Changes in Electricity Use following COVID-19 Stay-at-home Behavior

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1. Motivations underlying the research

The COVID-19 pandemic and associated stay-at-home policies and behaviors have significantly damaged the health and livelihoods of millions of individuals worldwide. Moreover, many energy scholars showed that electricity demand had sharply declined during the early months of 2020, noting that electricity demand could serve as a real-time proxy for overall economic activity. In addition, one of the few "silver linings" expected to come out of the pandemic is a reduction in local and global pollution from a reduced demand for fossil fuels used for transportation and electricity generation. However, as stay-at-home policies expired in areas where the initial outbreak of the virus had subsided, commercial activity resumed to an extent, and individuals and firms had the opportunity to make up for lost economic activity during earlier months. In addition, as households spent more time in quarantine, they had the opportunity to adapt behavior to the home environment, potentially increasing the use of electrical appliances for work in new home offices or acquiring additional electronics for at-home leisure. Any long-run economic losses or environmental health benefits from changes in energy use during the pandemic would have to be from permanently *displaced* consumption of energy rather than *delayed* consumption of energy.

2. A short account of the research performed

Similar to the approach used by the agencies, we estimate benefits and costs by comparing a scenario with the new standards and a scenario that holds the standards fixed at their 2011 levels. We examine the effects of low gasoline prices by comparing benefits and costs under high and low gasoline price scenarios.

This paper provides the first empirical evidence that electricity use increased following the expiry of initial stay-at-home policies and behaviors. To evaluate the longer-term impact of staying at home on electricity consumption, I analyze data on hourly electricity use in the PJM Interconnection of the United States during 2020. The analysis uses a nonparametric matching algorithm to predict electricity consumption for 2020 based on weather patterns and hourly, daily, and monthly seasonality if 2020 consumption resembled consumption from the previous five years. This predicted consumption serves as the counterfactual electricity consumption for a difference-in-predicted-differences estimation that compares the difference between actual electricity consumption and predicted consumption during 2020 before and after the start of the pandemic. This empirical strategy allows me to control for weather patterns, seasonality, and unobserved differences between 2020 and previous years. The results show that during the initial surge of COVID-19 cases and stay-at-home policies from March through May 2020, total electricity use was 2.7-3.8% lower than predicted consumption each month; however, after these policies expired in June 2020, total electricity use increased relative to the predicted baseline and in August was and 3.5% *higher* than predicted consumption.

To understand the mechanisms behind these dynamics, I analyze the relationship between stay-at-home behavior and electricity consumption using cell-phone location data provided by SafeGraph. These data include the median amount of time devices spent at home in each US census block. After matching census blocks to PJM zones, I use the amount of time spent at home as a third difference in the aforementioned difference-in-predicted differences strategy. In addition, I analyze monthly nationwide reported electricity consumption data by sector at the utility level to determine whether residential demand or recovering commercial and industrial demand can explain the summer increases in electricity consumption. Finally, I estimate the summer temperature-electricity exposure-response relationship

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for 2014-2019 versus 2020 to test the hypothesis that cooling more residential homes during the day is more costly than cooling workplaces.

3. Main conclusions and policy implications of the work

Using hourly electricity consumption data in a difference-in-predicted-differences strategy, this article shows that while electricity consumption declined by 3.8, 3.8, and 2.7% in the first three months of the COVID-19 pandemic, electricity use was 3.5% higher in August 2020. Electricity consumption in September through November was roughly normal compared to the predicted baseline, while consumption in December was 3.0% higher than the predicted baseline. Cell-phone location data on stay-at-home behavior show that more time spent at home decreases electricity consumption and that time spent at home substantially decreased after May. Nationwide monthly data on electricity consumption by load class reveals that commercial and industrial consumption was below its expected baseline from March-November 2020, while residential consumption was above its expected baseline, peaking in July. As a whole, the early reductions in electricity consumption were offset by the summer increases, with an overall effect of an increase in electricity consumption of 1.08%. The zone serving electricity to Chicago experienced consistent declines in electricity consumption, while zones covering rural areas saw the largest summer rebounds.

These results have several key policy implications for future pandemics or for a work-from-home environment where households spend substantially more time at home. Increased electricity consumption has important implications for the growing literature examining ``silver linings" of the pandemic. To the extent that electricity generation contributes to local and global air and water pollution, the gains will be smaller than expected due to increased demand for cooling in the summer months. Future work in this area should focus on air and water quality improvements from reduced commuter traffic and should acknowledge that the pandemic did not uniformly decrease electricity consumption. Policies targeting residential electricity consumption will target a larger proportion of load in these scenarios. More residential load means residential energy efficiency has additional value relative to previously, which may increase the payoff of residential energy efficiency programs.

