The Texas Deep Freeze of February 2021: What Happened and Lessons Learned?

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1. Motivations underlying the research

Extreme freezing temperatures, snow, and ice from winter storm Uri afflicted Texas February 14-18, 2021. Houston, Dallas, and San Antonio saw record-low temperatures of 13, -2, and 5 °F. The power grid operated by Electric Reliability Council of Texas (ERCOT), which serves most Texas power consumers, came close to catastrophic failure. Millions of ERCOT customers suffered blackouts for multiple days. Although true electricity demand was not measured, forecasted demand matched mid-afternoon 4-hour August peak demands, but for 72 consecutive hours.

Scapegoats for the widespread outages included wind generators, thermal generators, natural gas suppliers, Texas opposition to interconnections, ERCOT management, and ERCOT market rules. Although these various factors were blamed for the extended power outage on the ERCOT electricity grid in February 2021, no single problem fully explains the calamity. All forms of generation experienced capacity deratings, but failure to identify and address risks along fuel supply chains was a major contributor. Moreover, the vent highlighted a growing risk associated with expanded intermittent generation resources without sufficient available, dispatchable generation capacity.

2. A short account of the research performed

We analyzed load and resources in the ERCOT market in early 2021 to provide a baseline for the events of winter storm Uri. We then provide a detailed summary of the events before, during, and immediately after the winter storm in order to highlight where failures occurred. This allows a discussion of the deep and growing interdependence of the natural gas and electricity systems in ERCOT, which reveals a potential single point of failure for the entire energy system. We also address resource adequacy and transmission to neighboring regions, recount lessons from previous winter storms that triggered outages in ERCOT, and provide recommendations to address the identified inadequacies.

3. Main conclusions and policy implications of the work

Wind underperformed relative to its nameplate capacity, but this is always true. Wind generation capacity is "rated" at a discount to nameplate capacity based on expected wind resources, and it often outperforms or underperforms relative to that rating. During the winter storm, wind underperformed since output was below what would have been anticipated given the forecasted and actual wind speeds. But Wind's underperformance during the winter storm only mattered for grid stability because resources that typically back up wind were unavailable. This highlights the need to fully evaluate availability of back-up resources in planning scenarios.

Longer term, the increased value of reliability as the fraction of non-dispatchable resources increases needs to be adequately reflected in prices. A resilient, reliable electricity system requires price signals adequate to ensure sufficient investment in all types of capacity and the right mix of generation capacity.

Thermal capacity deratings varied across generation types, and natural gas had the largest cumulative capacity outages. Winterization of thermal capacity, and wind capacity, can be an important first step, especially under a favorable cost-benefit analysis. If all thermal capacity had remained operable

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during Uri, load shed likely still would have been necessary, but remained voluntary, thereby avoiding the EEA level 3 declarations.

Fuel supply issues must be addressed. Variability in wind generation requires flexibility in back-up sources of generation including the supporting infrastructure such as pipelines, storage and processing facilities, and wellhead production. During the February 2021 event, natural gas generation was needed far in excess of a typical February day, but power cuts negatively impacted the fuel supply chain and compromised generation. Fuel supply infrastructures should be mandatorily designated as critical load.

Interconnecting ERCOT with SPP, MISO and WECC might have yielded some short-term benefits. But surrounding regions were also stressed, as existing interconnectors were curtailed multiple times February 15-18. Longer term, increased transmission capacity would alter the location of capacity investments, and the impacts on reliability are uncertain. A study of the long-term effects of expanding interconnections between ERCOT and neighboring regions is warranted.

Assessments of ERCOT's management of the grid need to account for the fact that ERCOT doesn't own, operate, or regulate generation assets. To maintain system stability, it schedules generation and invokes previously arranged voluntary load reductions. During Uri, ERCOT's real-time management avoided catastrophic failure. Long-run planning, however, can be faulted for not adequately assessing the impact of extreme events across the entire energy supply chain. Better coordination among state regulatory agencies would allow long-run planning to extend beyond the electricity market into the various fuel supply chains.

Market structure rules might be improved to ensure adequate reserve capacity. Factors such as the social value of reliability, the value of lost load, and increased demand management need to be more actively integrated in market rulemaking. A full exploration of changes in market rules to cope with zero marginal cost, subsidized, non-dispatchable generation is beyond the scope of this research, but such exploration would usefully contribute to future planning.

Enhancing the reliability of bulk power systems against the threat of extreme weather: lessons from the 2021 Texas electricity crisis

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In February 2021, Texas experienced a 1-in-30-year cold weather event that resulted in sub-freezing temperatures well below average for over six days. Given the state's reliance on electric heating, the extreme cold weather drove winter electricity demand to unprecedented levels. Meanwhile, electricity supply fell significantly, and the grid operator managing about 90% of the state's electric load, the Electric Reliability Council of Texas (ERCOT), was forced to initiate customer load-shedding. More than 10 million people in Texas lost electric distribution service, and a large swath of electricity customers in ERCOT were without power for up to 96 hours. At least 210 people died during the event, and losses to the Texas economy were estimated between $80 and $130 billion.

