their economies were headed and how public policies could be implemented to shift or accelerate the direction.

The Government of Portugal awarded Eckaus the Great-Cross of the Order of Prince Henry the Navigator after he brought teams from MIT to assist the country in its peaceful transition to democracy following the 1974 Carnation Revolution. Initiated at the request of the Portuguese Central Bank, these graduate students became some of the most

"Dick was a stalwart supporter of energy-related research at MIT, starting with his work with the Energy Lab in the 1970s. At CEEPR, Dick stepped in at a particularly difficult time for the Center in the early 1990s to become director. He was a constant at CEEPR workshops all the way to the pandemic, always making insightful comments and keeping our attention on what was most important.

We will be forever grateful for his contributions to our program and to MIT and the world more generally."

—Christopher Knittel, Director of MIT CEEPR
Email to the CEEPR community. September 30, 2022.

prominent economists of their generation in America. They include Paul Krugman, Andrew Abel, Jeremy I. Bulow, and Kenneth Rogoff.

His colleague for five decades, Paul Joskow, the Elizabeth and James Killian Professor of Economics at MIT, says that's no surprise. "He was a real rock of the economics department. He deeply cared about the graduate students and younger faculty. He was a very supportive person."

Eckaus was also deeply interested in economic aspects of energy and environment, and in 1991 was instrumental in the formation of the MIT Joint Program on the Science and Policy of Global Change, a program that integrates the natural and social sciences in analysis of the global climate threat. As Joint Program co-founder Henry Jacoby observes, "Dick provided crucial ideas as to how that kind of interdisciplinary work might be done at MIT. He was already 65 at the time, and continued for three decades to be active in guiding the research and analysis."

Although Eckaus retired officially in 1996, he continued to attend weekly faculty lunches, conduct research, mentor colleagues, and write papers related to climate change and the energy crisis. He leaves behind a trove of more than 100 published papers and eight authored and co-authored books.

"He was continuously retooling himself and creating new interests. I was impressed by his agility of mind and his willingness to shift to new areas," says his oldest living friend and peer, Jagdish Bhagwati, Columbia University Professor of Economics, Law, and International Relations, Emeritus, and director of the Raj Center on Indian Economic Policies. "In their early career, economists usually write short theoretical articles that make large points, and Dick did that with two seminal articles in the leading professional journals of the time, the Quarterly Journal of Economics and the American Economic Review. Then, he shifted his focus to building large computable models. He also diversified by working in an advisory capacity in countries as diverse as Portugal and India. He was a 'complete' economist who straddled all styles of economics with distinction."

Eckaus is survived by his beloved wife of 32 years Patricia Leahy Meaney of Brookline, Massachusetts. The two traveled the world, hiked the Alps, and collected pre-Columbian and contemporary art. He is lovingly remembered by his daughter Susan Miller; his step-son James Meaney (Bruna); step-daughter Caitlin Meaney Burrows (Lee); and four grandchildren, Chloe Burrows, Finley Burrows, Brandon Meaney, and Maria Sophia Meaney.

A memorial in his honor will be held later this year by the MIT Department of Economics.

Personnel.

CEEPR Welcomes New Researchers in 2022

In addition to Gilbert Metcalf joining CEEPR as a Visiting Professor (featured on page 12 of this newsletter), a number of new researchers have joined the group in 2022:

Benjamin Krebs, *Postdoctoral Associate*

Benjamin Krebs is an applied economist with a focus on environmental and energy topics. He works on human-related outcomes of air pollutants, on particulate matter monitoring, and how public policies influence air pollution. At CEEPR, Ben takes part in a research project led by NREL, that aims to improve the efficiency of and participation in electricity markets, with an emphasis on demand-response mechanisms. Before joining CEEPR, Ben completed his Ph.D. at the University of Lucerne, Switzerland.

Shereein Saraf, *Research Associate*

Shereein Saraf is interested in the research fields of development, labor, and energy economics. She completed her Masters in International and Development Economics from Yale University. Before coming to CEEPR, she had worked on a portfolio of research projects ranging from women's economic empowerment through digital financial inclusion to conducting time-series econometric analysis using 700 years of real interest rate data.

Adrien Concordel, *Graduate Research Assistant*

Adrien Concordel's research focuses on the resources issues and energy-returns challenges of the energy transition. He is passionate about merging interdisciplinary approaches in economics, systems modeling and engineering to assess energy policies and strategies. Before joining CEEPR, Adrien worked as a consultant in the Middle-East where he participated in designing Iraq's long term energy strategy and power sector reform. Adrien holds a Diplôme d'Ingénieur from École Polytechnique, France.