Differential Impact of COVID-19 on the Energy Consumption of Residential and Business Sectors

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1. Motivations underlying the research

The COVID-19 pandemic upended the world and altered human behavior, changing the patterns of energy consumption in the residential and non-residential sectors. Earlier research on the impact of the pandemic on energy consumption documented two important trends. First, an increase in residential energy consumption as a result of the measures adopted to contain the spread of COVID-19, such as lockdowns, curfews, and stay-at-home orders. Second, a decrease in non-residential energy consumption largely due to closures of non-essential businesses and the overall reduced economic activity brought by the pandemic. Nonetheless, little is known about the heterogeneous impacts of the pandemic on the energy consumption across households from different income levels and across different types of businesses.

There is a growing literature on the effects of the pandemic on energy consumption. Despite this, most of the research conducted so far has focused on the first few months of the pandemic, thus quantifying only the short-run impacts of lockdowns and stay-at-home orders. Moreover, most of the research

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has focused on quantifying the effect on electricity consumption, and as a result, the evidence regarding the impacts of the pandemic on natural gas consumption is limited.

Unlike previous studies, our analysis benefits from data at the address level over a longer period and provides evidence regarding the heterogeneous impacts on both electricity and natural gas consumption during the pandemic and subsequent reopening periods across the residential and business sectors.

2. A short account of the research performed

In this paper we use address-level data from Gainesville Regional Utilities (GRU), a local utility in Gainesville, Florida, to quantify the impacts of the COVID-19 pandemic on energy demand. Our monthly panel data covers the period that spans from January 2018 to December 2020 and includes the energy consumption of all the single-family homes and business establishments with an active license in GRU's service area. Specifically, we study the effects of the pandemic on the electricity and natural gas consumption of single-family homes across different income levels by sorting the homes according to income quintiles based on the 2019 median household income in the census block group where they are located. In addition, we study the impacts on the electricity and natural gas consumption of businesses, considering whether they were deemed essential or not during the pandemic.

3. Main conclusions and policy implications of the work

The main findings are as follows. Households significantly increased the electricity consumption at the beginning of the pandemic and kept consuming relatively more than previous years until October 2020 when the final business re-opening phase was completed and electricity consumption decreased. Hence, comparing with previous years and controlling for weather conditions, electricity consumption increased 20.4% in March-April 2020 (lockdown), 15.5% in May 2020 (phase 1 of the recovery plan), and 7.3% in June-September 2020 (phase 2), whereas it decreased 7.6% in the last quarter of the year 2020 (phase 3). In the case of natural gas, residential consumption fell during March-April 2020, then increased between May and September 2020 and collapsed in the last quarter of 2020. However, as electricity is the main source of energy used in homes, when both energy sources are jointly considered, consumption followed a similar evolution to that of electricity during the pandemic. Moreover, there were differences in the impact that the pandemic had on energy consumption across income quintiles. Although the percentage changes in consumption were relatively homogeneous along the income distribution, the changes in electricity bills affected significantly more the disadvantaged households. Therefore, it is necessary to consider the distributional effect on household energy consumption and expenditure. Spending increases coupled with job losses or income reductions can be destabilizing. The effects of such changes tend to exacerbate preexisting energy poverty and should be considered in analyzing the effects of economic crises like the one experienced during the early stages of the COVID-19 pandemic.

In the case of firms, overall energy consumption fell during the pandemic and, in particular, natural gas consumption significantly decreased during the entire year 2020. However, the distinction between essential and non-essential activities is crucial to understanding the evolution of electricity consumption. Non-essential businesses significantly decreased electricity consumption from May 2020 onward. In contrast, essential businesses increased their consumption from March to September 2020. In the last quarter of 2020, both types of businesses significantly reduced their electricity consumption. Our results suggest that researchers and policymakers need to take into consideration the heterogeneity that exists in initial conditions of companies as well as the differential impacts on essential and non-essential businesses. Most people will agree that economic relief measures for companies should be taken after health and prevention policies, but complementary economic measures can also improve social welfare by preventing initially successful companies from dying out under economic restrictions.

Even though our research focused on one city in Florida, our main findings are applicable to many other cities and could serve as a guide in designing new policies for communities still affected by new COVID-19 waves or future outbreaks.