The event was followed by extensive finger-pointing, and some immediate reactions blamed competition, ERCOT's market structure and grid management, wind's underperformance and limited connectivity with neighboring states. In our view, the major causes of the crisis were not due to wholesale electricity market design, but to problems in planning and awareness of system interdependencies. As of the time of writing, the most significant energy-related bills passed by the Texas Legislature will result in a $18-billion out-of-market directive to build up to 10 gigawatts of new natural gas-fired power plants sitting in reserve; substantial changes to the governance of ERCOT and certain aspects of the ERCOT market (e.g., emergency pricing); a mandate for electricity suppliers in the state to purchase dispatchable power services as insurance; and the ban of wholesale-indexed products that include a

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direct pass-through of real-time prices for residential customers. To varying extents, these steps are reactions to a particular event, and may address pieces of what was a highly complex failure across multiple infrastructure and regulatory systems. By and large, however, reforms in Texas and elsewhere have not addressed fundamental systems-level practices to enhance the reliability of bulk, i.e., transmission-scale, power systems against the threats of extreme weather.

We contribute to the literature on the Texas electricity crisis by discussing three systems-level strategies to prevent and mitigate the adverse consequences of extreme weather events. Two of these strategies, in particular, have received limited attention in previous analyses.

First, generation resource adequacy and planning processes in the electric power sector should be enhanced to include multiple adverse conditions occurring simultaneously, common mode failures, growing system variability and potentially severe future weather events as part of the calculus. Actions to enhance understanding of the potential impacts of climate change on system load and resource availability are being undertaken in other regions of the U.S. and Europe. The Texas crisis also illustrates that performance incentives and non-performance penalties do not fully solve the market failure due to the misalignment between social welfare maximization and private objectives. Further, markets are not well suited for managing risks associated with catastrophic events, and private incentives often do not provide efficient and socially acceptable solutions under such circumstances. As a result, regulation and standards will likely play an important role to ensure provision of reliability against the threat of extreme weather.

Our second recommendation centers around demand-side solutions, which are vastly underutilized to address reliability challenges. Tools such as energy efficiency in homes, customer-side curtailment beyond existing industrial and commercial programs, and dynamic pricing options that do not expose residential customers to bill volatility could reduce peak demand during emergency conditions. Opportunities for improvements in this area are likely larger for Texas than in other regions of the U.S. Further, in our view time-varying pricing should not be abandoned just because of what happened in Texas, although it may not be effective for long-duration power interruptions.

Third, resource adequacy and planning processes in the electric power sector should evolve to better capture critical infrastructure interdependencies and associated vulnerabilities. Strengthening alignment of planning and operating practices across the electric and natural gas industries is especially important, but poses practical implementation challenges in settings where decisions are made by myriad market actors and institutions. Further, reforms in the natural gas market that improve fuel allocation between local distribution companies and power plants during periods of scarcity would help support electric system reliability.

Making Electricity Capacity Markets Resilient to Extreme Weather Events

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As the 2021 events in Texas demonstrate, extreme weather events (EWEs) such as hurricanes and winter storms cause devastating power outages and blackouts, resulting in fatalities, human suffering and significant economic damage. Climate change may also increase the frequency, duration, and magnitude of EWEs, making it challenging to develop cost-effective policies to limit the effects of EWEs on power systems. Furthermore, EWEs create significant challenges for achieving reliable and resilient power systems. EWE is a common-cause failure that results in multiple equipment failures over short periods, thus quickly reducing the ability of the power system to function (i.e., reliability) and prolong-

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ing its recovery (i.e., resiliency) from large blackouts. EWEs also challenge power systems in the long term because system components must withstand increased EWEs (with low and uncertain probabilities) and changing electricity demand.

In liberalized power systems, extreme events such as the 2021 blackout in Texas have raised questions about whether electricity markets can ensure a sufficient level of reliability and resiliency, and if they can do so cost-effectively. Texas liberalized its electricity system in 2002, and since then, it has relied solely on energy (and reserve) markets, i.e., there is no market, to meet reliability and resiliency expectations. Texas is considered, or at least had been considered until its recent blackout, by many economists as a role model in market design. Although capacity markets have been introduced in many regions to ensure resource adequacy, the 2021 Texas blackout questions whether introducing a capacity market in Texas could have limited the 2021 event and what features capacity markets should have in the context of EWEs.

This article investigates what capacity market reforms could be undertaken to address EWEs and climate change better. It highlights that accounting for infrequent common-cause events such as EWEs is challenging but necessary to ensure future resource adequacy.

Based on our analysis of current practices in Europe and the U.S., we identify that regulators have acknowledged the importance of EWEs and climate change, but further improvements are necessary to consider them in reliability and resiliency analyses better. In Europe, resource adequacy considers climate change's impact on electricity demand and electricity generation, but EWEs are not explicitly assessed. In the U.S., policies addressing EWEs and climate impacts are being considered, but they do not specifically focus on capacity markets.

