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Climate Change, Climate Policy, and Economic Growth

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The topics of climate change and climate change policy encompass a complex mixture of the natural sciences, economics, and a mass of institutional, legal, and technical details. This complexity and multidisciplinary nature make it difficult for thoughtful citizens to reach their own conclusions on the topic and for potentially interested economists to know where to start.

This essay aims to provide a point of entry for macroeconomists interested in climate change and climate change policy but with no special knowledge of the field. I therefore start at the beginning, with some basic background on climate change, presented through the eyes of an econometrician. I then turn to climate policy in the United States. That discussion points to a large number of researchable open questions that macroeconomists are particularly well suited to tackle.[1]

Let me summarize my four main points. First, although a healthy dose of skepticism is always in order (as academics it is in our DNA), simple and transparent time series regression models familiar to macroeconomists provide independent verification of some key conclusions from climate science models and in particular confirm that essentially all the warming over the past 140 years is because of human activity, that is, is anthropogenic. Figure 1 shows time series data on annual global mean temperature since 1860, when reliable instrumental records start. As seen in the figure, the global mean temperature has increased by approximately 1 degree Celsius, compared with its 1870–90 average value. This increase in temperatures drives a wide range of changes in climate, including droughts, more hot days, and more intense rainfalls and storms, all of which vary regionally. Because climate science uses large, opaque calibrated models of the climate system, there is room for confusion among legitimately skeptical outsiders about just how much of the global warming observed since the industrial revolution results from human

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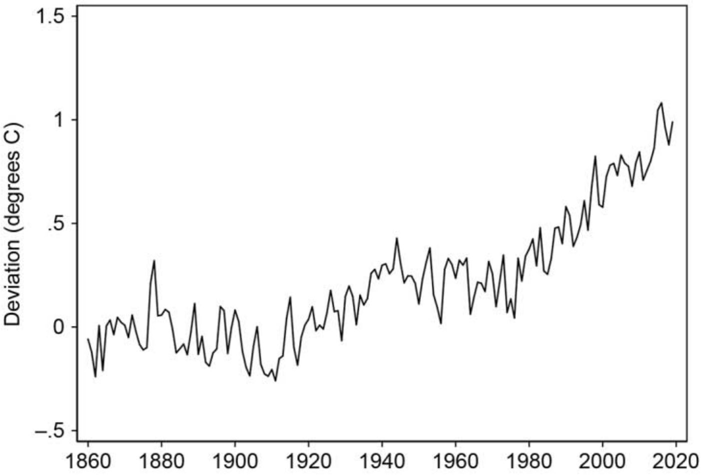

Fig. 1. Global mean temperature deviated from its 1870–90 mean (Hadley Earth Observatory, HadCRUT4 series at https://crudata.uea.ac.uk/cru/data/temperature).

activity, that is, is anthropogenic. Standard time series regressions provide a simple, transparent, and (I argue) reliable alternative, at least for modeling the relation between emissions and temperature. According to a regression decomposition I present later, anthropogenic sources account for essentially all of the warming in figure 1. The main driver of that warming is anthropogenic emissions of carbon dioxide (CO_2) from burning fossil fuels. The simple regression on which these estimates are based lacks nuance but the results accord with and, therefore, provide support for the more complex models used by climate scientists.

Second, policy will play a crucial role in decarbonizing the economy. As shown in figure 2, in the United States, energy-related CO_2 emissions peaked in 2007 and then fell 12% by 2018. This fact has led some on the environmental left to argue that we have turned a corner and are on an inevitable path to decarbonization and some on the right to argue that the free market will lead to decarbonization so policy interventions are costly and superfluous. But this narrative, however appealing, is false. Instead, the decline in emissions since 2007 is mainly the consequence of the financial crisis recession and the fracking revolution, which made natural gas cheap enough that it has partially replaced a higher-carbon fossil fuel, coal, for generating electricity. In contrast to the rosy narrative, the most recent projections by the US Energy Information Administration (EIA) indicate that, under current policy, the United States will not be close to hitting its pledged 2025 emissions-reductions target under the now abandoned Paris climate accord.

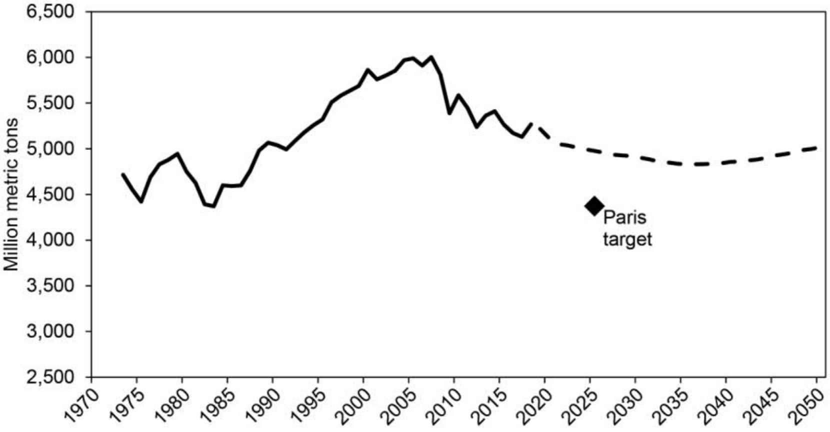

Fig. 2. US CO_2 emissions from energy consumption, 1973–2018, with US Energy Information Administration projections (dashed), 2019–50 (US Energy Information Administration, *Monthly Energy Review* [June 2019] and 2019 *Annual Energy Outlook*, reference case).