Cheap Money, Geopolitics and Supernormal Backwardation of the WTI Forward Curve

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Debate continues regarding how geopolitical risk and speculation in oil futures markets influence price outcomes. As oil prices skyrocketed into triple-digits in the late 2000s and early 2010s—levels not seen since the immediate aftermath of the Iranian Revolution—a large literature emerged to assess how much, if any, of this rise in prices was due to "speculation" as oil futures contracts had been "financialized." As oil prices rose above $100 a barrel in 2008, alarms were raised before the U.S. Senate Committee on Homeland Security and Government. Proposals were presented to the Commodity Futures and Trading Commission (CFTC) for stricter regulations on derivative positions to limit speculation in futures markets. Several comments submitted to the CFTC in 2011 supported stricter regulation, arguing that commodity index funds and other vehicles had indeed allowed speculative activities in futures markets to exceed significantly the more tethered trading that supported physical-market activity and hedging.

The CFTC approved a final rule for position limits on futures and swaps on October 18, 2011. The new rule, which CFTC said was authorized by the Dodd-Frank Wall Street Reform and Consumer Protection Act legislation, included the New York Mercantile Exchange WTI contract and "establishes that no trader may hold or own a position in the same commodity if the position exceeds a spot-month position limit of 25% of the 'estimated spot-month deliverable supply'." The rules also provided that non-spot month limits would bar traders from holding positions that exceed 10% of the first 25,000 contracts and 2.5% thereafter for either all months combined or an individual month. At the time, it was suggested that these rule details were not sufficiently restrictive. The rule was challenged in court and reissued in 2016 but in the end, no final rulemaking has been implemented. The CFTC published a new notice of proposed rule-making in the Federal Register on February 27, 2020.

The same debate on the influence of speculation on oil price formation in WTI futures pricing took hold again during the period in 2021 and early 2022 when Russia amassed troops on the border of Ukraine. Oil prices rose from $76 a barrel at the beginning of January 2021 to $120 in early June 2022. The policy salience of the issue was driven home over the course of 2022 by rising global concerns about inflation and US President Biden's intense focus on the impact of high gasoline prices on American consumers. As the US President seeks policy levers to bring down the price of oil, surprisingly little debate has focused on the inflationary role of money manager speculation in oil futures markets and related policy remedies. A rare exception was the Citi research brief from June 2022, which explained that passive investors were "longer positioned than ever" based on "price momentum and strong backwardation" and it noted that "investor positioning remains tilted toward West Texas Intermediate US based futures markets given higher margin requirements on European exchanges."

Our inquiry, which does not cover the period of extreme volatility that erupted after Russia's invasion of Ukraine, albeit consistent with price movements in the ensuing months, offers further evidence that speculative activity linked to geopolitical risk is influencing oil price outcomes. Specifically, we investigated the possibility that speculative activity in the most liquid short tenor spot month contracts for West Texas Intermediate crude oil (WTI) on the New York Mercantile Exchange (NYMEX) has contributed to repeating patterns of sharply steepening slopes in the WTI forward curve in the 10-year time period from 2011 to 2021. After controlling for macroeconomic variables, physical market fundamentals, and basic arbitrage, we find statistically significant evidence that calendar spread behavior is partly explained by speculative activity related to assessed geopolitical risk. Specifically, we

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find evidence that speculators buy the geopolitical risk and sell the event. Moreover, we find that cheap credit has served as a catalyst for amplifying the effects of geopolitical risks on oil futures prices. This research thus contributes to the body of empirical evidence that justifies stricter position limits and/or margin requirements for early tenor oil futures contracts.

Since financial and geopolitical variables together explain a very significant percentage of the variation in WTI forward curve slope historically, we suggest that regulators need to pay special attention to the effect of speculative activity during and around periods of low interest rates and heightened geopolitical risk. Our analysis contributes to evidence needed to support mechanisms to limit volumes for early tenor oil futures contracts and to investigate the large role of passive investors in fueling upward price movements, with an eye to discouraging such investors from exacerbating the negative financial effects of geopolitical crises. This is consistent with recent recommendations that US exchanges need to strengthen volatility-based margin requirements. We sharpen this policy recommendation by suggesting that CFTC should require US exchanges to set margin call requirements, especially for early-tenor contracts, based on volatility not only of the front month contract but also on the degree of market backwardation. Needless to say, these margin requirements should be lowered for positions that are probably held to hedge physical exposure as contrasted with speculative positions. Toward that end, to aid policy makers in acting under Section 5 authorities to address unreasonable fluctuations, and to allow researchers like ourselves to shed further light on the problem and potential remedies, we suggest that CFTC should require and release to the public a more transparent and detailed breakdown of positions held in WTI futures in order more easily to identify the volume of positions held by passive investors and/or financial speculators and their effects on price fluctuations.

