The Implications of Carbon Pricing for Environmental Inequality

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Submitted in Partial Fulfillment
for Graduating with Distinction

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Coe College
Cedar Rapids, IA
April 2023

Contents

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Version: March 10, 2023

Preface

Economists widely support the implementation of carbon pricing policies to reduce greenhouse gas emissions and mitigate the damages of climate change. The primary justification for carbon pricing policies, such as carbon taxes and cap-and-trade programs, is that they are efficient in the sense that they minimize the total cost of abatement. Alternative command-and-control policies could induce the same level of abatement, but they would likely come with a higher cost. Although this feature of environmental markets ensures the greatest net benefit for a given level of abatement, it does not make any guarantees about the distribution of these benefits. That is to say, the distributional implications of carbon pricing schemes are generally ambiguous.

Given that equality and justice have become cornerstones of the contemporary public discourse on climate change, it should not be surprising that leading voices within the environmental community remain skeptical of carbon pricing.

Contemporary carbon pricing programs take these concerns into account and typically feature some form of a "carbon dividend" as a way to redistribute revenue generated through carbon pricing towards those who are most exposed to climate change risk. Many jurisdictions with carbon pricing schemes do redirect sizeable portions of the revenue generated through these programs into communities that already face the worst environmental degradation. The carbon price provides individuals with an incentive to reduce their emissions, while the carbon dividend ensures a progressive distribution of the benefits from emissions reductions.

However, less attention has been paid to the potential of carbon pricing to contribute to environmental inequalities. Many of the processes that create greenhouse gas emissions also create local air pollutants, like particulate matter, nitrous oxides, or sulfur oxides. Unlike the greenhouse gases covered under the carbon price, the spatial distribution of these co-pollutants matters; the location of this pollution matters. In this context, the carbon price might create abatement cost-effectively, but there is no guarantee that it will redistribute economic activity and the local air pollution associated with this activity in a way that avoids placing a greater air pollution on disadvantaged communities. That is, because they do not have any mechanism to explicitly prevent redistribution of local air pollutants, carbon pricing might incidentally reproduce inequitable environmental outcomes.

The objective of this paper is to analyze the implications of these carbon pricing schemes for environmental inequality. To do this, I focus on local air pollution from the electric power industry across the Western US and study how carbon pricing in this industry affects the difference in air pollution concentrations between low- and high-socioeconomic status communities.

This analysis falls into five chapters. The first two chapters provide a broad introduction to climate economics, with Chapter 1 reviewing the physical science of climate change and Chapter 2 reviewing the fundamental economic elements of climate policy design. A basic understanding of carbon pricing and emissions leakage are key to later work in the paper, so Chapter 2 takes a detailed look at both of these ideas. Using the foundational ideas from the first two chapters, Chapter 3 reviews the specific context of the analysis, reviewing wholesale electricity markets, local air pollution, relevant policy, and the immediately adjacent literature. Chapter 4 outlines a novel economic model of environmental inequality associated with electric power generation. The model relies heavily on the model in Weber (2021), but generalizes it into a multi-region model that can accommodate region-specific carbon prices and includes a measure of air pollution disparities inspired by Hernández-Cortés and Meng (2023). It features generators that make investment and operating decisions within perfectly competitive wholesale markets for electricity. Chapter 5 confronts the model from Chapter 4 with data by simulating generator investment and operating decisions over a three year period across the US Western Interconnection. I use the simulation model to measure how a carbon tax on electricity generation in California affects air pollution disparities. This involves creating the relevant counterfactual by simulating air pollution disparities with and without the carbon tax. **Specific results are forthcoming.**

1 An Introduction to Climate Change

1.1 The Earth is Warming (and it's Our Fault)

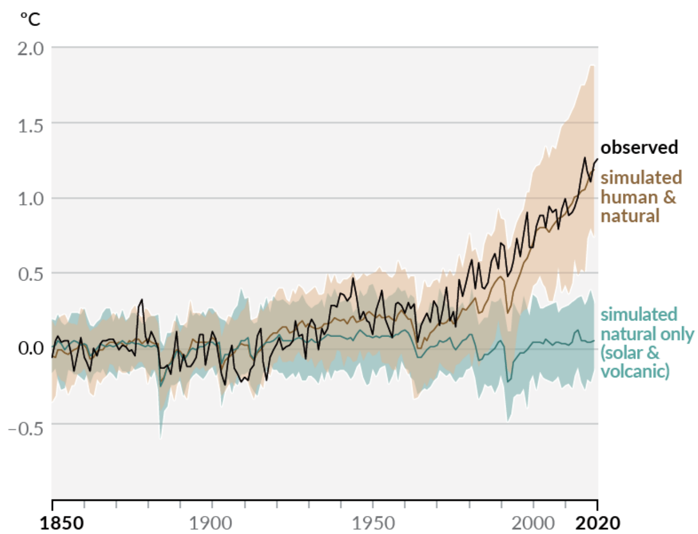
In its most recent report, the United Nations' Intergovernmental Panel on Climate Change (IPCC) states:

> "It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred." (IPCC, 2021c)

The IPCC's statement, which follows from possibly the single largest scientific endeavor in human history, is the foundation for all research, activism, and policy on climate change. This section explores this statement by summarizing why the scientific community is certain that (1) climate change has already started, and that (2) human activity is responsible for climate change.

In daily life, we are most familiar with the weather—the day-to-day fluctuations in temperature, precipitation, cloud cover, and severe storms. Because the weather is instantaneous and observable at anytime by just taking a walk or looking out of the window, the weather is easy to notice. This is not the case with climate. Climate describes weather outcomes in the long-run. For instance, an important climate measurement is the 10-year average daily temperature. To the statistician, weather is just a random variable drawn from the climate distribution (Auffhammer, 2018). That is, weather is like rolling a dice. It occurs in random ways and is immediately observable. Climate is like rolling a dice 10,000 times, and we can use numerical summaries to describe the full set of these 10,000 rolls, such as the value of the average roll. Although no one can accurately and easily perceive the global climate in daily life, people have long kept detailed records of the weather. By averaging together weather measurements like temperature, scientists can measure how the planet's climate has changed.

Figure 1: The Plant is Warming



Note: Figure is from IPCC (2021c). The vertical axis is degrees Celsius relative to global average surface temperatures from 1850–1900. The black series plots observed annual average global surface temperatures. Simulated series come from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Shaded areas represent the "very likely" range of simulated outcomes. While it is true that there are natural, non-human reasons for the planet to warm, the figure clearly shows that these factors do not explain observed warming. Simulated warming with anthropogenic warming closely matches observed warming from the past 170 years.

There is absolutely no question that climate change is occurring. The black line in Figure 1 displays the change in annual average global temperatures since 1850. The average global surface temperature from 2011–2020 was 1.09°C warmer than the average global surface temperature from 1850–1900 (IPCC, 2021c). The ten warmest years in the historical record have all occurred since 2010 (Lindsey and Dahlman, 2023). The Earth is warming, and even though we cannot go outside and immediately see this, it is still an empirical reality. There is also no question that climate change is driven almost exclusively by human activity. The tan series in Figure 1 is simulated results using both human and natural drivers of climate, and the green series is simulated results using only natural drivers of climate. These simulations come from heavily reviewed and highly accurate climate models.[1] Natural factors alone cannot explain the rise in global temperatures. Only when we incorporate the impact of humans into climate models does the observed warming make any sense.

As intelligently crafted as these climate models are, they are remarkably complex. This complexity makes it difficult to understand why the scientific community knows humans are responsible for contemporary climate change. Rather than unpacking the models climate scientists use to study the warming of the planet, we instead start by investigating the factors that can cause the climate to change in general.

Climate does not change without reason. The energy that warms the Earth and controls the climate comes from the Sun. Of the radiation that reaches the Earth, 30% is immediately reflected back into space by the atmosphere and surface, 19% is absorbed by the atmosphere, and the remaining 51% is absorbed by the surface. When absorbed by the Earth's surface, the surface emits infrared radiation, or heat. Surface heat accounts for some of the planet's warmth, but most of this actually

[1] See Figure 23 for an examination of the accuracy of climate models.

comes from the atmosphere (Lambert et al., 2016). When the surface emits infrared radiation, this moves out into the atmosphere. Certain particles sometimes absorb this infrared radiation and send it back to the surface. These particles are known as *greenhouse gasses*. Greenhouse gases keeps some energy from leaving the planet, similar to how a blanket keeps some heat from leaving your body. This heat is not inevitably trapped on the planet, but allows the same energy to be reabsorbed by the surface before attempting to leave the atmosphere again.

The planet's global temperature is stable when the radiative energy that coming into the Earth is equal to the radiative energy that the Earth emits back into space. When the radiative energy that comes to Earth is greater than the radiative energy that leaves the Earth, then this surplus energy causes warming (NOAA, 2022). This imbalance that causes changes in global temperatures is called *radiative forcing* or *climate forcing*.

There are several major factors that impact radiative forcing: solar irradiation, volcanic eruptions, land use, aerosols, and greenhouse gases (Bjørke and Ahmed, 2011). Solar irradiation refers to the power the Sun gives to the Earth on a per unit of land basis (W/m^2). One important factor affecting solar irradiation is the Earth's orbit and rotation. Currently, the Earth rotates on a 23.5° axis, but the tilt of this axis can change over the course of millennia. This change in rotation and the subsequent climatic changes are known as Milankovitch cycles (Buis, 2020). These cycles also incorporate slight changes in the Earth's orbit that make it more elliptical, bringing the planet closer to the Sun during certain periods. While this does affect climate, it does so over the course of thousands of years rather than decades. Other fluctuations from the Sun have the potential to create radiative forcing and changes in the climate over somewhat shorter periods of time. For instance, reduced solar output is a leading explanation for the period of cooler climate in Europe and North America from the early 14th century to the early

19th century, an event known as the Little Ice Age (Jackson and Rafferty, 2023).