Third, looking beyond the short-term Paris target, the multitude of climate policies currently in place in the United States, from federal to state to local, fall far short of what is needed to achieve decarbonization on a timescale consistent with avoiding very severe damages from climate change. With some exceptions, existing policies interact in complex ways that lead to inefficiencies, are subject to industry capture, tend to be expensive as measured by cost per ton of CO_2 avoided, and are small bore in the sense that their scope for emissions reductions is small. The large-scale, more efficient policies typically favored by economists, such as a carbon tax or its cousin, cap and trade, have dim prospects because they either have already been rejected politically (e.g., cap and trade), create significant political liabilities (e.g., a carbon tax), or have been weakened or reversed through the regulatory process (e.g., the Clean Power Plan [CPP], the Obama administration's plan for a cap-and-trade system within the power sector). Moreover, the absence of a price on carbon is but one of the externalities plaguing climate policy, and carbon pricing alone at politically plausible levels is unlikely to be particularly effective in reducing emissions from the oil and gas used in the transportation, commercial, and residential sectors.

Fourth, the political constraints on and intrinsic limitations of Pigouvian carbon pricing mean that economists need to look elsewhere for efficient climate policies. I believe that the most important place that economists can add value to the climate policy discussion now is by focusing on policies that drive low-carbon technical innovation. This view is informed by positive political economy—what politicians seem willing to do, by empirical evidence and some key success stories about technology-pushing policies, and by a small but insightful literature on carbon prices, research and development (R&D) subsidies, and induced technical change. Ultimately, decarbonization will occur not by forcing consumers and businesses to choose expensive low-carbon technologies over inexpensive fossil fuels but by ensuring that those green alternatives are sufficiently low cost that they are largely chosen voluntarily. Consumers and firms will need to choose low-carbon energy not because it is the right thing to do, but because it is the economical thing to do, even if there is not a meaningful price on carbon. The transition to a low-carbon economy will require a low-cost alternative to fossil fuels. The key policy question is, How can we most efficiently promote the development of advanced low-carbon technologies? This difficult question is one that economists are well equipped to tackle.

I. Some Climate Change Econometrics

The increase in global mean temperature in figure 1 happened in stages, initially rising starting around World War I, followed by a plateau in the 1950s through 1970s, then taking off in earnest around 1980. A natural question is, How much of this increase is anthropogenic? An oft-cited response is that 97% of climate scientists agree that global warming is mainly because of human activities (Cook et al. 2013). As part of the scientific community, we should trust in the peer review process and thus in the science underlying that consensus. That said, the models on which those conclusions are based are large, complex, and difficult for outsiders to evaluate. This complexity has opened the door to debate about the scientific consensus, which in turn raises the question of whether there are ways to estimate the extent to which this warming is anthropogenic that are simpler, transparent, and stay close to the data. Fortunately, the tools of time series econometrics provide such estimates.

The starting point is the principle that Earth's temperature is proportional to the thermal energy flux hitting its surface. This includes energy from the sun and energy radiated from Earth that is absorbed by atmospheric gasses and reradiated back to Earth. This latter source is the greenhouse effect. These energy fluxes, called radiative forcings, are shown in figure 3: CO_2, methane, trace gasses like hydrofluorocarbons, solar radiative forcing (the wiggles are sunspot cycles), and sulfur oxides, which have negative radiative forcings because they reflect sunlight back into space. All the gasses have natural components, but the changes in these

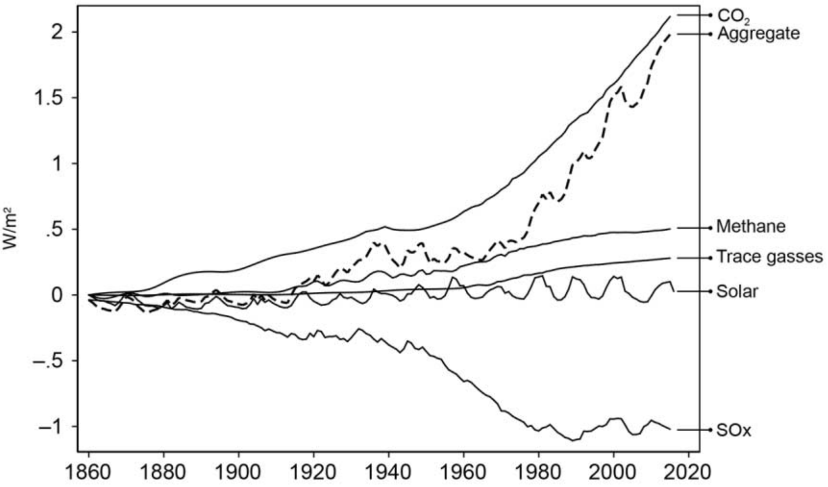

Fig. 3. Radiative forcings (see Montamat and Stock 2019 for original data sources).

radiative forcings over this period are almost entirely anthropogenic (sulfur oxides are also emitted from volcanic eruptions in addition to burning high-sulfur fossil fuels; however, their presence in the atmosphere is transitory). The dashed line is the sum of these radiative forcings.