Energy Network Innovation for Green Transition: Economic Issues and Regulatory Options

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Innovation is key to decarbonisation of the energy sector and sustainable development. However, in the post liberalisation period, sector regulators have found it difficult to incentivise innovation. We explore the reasons for the slow uptake of new technologies in energy networks and discusses remedies to promote research and innovation in the EU energy networks and infrastructure.

The existing technologies need to develop further in order to achieve the ambitious decarbonisation objectives. We argue that technological innovation coupled with economic incentives and behavioural changes are necessary to achieve the goals of the European Green Deal. In the wake of the liberalisation of the energy industry in the 1990s, it was believed that competitive markets and private sector would efficiently determine the appropriate amount and type of Research and Development (R&D). However, as the primary objective of the reforms was to improve cost efficiency, the long-term importance of R&D was downplayed.

We examine several economic concepts to delve into the reasons for the slow pace of innovation in energy networks. As the energy networks are regulated, the concepts discussed are mainly viewed from the viewpoint of economic regulation of the utilities and sector regulators. In order to ensure the preservation, dissemination, and retention of generated knowledge in innovation, we consider the establishment of a European research hub. A collaborative approach could compensate for the diminishing

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economies of coordination in the sector resulting from unbundling in terms of a vertical separation into competitive (generation and retail) and regulated (transmission and distribution networks) segments.

The collaborative approach of a research hub contrasts with the alternative of funding models such as Ofgem's Low Carbon Network Fund (LCNF), where the utilities and their projects 'compete' for their own and others' share of R&D allowance. In competition-based mechanisms for funding the most promising research and innovation efforts, utilities allocate a specified share of their revenue to a collective innovation fund. The companies subsequently take part in a competitive process in order to secure funding for their proposed innovation projects.

From a regulatory standpoint, the focus of European energy network economic regulation has traditionally been on short-term cost-efficiency improvements, whereas R&D and innovation have not been explicitly promoted to the same extent. Given that innovation can be costly at the pilot phase and only resulting in significant efficiency gains in the long-term, the suggestion arises for regulatory models to adopt long-term goals. From a risk perspective, it is also important that incentive mechanisms consider the risk profile of innovation to avoid a focus on low-risk normal efficiency improvements. Furthermore, innovation in energy networks is often perceived to have high costs and risks, as well as high sunk costs.

Input-based mechanisms that are commonly used to promote R&D and innovation include:

(i) Regulated Asset Base (RAB) models to overcome the issue of financing long-term low-carbon generation assets with low funding costs, an approach that includes innovation expenditure in the regulatory asset base of the utility,

(ii) Weighted Average Cost of Capital (WACC) approaches that attempt to distinguish between the capital used in innovation and other forms of capital to fairly reflect the perceived higher risk of innovation investments. Note that both approaches assume that the capital spent on innovation is in the form of equity or debt,

(iii) a cost pass-through approach to innovation-spend, which implies that spending on R&D is a current expenditure funded by rate payers through charges or prices.

Finally, we emphasize a 'value-based' approach to innovation funding and incentives rather than a cost-efficiency approach. Not only because the value of the benefits of green energy increases with our dependence on these, but because the value goes beyond the energy sector to also benefit social and economic objectives. Thereby, it makes economic sense to adopt a long-term view that regards innovation spending as opportunities for the future economy rather than one-off spending musts.

Who Knows What: Information Barriers to Efficient DER Roll-out in the U.S.

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1. Motivations underlying the research

Distributed Energy Resources (DERs)—rooftop solar, batteries, demand response, and other resources in the electricity distribution system, which are often located behind the customer's meter—are increasingly wide spread. The multilayered effects they cause, including emission impacts and changes to energy system operations, have spurred a flurry of policy discussions and research into the measures needed to optimally facilitate the roll-out and integration of these resources: market design reforms,

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adjustments in DER compensation and retail rate design, potential changes to network ownership, changes to network planning processes etc.

The majority of the present analyses in this space relies on the assumption of electric power distribution system being characterized by complete and perfect information. However, in practice these assumptions may not hold true, especially for non-utility stakeholders. This limits the insights that can be gained from such "first-best" analyses for real outcomes and implies that research would need to account for the true distribution of information across agents to understand the impacts of DER-related policies.

This paper attempts to identify and analyze the information barriers facing DER deployment in the U.S. We argue that DERs not only amplify the existing information deficiencies in the electricity sector, but also introduce a novel set of information issues.