Other factors that can induce radiative forcing—like changes in land use, volcanic eruptions, and aerosols—do so by influencing the Earth's albedo. The Earth's albedo is the reflectivity of the planet. Recall that the Earth's atmosphere and surface reflect about 30% of incoming radiation from the Sun. This percentage can change based on the presence of reflective and absorbent features on the surface and in the atmosphere.

On the surface, white ice reflects radiation, and the black pavement of roads absorbs radiation, emitting back heat. Agricultural land is generally more reflective than dark forests. Land use changes like these can affect how much energy the surface absorbs or reflects, and consequently change the planet's albedo and climate.

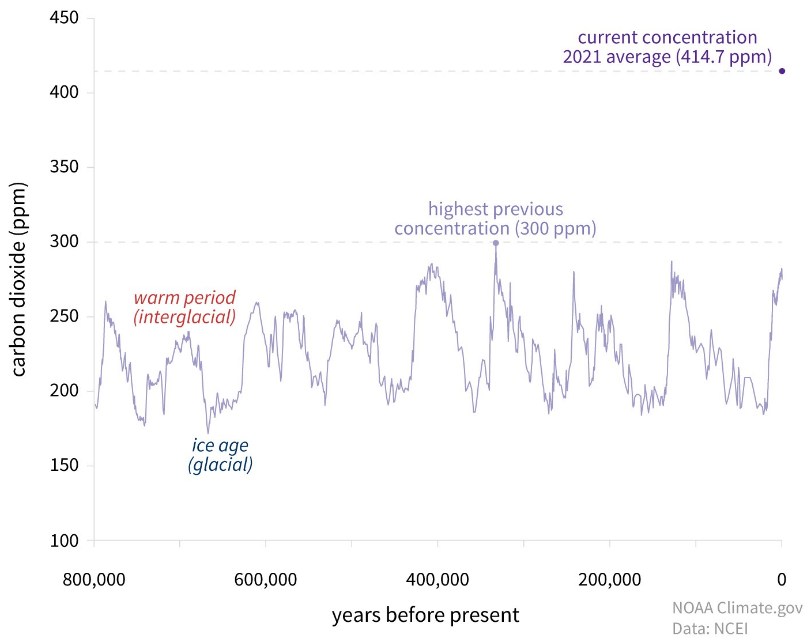
In the atmosphere, aerosols are the primary source of changes in the planet's albedo.Aerosols are small solid or liquid particles in the atmosphere that can influence the development of cloud cover. Around 90% of all aerosols in the atmosphere come from natural sources including dust, sea salt, and wildfire ash. Humans emit the remaining 10% of aerosols. Burning coal releases sulfur dioxide and driving cars releases fine particulate matter, both aerosols. Aerosols affect climate in two ways: (1) the direct effect of either absorbing or reflecting radiation in the atmosphere, and (2) cloud formation (GFDL, 2014). Most aerosols reflect light and have a cooling effect, with the notable exception of black carbon. Black carbon absorbs light and can be particularly destructive if it coats glaciers, turning these reflective surfaces black. This is the direct effect of aerosols. The second, indirect effect of aerosols is in the creation of clouds. Clouds require aerosols in order to form. Additional aerosols in the atmosphere make cloud formation easier and can even lengthen the lifespan of a cloud. This additional cloud cover reflects radiation and keeps the surface cooler. Unfortunately many common aerosols like sulfur dioxide are dangerous for human health and create acid rain in large concentrations.

Volcanic eruptions can also influence the planet's albedo. It is true that volcanic eruptions emit greenhouse gases like carbon dioxide. However, volcanic greenhouse gas emissions are less than one percent of all anthropogenic emissions (USGS, 2018; Gerlach, 2011). The suggestion that higher concentrations of carbon dioxide in the atmosphere are the result of volcanic eruptions rather than human activity is utterly false. Volcanic eruptions more likely have a cooling effect on the climate (negative radiative forcing). These eruptions send large quantities of sulfur dioxide, an aerosol, into the troposphere. This creates large and long-lasting clouds that reflect solar radiation and raise the Earth's albedo.

Lastly, greenhouse gases can create radiative forcing. Higher concentrations of greenhouse gases make it more likely that any infrared radiation emitted on the planet's surface will be re-absorbed by the atmosphere and continue to heat the surface. The most common greenhouse gas is water vapor. Water evaporates from the surface, enters the atmosphere, absorbs heat from the planet, and keeps this heat around the surface. Eventually the water vapor condenses and falls to the surface for the cycle to repeat. Although water vapor is the most common greenhouse gas, it is best understood as an accelerant of warming, not as a cause of warming. The quantity of water on the Earth is essentially fixed, and water will only evaporate and enter the atmosphere in response to some external warming. For this reason, water vapor will always act as an accelerant of warming, but never the underlying cause of warming.

The most recognized greenhouse gas is carbon dioxide or CO_2. Carbon dioxide makes up the bulk of all human-induced greenhouse gas emissions and, other than water vapor, is the most prevalent greenhouse gas in the atmosphere. Figure 2 shows the concentration of carbon dioxide in the Earth's atmosphere over

Figure 2: Current Carbon Dioxide Concentrations are Unprecedented



Note: Figure is from Lindsey (2022a). Carbon dioxide concentrations are measured in parts per millions (ppm). The purple series displays carbon dioxide concentrations measured from air bubbles trapped in ice cores. The natural cycles apparent in the series are related to Milankovitch cycles. This natural variation in carbon dioxide concentrations (shown) occurs over thousands of year. Not only are current carbon dioxide concentrations greater than they have been in the hundreds of thousands of years previous, there is a clear departure from the natural cycles of carbon concentrations. On this geologic timescale, the increase in carbon dioxide within the last few generations has been essentially instantaneous.

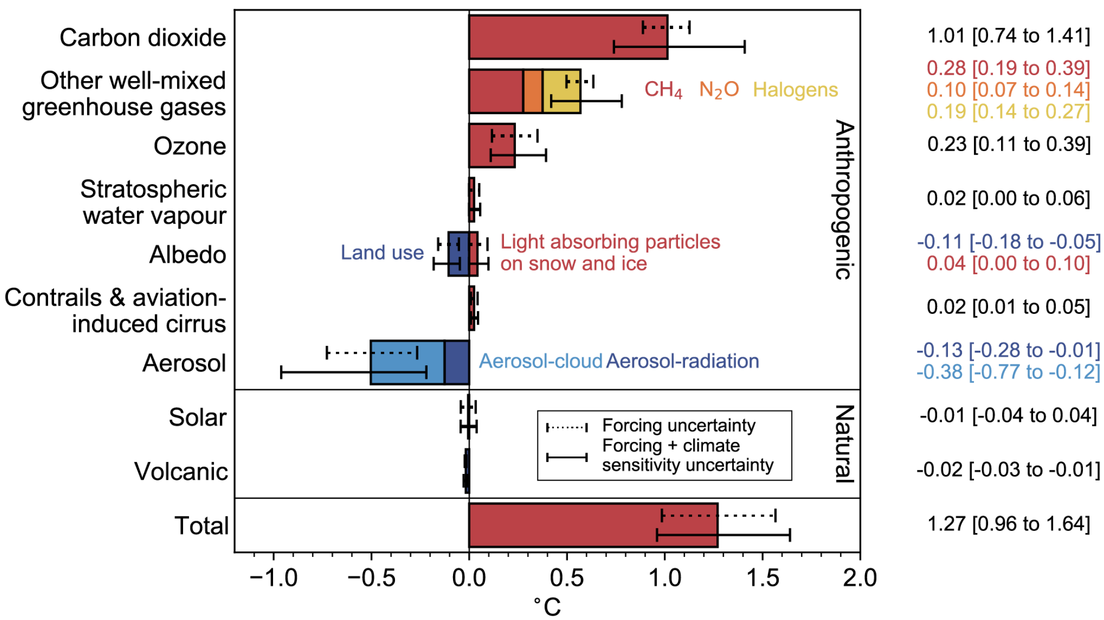
the previous hundreds of thousands of years. In all this time, the concentration of carbon dioxide in the atmosphere never exceeded 300 parts per million (ppm). In 2021, the atmospheric concentration of carbon dioxide reached 414.7 part per million. Historically, the increase in carbon dioxide is practically instantaneous, and this result is completely attributable to humans. Natural fluctuations have played out for hundreds of thousands of years—what we see today is unprecedented and undoubtedly the result of human activity, not natural causes. Elevated concentrations of greenhouse gases can keep additional infrared radiation around the surface of the Earth, warming the planet. The next section takes a closer look at greenhouse gas emissions in the US and globally.

These various sources, solar irradiance, land use, aerosols, volcanic eruptions, and greenhouse gases, represent a comprehensive list of the factors that could even potentially change global temperatures at the observed scale. From this point, scientists can measure how each of these factors have changed over the period we have seen warming. Incorporating some physical constants, researchers calculate the radiative forcing of each of these factors. Figure 3 displays the results of these radiative forcing studies and makes it remarkably clear that humans are responsible for climate change.

Natural radiative forcing from solar drivers, volcanic activity, and internal variability is not perceptible. Given how gradually these natural drivers act, it intuitively seems far-fetched that any of these could be behind the relatively rapid warming seen today. Instead, Figure 3 shows that warming is attributable to increases in greenhouse gases like carbon dioxide, methane, nitrous oxide, and others. This warming is partially offset by increasing concentrations of aerosols. Furthermore, we know that humans are responsible for the large increases in these greenhouse gases.