A very simple model of Earth's temperature is that it is proportional to the sum of the radiative forcings. With the additional assumption that total radiative forcings are an integrated process, this simple model implies that global mean temperature and radiative forcing are cointegrated (Kaufmann, Kauppi, and Stock 2006; Kaufmann et al. 2013); that is, there is a cointegrating relationship of the form $T_t = \alpha + \theta \mathrm{RF}_t + u_t$, where RF_t is the sum of the radiative forcings in figure 3 and u_t is integrated of a lower order than RF_t and θ is the cointegrating coefficient.[2]

Figure 4 overlays the global temperature series in figure 1 with the predicted value of temperature, $\hat{\theta}\mathrm{RF}_t$. The estimate of θ used in figure 4 (0.489, standard error [SE] = 0.041) is the benchmark estimate from Kaufmann et al. (2006, table 2, col. 2), which was estimated using data from 1860–1994, the full data set available at the time. The in-sample fit of the dynamic ordinary least square estimate (through the vertical line in 1994) captures the overall pre-1994 trend, although there are short-run fluctuations in temperature around this trend that are not captured by this long-run relationship.

Because this model was fit using data through 1994, there is a clean out-of-sample test of this very simple model. The test is nontrivial: temperatures increased since 1994, but irregularly, with a famous decade-long "hiatus" starting in 1998. How did this simple model do?

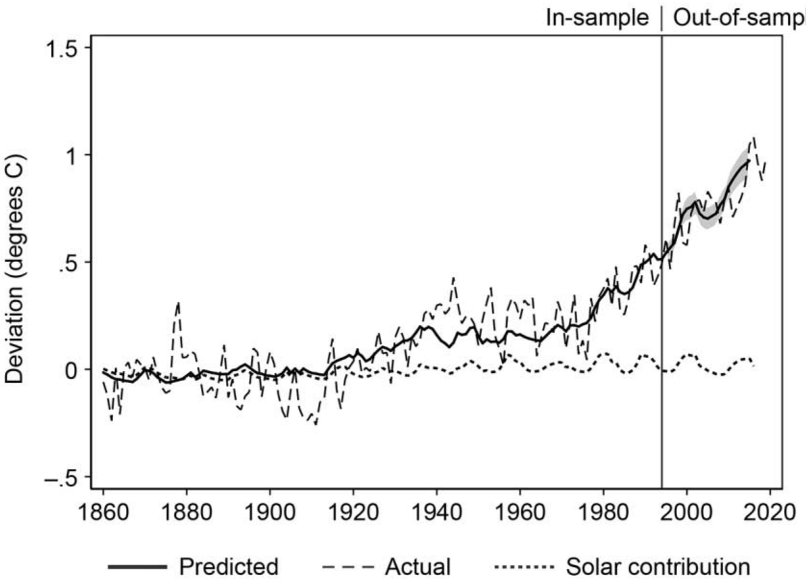

Fig. 4. Temperature and fitted values based on radiative forcings. Estimation 1860–1994. Shading is 67% confidence interval conditional on radiative forcing. Predicted value uses dynamic ordinary least square cointegrating vector from Kaufmann et al. (2006, table II[2]). Temperature (dashed line) is deviated from its 1870–90 mean. The solid line is the predicted value from the benchmark cointegrating regression in Kaufmann et al. (2006) ($\hat{T}_t$ = const + 0.489RF_t), which they estimated using data from 1860 to 1994. The vertical line demarks the in- and out-of-sample time periods for that estimate. The shading around the predicted value post-1994 is a one SE band for the predicted value using their reported SE of $\hat{\theta}$. The dotted line is the contribution of natural variation in solar radiation to temperature, estimated using the Kaufmann et al. (2006) regression.

It turns out that it did quite well. As discussed in more detail in Kaufmann et al. (2011), the model provides a parsimonious explanation of the hiatus as due in part to a lull in solar activity and to new dirty coal-fired power plants coming online in China, which produced sulfur oxides and a cooling effect.[3]

This simple model provides a standard regression decomposition of the post-1880 warming into a natural component, an anthropogenic component, and a residual. One way to do this is to consider the counterfactual in which all the gasses simply equaled their averages in the late nineteenth century. The dotted line in figure 4 is the predicted natural component arising from variation in solar flux. Initially, nearly all the variation in the predicted value of temperature was from variation in solar radiation. But starting around 1920, greenhouse warming started to kick in. During the 1950s through the 1970s, the warming effect of CO_2 and methane was largely offset by sulfur oxides emitted from coal power plants. As those emissions were cleaned up to mitigate local pollution and acid rain, CO_2 took over as the main driver and warming accelerated.

According to this very simple model, of the 0.81 degree Celsius of warming from the 1870–90 average through the 2006–15 average, 0.84 degree (SE = 0.07) is due to greenhouse gasses, 0.01 degree (SE = 0.004) is due to an increase in solar intensity, and –0.04 degree is an unexplained residual.[4] Thus, according to this decomposition, essentially all of the observed warming is anthropogenic in origin, up to a residual of approximately 5%.

The full decomposition based on this simple regression model is given in table 1. As this decomposition shows, the key driver is CO_2, and its impact on warming would have been greater had it not been for the additional, and unhealthy, increase in SO_x pollutants produced by burning high-sulfur fossil fuels, especially high-sulfur coal.

The virtue of this model is its transparency and its good performance in a 2-decade, true out-of-sample test. But the model is an extreme simplification of highly complex climate processes and is silent about the wide variation in climate change effects stemming from this temperature increase. Those effects are extensively documented in the climate science literature.[5] Many are also amenable to validation using econometrics.[6] To me, the numerical alignment of the estimates from this very simple model with the climate models justifies confidence in the climate science models.