When capacity markets are implemented, we propose criteria for evaluating whether and how to use capacity requirements and associated markets to address severe weather conditions. These criteria intend to apply to any region and would require to be complemented by additional features tailored to the specificities of each region. First, capacity requirements must achieve policymakers' reliability and resiliency objectives by reducing the frequency, magnitude and duration of blackouts. Second, any capacity requirement should be cost-effective and integrated with other non-capacity requirements, such as transmission, distribution, fuel supply and other infrastructure systems. Considering the entire power supply chain and its interrelationships with other critical infrastructures is necessary to ensure resiliency. Third, a well-defined and measurable capacity product must be developed for a capacity market to produce the desired efficiency benefits. Sufficient credit and other policies are also necessary to ensure providers have sufficient incentive to perform when called.

In conclusion, reforming capacity markets to account for EWEs and other common-cause events is challenging. It requires updating resource adequacy modeling to incorporate common-cause capacity and demand dependencies and adjusting the definition of capacity. It also requires trading off between regulatory and market-based mechanisms to ensure capacity performs as desired and to have a cost recovery mechanism that effectively induces the desired resource adequacy investment cost.

How Should We Think About Pricing Electricity in the Context of Potential Life-Threatening Weather Events?

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1. Motivations underlying the research

While undeniably tragic, the events related to Winter storm Uri point to the benefits of reflecting on the implications of regulatory designs for power markets; both academics and practitioners are likely

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to revisit the regulation of power markets. Many markets have historically relied on a retail price structure that completely shields consumers from volatile prices, say by using fixed-price electricity contracts. contracts of this sort provide no incentive to consumers to economize on their usage during extreme weather events, and force sellers to bear all the risk. Taking note of these points, a number of scholars have argued in favor of real-time prices as transportation systems become more reliant on electric vehicles and power systems evolve towards a greater reliance on renewables. Additionally, to the extent that one wishes to pursue demand management as an avenue towards reducing carbon emission, real-time prices can play an important role. But in markets characterized by highly inelastic demand, such as markets for electricity, market-clearing can force some individuals -- particularly those with limited financial resources -- out of the market, subsequently exposing them to significant risk. In the particular case of abnormally cold temperatures, as with the Texas deep freeze, or particularly hot temperatures, as may become more common with climate change, these risks can be life-threatening. My goal in this paper was to analyze such a retail market, where demand (and perhaps also supply) is highly inelastic – so that balancing supply and demand may require that some buyers are driven from the market. In this way, market-clearing implies that society is confronted with what economists who study decision-making under uncertainty refer to as a ``lottery," where there are multiple potential outcomes with associated probabilities; one potential outcome here reflects loss of life. In my view, thoughtful policy would take this risk into consideration.

While buyers' reservations prices reflect willingness-to-pay they also capture *ability* to pay. In particular, each household has to choose a combination of goods and services – including electric service – subject to that households' budget constraint. However buyers' desires for electricity are distributed across households, when customers are heterogeneous with respect to ability to pay – as is almost surely the case – reservation prices will vary across households; as such, those who are driven from the market in the scenario I described above are likely to be disproportionately less well off – raising equity considerations.

2. A short account of the research performed

The concerns I raise above lead naturally to consideration of policy interventions that might shield individuals from the risk associated with being forced out of the electricity market. In broad terms, this risk arises because the consumer in question struggles to afford electricity, particularly during periods where prices have risen dramatically – for example because of extreme weather events. To the extent that society sees this outcome as undesirable, there is a reason to contemplate a policy that mitigates the risk of that outcome. I discuss four possible policies: price caps, encouraging energy efficiency, bill protection and insurance. Of these, I argue that insurance – specifically, catastrophic insurance, is the most desirable. One may conceive of such insurance as a contract under which a consumer pays some amount in exchange for protection against the dramatic impact following the occurrence of a sufficiently adverse event (such as a life-threatening event).

By its nature, this policy intervention blunts the forces that would otherwise have led to a balancing of supply and demand are reduced or eliminated, which implies excess demand. As a result, electricity supplies will invariably be rationed in some non-market way, most likely via rolling blackouts – implying a second form of risk, namely that of incurring the inconvenience of losing access to power for a period of time. While the goal of this paper is not to propose an appropriate resolution of the comparison of these two gambles, consideration of some key numbers based on the impacts of Uri may be instructive. Using numbers proposed for the "value of lost load," the number of people who died as a result of hypothermia and estimates of the so-called "statistical value of life," a back-of-the-envelope comparison of expected values is $1.65 billion from the potential loss of life as compared to $40.5 billion from the value of lost load. My point here is not to argue that the latter is the larger, but rather to point out that the former is both large in absolute terms and reasonably close to the latter in absolute terms.