The Fourth National Climate Assessment makes the summation of all these

Figure 3: Warming is Driven by Human Activity



Note: Figure is from IPCC (2021b). The horizontal axis displays simulated changes in global temperatures between 1750 and 2019. Temperature simulations use the estimated radiative forcing from each component combined with feedbacks from the climate system—the climate sensitivity. Dotted error bars display the 95% confidence interval that corresponds with uncertainty with radiative forcing estimates. Solid error bars display the 95% confidence interval that corresponds with uncertainty in both the radiative forcing and climate sensitivity estimates. The figure shows that natural radiative forcing in the middle panel is negligible, and warming is driven by human activity. Anthropogenic greenhouse gas emissions (represented by the bars labeled "Carbon dioxide", "Other well-mixed greenhouse gases", "Ozone", "Stratospheric water vapor") are responsible for the bulk of all warming. Anthropogenic aerosol emissions have a large cooling effect on the planet, by both creating cloud cover and by reflect radiation back into space.

scientific observations clear:

> "Global average temperature has increased by about 1.8°F [1.0°C] from 1901 to 2016, and observational evidence does not support any credible natural explanations for this amount of warming; instead, the evidence consistently points to human activities, especially emissions of greenhouse or heat-trapping gases, as the dominant cause." (Hayhoe et al., 2018)

We call the climate change caused by humans, rather than natural forces, *anthropogenic* climate change. The existence and magnitude of anthropogenic climate change is not s finding to be taken lightly, representing a shift in the planet's history into an unprecedented era where humans dominate the environment itself—the *Anthropocene*.

1.2 Greenhouse Gas Emissions: Structure & Trends

Anthropogenic greenhouse gas emissions drive climate change. The previous section established carbon dioxide as the preeminent greenhouse gas causing climate change, but methane and nitrous oxide both play major roles as well. Florinated gases, also called F-gases, are less common, but make up a non-negligible proportion of greenhouse gas emissions in the US and are growing at an alarming rate.

Not all these greenhouse gases are created equal. Some greenhouse gases remain in the atmosphere longer than others and absorb more infrared radiation from the Earth than others. Greenhouse gases may also react and create different greenhouse gases in the atmosphere, which themselves can have different warming effects. To improve the accounting of greenhouse gases, researchers standardize the varied warming effect of these greenhouse gases through a measure called global warming potential (GWP). GWP measures the warming effect of other greenhouse gas emissions relative to the warming effect from a ton of carbon

Table 1: Global Warming Potential (GWP) by Greenhouse Gas

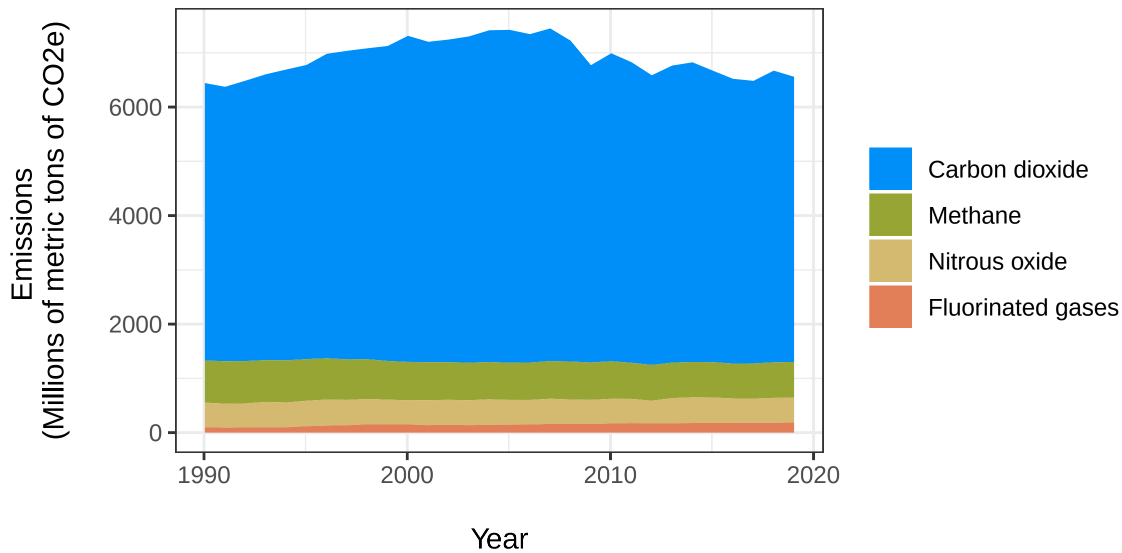
Gas Name	Chemical Formula	Atmospheric Life (years)	GWP
Carbon dioxide	CO_2		1
Methane	CH_4	11.8	27.9
Nitrous oxide	N_2O	109	273
HFC-134a	CH_2FCF_3	14	1530
HFC-23	CHF_3	228	14,600
Nitrogen trifluoride	NF_3	569	17,400
Sulfur hexafluoride	SF_6	1000	24,300

Note: Table adapted from IPCC (2021d). Global warming potential (GWP) displayed is based on 100-year time horizon. Carbon dioxide does not have a specific atmospheric lifespan as its removal from the atmosphere is dependent on the speed of the carbon cycle. The table shows there is significant variation in the lifespan and warming effect of greenhouse gases.

dioxide. For instance, in the IPCC's Sixth Assessment Report, methane has a GWP of 27.9, meaning that a ton of methane emissions has the same warming effect as 27.9 tons of carbon dioxide. This metric then leads to carbon dioxide equivalent emissions, denoted CO_2e, a standard unit of account for different greenhouse gas.

Table 1 lists the GWP for the most common greenhouse gases and a handful of F-gases as calculated in the IPCC's Sixth Assessment Report. Carbon dioxide is always one because it is the standard unit. Methane has a shorter atmospheric lifespan than carbon dioxide, but absorbs much more energy during this time. In the US, agriculture accounts for the largest share of methane emissions, followed closely by the mining and processing of fossil fuels (EPA, 2020). Nitrous oxide emissions occur almost entirely from agriculture, particularly from the application of fertilizers and other soil management practices. These emissions linger in the atmosphere longer than methane and absorb heat better than carbon dioxide. The IPCC's latests estimates indicate one ton of nitrous oxide equates to 273 tons of carbon dioxide. F-gases like HFC-134a (the most common hydroflorocarbon in the atmosphere), HFC-23, nitrogen trifluoride, and sulfur hexafluoride are rare. These gases emerged to replace chlorofluorocarbons following the Montreal Pro-

Figure 4: US Greenhouse Gas Emissions 1990–2019

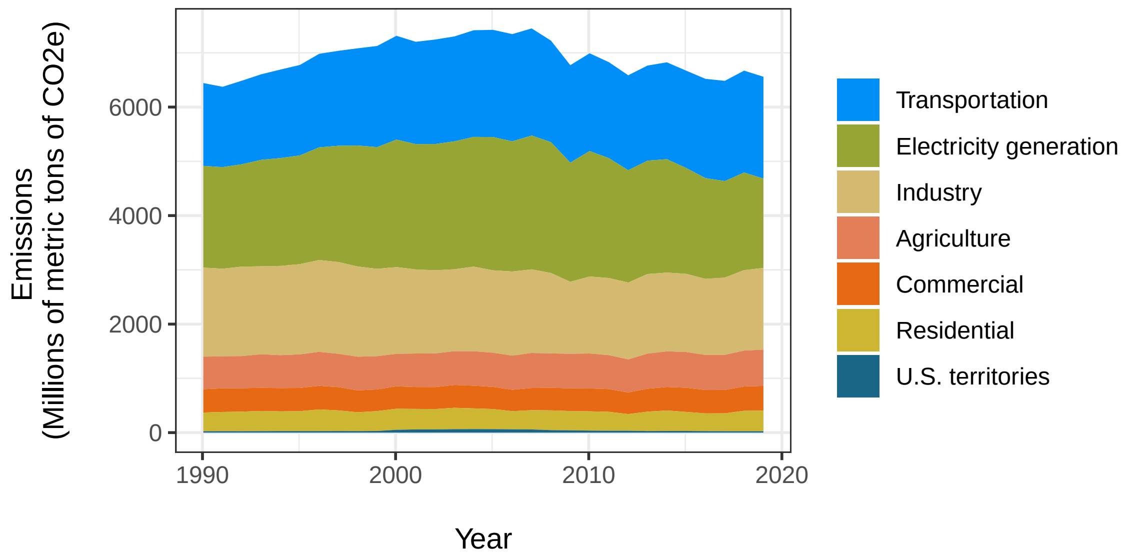


Note: Data from Ritchie et al. (2020). The figure displays annual emissions in the US for the three major greenhouse gases—carbon dioxide, methane, nitrous oxide—and all florinated gases. All emissions measurements are in metric tons of CO_2 equivalent emissions to account for differing global warming potentials. Annual US emissions have fallen since they peaked in 2007. Carbon dioxide emissions account for the vast majority of greenhouse gas emissions in the US.

tocol. While these gases do not have quite the same ozone-destroying effect of their predecessors, they can have huge GWP in even small quantities. They tend to remain in the atmosphere for a much longer time and absorb far more energy than more common greenhouse gases. For this reason, F-gases are also often called high GWP gases.