Table 1
Decomposition of the Change in Global Mean Temperature from 1870–90 Average to 2006–15 Average

	Change or Predicted Change (°C)	Standard Error
Greenhouse gasses:		
CO_2	.96	.08
Methane	.24	.02
Trace gasses	.13	.01
SO_x	–.49	.04
Subtotal, gasses:	.84	.07
Solar	.01	.004
Subtotal, predicted:	.85	.07
Actual	.81	
Residual	–.04	

Note: Predicted values and standard errors are based on the cointegrating regression used for the predicted values in figure 3 and described in Section I.

II. What Is the Progress to Date on Reducing Carbon Emissions?

As I mentioned, a popular narrative is that the downturn in US CO_2 emissions since 2007 demonstrates that we have turned a corner and are on a path toward decarbonization. According to this narrative, we are reducing emissions because of energy efficiency improvements, the expansion of wind and solar for electricity generation, and an increasing cultural awareness of the importance of conserving energy and going green. This narrative is popular among environmentalists, who say that decarbonization will be cheap; conservatives, who say that market forces are resulting in decarbonization already; and green investors, who proclaim a bright future for their low-carbon investments.

I wish that this rosy narrative were true, but it is not. Macroeconomists will not find it surprising that the big drop in emissions occurred in 2009, when energy demand plummeted as the economy tanked. Since then, the fracking revolution has resulted in low natural gas prices, which has led to replacing coal generation with natural gas generation.[7] Because burning coal emits more CO_2 than burning natural gas per kilowatt-hour of electricity generated, switching from coal to natural gas reduces CO_2 emissions.

Because the 2009 recession and the advent of fracking were one-time events, they do not constitute a change in the trend, just a shift in the level of emissions. Indeed, in 2018, US energy-related CO_2 emissions increased by 2.9%. The US EIA projects coal use for electricity to be roughly flat from 2020 to 2050.[8] As shown in figure 2, emissions are projected to plateau at current levels, as energy efficiency improvements and renewables just offset growing energy demand. Indeed, the silver lining of the substitution of natural gas for coal resulting from fracking hides a cloud, which is the substantial investment in natural gas pipelines and generating facilities that could lock in future emissions else risk the political and economic disruption of stranded natural gas assets.

This projection leads to the question: If CO_2 emissions remain at their current rate, what is their short-run effect on temperature? In recent work with Giselle Montamat, we use a natural experiment instrumental variables approach to estimate the short-run temperature effect of emission without adopting any particular model of long-run persistence. We estimate that 10 years of emissions at the current rate would increase temperature over those 10 years by 0.13 degree Celsius (Montamat and Stock 2019). This might not seem to be by much, but it is more than one-eighth the total warming to date and amounts to 1 degree Fahrenheit over

3 decades. Moreover, this is just the impact effect, and the cumulative effect would be even larger as the pulse works through Earth's system.

In short, climate change is anthropogenic and it is happening now on a human timescale. The planet is already experiencing temperature records and increasingly damaging hurricanes and typhoons, wildfires, droughts, and heat waves. Additionally, sea levels have been and will be rising because of thermal expansion of water and melting of glaciers and ice sheets. Under a business-as-usual scenario, the mean sea level is projected to rise by between 55 and 95 centimeters by the end of this century.[9] These consequences of human emissions of greenhouse gasses are not a "new normal." Rather, they will become more severe as temperatures rise.

The future consequences of climate change remain uncertain. For example, the amount by which sea levels rise depends in part on the extent to which glaciers and ice sheets melt. In climate science, events such as the melting of the West Antarctic Ice Sheet or, much worse, the melting of the Greenland Ice Sheet, are referred to as abrupt irreversible events. Those events are not expected to happen in this century, although they could be triggered irreversibly in the first half of this century. They could add multiple meters to sea level rise. Similarly, there is considerable uncertainty about the pace of extinctions that are being and will be induced by climate change. The severity of these and other aspects of climate change depends on whether cumulative emissions get high enough to trigger such transformations.[10] That, in turn, depends on climate policy decisions made by our generation, arguably within the next decade or two.

III. US Climate Policies: Historical Evidence on Efficiency and Effectiveness

This brings us to a discussion of climate policies, where I focus on the United States. First, however, I digress briefly on the externalities these policies aim to address and on current estimates of the value of one of these, the carbon externality.

A. Digression on Externalities

There are two main market failures that climate policy aims to address: the carbon price externality and the R&D externality. In some instances, network externalities are also important, such as the chicken-and-egg problem of electric vehicles and charging stations.

The climate externality that has received the most attention by economists is the carbon price externality. The starting point estimate for assigning a value to this externality is the social cost of carbon (SCC), which is the monetized net present value of the damages from emitting a marginal ton of CO_2. The final estimate of the SCC released under the Obama administration is approximately $50 per ton for emissions in 2020 (US Government Interagency Working Group on the Social Cost of Greenhouse Gasses 2016). (To get a sense of orders of magnitudes, a short ton of subbituminous coal from a federal mining lease in the Powder River Basin currently sells for approximately $12; when burned, it emits 1.7 metric tons of CO_2, which has approximately $84 of climate damages evaluated at an SCC of $50. The climate damages from burning a gallon of gasoline are approximately $0.45, also evaluated at an SCC of $50.) There is widespread recognition that the scientific basis for this $50 estimate of the SCC needs to be solidified. To this end, Resources for the Future is coordinating a major research project involving energy-climate labs at Chicago and Berkeley, along with academics from other universities, which (among other things) is implementing suggestions made by the National Academy of Sciences (2017) for improving the estimate of the SCC. Because this work is still in progress, for this paper I use the provisional $50 per ton estimate for the SCC.