3. Main conclusions and policy implications of the work

The nature of power markets, in particular their vertical structure, entails important nuances. While such markets ultimately exist because end users desire energy commodities they function in large part because of a vertical structure: retail suppliers are wholesale buyers, while wholesale sellers obtain the commodities they (re)sell from primary producers. Any structural design at the retail stage, in particular a regulatory intervention, will impact incentives farther back the supply chain. Accordingly, thoughtful interventions in retail markets also need to consider impacts on wholesale and primary production markets. Indeed, there is a tension between incorporating the potential for life-threatening outcomes in the determination of price caps versus the desire to properly motivate capacity investments and manufacturer responses into analysis of the costs and benefits of fuel economy regulations. Catastrophic insurance offers the potential for addressing possible life-threatening events without amplifying the "missing money" problem that would otherwise impede investments in grid expansion. The themes and policy considerations developed in this paper would seem appropriate to any market characterized by highly inelastic demand that was confronted by some form of lingering substantial supply disruption could qualify.

Winter Ends

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Many views of electric vehicle adoption focus on the reduction in greenhouse gas emissions (GGEs). But there are significant problems that are overlooked in this sole focus: the cost to consumers, the ongoing need for recharging the batteries, the significant environmental and political opposition to the increase in mining and production that will be necessary, and the vast amount of stranded assets in fossil fuels that the wholesale switch (without modification) will produce. The most wealthy countries can afford this, whether they choose to or not, and others that do not rely primarily on markets, such as China, may also achieve this. Poorer countries may not, and there are valid reasons to expect battery prices to remain high, financing the Salton Sea lithium project not least.

Hydrogen fuel-cell vehicles (HFCVs) are an alternative that can help meet GGEs reduction goals, and HFCV technologies, which can be combined with much reduced fossil-fuel consumption, or reduced need for batteries, may have lower costs. Conditions in Brazil and India that may be conducive to such alternatives, are discussed, as are carbon tariffs, which are imminent in Europe, and may be politically feasible in the U.S. Photovoltaic (PV) cells, as an addition for transport, can also play a significant role. Some "colors" of hydrogen production are discussed. A new category of hydrogen, "jade" hydrogen, renewable production of hydrogen from fossil fuel substrates, and renewable transportation, is proposed. Jade hydrogen could also reduce the stranded asset problem (including infrastructure) and increase political feasibility.

Alternative battery technologies, including but not solely lithium-ion, are likely to dominate market for GGE-reducing transport in the near future. But these advantages for HFCVs may come to play a larger role than expected thereafter.

a I am a consultant with Kapur Energy Environment Economics (KEEE). The opinions expressed here, and all errors, are solely my own, and do not represent KEEE in any way. KEEE does not endorse any technology or any specific government policy. Thanks to William Halal, Daniella Taveau, Rafael Herzberg, Aaron Krol, and two anonymous referees for helpful comments.

Electric Vehicles are Good, Actually

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1. Motivations underlying the research

Electric vehicles (EVs) are the primary alternative to transportation based on internal combustion engines and the most promising route to decarbonization of light- and medium-duty transportation systems. They are not perfect, though, and face a number of obstacles, including concerns about life-cycle energy and material footprint, consumer concerns with changing to a new technology, and scalability of EV adoption around the world. The motivation for this article is to confront each of the major concerns about large-scale EV adoption, using data and existing research to show that EVs are currently a good choice for decarbonization of transportation and are becoming better over time.

2. A short account of the research performed

This survey article begins by discussing the costs of EVs, which are currently competitive with traditional vehicles on a lifetime basis. EV costs are falling over time, though, and will soon reach the point where they have an equivalent or cheaper upfront cost (in addition to lower operating costs). This process will not be a smooth one: as the industry grows at 10-30% per year, it will have to double in size every 5-10 years, meaning that improving technology and economy of scale will compete with supply chain issues and other growing pains. These supply chain questions are discussed and compared to supply issues in the existing oil market. In either case, vehicles are dependent on global supply chains for minerals, but EVs are reliant on minerals mainly for their production while combustion vehicles require continual supply of oil for their operation. This makes EVs more robust against temporary supply chain issues, because consumers can more easily defer purchasing of a new vehicle than defer usage of their existing vehicle.

A broad shift to EVs will require a significant amount of electricity as fuel – an increase in total US electricity use of perhaps 40%. This will require new infrastructure, new services, and new generation. But the most important question about EV effects on the electricity grid is not the total amount of energy needed but when and where that energy is required. In a future where EV charging is highly coordinated with grid needs, the additional energy required by EVs will be much easier to provide. Life-cycle emissions of EVs are lower than combustion vehicles and decreasing over time due to two effects: the carbon footprint of producing EV batteries is decreasing and the electricity used to charge vehicles is getting cleaner due to grid decarbonization progress.

Globally, many high-price EVs are sold in developed countries but the largest EV market in the world is in China, where EVs are designed and sold as smaller, cheaper alternatives. Like other technologies (air conditioning, cell phones), EVs are likely to become a technology that is developed and marketed at high cost in wealthy countries then brought to developing countries, where their design can be modified to meet local needs.