When we put all anthropogenic emissions into a common measurement, carbon dioxide equivalent, then we can compare greenhouse gas emissions and accurately evaluate the composition of greenhouse gases and the threat of certain gases relative to others. Figure 4 plots total greenhouse gas emissions (in millions of metric tons of carbon dioxide equivalent, CO_2e) in the US from 1990 to 2019 by the offending greenhouse gas. First, US greenhouse gas emissions have fallen over the past ten years. Second, it is clear why there is so much emphasis on carbon dioxide. Carbon dioxide makes up a wide majority of all anthropogenic greenhouse gas

Figure 5: US Greenhouse Gas Emissions by Economic Sector 1990–2019

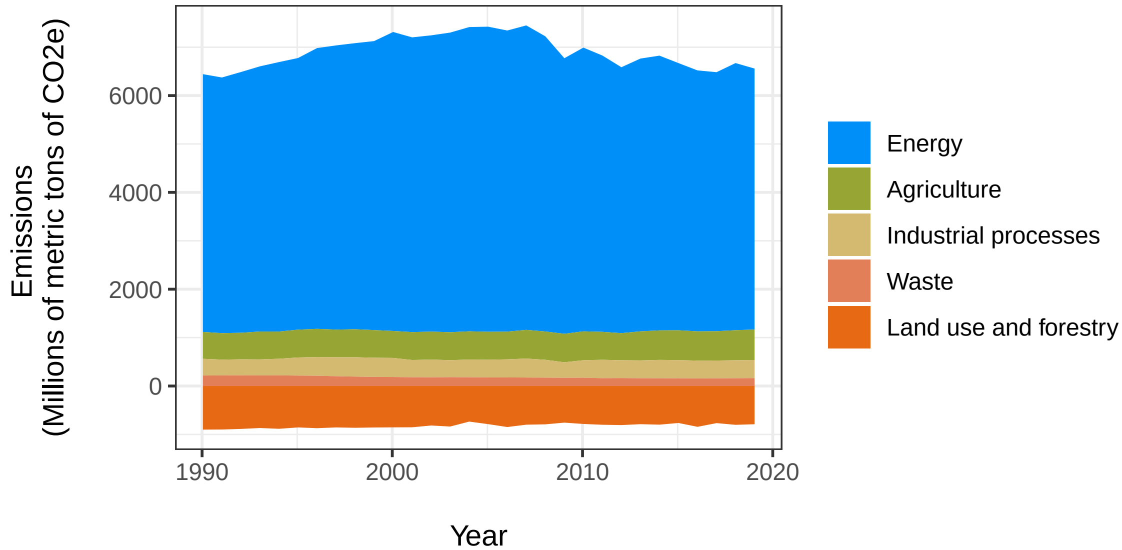


Note: Data from Ritchie et al. (2020). The figure displays annual US greenhouse gas emissions in metric tons of carbon dioxide equivalent by economic sector. Over the last thirty years, transportation, electricity generation, and industrial emissions have accounted for the vast majority of all US greenhouse gas emissions.

emissions in the US. Most of the recent reductions in greenhouse gas emissions are attributable to falling carbon dioxide emissions. Although they still make up just sliver of emissions, F-gases have seen the most growth over the period, up 86.3%.

There are several methods to study where these emissions come from. One way to breakdown these emissions is by looking at greenhouse gas emissions by economic sector. Figure 5 plots the greenhouse gas emissions of major US economic sectors in carbon dioxide equivalent from 1990 to 2019. The emissions reductions from electricity generation and industry have driven the most recent decline in greenhouse gases. Transportation has consistently been the largest source of emissions, making up 28.6% of all US greenhouse gas emissions in 2019. Electricity generation makes up a slightly smaller share with a clearer path to zero emissions through the expansion of renewable electricity generation and other low-carbon intensity fuel sources. Industrial greenhouse gas emissions have fallen by just about 8% since 1990, and 22.9% of all US emissions were from industry in 2019.

Figure 6: US Greenhouse Gas Emissions by Inventory Sector 1990–2019



Note: Data from Ritchie et al. (2020). The figure displays annual US greenhouse gas emissions in metric tons of carbon dioxide equivalent by inventory sector. Energy production (e.g., burning gasoline in a car, burning coal in a power plant, or burning natural gas for heat in residential housing) make up the vast majority of all US greenhouse gas emissions.

The agriculture industry contributed 10.2% of all US emissions in 2019. Commercial and residential emissions occur mostly from burning fossil fuels to heat buildings and homes. Together, these accounted for 12.7% of all emissions in 2019.

The US also reports greenhouse gas emissions by inventory sector, which considers the physical sources that create and remove emissions. This can be more useful than looking greenhouse gases by economic sector if different economic sectors create emissions for similar reasons. Indeed, we see that energy generation commands the majority of greenhouse gas emissions across economic sectors. Energy makes up 82% of gross greenhouse gas emissions in the US. This is driven by the burning of fossil fuels, releasing carbon that was trapped in the ground into the air. Agriculture and waste both make meaningful contributions, mostly through methane and nitrous oxide emissions. Hydroflorocarbons and other high GWP gases are responsible for a considerable portion of emissions that occur during industrial processes. The EPA also reports data on the nation's carbon sink.

Table 2: US Electricity Generation by Source

Energy source	Billion kWh	Share of total
Fossil fuels	2,427	60.6%
Natural gas	1,624	40.5%
Coal	773	19.3%
Petroleum	17	0.4%
Other gases	11	0.3%
Nuclear	790	19.7%
Renewables	792	19.8%
Wind	338	8.4%
Hydropower	291	7.3%
Solar	91	2.3%
Biomass	56	1.4%
Geothermal	17	0.4%
Other sources	8	0.2%
Total: All sources	4,007	—

Note: Data from EIA (2021). These data reflect US power generation, rather than consumption, over 2020. One kilowatt-hour (kWh) is approximately the amount of electricity required to run a dishwasher.

Carbon dioxide cycles naturally through the environment, emitted into the atmosphere by decomposing organic matter and reabsorbed by plants life. This natural carbon sequestration creates the carbon sink. Forestry and other plant life remove emissions from the air and store them, a flow of greenhouse gas emissions out of the atmosphere. For the US to reach net zero greenhouse gas emissions, this carbon sink must be equivalent to all other greenhouse gas emissions.

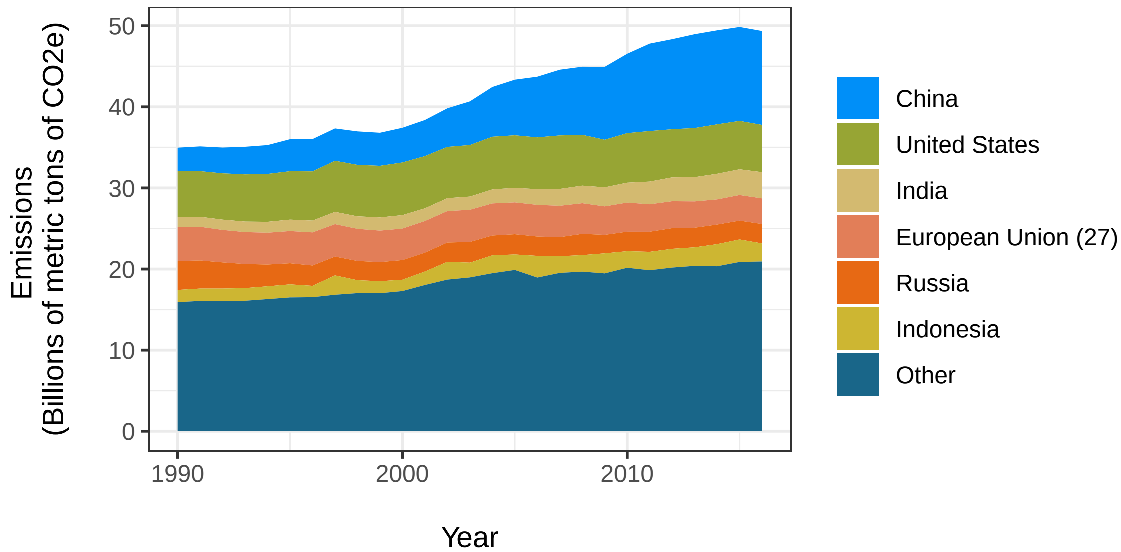
With electricity generation and energy broadly making up such a considerable portion of US greenhouse gas emissions, it is important to understand the composition of electricity generation by fuel source in the US. Table 2 shows the fuels that drive US electricity generation. Fossil fuels make up the majority of electricity generation with 60.6% of all electricity coming from fossil fuels. Natural gas is the single largest fuel source for US electricity generation, with more electricity from natural gas than the next two most common fuels (nuclear and coal) combined. Natural gas burns much cleaner than coal; coal emits 95.74kg of carbon dioxide per million BTUs on average while natural emits 52.91kg of carbon dioxide per million BTUs.[2] Still, Figure 5 shows that despite the low emissions intensity of natural gas relative to other fossil fuels, it is still a fossil fuel that produces significant emissions. Fuels with low carbon intensities, like nuclear and renewables, make up the remainder of electricity generation, around 40% of all US generation.

Climate change and excess greenhouse gas emissions might be a much simpler problem to address if they were unique to the US. They are global problems, and while the US is a major emitter of greenhouse gases, it is not the only nation with significant emissions. Figure 7 shows the greenhouse gas emissions by country from 1990 to 2016. China is the largest producer of greenhouse gases, followed by the US. India and the European Union currently put similar quantities of greenhouse gases in the atmosphere, but are trending in opposite directions. As India develops, its emissions are growing, while Europe's emissions are falling. We see here that just a few countries, particularly the US and China, make up a significant portion of all greenhouse gas emissions. In these countries, emissions reductions are especially important.

Although the US is a major contributor to global greenhouse emissions, it is not the largest. When we consider greenhouse gas emissions in per capita terms though, the situation in the US seems even more imperiled. Figure 8 looks at greenhouse gas emissions per capita for the leading greenhouse gas contributors. The US far outpaces other developed nations. Notably, the US has more than double the greenhouse gas emissions per capita as China. The US stands out on the global stage as in terms of wealth, size, and apparent inability to reduce its greenhouse gas emissions.