I now return to the discussion of US climate policies.[11] These policies fall into four categories: regulation, narrowly targeted policies, carbon pricing, and technology-pushing policies.

B. *Sectoral Regulation Based on the Clean Air Act*

The Clean Air Act is the legal authority used for the two most ambitious regulatory attempts to date to reduce greenhouse gas emissions, the CPP that applied to the power sector and the Corporate Average Fuel Economy (CAFE) standards that applied to automobile emissions (and thus mileage). With careful attention to detail, regulations under the Clean Air Act can be efficient and effective. For example, the CPP developed by the Obama administration used Clean Air Act authority to construct a mass-based cap-and-trade system for the power sector that is broadly considered to be workable and cost-effective. Estimates are that the CPP would have achieved substantial emissions reductions with an average cost around $11 per ton CO_2, which is well below the SCC benchmark.[12] Initial estimates suggest that the CPP would have led to significant emissions reductions and would have been a meaningful step toward decarbonizing the power sector. The CPP was, however, stayed by the Supreme

Court and subsequently was replaced by the Trump administration with an alternative, the Affordable Clean Energy plan. Under that plan, there are strict limits on the measures that states can require, and states have the ability to waive or reduce the emissions reduction measures specified in the federal plan. As a result, the Affordable Clean Energy plan is projected to have negligible effects on emissions.[13]

Regulatory approaches, whether under the Clean Air Act or more generally, have multiple drawbacks. Although some regulations can be efficient (the CPP being a prime example), many are not, in the sense that they result in emissions reductions that are costly per ton compared with the SCC. For example, there are many papers in environmental economics highlighting inefficiencies in the CAFE standards on automobile emissions.[14] Estimates of emission reduction costs from that program range from \$50 to more than \$300 per ton. In addition, under existing legislative authority, regulatory approaches are limited in scope and are at best a partial solution to the climate problem. Moreover, regulations can be changed, and indeed the climate policy of the Trump administration largely consists of reversing Obama-era climate regulations. Finally, recent changes at the Supreme Court increase the odds that expansive interpretations of Clean Air Act authority to regulate greenhouse gasses will not be upheld. It is important to study the history of these regulatory approaches to inform policy design, and there are circumstances in which narrowly proscribed regulation might be the most efficient way to regulate emissions (e.g., command-and-control regulation of methane emissions in oil and gas drilling). That said, because of its limitations, I expect that regulation under the Clean Air Act is unlikely to play a major role in reducing emissions going forward.

C. Narrowly Targeted Policies

The second category of climate policies is what I will call narrowly targeted. Examples include home weatherization programs, mandates to use biodiesel and corn ethanol in our fuel supply, and state-level renewable portfolio standards (RPSs). The costs of these policies vary widely. In a few cases, such as blending corn ethanol to comprise 10% of retail gasoline (the dominant blend in the United States), costs per ton are low or even negative. In many cases, however, the costs are high. For example, replacing petroleum diesel with biodiesel has a cost per ton of between \$150 and \$420, depending on the feedstock and how the incidence of the biodiesel tax credit is treated. Moreover, many of these policies interact in ways that increase costs but do not materially reduce emissions.

For example, some states both have a RPS and participate in a regional cap-and-trade program for the power sector, such as the Regional Greenhouse Gas Initiative in the Northeast. Because electricity is provided on a multistate grid and cap-and-trade allowances are tradable across states, mandating clean energy in one state increases the number of allowances, reducing their cost and allowing more carbon emissions in other states in the regional program, a phenomenon that environmental economists refer to as "leakage."

Within this catch-all group, one set of policies—namely, RPSs—does have the possibility of being impactful and cost-effective. Concerning impact, 29 states have renewable energy standards and some states, including California and New York, have announced midcentury goals of generating electricity that emits no greenhouse gasses. In theory, RPSs could become much more effective and efficient if all or nearly all states were to adopt them and if interstate trading of RPS allowances were introduced. With the important caveat that RPSs do not cover nuclear or other nonrenewable zero-carbon sources, a nationally tradable RPS system would approximate a national clean energy standard. This system would be less efficient than having a uniform price on carbon for the power sector, but it could come close (Goulder and Hafstead 2016, 2018), at least for the initial tranche of reductions. A noteworthy political economy feature of a nationally tradable RPS allowance market is that it would facilitate decarbonization in participating states with low RPS targets, more than achieving their targets with the cost underwritten by states with ambitious targets.

With the exception of RPSs, this family of narrowly targeted policies tends to be small bore and in this sense is at best complementary in a broader package of solutions.

D. Pricing Carbon

The third set of policies are carbon pricing policies. Although efforts to adopt a cap-and-trade program in the United States with the Waxman-Markey bill of 2009 failed, other countries and some states have adopted cap-and-trade systems or a carbon tax or fee on at least some sectors.

The cost of a carbon tax depends on how the revenue is recycled. Here, I focus on the case in which it is returned by lump-sum rebates, as proposed by the Climate Leadership Council. In a recent book, Goulder and Hafstead (2018) use a multisector computable general equilibrium model to estimate the effect of carbon taxes with this and other revenue recycling schemes, along with other economy-wide climate policies. For a $20 per ton tax that increases by 4% per year and lump-sum recycling, they estimate that the level of gross domestic product (GDP) would be reduced by 1% over 30 years, amounting to an average reduction of GDP growth of just three basis points per year.