2. A short account of the research performed

Our analysis draws on insights from three sources. First, we survey various U.S. electricity sector stakeholders. We want to gauge the importance of the information issues and the information needs remaining unfulfilled. We thus ask the respondents to quantify the effect of missing or incomplete DER-relevant information on their organization and to state whether they see the need for new regulation to ensure the availability of DER-related information. We also provide a list of information areas, asking to evaluate the relevance and the availability of the individual items.

Second, we review state-level proceedings to identify what processes information problems affect and the various ways in which policymakers tackle them. Finally, we review engineering and economic literature on DERs for findings on the role of information in the context of DERs and the optimal policy response.

In the paper, we present the survey results and use them to identify the aspects of DER roll-out that are particularly affected by information problems. We study four of these aspects – interconnection, optimal DER remuneration, NWA and consumer information – in greater detail, discussing the reasons for information problems and the current solutions. That analysis is largely informed by state-level proceedings.

3. Main conclusions and policy implications of the work

Survey results indicate substantial but heterogenous information problems around DERs. In particular, representatives of DER-centric organizations, such as DER developers, and environmental groups reported experiencing systematically greater information barriers than utilities and consumer representatives. Information about distribution networks characteristics is identified as the main information bottlenecks: most of the surveyed non-utility stakeholders perceive that this information is highly important but insufficiently available. As distribution network characteristics drive location-specific social and private values of DERs, lacking access to distribution network characteristics, can affect the interconnection processes as well as the ability to set optimal DER renumeration and optimally use non-wire alternatives (NWAs). Consumer data is also frequently missing in the DER context. We then outline some of the policies necessary to ensure an efficient DER roll-out.

Vehicle-to-grid Policy in South Africa: State-led v. Market-directed Approaches

Fadiel Ahjum[a] *and Andrew Lawrence*[b]

1. Motivations underlying the research

For economic, no less than ecological and energy security reasons, transitioning from coal to less expensive, cleaner, and more reliable renewable energy sources has become increasingly urgent for South Africa. Energy parastatal Eskom provides more than 90 percent of the country's electricity, and depends on coal for more than 90 percent of its generation; yet this source is proving to be increasingly expensive and unreliable, with power reductions and outages costing more than 1 percent of GDP loss in recent years. While the country's world-class wind and solar endowment has already proven to be less expensive than current (let alone new) coal and gas generation, it presents the challenge of intermittent generation, and thus of energy storage.

This article presents the first exploratory study of a solution to South Africa's energy storage challenge that would cost a fraction of the chronic blackout losses: the provision of bi-directional or Vehicle-to-Grid (or V2G) charging infrastructure, using electric vehicle (EV) batteries as complementary storage. Because South Africa's current rate of electric vehicle uptake is low compared to most Organization for Economic Cooperation and Development (OECD) countries, we explore the option of providing V2G infrastructure to the most widely used subgroup of vehicles for mass transportation, minibus taxis. An additional advantage is that, because the minibus taxis are heavily concentrated in urban areas with relatively short commuting routes (well within the typical electric minibus range of 150-200 km per charge), the oft-cited "range anxiety" that prospective electric vehicle drivers face is far less of a concern.

We model for the effect of V2G adoption v. the rollout of uni-directional EV charging infrastructure, while also comparing stipulated charging – using time slices (TS) to account for daily variation in demand, such as morning and evening commutes – to unstipulated charging. Whereas uni-directional infrastructure is less expensive, it does not afford the storage capacity of V2G infrastructure. With approximately 300,000 minibus taxis currently in use in South Africa, the combined storage potential of a completely electrified fleet would approach 6 GWh—almost twice that of the country's combined pumped storage capacity.

2. A short account of the research performed

Our study provides the first national modelling study investigating the feasibility of adapting V2G policy to an African context. To this end, we use the South African Times model (SATIM) for energy and transport, and for economic modelling, the South African General Equilibrium model (SAGE), together known as SATIMGE. We calculate alternative scenarios to 2050, using 2030 and 2040 as milestone years for a scenario of V2G against a reference scenario of no V2G. We assume purchase parity for all EV vehicle types by 2030. Taking into account the two variables of the presence or absence of V2G infrastructure and of time slice charging stipulations yields five scenarios: (1) Minibuses are provided with V2G charging stations, including time slice (TS) charging stipulations; (2) Minibuses are provided with V2G charging stations, excluding TS charging stipulations; (3) No investment in either EV charging infrastructure, or in V2G infrastructure, excluding TS charging stipulations; (4) Investment in EV charging infrastructure, but not in V2G infrastructure, including TS charging stipulations; and

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(5) Investment in EV charging infrastructure, but not in V2G infrastructure, excluding TS charging stipulations.