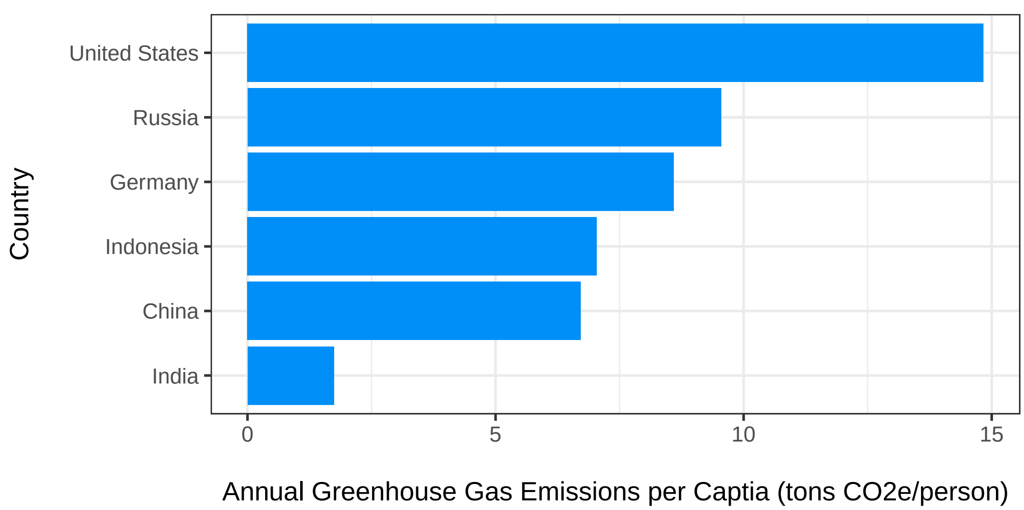
[2] British thermal units (BTUs) measure thermal energy. One BTU is the amount of heat energy required to warm one pound of water by one degree Fahrenheit.

Figure 7: Global Anthropogenic Greenhouse Gas Emissions 1990–2016



Note: Data from Ritchie et al. (2020). The figure displays annual greenhouse gas emissions measured in billions of metric tons of carbon dioxide equivalent for the nations with the most emissions. The European Union includes all of the 27 member states in the European Union. Although US greenhouse gas emissions have peaked, global emissions continue to grow.

Figure 8: 2016 Greenhouse Gas Emissions per Capita of Leading Emitters



Note: Data from Ritchie et al. (2020). The figure displays annual greenhouse gas emissions per capita, measured in metric tons of carbon dioxide equivalent per person. The US has the highest emissions per capita of any world power.

1.3 Risks & Impacts of Climate Change

The previous sections have demonstrated that human activity, particularly the burning of fossil fuels, has caused climate change. While the evidence of anthropogenic climate change and the continued growth in global greenhouse gas emissions are both jarring, alone, these are not enough to warrant serious concern. To complete this background on climate change, this section considers the implications and impacts of anthropogenic climate change. Analyzing these impacts in a systematic manner requires a deep understanding of both the physical mechanisms of climate change and the social systems they affect. This section proceeds by first discussing the risk assessment strategy used by the IPCC in its latest report, and then discusses the aggregative approach to climate impact modeling popular with economists.

1.3.1 Representative Key Risks

In Working Group II's contribution to the IPCC's Sixth Assessment report, researchers identify the risks climate change poses to specific regions and to specific economic sectors. Chapter 16 of Working Group II's report uses expert solicitation to consolidate the 120 specific risks identified earlier in the report into eight Representative Key Risks (O'Neill et al., 2022). These Representative Key Risks (RKRs), lettered A–H, are:

(RKR-A) Risk to low-lying coastal socio-ecological systems

(RKR-B) Risk to terrestrial and ocean ecosystems

(RKR-C) Risks associated with critical physical infrastructure, networks, and services

(RKR-D) Risk to living standards

(RKR-E) Risk to human health

(RKR-F) Risk to food security

(RKR-G) Risk to water security

(RKR-H) Risks to peace and to human mobility

The remainder of the section reviews the evidence and the extent of these risks. Although each RKR has its own sizable literature, the discussion focuses on the contributions of economists where possible. Apart from the IPCC reports, Carleton and Hsiang (2016) provide a thorough review of the climate change impacts literature, with a strong focus on recent empirical contributions made by economists.

(RKR-A) Risk to low-lying coastal socio-ecological systems. This risk category primarily relates to the implications of sea level rise. Lindsey (2022b) notes that climate change leads to sea level rise primarily through two mechanisms. First, warming temperatures melt glacial ice thereby shifting water stored as a solid on land to water stored as a liquid in the oceans. Second, warmer oceans are less dense leading the liquid water already in the ocean to expand. Sweet et al. (2022) estimate that by 2100 sea levels along US coastlines will rise between 0.6 and 2.2 meters (2–7.2 feet) relative to sea levels in 2000. Without adaptation efforts, these elevated sea levels will increase the frequency of major high tide flooding events (flooding 1.2 meters above average high tide) from 0.04 events per year in 2020 to 0.2 events per year by 2050. These coastal flooding events, and related events like tropical storms, affected a substantial population. Hauer et al. (2016) estimate that sea level rise of 0.9 and 1.8 meters will lead to frequent flooding of areas that currently house 1.8 and 13.1 million Americans respectively. Although it may be difficult to gauge how Americans perceive heightened risks associated with sea level rise in general, there is evidence that suggests the threat of sea level rise is taken seriously by at least some. A growing body of evidence in the climate finance

literature confirms that investors have already started to react to the threat of sea level rise. Goldsmith-Pinkham et al. (2019) find evidence that school districts that are more vulnerable to sea level rise had cheaper 10-year bonds, an effect that adjusts following the release of major sea level rise reports. This indicates that investors consider the risk of flooding induced default for even relatively short-termed bonds. For a consideration of longer-term, 30-year public bonds, Painter (2020) estimates that counties with a greater risk of sea level rise pay more in underwriting fees and initial yields. Again, these results suggest that the threat of sea level rise is significant and increasingly well understood by investors.

(RKR-B) Risk to terrestrial and ocean ecosystems. One of the most familiar threats of climate change is species loss and the related loss of biodiversity. For instance, the polar bear and its struggle amidst the melting arctic has been an important symbol for climate activists and the environmental movement more broadly since the 1990s (Slocum, 2004). Despite their iconic status, wild polar bears will likely be near extinct within the century. Simulating anthropogenic climate change over the course of the century, Hunter et al. (2010) estimate that there is 80–94% likelihood that 99% of the wild polar bear population will be lost. Although polar bears face extreme consequences from climate change, the direness of their situation is not at all unique. Polar bears are an example of a broader group of organisms known as an endemic species: a species that is confined to a specific geographic region and does not appear elsewhere. These species are often highly adapted to their pre-anthropogenic climate change environment and sensitive to changes outside of their climatic niche. Endemic species have three paths forward in the face of climate change: (1) evolve and adapt to a new climate, (2) migrate to another geography with a similar climatic niche, or (3) extinction (Wiens, 2016).

If the local effects of climate change are significant, then this first path may not be a suitable option. Evolution is not typically viewed as a process that can keep pace with current climate change. Migration to a more favorable climate, the second path forward, occurs in some cases but is implausible in others. For instance, the terrestrial species of Madagascar—90% of which are endemic—cannot escape the island (Ralimanana et al., 2022). Unfortunately, this leaves many endemic species to extinction. Rare, endemic species are also incredibly common; 36% of all known plant species are "rare" (Enquist et al., 2019). Climate change has already been tied to mass extinction events for aquatic species (Till et al., 2019), land animals (Fey et al., 2015), and plant life (Wiens, 2016).

(RKR-C) Risks associated with critical physical infrastructure, networks and services. This risk category includes both transportation infrastructure (e.g., roads, bridges, ports) and energy infrastructure (e.g., power lines, oil rigs, power plants). Critical transportation and energy infrastructure are vulnerable to climate change much like other elements of the built environment are vulnerable to climate change. What makes these worthy of their own key risk category is their tendency to fail in the midst of crisis, thereby compounding the risks of anthropogenicly intensified natural disasters. For instance, simulating scenarios of sea level rise consistent with the ranges provided by Sweet et al. (2022), Jenkins et al. (2020) find that 7 of the 13 coastal nuclear spent fuel disposal sites in the US will either be surrounded by water or otherwise at severe risk of flooding by 2100. In Europe, Forzieri et al. (2018) estimate that climate change alone will lead to a ten-fold increase in annual damages to critical infrastructure over the course of the century. Hydroelectric power generation—the most common form of renewable energy worldwide—is also susceptible to the weather conditions induced by climate change. During summer 2022, factories and industrial centers across Sichuan, China halted all production when the region's severe drought led to decreased generation from hydroelectric power plants (Davidson, 2022). Although it is difficult to attribute Sichuan's drought to anthropogenic climate change, it is clear

that climate change will make events like this more common. Extreme drought has also affected the reliability of the US electric power by creating the conditions necessary for wildfires, and inducing the associated rolling-blackouts. In an analysis of California's power gird decarbonization, Borenstein et al. (2021) identify the growing frequency of wildfire in the state as a threat to the market. Not only does the aging power transmission infrastructure coupled with elevated temperatures and a severe drought inevitably lead to wildfires, but the heightened risk of wildfires in general already poses a serious threat to the reliability of the power grid across California. Together, these provide a clear indication that climate change poses a serious risk for the reliability of the infrastructure needed to ensure both public safety and wellbeing.

(RKR-D) Risk to living standards. Understanding the threat climate change poses to living standards is a prerequisite for understanding the true cost of climate inaction. Thankfully, economists have an expansive toolkit for unpacking the relationship between the climate and economic growth. By analyzing within country growth rates and controlling for a wide variety of potential confounders, Burke et al. (2015) present a robust and careful analysis of the relationship between surface temperatures and income growth. This leads to three main findings. First, based on estimated country-specific relationships between temperature and incomes, they estimate that incomes in 2100 are 23% lower in a business-as-usual climate change scenario compared to a scenario without any additional anthropogenic climate change. Note also that this includes only damages from temperature shocks, and does not include damages from a range of other risks associated with climate change that surely have an influence on incomes (e.g., natural disasters, conflict, mortality). Second, the effect of climate change on incomes is highly unequal. High-income countries in Europe and parts of North America are more productive under a business-as-usual warming, whereas, low- and middle-income

countries across South America, Africa, and Southern Asia experience substantial reductions in productivity by 2100. Third, there is little evidence that economic development is a successful strategy for creating climate-resilient economies. The relationship between temperature and incomes is not significantly different for high-income countries in the period 1960-1989 and the period 1990-2010, and the relationship between temperature and incomes is not significantly different for high- and low-income countries. Despite economic development, even wealthy countries are still vulnerable to climate shocks. Zhang et al. (2018a) find a similar relationship between temperatures and the productivity of Chinese manufactures. A business-as-usual warming scenario leads to a 12% reduction in productivity for Chinese manufacturing relative to scenario with no warming—a significant finding considering that manufacturing composes about of third of China's GDP and 12% of global exports are from Chinese manufacturers.