It is also possible to look at actual macro outcomes for countries that have adopted a carbon tax. Preliminary empirical results for European countries, some of which have adopted carbon taxes, suggest small and statistically insignificant macroeconomic effects of a carbon price on growth (Metcalf and Stock, forthcoming; Metcalf 2019). These preliminary findings are consistent with the small GDP effect predicted by Goulder and Hafstead (2018).

Goulder and Hafstead (2018) estimate that US emissions would be reduced by about one-third by 2050 if a $20 per ton tax were implemented. This finding aligns with estimates by the US EIA (2014, side case GHG25) and others (e.g., Larsen et al. 2018). These estimates underscore a key point: a carbon tax alone, at least at levels that are potentially politically viable, is insufficient to decarbonize the economy. An economist might retort that this statement is a non sequitur: if the carbon tax is set at the Pigouvian amount to equal the externality, then marginal cost equals marginal benefit and that is the optimal path and we should not adopt decarbonization as a goal or standard. But that reaction assumes that we can estimate the marginal benefit with some precision, it ignores the fact that other externalities are involved, and it fails to grapple with the deep uncertainty and potentially very negative outcomes arising from climate change.[15]

It is important to understand that the emissions reduction from a carbon tax is nonlinear in the tax rate. A relatively small tax, say $20 to $30, essentially decarbonizes the power sector. But a tax of $20 per ton corresponds to $0.18 per gallon of gasoline. The demand reduction effects of this increase in driving costs are negligible: using the gasoline demand elasticity of –0.37 from Coglianese et al. (2017) and $3.50 per gallon gasoline, a $20 per ton carbon tax would decrease gasoline demand by only 2%. As inexpensive electric vehicles become increasingly available, the gasoline price elasticity could increase as buyers switch from gasoline to electric vehicles. Still, it is hard to imagine that many consumers will decide to purchase an electric vehicle simply because gasoline prices go up by $0.20, or even by $0.50. Thus, increasing the tax has a declining marginal effect on emissions reduction. A similar argument applies to other large sectors that are technologically difficult to decarbonize, such as aviation and building heating. Said differently, marginal abatement costs are sharply increasing so with current technology initial emissions reductions are relatively inexpensive, but deeper emissions reductions are not.

Clearly, a carbon tax gets the vote of economists: a petition spearheaded by Janet Yellen supporting a carbon tax with per-capita lump-sum rebates was signed by more than 3,500 economists (including all living former chairs of the Federal Reserve, 27 Nobel Laureates, and 15 former chairs of the Council of Economic Advisers). But support for a carbon tax outside this core voting group is less clear. In 2014, Australia terminated its experiment with a carbon tax, which had been passed just 2 years earlier. Indeed, one of the virtues of a carbon tax is that its price certainty stimulates investment—price certainty, that is, unless the tax is repealed. In the United States, climate has become a partisan issue and it is hard to see how a carbon tax will be passed anytime soon. And these political considerations aside, it is important to remember that a carbon tax by its nature plucks only the currently low-hanging fruit and addresses but one of the externalities that vex climate policy.

E. Technology-Pushing Policies

This brings me to the fourth set of policies, technology-pushing policies. Energy R&D subsidies directed by the federal government have a decidedly mixed record (think fusion energy). But if one interprets technology-pushing policies more broadly, there are policies that arguably have been quite effective as well as some that have not. Here, I provide three examples of the former and one of the latter. My evidence is hardly rigorous by the profession's standards for identification of causal effects, but (as I return to it later) it is sufficiently suggestive to be informative and to suggest directions for future policy research.

The basic story line of this family of policies is induced technological progress. This goes under a number of other names, such as learning by doing or moving down the cost curve. Even if there were a carbon price, there would be technical innovations that would not happen, or would be inefficiently slow to happen, because the benefits of that innovation are not fully appropriable. This situation is exacerbated by the absence of a carbon price.

The first example is the suite of policies that have mandated or subsidized purchases of photovoltaics. From 2010 to 2015, the price of solar panels fell by two-thirds.[16] This decline coincided with a 250% expansion in purchases. Of course, the fact that sales increased when the price went down does not prove anything and points to the key identification problem when studying learning by doing. There is strong anecdotal evidence, however, that these purchases were in part exogenous, driven by political dynamics. Three key mass-purchase programs were the German feed-in tariffs of the mid-2000s, the California Solar Initiative starting in 2006, and the US federal residential solar tax credit starting in 2008. A small number of well-identified studies support this narrative, notably Gerarden (2018), but more work is needed.

The second example is battery electric vehicles. The biggest driver of electric vehicle costs is battery costs. As figure 5 shows, one can think of a price-mileage frontier that has shifted to the right and flattened over the 9 model years from 2011 to 2019. The regression line estimates a linear frontier, in which the slope represents the marginal cost of additional range (additional battery capacity) and the intercept represents all the other features of electric vehicles, most of which are common to gasoline vehicles. (This line is illustrative only because it does not control for other vehicle attributes, which could be correlated with range especially for luxury vehicles.) With the introduction of the Chevrolet Bolt in 2017, prices of battery electric vehicles with ranges that are useful for most urban driving are now approaching mass-market pricing, especially when