3. Main conclusions and policy implications of the work

A transition to electric vehicles does face important challenges in terms of scaling of battery production, charging infrastructure, and grid coordination, which may make aggressive EV targets difficult to meet. However, these known challenges are surmountable given the historical and expected future trend of falling costs and improved technical and environmental performance of these vehicles. Transportation has been something of an outlier in the energy world, as a complex system that has been predominantly reliant on a single technology - internal combustion of petroleum-based liquid fuels - for 100 years. As that technological monopoly breaks up, it would be simplistic to propose that battery electric vehicles will become a new monopoly. The exact mix of future technologies and the roles that they play depends on technology and cost developments as well as the preferences of governments and

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consumers, but the future transportation system will benefit from greater diversity in energy sources and conversion technologies. And as the front-running challenger to the traditional internal combustion engine, electric vehicles will surely be a central component of that system.

From Diesel to Electric: Overcoming Grid Integration Challenges in the Medium- and Heavy-Duty Vehicle Sector

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1. Motivation

Medium- and heavy-duty vehicles (MHDVs) contribute an outsized share of local air pollution and greenhouse gas emissions within the transportation sector. Decarbonizing these vehicles is crucial for achieving the clean energy transition and for improving the health and wellbeing of communities most affected by transportation pollution. Electric trucks and buses are a promising solution but electrifying these vehicles will not be easy. One of the greatest challenges is the massive amount of electric grid investments required to support MHDV electrification and integrate these new vehicles onto the grid.

2. Approach and Findings

This paper details the grid investments required to support MHDV electrification and the technological solutions, existing policies, and new policies that can help reduce costs and accelerate grid integration. The paper concludes with a discussion of open research questions that can enable a more equitable, efficient, and cost-effective transition to medium- and heavy-duty electric vehicles (MHD EVs).

Grid investments required to support vehicle electrification

Generation capacity and renewables integration: MHDV electrification may require significant generation investments to meet increased electricity demands, depending on charging patterns. Integrating greater generation into the grid will also require more transmission lines, which are costly and require community support and siting approval subject to numerous regulations at all levels of government.

Distribution grid: MHD EVs have massive batteries; a single fleet's depot is likely to exceed the locally available capacity. Meeting electricity demand will require investments in the distribution grid, including upgrades to the local system and potential substation expansions and replacements. Electric utilities face significant challenges in making these investments due to high costs and uncertainty about where these new electric fleets will emerge. These uncertainties can lead to regulatory hurdles, increasing the total long-run investment cost and delaying fleets from electrifying.

Charging station investments: Required charging station infrastructure includes significant and costly investments into the charger on a fleet's lot and the "make-ready" infrastructure. Public MHD EV charging stations can help reduce fleets' investment burdens, but the availability of such stations is minimal.

Technological solutions

Technological solutions exist to reduce and overcome some of the barriers described above; including managed charging, vehicle-to-grid (V2G) technology, co-located storage and solar, and battery swapping. Managed charging software can optimize charging patterns to reduce grid costs. V2G technology can allow a vehicle owner to return excess energy stored in their battery to the grid when the vehicle is not in use or charging and provide ancillary services such as voltage regulation. However, payments for V2G services are uncertain, and frequent charging and discharging may degrade the battery.

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Investing in rooftop solar and storage at the charging station site can reduce fleets' total net loads, reducing generation and transmission investments and mitigating peaks during congested hours. However, the benefits of these investments are limited by space constraints and potentially high investment costs.

Battery swapping technology can also improve charging patterns and lower the upfront payment for the vehicle. However, it doesn't work well for larger vehicles, investment and maintenance of battery swapping stations can be high, and it requires battery compatibility across different vehicle types and use cases.

Current Policies and Incentives

Governments at all levels have engaged in and implemented policies to help integrate MHD EVs onto the grid. At the federal level, the Inflation Reduction Act incentivizes new renewable energy investments by expanding and extending existing production and investment tax credits for clean energy projects.

The Infrastructure Investment and Jobs Act created the National Electric Vehicle Infrastructure Formula Program and the Charging and Fueling Infrastructure Discretionary Grant Program to fund public charging station investments. It also broadened the definition of a National Interest Electric Transmission Corridor, which can help accelerate transmission siting.

At the state level, policymakers have implemented programs to meet their renewable energy goals such as renewable energy standards. Twelve eastern states have joined the Regional Greenhouse Gas Initiative – a regional cap-and-trade program that covers carbon dioxide emissions from the power sector. California has its own cap-and-trade program, AB32, which sets a declining cap on power sector emissions.

At the local level, utilities can implement programs that help fund make-ready infrastructure for charging stations.

3. Policy Implications of the Work

Future policy pathways

Though policymakers at all levels of government have taken steps to integrate MHD EVs onto the grid at the least cost, there are still substantial opportunities for complementary policies. Two such policies include providing government funding to help cover electric utility distribution costs, which can help mitigate increases in electricity prices; and electric tariff reform, which can help shift demand toward cleaner and cheaper times of day.

How research can improve outcomes

Future research can help enable a cost-effective and environmentally friendly integration of MHD EVs onto the electric grid. The paper discusses several areas which require further investigation to improve policymaking. For example, as adoption begins to increase, conducting ex-post analyses of the new federal incentives can help identify the effectiveness of these policies in accelerating adoption; these learnings can shape future decisionmaking and potential extensions to subsidies.