Although temperatures clearly have a dramatic impact on incomes, the mechanisms that this occurs through can be ambiguous. A more visible mechanism for climate change to affect incomes is through natural disasters. The long-run implications of natural disasters on economic growth have been the subject of some debate amongst economists,[3] but the bulk of this evidence seems to support the hypothesis that the increased frequency of intense natural disasters leads to sustained reductions in economic growth (CEA, 2022). In what is likely the best empirical study in the literature, Hsiang and Jina (2014) compile a novel dataset that uses meterological data on over 6,700 tropical cyclones to create annual measurements of tropical cyclone exposure between 1950 and 2008 globally at a spatial resolution of $0.1° \times 0.1°$. Leveraging within-country variation in tropical cyclone exposure, they find that a 90th percentile exposure event depresses incomes by

[3]See Hsiang and Jina (2014) for a review of the primary hypothesized relationships between long-run economic growth and natural disasters. These include the creative destruction hypothesis, build-back-better hypothesis, recovery to trend hypothesis, and no recovery.

7.4%, *twenty years later*. In an analysis of developing economies, Cuaresma et al. (2008) find evidence that natural disasters reduce technology spillovers and impede future economic development. Through both temperature shocks and intensified natural disasters, anthropogenic climate change reduces living standards and threatens economic development.

(RKR-E) Risk to human health. The impact of climate change on human health is perhaps the most important and distressing of the RKRs. This risk category focuses on the implications of a warming planet on mortality rates due to health threats. Climate change primarily affects mortality rates by increasing the number of especially warm days, which can induce heat-stress events such as stroke or heart attack and lead to death. Additional mechanisms include the increased spread of vector-borne and water-borne illness. In many places, warming increases humidity, fostering larger mosquito populations and leading to increased deaths from vector-borne illnesses like malaria (Rocklöv and Dubrow, 2020). The warmer days and nights associated with climate change improve survival odds for dangerous water pathogens, leading to increased deaths from contaminated water supplies (Levy et al., 2018).

Currently, Carleton et al. (2022) provide the best estimates of climate-induced mortality rates—estimates that are worth discussing in greater detail. In this paper, the researchers goal is to first estimate the relationship between the climate distribution and the *full mortality risk of climate change*. This measure includes both the costs of climate mortalities and the cost of adaptation efforts undertaken to mitigate climate mortality risk.[4] The researchers assemble several novel and remarkable datasets that compose decades of age-range specific mortality data across 40 countries, historic daily weather data, and socioeconomic data. They use these data to calibrate a model for the full mortality risk of climate change.

[4]A more detailed discussion of climate adaptation and the issues it presents in the measurement of climate impacts appears in the proceeding section.

With this model in hand, the researchers then partition all land on the planet into over 24,000 regions, and use leading climate and socioeconomic models to predict climate and socioeconomic outcomes for each region through 2100. Finally, they use the calibrated model to estimate the full mortality risk of climate change annually for each region through 2100. The effort is remarkable for both the heroic data collection involved and the robustness of its results.

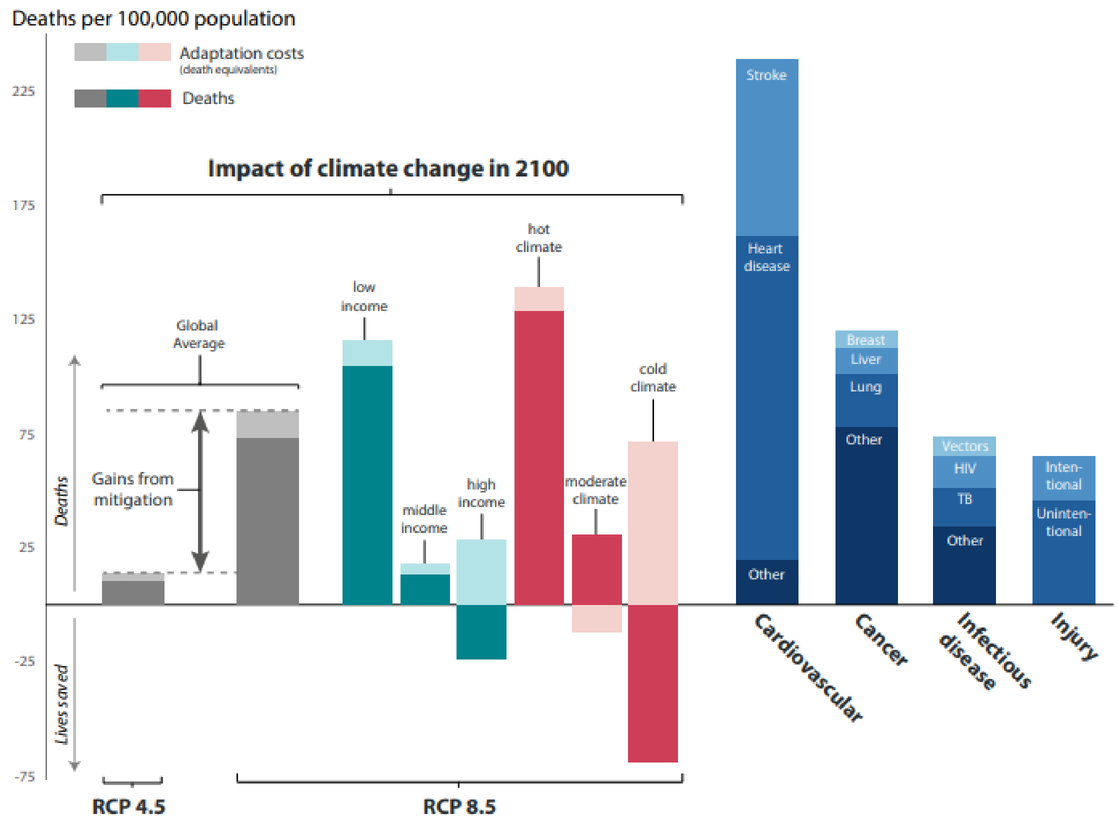
Figure 9 summarizes the main results of Carleton et al. (2022). Solid bars represent climate mortality changes and shaded bars represent climate mortality adaptation costs, measured in deaths per 100,000 people or the equivalent.[5] The left side of the figure displays the estimated climate mortality rates in 2100. This includes the results from an emissions-stabilization scenario and a business-as-usual scenario, labeled RCP4.5 and RCP8.5 respectively.[6] Gray bars display global averages, teal bars display averages by regional income, and pink bars display averages by current climate. The right side of the figure displays current global average mortality rates for the most common causes of death including cardiovascular disease/events, cancer, infectious disease, and injury.

This figure provides three takeaways. First, anthropogenic climate change presents an immense threat to the health and safety of humanity. The gray bar above RCP8.5 shows that estimated climate change mortalities will be higher by then end of the century than infectious disease mortalities are currently. Second, reducing

[5]To convert monetary adaptation costs into deaths, Carleton et al. (2022) use the *value of a statistical life* (VSL). The VSL goes back to Thaler and Rosen (1976) and uses hedonic techniques to measure the average willingness to pay for reductions in mortality risk. It is standard practice to adjust the VSL for the income of a region, and the authors follow suit in this figure. However, many are increasingly critical of this practice, and the authors do consider unadjusted adaptation costs in an appendix. If the VSL were not adjusted for income differences in the figure, then the figure would display higher adaptation costs for low-income regions.

[6]These scenarios and the corresponding labels are standardized by the IPCC. A Representative Concentration Pathway (RCP) is a panel of potential greenhouse gas concentrations through 2100. The number following RCP describes the level of warming associated with the scenario, and denotes the expected radiative forcing associated with the greenhouse gas emissions concentration pathway. For instance, RCP8.5 is a Representative Concentration Pathway that is expected to produce 8.5 W/m^2 of radiative forcing by 2100.

Figure 9: The Mortality Threat of Climate Change



Note: Figure from Carleton et al. (2022). The left side of the figure displays projected climate change induced mortality rates by 2100 under a business-as-usual scenario (RCP8.5) and an emissions-stabilization scenario (RCP4.5). Solid bars represent annual deaths per 100,000 people and shaded bars represent the annual adaptation costs in death equivalents per 100,000 people. The death equivalent conversion uses the EPA's value of a statistical life and an income adjustment elasticity of 1.1. Gray bars display global averages for mortality rates and adaptation costs, teal bars display mortality rates and adaptation costs broken down by regional income, and pink bars display mortality rates and adaptation costs by regional climate. The right side of the figure displays the current mortality rates associated with leading leading causes of death for comparison purposes.

greenhouse gas emissions has the potential to dramatically reduce the mortality risks of climate change. Under RCP4.5, a pathway where global greenhouse emissions peak by 2040 and fall for the remainder of the century, climate change mortalities fall by 85 per 100,000. A back-of-the-envelope calculation using the projected global population of 10 billion by 2100 finds that mitigating emissions will save 8.5 million lives annually. Third, the mortality risks from climate change are highly unequal. In the figure, high-income and cold-climate regions actually have fewer mortalities from climate change. Cold weather can be deadly, and reductions in cold days in many high-income, cool-climate regions like much of Europe and parts of North America will actually save lives. There are substantial adaptation costs associated with warming for these regions. Even in these regions with the potential for fewer mortalities, this change comes with substantial adaptation costs. Note also that adaptation is not an "automatic" byproduct of market-based economies in this instance—reductions in mortality rates would depend on adaptation induced by public policy as well. The mortality cost of low-income and hot-climate regions is staggering in comparison and rivals the mortality cost of cancer. Considering the emissions per capita of many of these low-income and hot-climate regions (e.g., India) relative to emissions per capita of high-income and cool-climate regions (e.g., the US), this immense inequality is extremely disturbing.