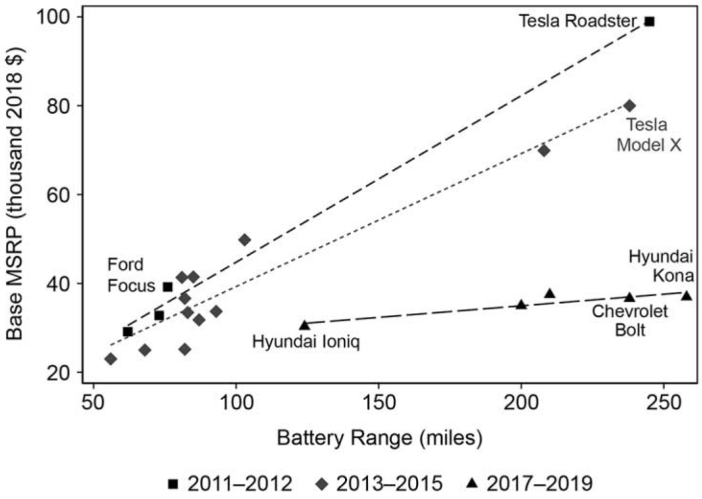

Fig. 5. Improvements in price-range trade-off in battery electric vehicles. The vertical axis is the base manufacturer's suggested retail price (MSRP) in thousands of 2018 dollars, and the horizontal axis is the driving range on a single battery charge. This figure updates figure 3 in Gillingham and Stock (2018; which uses data provided by Jing Li) to include vehicles introduced in model year 2019.

one considers that the marginal cost of driving is substantially less for an electric vehicle than a gasoline vehicle. Although these prices are manufacturer's suggested retail prices, which are before the federal income tax subsidy and any state incentives, these prices do not necessarily reflect marginal cost of production because there are hidden subsidies in this market through the CAFE standards and California low-carbon fuel standard credits. Moreover, there is anecdotal evidence that pricing is below marginal cost as automakers compete for shares in this emerging market. In any event, this shift of the frontier to the right and its flattening are consistent with demand pull policies reducing costs of producing electric vehicles, regardless of range, and of reducing battery prices through learning by doing and economies of scale.

The third example is offshore wind, where too prices have come down by more than 60% in 10 years (US Department of Energy 2018, 50). These systems remain noncompetitive with fossil fuels so essentially none of this production would have occurred without policy-induced demand. Here too, anecdotal evidence suggests that the price reductions stem in large part from learning by doing in construction, design, and installation of offshore wind turbines.

The fourth example is low greenhouse gas, second-generation biofuels stimulated through the Renewable Fuel Standard. Unlike the other three examples, this program has failed to induce meaningful cost declines or production increases. As argued in Stock (2015, 2018), in my view the key reason for this failure is not the technology but rather fundamental design flaws in the Renewable Fuel Standard program that led to a high degree of uncertainty in the value of the subsidy and even in whether the program would be in existence for the productive lifetime of a second-generation plant. The result was an initial flurry of investment as the program started, which turned into plant closings and canceled plans as investors avoided investment in the face of unexpectedly high uncertainty. The story of investment collapsing in the face of uncertainty is familiar to macroeconomists (Bernanke 1983; McDonald and Siegel 1986), and the failure of the Renewable Fuel Standard to promote second-generation biofuels provides a cautionary example in the energy area.

IV. Looking Ahead

For decarbonization to happen in the time frame that avoids large climate changes, its cost must be contained. The technologies of today—namely, wind and solar generation and, perhaps in the near future, electric vehicles—are cheap enough that they provide a meaningful first step. But deep decarbonization hinges on the development of low-cost clean technologies, including negative-emission technologies.[17] Although a carbon tax is likely to be effective and efficient, were it to be adopted, it seems that its core support base is the membership of the American Economic Association; moreover, it is but a partial solution. Technology-pushing programs comprise climate policies that we have seen both to be politically acceptable and to be effective, at least based on the limited research to date. Normally we worry that such programs can be captured, and certainly the biodiesel mandate is one such example. But there is ample evidence of capture of energy policy by fossil fuel interests, so maybe some capture by, for example, the solar installation industry or the offshore wind industry provides some balance; at least, this seems like a defensible and researchable proposition.

These observations suggest that the path forward, at least among efficient and effective policies, is likely to involve technology-pushing policies and, perhaps, infrastructure investment to address specific network externalities. A carbon price, however meritorious, can wait. To some economists, this view might sound like apostasy, but in fact it has some support in the theoretical literature.[18] For example, Acemoglu et al. (2016) show that in an endogenous growth model, research subsidies early on can substantially reduce the size of a carbon tax needed for a given carbon reduction. Their result has been generalized by Lemoine (2018), who underscores that innovation is critical to climate change policy.

The view that the key to avoiding the worst outcomes of climate change is developing efficient technology-pushing policies leads to many researchable problems. To name but a few: What is the evidence on induced technical change in the energy industry? What is the optimal design of technology-pushing policies? How does this relate to dynamics and uncertainty? What is the right trade-off between credibility and flexibility in policy making that spans decades? There is a base of high-quality recent work to start from, including Acemoglu et al. (2016), Aghion et al. (2016, 2018, 2019), and Akcigit, Hanley, and Stantcheva (2017). That said, the remaining researchable questions abound. Macroeconomists have much to contribute to this research. The research questions are interesting, policy is evolving rapidly, and the stakes are high.

Endnotes

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1. Not coincidentally, the organization of this talk tracks my own interest and involvement in the topic, which started in the 1990s with some latent skepticism regarding large climate science models. From 2012 to 2014, I had the energy-economics portfolio at the Council of Economic Advisers, a period in which the Clean Power Plan and other federal climate initiatives were being developed and proposed. Since returning to academics, I have continued to conduct research in climate economics and policy.