3. Main conclusions and policy implications of the work

We find that from the exclusive perspective of maximizing renewable energy generation capacity, the most preferable scenario would be (2): minibuses are provided with V2G charging stations, excluding TS charging stipulations; followed by (4): investment in EV charging infrastructure, but not in V2G infrastructure, including TS charging stipulations; (3): no investment in either EV charging infrastructure, or in V2G infrastructure, excluding TS charging stipulations; (1): minibuses are provided with V2G charging stations, including time slice (TS) charging stipulations; with (5): investment in EV charging infrastructure, but not in V2G infrastructure, excluding TS charging stipulations, being the least preferable. Our findings suggest that V2G policy could increase storage capacity by ~4-6 GWh: almost 25 percent of current levels. As presently configured in the model, therefore, V2G policy with an emphasis on the minibus taxi as an energy service provider could potentially play a role in the electricity sector by 2040 if network augmentation costs are addressed along with flexible charging infrastructure.

Several policy implications may be inferred from these findings, albeit ones that are contingent upon model refinement, future cost inputs (e.g. for batteries and V2G infrastructure), and specificities of policy implementation. If EV battery prices or estimated feasible minibus battery capacity maintenance level should fall further than estimated, the scenarios excluding V2G infrastructure could become more competitive. Conversely, a price rise (or bottlenecks in scaling up battery production) could make the minibus V2G scenarios more attractive. The level of interest in minibus V2G implementation is most obviously contingent upon engagement with the minibus taxi industry, and the state's terms of inducement to convert the taxi fleet. Uncertainties pertaining to these and other variables may suggest the desirability of engaging in policy experimentation at the local or provincial level as a precondition for national policy adoption.

Who's Responsible for Climate Change? New Evidence Based on Country-level Estimates of Climate Debt

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1. Motivations underlying the research

Persistent increases in average global temperatures, in the absence of mitigation policies, risk catastrophic climate change as well as reduced world GDP per capita. In the absence of policy changes, fossil fuel consumption and global CO_2 emissions are projected to continue to rise, with an increase in global CO_2 emissions of 4 percent by 2030 relative to 2019. Over the longer term, even scenarios that maintain global emissions at present levels, before dropping after 2050, are troubling. For example, the intermediate scenario of the Intergovernmental Panel on Climate Change predicts an increase in average global temperatures from the present 1.2 degrees Celsius above the pre-industrial average (1850–1900) to an average of 2 degrees in 2041–60 and 2.7 degrees in 2081–2100.

In order to avoid the adverse consequences of this scenario of increasing global temperatures, a number of countries have pledged to reduce emissions beyond their initial commitments in the 2015 Paris Agreement (COP21). under which countries agreed to limit global warming to well below 2 degrees relative to pre-industrial levels and aim for 1.5 degrees.

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Under the present framework, mitigation pledges in countries' nationally developed contributions (NDCs) are voluntary. However, pledges would only cut global emissions by 1/3–2/3 of the reductions consistent with Paris warming targets. As such, there is a large gap between what countries have committed to do and what needs to be done. In this context, a key issue in deciding which countries should do more is an assessment of which countries have contributed the most to climate change (through their CO_2 emissions) and its associated economic damages. The total sum of these damages can be conceptualized as a "climate debt" in the sense that these costs have been imposed on the globe without any compensation. This paper seeks to contribute to this debate by providing an assessment of the climate debt of each country, based not only on historical emissions, but emissions that are likely in the near future. These estimates could be used to address the appropriate size of climate finance assistance, where countries with large climate debt may be seen as needing to contribute proportionately more to these efforts.

2. A short account of the research performed

Climate debt is estimated on the basis of historical data on emissions and estimates of the social cost of carbon (SCC), which measures the economic damage per ton of CO_2 emissions. We estimate this climate debt for 131 countries in a number of ways (in dollars, in per capita terms, and as a share of a country's GDP). In absolute terms, global CO_2 emissions from 1959 to 2018 amounted to 1,259 gigatons, or about 83 percent of historical global emissions. These estimates capture CO_2 emissions from both the burning of fossil fuels and those arising from cement production and the flaring of natural gas. We estimate projections for CO_2 emissions for 2019-2035 on the basis of country level projections for greenhouse gases from the IMF's Fiscal Affairs Department, which follow the methodology described in the IMF's 2019 Fiscal Monitor. Future emissions are estimated under a "business-as-usual" scenario, which is grounded on data on energy consumption by product in 2018 and projected economic growth.