Although Carleton et al. (2022) likely provide the most authoritative estimates of the effect of climate change on mortality rates globally, there is a wide body of literature that studies the implications of climate change on public health. Deschênes and Greenstone (2011) analyzes within-country disparities of climate change mortalities. Using methods similar to those in Carleton et al. (2022), they estimate that a one standard deviation increase the number of "high-temperature days" in India leads to an increase in the mortality rate for rural populations of 7.3%

and virtually no change in the mortality rate for India's urban population. Most the literature looks at the mortality effects of temperature of daily variation, but climate change can of course threaten health in many other ways as well. For instance, climate-change-intensified natural disasters can cause many people to lose their lives as well as create significant disruptions to public health capital. Anttila-Hughes and Hsiang (2013) find that in the Philippines, infant mortalities caused by the destruction of health infrastructure following a typhoon are fifteen times greater than the mortalities from the initial impact of the storm. Their results imply that 13% of all infant mortalities in the Philippines are attributable to economic damages sustained by typhoons. Exacerbated natural disasters will undoubtedly lead to greater threats to human health in the future.

(RKR-F) Risk to food security. Agriculture is likely the economic sector most directly affected by climate change. It is no surprise then that some of the earliest work on climate change impacts focused on agriculture. Nevertheless, creating reliable estimates for the impact of climate change presents several unique challenges. First, it is reasonable to expect adaptation to dampen the impacts of climate change in agriculture more so than other industries. For instance, when the local climate becomes warmer or more arid, a homo economicus-style farmer would switch crops to one that fairs better in the new climate. Mendelsohn et al. (1994) make the argument that impact forecasts that fail to consider the role of adaptation in future and use "dumb farmers" constitute an upper bound on future impacts. Unfortunately, the alternative approach they propose allows for costless adaptation, which others have subsequently criticized as constituting a lower bound on future impacts (Quiggin and Horowitz, 1999). Outside of adaptation, there is still debate within the scientific community on the effect of increased CO_2 concentrations—which can augment photosynthesis—on agricultural yields (Long et al., 2006; Hatfield et al., 2011; Myers et al., 2017).

Although it may be difficult to forecast the future impact of climate change on agricultural yields, there is still a rich literature that reviews historical impacts on agricultural yields attributable to climate change. Lobell et al. (2011) evaluate the impact of observed warming on the yields of the four major crops (maize, wheat, rice, and soybeans) from 1980 through 2008. They find that climate change was responsible for global yield decreases of 3.8% for maize and 5.5% for wheat relative to a scenario without climate change. Rice and soybeans did not see a significant change in total yields attributable to climate change, but did see meaningful redistributions in yields. Although the global volume of food production associated with these crops might not have changed, the redistribution of this production could have negative implications for the global supply chains that connect agricultural centers to processing and population centers. In a similar study, Moore and Lobell (2015) estimate that climate change between 1989 and 2009 lead to a decrease in European wheat yields of 2.5% and European barley yields of 3.8%.

(RKR-G) Risk to water security. Of all its impacts, climate change's impact on global water supplies is among the most visible. Using a genre of photographs that have become all too common, Kolbert (2021) presents a detailed and intimate history of recent drought in the Western US and its effects on Lake Powell, the nation's second largest reservoir. Water levels in Lake Powell have dropped by 140 feet since 2000, nearly the height of the Statue of Liberty, leaving behind a "bathtub ring" of white mineral deposits where the water level was only a few years ago. Although attribution of drought and its effects to anthropogenic climate change is difficult, the prospect that these scenes will only become increasingly common under a warmer climate is jarring to say the least.

Global water systems are already in a tumultuous position as is, even as much of the strains of climate change have yet to set in. Mekonnen and Hoekstra (2016) create a fine-geographic-resolution measurement of the severe water scarcity, a situation where water withdrawals in an area are more than twice the rate of replenishment. They find that 4 billion people live with severe water scarcity at least one month of the year, with 1.8 to 2.9 billion people living with severe water scarcity 4 to 6 months of the year. Under even a somewhat mild emissions scenario, Gosling and Arnell (2016) estimate that 0.5 to 3.1 billion more people encounter severe water scarcity due to climate change by 2050.

(RKR-H) Risks to peace and to human mobility. Given the threat climate change poses to the essential components of human life (e.g., food, water, incomes, critical infrastructure), it is reasonable to suspect that climate change might also lead to political unrest and violence. The wave of international data on social unrest and climatic records have made quantitative research on the relationship between climate and violence possible. For example, Hsiang et al. (2011) leverage the variations in the El Niño-Southern Oscillation cycles to measure the impact of these medium-run climate on civil conflict—conflict between a country and another political organization that results in at least 25 fatalities. Using data covering 1950–2004, they find that for the regions connected to the El Niño-Southern Oscillation the probability of civil conflict doubles in El Niño years (warmer climate) relative to La Niña years (cooler climate). There is no evidence of this same relationship for regions unconnected to the El Niño-Southern Oscillation, providing robust evidence that climate is an important driver of conflict.

Many other studies have used similar climate variations to analyze the relationship between climate an conflict. Synthesizing this body of research, Hsiang et al. (2013) provide the definitive meta-analysis. The authors compile the datasets from 60 different quantitative analyses of the climate effect on conflict, creating a dataset with various sample geographies, time resolutions, spatial resolutions, and conflict variables. Using this dataset, they apply a series of common models to obtain causal estimates of the effect of climate on conflict. The effect size from this meta-analysis is both large and highly robust. A one standard deviation increase in temperatures leads to a 4% increase in interpersonal violence (e.g., violent crime) and a 14% increase in intergroup conflicts (e.g., war). The authors are careful to note that this relationship cannot easily extrapolate to future climate change as the measured effects stem from climate variation that is regional and not sustained. It is entirely possible that the relationship between the climate and conflict could change over the next century of warming. However, the available data do not suggest this will be the case; the measured relationship appears to be stable over time.

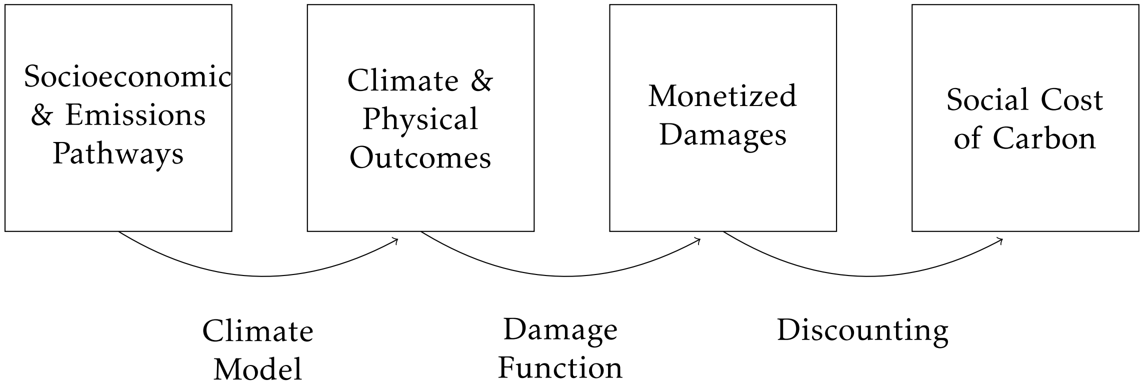
1.3.2 Integrated Assessment Models & the Social Cost of Carbon

Although the risk framework the IPCC uses can successfully describe many ways climate threatens the planet, using this information is difficult in part because it is so disaggregated. For better or for worse, economists typically prefer a single aggregated measure of the impacts of anthropogenic climate change known as the social cost of carbon (SCC). The SCC measures the present value of the damages stemming from one additional metric ton of carbon dioxide emissions (Rennert and Kingdon, 2022).[7] This measurement is valuable in that it connects the human activity responsible for climate change (greenhouse gas emissions) directly to its impact in dollars. Public policy relies on the SCC to measure the cost of abatement against the cost of climate inaction. There is a wide distribution of SCC estimates, but currently, the best available measurement of the SCC is $185 (Rennert et al., 2022).

To make this measurement, economists rely on Integrated Assessment Models (IAMs). These IAMs estimate the SCC by simulating the climate and economic effects of an additional (one metric ton) "pulse" of carbon dioxide emis-

[7] The naming convention "social cost of carbon" is imprecise. More modern approaches accurately use "social cost of carbon dioxide" instead Rennert et al. (2022). Analogous measures exist for the other two major greenhouse gases—methane and nitrous oxide. See Rennert and Kingdon (2022) and Auffhammer (2018) for excellent histories of the SCC and political turmoil around it.

Figure 10: Structure of an Integrated Assessment Model



Note: Figure adapted from the decriptions in Rennert and Kingdon (2022), Rennert et al. (2022), and Carleton and Greenstone (2022). The boxes in the figures display model inputs and outputs, including intermediate inputs and outputs. The arrows, as well as the first box, form what are commonly known to be the four "modules" of an IAM.

sions. William Nordhaus developed the earliest IAM called the Dynamic Integrated Climate-Economy model, or more commonly known as DICE (Nordhaus, 1992, 1993). Since then, there have been a handful of other popular IAMs including PAGE (Policy Analysis of the Greenhouse Effect) and FUND (Framework for Uncertainty, Negotiation and Distribution) (Hope, 2006; Tol, 1997). Today, the state of the art IAM is the Greenhouse Gas Impact Value Estimator, or GIVE (Rennert et al., 2022). Whereas other popular IAMs rely on climate research twenty to thirty years old, GIVE follows from the recent recommendations given by the National Academies of Sciences, Engineering, and Technology as well as the recommendations of prominent climate economists (NASEM, 2017; Carleton and Greenstone, 2022). To establish a base understanding of how IAMs function, Figure 10 diagrammatically displays how IAMs compute the social cost of carbon.