2. This relationship can be derived from a single-equation energy balance model. In discrete time, the energy balance model is $\Delta T_t = -\lambda T_{t-1} + b\mathrm{RF}_t$, where T_t is temperature, RF_t is radiative forcing, t is measured in years, and b adjusts for units. This solves for $T_t = b(1 - (1 - \lambda)\mathrm{L})^{-1}\mathrm{RF}_t = (b/\lambda)\mathrm{RF}_t + c^*(\mathrm{L})\Delta\mathrm{RF}_t$, where $c^*(\mathrm{L})$ is the summable residual lag polynomial from the Beveridge-Nelson decomposition. If RF_t is well approximated as integrated of order 1, then this mass balance equation implies that T_t and RF_t are cointegrated of order (1,1) with cointegrating coefficient b/λ. If RF_t is persistent but not necessarily integrated of order 1, then T_t will inherit the persistence properties of RF_t and will share a common long-run trend with RF_t. Here, we follow Kaufmann et al. (2006) and adopt the cointegrated of order 1 model. For more on the energy balance model derivation sketched here, see Kaufmann et al. (2013) and Pretis (2020).

3. The story of the hiatus is interesting and more nuanced than the curtailed account here. Other proposed explanations (not mutually exclusive) include possible temperature mismeasurement (Karl et al. 2015; but see Hausfather et al. 2017), reductions in radiative forcing due to volcanic activity (Gregory et al. 2016), and natural fluctuations in ocean circulation cycles that increased heat uptake in the deep oceans (Balmaseda, Trenberth, and Källén 2013; Liu, Xie, and Lu 2016).

4. As of this writing, 2015 is the final year for which all radiative forcings are available.

5. See, for example, IPCC (2014) and US Global Change Research Program (2018).

6. See, for example, the research associated with the Oxford Climate Econometrics program at http://www.climateeconometrics.org/.

7. From 2008 to 2016, total US coal production (including metallurgical coal) fell by 433 million tons. Coglianese, Gerarden, and Stock (2018) estimate that 92% of this decline was because of the large drop in the price of natural gas, with an additional 6% due to environmental regulations that came into effect during that period. Fell and Kaffine (2018) focus on daily shifts in generation and find that wind prices also play a role in the decline.

8. US EIA, *2019 Annual Energy Outlook*, reference case projection table 15.

9. IPCC (2014), AR5 chapter 13, figure 13.11. The local incidence of sea level rise is affected by ocean currents and other factors. It turns out that Boston is on the high end of these effects, so that local sea level rise is projected to be 20% to 70% greater than the global mean rise. To visualize what 1.5 meters of sea level rise means for Cambridge (where the NBER Macro Annual conference is held), launch the National Oceanographic and Atmospheric Administration's Sea Level Rise Viewer at https://coast.noaa.gov/slr/.

10. For an in-depth introduction to the science of abrupt irreversible events, see National Academy of Sciences (2013).

11. This discussion focuses on public policies. There has been increasing interest in voluntary personal actions that can result in a greener lifestyle and reduce the carbon footprint of an individual or an organization. Such actions range from investing in green bonds, to purchasing carbon offsets for air travel, to purchasing a hybrid or electric vehicle, to eating less beef. Some of these voluntary actions can have meaningful impacts; for example, in 2018 Xcel Energy, a large, coal-heavy electric utility based in Minnesota, announced a target of 100% carbon-free electricity by 2050 and is retiring coal plants early as it works toward that goal. But as long as it is it is cheaper or more convenient to emit carbon than not, voluntary programs can go only so far.

12. Unless explicit references are provided, costs per ton for climate policies are taken from and documented in Gillingham and Stock (2018).

13. The US EPA estimates that the Affordable Clean Energy plan will reduce power sector $\mathrm{CO_2}$ emissions by 0.5% in 2035, relative to the no-regulation alternative (US EPA 2019).

14. See, for example, Jacobsen (2013), Sarica and Tyner (2013), and Ito and Salee (2018).

15. In a seminal contribution, Weitzman (2009) lays out a model in which the possibility of so-called climate catastrophes provides reasons for action to decarbonize now, even if the probabilities of those events are unknown. Also see Pindyck (2012).

16. See Gillingham and Stock (2018) for sources, discussion, and references.

17. A negative-emissions technology removes CO_2 from the atmosphere, on net. Examples include some biofuels (through sequestration in the root system), air capture and sequestration of CO_2, and electricity generated by burning biomass with carbon capture and sequestration. Broadly speaking, sequestering carbon is more expensive than not doing so; thus, regardless of technology developments, the deployment of negative-emissions technologies requires a price on carbon.

18. Although a carbon tax has the votes of economists generally, views on it are somewhat mixed among environmental economists. At one extreme, a senior environmental economist recently said to me in complete seriousness, "If we can't have the first best [a carbon tax] then we should all just burn in Hell." At the other extreme, Wagner and Weitzman (2015, 26–27) write, "So instead of shouting 'Carbon tax' or 'Carbon cap,' economists ought to work constructively with what we have—second, third, and fourth-best solutions and worse—that create all sorts of inefficiencies, unintended consequences, and other problems, but that roll with the punches of a highly imperfect policy world and may even remove some existing imperfect policy barriers at the same time." I fall much closer to the latter than the former end of this spectrum.

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