We find that the climate debt is extremely large, equaling some $59 trillion over the 1959–2018 period. Climate debt is also substantial relative to other government liabilities; in the G-20, it equals about 81 percent of GDP. Looking forward to 2035, cumulative climate debt will rise another $80 trillion.

3. Main conclusions and policy implications of the work

Climate debt from CO_2 emissions is large and unevenly spread across the world's economies. In the advanced economies, the climate debt accumulated up to 2018 equaled about $22,065 per person, some 2 times that of emerging economies and 11 times that of low-income economies. Among the biggest emitters, climate debt per capita is the highest in the United States and 6 times as high as that of China (and 25 times as high as that of India). While fiscal policy will face constraints going forward, the large size of the climate debt, and the disparities in climate debt by countries, portends contentious discussions on what constitutes a country's fair burden in slowing climate change and the level of assistance that should be given to developing countries to aid this effort. The cumulative climate debt of the US in 2035, for example, is projected to equal about 117 percent of GDP, compared to its annual official development aid of 0.17 percent of GDP. Climate debt per capita is projected to be much higher in the advanced economies than in developing economies, even under the full implementation of NDCs by G-20 countries. This implies that additional effort by advanced economies may be needed to achieve a fair burden in the fight against climate change. If countries were to fully meet the Paris targets for limiting increases in temperatures, there would be a sizeable reduction in climate debt. However, implementing the required reductions in emissions would be problematic, given that advanced economies—which have accumulated a large share of the stock of climate debt—are already reducing their emissions sharply under their NDCs. Thus, a more pragmatic approach to achieving a fair distribution of the burden is for advanced countries to ramp up their assistance to developing countries, including through climate finance. Current levels of climate finance, which have not yet reached the goal of $100 billion per annum, are clearly inadequate in light of the large size of climate debt accumulated by advanced economies.

The (indirect) Effects of Windfall Funds on Sustainability Behavior: Insights for Carbon Fee Dividends

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1. Motivations underlying the research

Addressing global climate change continues to challenge decision-makers and citizens alike. In the United States, legislation involving a carbon tax and dividend is increasingly discussed to help move away from the heavy reliance on carbon-based fuels and encourage investment in energy innovations that meet energy demands. The purpose of the dividend would be to reallocate collected fees to American residents who may spend it as they choose. Analysis suggests that many households (60%+) will receive a larger dividend payment than their increased energy cost from the tax. However, whether the reallocation and spending of such funds would support or detract from efforts to pivot away from carbon fuels and towards energy conservation and/or innovation remains unknown.

A growing body of work indicates that people act quite differently depending on how money, including policy incentives such as the proposed reallocation of fees in the Carbon Dividend Trust Fund, has become entrusted to them. Of particular importance to the current study is whether all types of windfall are perceived, and acted upon, equally. Specifically, if the government (in the form of the Carbon Dividend Trust) is taxing carbon (or carbon-equivalent) emissions to encourage lower individual use, will people change their behavior and limit or expand their own conservation efforts because the government is involved? Our paper is motivated by this open question and broader inquiries from the literature regarding behavior from windfall funds and linked sustainability behaviors.

This article contributes three ways to the literature on windfall effects and behavioral spillover. First, we examine whether the source of windfall funding (a subsidy, tax refund, or no information on the source) impacts an individual's stated future sustainability behavior. Second, we investigate if a threshold windfall amount must exist before we see changes in stated sustainable behavior. Third, we explicitly examine heterogeneity in response to windfall funding. Moreover, this study was designed to directly investigate important policy questions surrounding legislation like the Carbon Dividend Act. Our results show that the source of money substantially influences behavior and must be carefully considered when analyzing policy that intends to reallocate funds for citizens to spend as they see fit. Importantly, our paper serves as a reminder that there is a lot we don't know about the indirect impacts of a carbon fee and dividend approach and provides insight into various avenues for future research.

2. A short account of the research performed

Our paper uses a nationwide survey conducted in September 2018 to measure whether information on the source or amount of windfall impacts an individual's intent to engage in sustainable behaviors.

The survey was designed so that each participant was randomly placed into one of three treatments regarding potential additional compensation for participation (subsidy, tax refund, neutral wording) and the source of these extra funds from parties related to energy efficiency and conservation in transportation and home energy. Each participant was asked an open-ended qualitative question about how they planned to use additional compensation, along with Likert-style questions to measure their future sustainable behavior intentions related to energy efficiency and conservation, environmental motivation, perceptions of climate change, and socio-demographics. We received 1,217 survey responses from United States residents over the age of 18. Given the bounded nature of our Likert scale data, we ran several Tobit regression analyses with a consistent set of control variables.