Given the bottlenecks in integrating renewables and local stakeholder challenges for investment siting, research can also help by identifying challenges, providing policy solutions to overcoming challenges, and engaging with local community groups to ensure increased support.

In the realm of charging station investments, more research is needed to understand the impact of these investments on fleet electrification decisions, logistics, total cost of ownership, range anxiety, and adoption incentives. Understanding private investment incentives and the role of government is also vital for facilitating greater public charging station investment and more affordable charging prices.

Finally, future research can quantify the benefits of technology such as V2G and regulatory frameworks to ensure that tariffs accurately compensate fleet owners for the environmental and economic benefits that the technology provides.

Household Environmental Kuznets Curves: Evidence from Passenger Transport Emissions

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1. Motivations underlying the research

Passenger vehicles are a key economic sector and represent a growing share of energy consumption and emissions in many countries. Understanding how emissions from passenger vehicles are linked to household income is important for assessing distributional impacts of decarbonization policies, evaluating potential trajectories for energy consumption and emissions, and ensuring an equitable energy transition. The goal of this analysis is to investigate the income-pollution relationship for passenger vehicles using detailed U.S. survey data. Specifically, the analysis tests for evidence of an Environmental Kuznets Curve (EKC) for household passenger vehicle CO_2 emissions, which refers to a non-monotonic U-shaped relationship between income and emissions.

Although the literature on economy-wide EKCs is vast, sector-specific analysis of household transport emissions is less common, is subject to considerable controversy, and is over a decade old in many instances, which does not account for recent trends in vehicle electrification and fuel economy. This analysis is the first to provide evidence for the U.S. transport, the highest-emitting sector in the world's second-highest emitting country. Over time, technological progress and regulatory standards can lower emissions of subsequent vehicle vintages, and higher-income households tend to have newer vehicles. At the same time, wealthier households are more likely to have a greater number of vehicles and drive them more, as this analysis demonstrates. More recently, electric vehicles are increasing as a fraction of new sales and may be correlated with income, which can lower emissions depending on the emissions intensity of the grid mix.

2. A short account of the research performed

This analysis uses microdata from the U.S. National Household Travel Survey (NHTS) conducted by the Federal Highway Administration, which provides nationally representative information about travel behavior. Data come from a stratified random sample of U.S. households conducted in 2017. The NHTS has a large sample size across different U.S. regions with a more extensive set of demographic variables such as household income, mileage, and number of vehicles. To test whether a non-monotonic relationship exists between household income and CO_2 for passenger transport, this paper uses an ordinary least squares regression model. This analysis separately estimates the impacts of pollution intensity (i.e., emissions and fuel consumption per distance traveled) and polluting activity (i.e., vehicle miles traveled) on emissions with respect to income.

3. Main conclusions and policy implications of the work

The analysis provides support for both polluting activity and pollution intensity following an inverse-U shape in income, which leads total emissions to a similar non-monotonic EKC relationship, albeit with different income turning points. Emissions increase with income at lower levels but reverse for the highest-income households with incomes of $200,000 or more. Although this effect is statistically significant, the effect size is relatively small, as household emissions decline by 1.2% between the second-highest income households and the highest.

Vehicle miles traveled (VMT) increases by more than a factor of three between the lowest- and highest-income households from about 7,800 mi/yr to 27,300 mi/yr, respectively, though this relationship is non-monotonic, as VMT declines for incomes greater than $125,000 to $149,999. The emissions intensity for the lowest-income households exceeds that for highest-income households (398

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versus 382 g-CO_2/mi, respectively), indicating that wealthy households drive more fuel efficient vehicles on average. However, fuel economy improvements are more than offset by the countervailing increase in driving intensity between income extremes.

An important caveat is that 2017 data are at the beginning of a significant electrification trend, as electric vehicle costs decline and deployment increases. Given how emissions are generally lower for electric vehicles relative to conventional fossil-fueled ones, this trend could lead to a more prominent EKC relationship, especially if higher-income households are more likely to purchase electric vehicles. Data from this study indicate this is the case for purchases through 2017, as shares of electric vehicles increase from 0.6% of lowest-income households to 5.0% for the highest-income ones.

This analysis has several policy implications. First, interventions that compress income distributions and increase income for the poorest households are not likely, by themselves, to reduce household transport emissions, given how this analysis finds that emissions increase in income across a large income range. Second, the small magnitudes of EKC effects indicate that emissions policies are likely more effective in reducing emissions rather than waiting for EKC effects from growing income, as wealthier households are not fully internalizing the social costs of emissions. Third, the evidence that electrification may be contributing to the decline in emissions for the highest-income households highlights the critical role of electric vehicles in lowering transport emissions. Finally, since poorer households spend a greater share of their income on energy, this analysis also has implications for the incidence of decarbonization policies, as the EKC relationship may slightly increase regressivity. The analysis also illustrates the substantial variation in household transport demand and emissions within income classes, which raises important horizontal equity issues for policymakers.