Johnattan Ontiveros, *Graduate Research Assistant*

Johnattan Ontiveros is a research assistant at CEEPR and the MIT Sustainable Urbanization Lab. His research focuses on estimating the cost of electrification for home and building owners. He is currently pursuing an M.S. in Technology and Policy at MIT's Institute for Data, Systems, and Society. Before entering MIT, Johnattan received a B.A. in Statistics at Harvard College, and worked in various roles as a software engineering and research intern.

Alejandro Valdez Echeverria, *Graduate Research Assistant*

Alejandro Valdez Echeverria's research focuses on understanding the technical, financial, and behavioral barriers in adopting decarbonization technologies. He is currently pursuing an M.S. in Technology and Policy at MIT. Before that, Alejandro worked as a consultant in the energy technology / policy space, in which he supported the development of energy efficiency regulations for the U.S. DOE and developed market assessments, investment strategies, and economic analyses on decarbonization technologies.

David Villegas, *Graduate Research Assistant*

David Villegas is a graduate student in the System Design and Management master's program at MIT. He holds a bachelor's degree in chemical engineering from McGill University in Canada. Prior to CEEPR, David spent five years working in the energy industry, where he helped design, develop, and support products derived from jet engines that provide flexible power to the grid. David is interested in the deployment of technology innovations to support the clean energy transition.

Hanna Won, *Graduate Research Assistant*

Hanna Won is a graduate student in MIT's System Design and Management program at the Sloan School of Management. She is interested in climate change and sustainability issues, especially energy transition and electric vehicles. Prior to MIT, Hanna worked as a design engineer in the petrochemical industry and as an in-house consultant for the chemical and battery sectors in Seoul, Korea. Her work was primarily focused on setting strategies for the Li-ion battery business and decarbonization technology.

Events.

Information on past and upcoming events is available on our website, where Associates can also access presentation slides and recordings: ceepr.mit.edu/events

Recent Conferences:

CEEPR & EPRG International Energy Conference

June 27-28, 2022
Seoul, South Korea
in partnership with Seoul National University, Chungnam National University, NEXT Group, and EPRG @ University of Cambridge

CEEPR & EPRG European Energy Conference

September 1-2, 2022
Brussels, Belgium
in partnership with EPRG @ University of Cambridge and Électricité de France

Fall 2022 CEEPR Research Workshop

November 17-18, 2022
Royal Sonesta Boston Hotel
Cambridge, Massachusetts

Upcoming Conferences:

Spring 2023 CEEPR Research Workshop
May 18-19, 2023
Royal Sonesta Boston Hotel - Cambridge, Massachusetts

Publications.

Recent Working Papers:

WP-2022-017
Carbon Abatement Costs for Hydrogen Fuels in Hard-to-Abate Transport Sectors and Potential Climate Policy Mixes
Jonas Martin, Emil Dimanchev, and Anne Neumann, November 2022

WP-2022-016
Five Myths About Carbon Pricing
Gilbert E. Metcalf, October 2022

WP-2022-015
Electricity Retail Rate Design in a Decarbonizing Economy: An Analysis of Time-of-Use and Critical Peak Pricing
Tim Schittekatte, Dharik Mallapragada, Paul L. Joskow, and Richard Schmalensee, October 2022

WP-2022-014
Rational Rationing: A Price-Control Mechanism for a Persistent Supply Shock
Reyer Gerlagh, Matti Liski, and Iivo Vehviläinen, October 2022

WP-2022-013
The Macroeconomic Effects of a Carbon Tax to Meet the U.S. Paris Agreement Target: The Role of Firm Creation and Technology Adoption
Alan Finkelstein-Shapiro and Gilbert E. Metcalf, September 2022

WP-2022-012
Long-term Equilibrium in Electricity Markets with Renewables and Energy Storage Only
Guillaume Tarel, Magnus Korpås, and Audun Botterud, September 2022

WP-2022-011
Population, Productivity, and Sustainable Consumption
Robert S. Pindyck, August 2022

WP-2022-010
Sustainable Hydrogen Fuels versus Fossil Fuels for Trucking, Shipping and Aviation: A Dynamic Cost Model
Jonas Martin, Anne Neumann, and Anders Ødegård, July 2022

WP-2022-009
When "Low-Hanging Fruit" Are Beyond Reach: Management Practices and Firm Energy Efficiency
Valerie J. Karplus and Da Zhang, June 2022

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

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Environmental Policy Research

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Photo: CEEPR visits Hydro Québec's Robert-Bourassa Generating Facility at James Bay, QC. From left to right: Tim Schittekatte, John Parsons, and Joshua Hodge.

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