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3. Main conclusions and policy implications of the work

Our results provide evidence that information on the funding source for unexpected compensation causes people to increase their stated desire to participate in transportation-related sustainable behavior. The tax refund treatment, in particular, led to consistently positive spillover effects. This result suggests that a carbon fee and dividend may result in a lower bound of GHG emissions reductions because current reports do not account for the indirect behavioral effects of the dividend. Our results also introduce the idea that a minimum threshold triggers a windfall response. This result would suggest that over time, as the dividend decreases (as jurisdictions move away from carbon-emitting technologies), we may see a reduction in the positive spillover or no additional behavioral effect. As a result, we hypothesize that the additional indirect decrease in emissions is likely the largest early in the lifespan of the policy when the refund is high. Importantly, our analysis reveals that pro-environmental behaviors are not treated equally and that the source of windfall payments can influence these behavioral outcomes. Future research will also benefit from a better understanding of how dividend-adjacent policies, such as using tax revenues to lower corporate and income tax rates, which indirectly act like a windfall, impact behaviors. Implementing a carbon tax has many moving pieces, and this study provides additional insight into the full accounting of its possible consequences.

Do Investments in Clean Technologies Reduce Production Costs? Insights from the Literature

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Adopting green or clean technologies is one of the primary responses to combat global climate change. Many fiscal and regulatory policies have been introduced globally to facilitate the increased deployment of clean technologies. National governments, international financial institutions, bi-lateral donors, non-governmental organizations, and the private sector have channeled hundreds of billions of dollars toward green or clean or low carbon economic development. The International Energy Agency (IEA) estimates that about US$600 billion was invested in clean energy technologies in 2019 (IEA, 2021a). It is estimated that US$130 billion annual investment would be needed globally on clean technologies to meet GHG mitigation targets set by various countries under the Paris Climate Accord (McCollum et al. 2018). Has the increased adoption of clean and low-carbon technologies helped increase productivity and thereby decreased production costs? Or will it do so? This study aims to answer these questions by exploring evidence of increased productivity and lowered production costs due to the increased adoption of clean technologies. To accomplish this research objective, we review relevant existing studies that investigate the relationship between the adoption of clean technologies and the reduction in production costs.

We find two types of studies in the literature—ex-post empirical studies and ex-ante modeling or analytical (numerical) studies. Some ex-post studies use global data pooling from all sectors (e.g., manufacturing, buildings, transportation, agriculture), whereas others use national-level data. Some studies use global data for a given sector (e.g., manufacturing). The ex-ante studies are focused more on the sectoral levels and examine the impacts of green/clean investments on the cost of energy services instead of sectoral productivity. They use economic/financial analysis at the technology level (e.g., electricity vehicle, refrigerator) or modeling at the network or sectoral level (e.g., solar and technologies for power generation).

Most of the ex-post or econometric studies we reviewed, particularly the more recent ones, show a positive relationship between investments in clean technologies and firms' productivity. They

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conclude that the increased adoption of clean technologies has caused a reduction in production costs. However, the relationships between the adoption of clean technologies and production costs can be influenced by factors such as the size of firms and types of investments. The findings of ex-ante studies are somewhat mixed. In the buildings sector, existing ex-ante studies mostly report that adopting clean (both energy efficient and clean energy supply technologies, such as solar home systems) saves energy and energy services. On the other hand, studies for the transportation sector show that vehicles utilizing cleaner fuels (electricity, hydrogen) are not yet economically attractive. Studies on the power sector suggest that the expansion of greener/cleaner renewable energy technologies, which is happening rapidly more recently, also has mixed effects on electricity supply costs. Despite rapid drops in their costs, renewable energy technologies, particularly solar and wind, do not necessarily reduce the average costs of electricity supply because of their intermittency and low level of penetration.

Since the existing studies using the observed data (i.e. empirical studies), in general, agree that adopting clean technologies reduces production costs and harmful environmental externalities, the adoption of clean and green technologies should be enhanced further. Policies to support the adoption of clean technologies should be continued or increased. Our study also reveals that reducing production costs is not the only incentive for the private sector to invest in green/clean technologies. Adopting green/clean technologies increases private companies' social images and market values. Since the investments in green/clean technologies increase productivity and enhance market values by improving social image, the private sector should increase the investments in green or clean technologies.