Marginal Emissions Pathways: Drivers and Implications

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Governments frequently use policies that target the expansion of a clean technology to achieve greenhouse gas emissions mitigation goals, such as those submitted by countries under the Paris Agreement. Policymakers need accurate estimates of emissions reductions expected to be achieved by these efforts both individually—to inform the level of mitigation sought by any given nation, as well as collectively—to attribute national contributions to global mitigation. However, evaluating mitigation from clean technology policies is difficult because each unit of clean technology added by a policy need not result in the same change in emissions. As a result of direct and indirect market adjustments induced by a particular policy, marginal emissions from expanding a clean technology may vary in the amount of clean technology, reflecting a *marginal emissions pathway*. This paper explores the drivers of marginal emissions pathways and assesses how the shapes of marginal emissions pathways affect the prediction and attribution of mitigation from clean technology policies.

To this end, we first illustrate the drivers of marginal emissions pathways using a simple conceptual model that illustrates that marginal emissions from a mandate and a subsidy—the most common clean technology policies—can be decomposed into input and output effects. Since input and output effects depend on economic conditions in affected markets and the output effect depends on how a particular policy distorts markets, marginal emissions may vary with respect to the amount of clean technology and/or the policy driving the clean technology expansion.

Using a rich sectoral economic model that is coupled to a detailed emissions model, we then evaluate the marginal emissions pathways arising from a mandate and subsidy to promote corn ethanol in

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the United States. Marginal emissions pathways from each policy are non-constant in the amount of biofuel and, due to differential impacts on output markets, move in opposite directions and eventually have opposite signs. The same drivers that cause marginal emissions pathways to be non-constant, also explain the sensitivity of marginal emissions pathways to alternative parameter assumptions.

Finally, we consider the implications of non-constant marginal emissions pathways for predicting and attributing mitigation. Efforts to predict emissions reductions that explicitly or implicitly ignore the channels by which marginal emissions vary (e.g., amount of clean technology in the baseline and/or added, policy driving the expansion) can give rise to significant prediction errors. Similarly, with respect to decentralized efforts to address climate change such as the Paris Agreement, simple estimates of collective mitigation, such as the sum of all countries' mitigation pledges, are unlikely to be accurate which, in turn, may make it difficult to attribute each country's mitigation contribution. Numerically, we show that failing to account for non-constant marginal emissions can give rise to predicted changes in emissions that are of the wrong sign and/or that diverge by an order of magnitude from true estimates. Due to differences in the shapes of the marginal emissions pathways, these errors differ drastically across policies. Taken together our findings illustrate the potential for sizeable harm from implicitly or explicitly ignoring non-constancy in marginal emissions pathways when predicting or attributing mitigation from non-marginal changes in a clean technology.

Modeling CO_2 Pipeline Systems: An Analytical Lens for CCS Regulation

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1. Motivations underlying the research

The deployment of CCS projects is increasing, with around 200 projects at various stages of development in 2022, representing a significant increase in capacity compared to previous years. However, the success of these projects relies heavily on the installation of costly CO_2 transportation infrastructure, which often takes the form of a pipeline system connecting a carbon capture facility to a storage site. The deployment of a CO_2 pipeline infrastructure depends critically on the institutional framework governing its provision. In the US, Norway, the UK, and the European Union, new regulatory frameworks are currently emerging to organize the provision of these infrastructures. However, there is no consensus on the pricing mechanisms that can be used to ensure the socially optimal economic regulation of CO_2 pipelines. examines how the legal frameworks governing CO2 pipeline networks affect society and the environment.

2. A short account of the research performed

This paper first reviews the different regulatory approaches envisioned for CO_2 infrastructures in these jurisdictions and then adopts an analytical perspective to examine the social and environmental impacts of CO_2 pipeline regulation. The authors prove that the engineering equations governing CO_2 pipeline transportation implicitly define a Cobb-Douglas production function and that the associated cost function is subadditive and thus verifies the technological condition for a natural monopoly. Because it lessens the information asymmetry between the regulator and the pipeline operator, this technical representation offers valuable insights to practitioners interested in preventing regulatory distortions.

That analysis then evaluates the substantial deadweight losses that are incurred in the absence of regulation. Lastly, the authors assess the impact of different pricing schemes for the transportation of CO_2

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emissions in CCS systems. Unsurprisingly, marginal cost pricing cannot allow the pipeline operator to break even. That said, imposing a second-best pricing scheme such as average cost pricing results in an important efficiency gap since only 69% to 75% of the socially desirable volume of CO_2 emissions are ultimately captured and sequestered.

3. Main conclusions and policy implications of the work

Overall, the paper highlights the importance of regulatory frameworks for CCS pipeline systems and suggests a new representation of the system that can assist regulators, policymakers, and academics in their deployment. The numerical analysis supports the idea that economic regulation and environmental regulation are interrelated since the imposition of uniform, non-discriminatory pricing on a pipeline operator results in substantial efficiency gap.

Future research could explore the heterogeneity of emitters' demand for transportation to determine the optimal pricing scheme. The authors suggest that price discrimination may be a relevant option for regulators to maximize social welfare.

In future research, the technical representation of pipelines described in this work could be integrated into dynamic models to provide more detailed policy recommendations, such as the timing of regulatory interventions. Finally, although the paper does not discuss social issues such as public acceptance or right-of-way, it shows that defining a clear regulatory framework and coordination among stakeholders are mandatory to reduce the social cost of achieving carbon neutrality.

Do auctions promote innovation in renewable energy technologies? An empirical analysis of solar PV

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1. Motivations underlying the research

The descarbonisation of energy systems represents a key element of the energy transition which is needed to meet the Paris Agreement target. In 2015, governments agreed to limit global warming to 2 degrees, and preferably 1.5 degrees, below preindustrial levels. Renewable electricity technologies (RETs) are a main pillar of this decarbonised energy transition, together with energy efficiency. However, progress has been modest to date.

Solar PV, the focus of this paper, has experienced an impressive increase in deployment in the last decade, driven by the interactions between technology cost reductions, innovation and diffusion fueled by support schemes. The greater diffusion of the technology is a key factor behind these cost reductions. In turn, this diffusion has been driven by demand-pull policies, with administratively-set feed-in tariffs and feed-in premiums (ASFITs/FIPs) being the most popular instrument in this regard. ASFITs/FIPs have been superseded in the last years by auctions as the dominant scheme for RET deployment worldwide.

Such ambitious growth in the deployment of renewable energy capacity requires that different RETs are available at low costs in the next decades. In turn, this requires innovation, including technological innovation. Innovation is not a manna that comes from heaven, but it requires investment and support. A combination of supply-push (support for R&D) and demand-pull (support for deployment) has traditionally been considered as needed for innovation. According to the chain-linked model, the diffusion (deployment) of RETs influences previous stages of the technological change process. Therefore, an

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instrument which supports deployment can also be expected to influence innovative activities[a]. As auctions are the most widespread deployment support instrument today, and as innovation is needed, we may wonder about the impact of different support schemes (and, particularly, auctions) on innovation.

Indeed, the impact of auctions on innovation is unclear. Economists assume that auctions are not only good to limit the costs of support for renewable electricity, but that they also encourage innovation. It is often argued that the competitive pressures generated by auctions provide incentives to reduce costs and improve renewable energy equipment throughout the whole value chain, which leads to innovation. However, auctions may not score so well in encouraging innovation. While the positive impact of competition on innovation is undeniable, there are probably other mechanisms at play (the expectation of the existence of a market in which equipment developers can sell their innovative products, learning effects and sufficient profit margins which can be reinvested (by project developers and equipment manufacturers) in private R&D. In the past, auctions have led to non-negligible rates of non-completion and delays and to tiny profit margins. This limits the perspective of a future market for the technology, the existence of learning effects and reinvestments into private R&D. If this is so, then, the positive innovation effects of auctions can be questioned. However, this is purely an empirical question: which effects dominate, competitive pressures or the other mechanisms? And how do auctions behave in this regard with respect to alternative support instruments, whether quantity-based (quotas with renewable energy certificates) or price-based ones (ASFITs/FIPs)? This paper tries to answer the following research questions: Do auctions promote innovation in RETs? Do they promote innovation more than other deployment-support instruments?

2. A short account of the research performed

This paper carries out an econometric analysis on the impact of auctions on innovative activities in solar PV using an unbalanced panel data set of 20 OECD countries with patent data and renewable energy auctions for the period 2000-2016. An econometric analysis with an estimation of a negative binomial model is performed. Data on patent applications is our dependent variable, whereas two categories of independent variables are included in the model specification: policy variables and control variables. Policy variables include three dummy variables for the demand-pull instruments and a continuous variable for the supply-push instrument (R&D support).

3. Main conclusions and policy implications of the work

Our results show that auctions have not had a statistically significant effect on PV innovation. Auctions do not show a significant influence on the realisation of innovative activities for solar PV technologies in any model specification. In contrast, administratively-set feed-in tariffs and renewable certificates have had a positive and significant impact on PV innovation. Thus, they support the hypotheses that the incentive to innovate in RETs provided by auctions is weak and that this incentive is lower than with alternative deployment support instruments and, particularly, ASFITs/FIPs.

These results have obvious policy implications. The innovation literature argues that policy-induced innovation requires a combination of supply-push and demand-pull instruments. However, if the demand-pull instrument is not present because the most widespread demand-pull instrument (auctions) is not effective in this regard, then innovation processes might suffer. Despite this, auctions may still have a valuable role to play in the energy transition. The potential negative innovation effects of auctions can be mitigated by combining them with other instruments and including appropriate design elements which encourage innovation.

a For example, Hoppmann et al (2013, p.1000) argue that "deployment policies are effective instruments for inducing innovation as they trigger investments in exploration and provide firms pursuing more mature technologies with the possibility to benefit from exploitation".