In the language of economists, the social cost of carbon looks at the impact of an additional metric ton of carbon dioxide emissions *all else equal*. The first step in the modeling process then is to establish what "all else" is equal to. Starting from the left side in Figure 10, researchers input projections of greenhouse gas emissions and key socioeconomic factors. For instance, the GIVE IAM takes probabilistic projections of emissions for the three major greenhouse gases (carbon dioxide, methane, and nitrous oxide), global population, and per capita economic growth (Rennert et al., 2022). Researchers take care developing these scenarios in a way that ensures they are internally consistent.[8] The IPCC has standardized a collection of these projections of emissions and socioeconomic variables called the Shared Socioeconomic Pathways (SSPs).[9] With the socioeconomic-emissions pathway set, IAMs simulate two alternative universes: one with an extra emissions pulse in a specified year and one without that emissions pulse. The comparison of damages between these two universes is describes the additional cost of the emissions pulse. In practice, IAMs never just consider a single socioeconomic-emissions pathway, but explore a wide distribution of these pathways.

Next, IAMs map these socioeconomic-emissions pathways to physical impacts. The limitations of the modeling environment mean that IAMs cannot consider all the physical and climatic outcomes that might change as a result of an incremental emissions pulse. Still, IAMs can consider some of the most significant changes in physical outcomes including changes in greenhouse gas concentrations (rather than emissions), temperatures, sea levels, and ocean acidity (Prest et al., 2022). As Figure 10 illustrates, IAMs rely on climate models to map an emissions pulse given a socioeconomic-emissions pathway to predict the climate and physical outcomes.

[8]The creation of these scenarios is often left to a separate class of IAM known as a process-based IAM. The chapters that follow will assume an understanding of the SCC, so this discussion focuses on aggregative IAMs that allow the estimation of the SCC rather than the process-based IAMs used to construct the socioeconomic and greenhouse gas concentration pathways.

[9]These SSPs are numbered and often appear in figures that display responses to climate change. For example, consider "SSP5-8.5." The first number, '5' in this case, indicates the SSP scenario.There are five SSP scenarios, each corresponding to a different narrative framing of the response to climate change. In this case, SSP5 is the "Fossil-fueled Development" pathway, representing a scenario where governments ignore climate damages and attempt to use fossil fuels as a way to develop fast enough to fully adapt to a changing climate (Hausfather, 2018). The second number is the expected radiative forcing by 2100. In this case, the expected radiative forcing by 2100 is 8.5 W/m^2 by 2100. SSP5-8.5 is commonly used as the "do nothing" scenario. This notation is similar for Representative Concentration Pathways (RCPs).

Climate scientists would usually predict resulting changes in these variables using a set of models known as General Circulation Models (GCMs). The advantage of GCMs is that they structurally model the mechanisms behind changes in the key physical outcomes. The disadvantage of GCMs is that they are computationally intensive, making them impractical when researchers need to consider a wide distribution of inputs. In practice, researchers use reduced-form versions of GCMs which can capture much of the accuracy of GCMs without all the thermodynamics.

Estimating the changes in the physical environment attributable to an emissions pulse is valuable, but this alone cannot produce a single aggregated impact measure. To produce this measurement, researchers next need to place a dollar value on these physical changes. Economists map physical changes in the climate to dollar values using damage functions, as shown in figure 10. The earliest IAM, DICE, utilizes a simple quadratic damage function, calibrated on sums of damage estimates from the IPCC. More contemporary IAMs (e.g., GIVE, FUND, PAGE) contain more sophisticated damage functions that focus on specific damage sectors and calibrate structural economic models to predict sectoral damages given socioeconomic and physical outcomes (NASEM, 2017).

Auffhammer (2018) notes that perhaps the greatest difficulty in using damage functions to map climatic scenarios into physical impacts is accounting for adaptation. To illustrate this, consider Auffhammer's example of air conditioning. Suppose researchers want a damage function to measure the impact of climate change on electricity use. In general, they can expect that consumers will rely more on air conditioners in a warming climate. The response on the intensive margin is measurable. Using data on daily air conditioner use and daily temperatures for instance, researchers could estimate how warming temperatures affect air conditioner use *for those who already have an air conditioner*. Unfortunately, predicting the response in air conditioner adoption and use for those who do not already have a air conditioner—the extensive margin—is much more difficult. This requires data on air conditioner adoption prior to and during anthropogenic climate change, as wells as a strong empirical strategy.[10] Although Auffhammer (2018) provides some guidance, it is clear that accounting for adaptation in damage functions is still an issue.

Auffhammer (2022) notes that a major focus of future IAMs will be calibrating and incorporating a more comprehensive set of sectoral damage functions. For instance, GIVE currently includes just four sectors in its damage function: agriculture, energy, mortality, and sea level rise. This research need presents a new opportunity for environmental economists to blend their traditional goals of pricing environmental goods with the contemporary tools of applied econometrics. For instance, Druckenmiller (2020) uses an instrumental variables approach that leverages the sensitivity of bark beetles to temperature shocks to place a value on changes in tree mortality rates. Similar research approaches will be important as economists attempt to incorporate more comprehensive damage functions into IAMs.

With a monetized pathway of damages, the final task of an IAM is to relate all these future damages back into present terms through a process called discounting. By converting the stream of future damages into present terms, economists can directly compare the current costs of climate action against the future costs of climate inaction. The key parameter in this conversion is called the *discount rate*, r. The equation below specifies how the discount rate $r > 0$ relates damages that occur n years in the future back into present terms:

$$\text{Present Value of Future Damages} = \left(\frac{1}{1+r}\right)^n \times \text{Future Damages.}$$

[10] A promising but limited approach to studying climate change adaptation is by estimating how people have adapted to climate changes in the past. For instance, Druckenmiller et al. (2023) are using historical aerial photographs of Western Africa to study land use and migration changes that occurred as a result of drought during the mid-twentieth century.

All else equal, the present value of future damages is low when the discount rate is high, and the present value of future damages is high when the discount rate is low.

Discounting is among the most controversial aspects of the cost-benefit approach at the core of IAMs and the SCC, raising serious ethical questions related to intergenerational equity. This is especially contentious when coupled with techniques to assess the value of mortality changes. For instance, if changes in the mortality rate were the only effect of climate change and changes in income over time were ignored, a discount rate of 5% would imply that 1 life today is equivalent to 100 lives 95 years in the future. This extreme example illustrates why discounting proves to be a controversial yet standard component of the cost-benefit framework behind the SCC. The choice of a discount rate is difficult not only because of the apparent ethical issues with devaluing future generations relative to the current generation, but because the final SCC is highly sensitive to the discount rate. This follows from the long-lived effects of greenhouse gases in the atmosphere.

Carleton and Greenstone (2022) describe the two primary justifications for a non-zero discount rate. First, a dollar of damages today will be relatively less expensive than a dollar of damages in the future, even when adjusting for inflation. This is because by just about any serious projection, the income per person will be higher in the future. The declining marginal value of consumption means that current costs will be less painful in the future when there is more income to cover them. The second justification for a non-zero discount rate relies on what economists call the *pure rate of time preference*. This says that even with fixed incomes over time, people still value current consumption more than future consumption. In the context of climate damages, this is often quite contentious. At a minimum, assigning a parameter value such that a human life in the future is not worth as mush as a human life today inherently feels wrong. Carleton and

Greenstone offer that even in the case of human life, a pure rate of time preference might be justified considering the non-zero probability of apocalyptic events like an asteroid strike or nuclear war. With this interpretation, it is not that we value human life in the future less than today necessarily, but that we never know if there will be a future.

Even if researchers rule out a discount rate of zero, the choice of discount rate is still highly ambiguous. There are two primary approaches to identifying the "correct" discount rate. The first sets the discount rate equal to the rate of return for capital assets. The motivation for choosing the discount rate to match the rate of return for capital assets follows neatly from Robert Solow's definition of sustainability: "[sustainability is] an obligation to conduct ourselves so that we leave to the future the option or the capacity to be as well off as we are" (Solow, 1991). Setting the discount rate equal to the rate of return for capital assets presumably ensures that future generations will be indifferent between current investments to reduce future climate damages and any other current investment that would compensate for these damages (a no arbitrage condition). Typically, economists consider the US Treasury Bonds to be the appropriate benchmark capital asset. Recent analysis finds that the Treasury Inflation-Indexed Security had average annual returns of just 1.01% from 2003 (when data are first available) through 2021. Of course, this approach lends itself to criticism surrounding uncertainty in future US Treasury yields.

A second approach to the discount rate comes through Ramsey (1928). This paper lays the foundation for what is now known as the Ramsey equation:

$$r = \delta + \eta g$$

where r is the discount rate, δ is the pure rate of time preference, η represents the elasticity of the marginal utility of consumption, and g is the real growth rate of consumption. The Ramsey equation is useful in IAMs in that it treats the discount rate as endogenous to the socioeconomic pathway given, providing an additional level of internal consistency. However, uncertainties around the growth rate of consumption present difficulties for Ramsey-style discounting (NASEM, 2017; Newell et al., 2022). Additionally, estimating the key parameter values often rely more on expert elicitation rather than clear derivations from market data, which is not always appealing.

In its authors' preferred specification, GIVE uses a discount rate of 2%. This is consistent with Carleton and Greenstone (2022), who recommend a discount rate of at most 2%. Increasingly, a discount rate centered around 2% appears to be the norm in SCC estimation.

The reality of policy design in the US requires cost-benefit analysis for environment and climate policy. Regardless of whether or not this is the ideal framework to use when crafting climate policy, IAMs and their ability to connect current economic activity directly to future climate damages will remain an important tool in developing climate policy. There is still considerable room for economists to advance our understanding of the implications of climate change going forward. What we do know is that today, our best estimates indicate that the impacts of climate change are troubling.

2 Designing Climate Policy

2.1 A Case for Economic Analysis in Climate Policy Design

This chapter shifts the discussion from describing climate change to describing the policy tools available to address climate change. Before delving too far into this topic, it is worth contemplating why the economics discipline has any role at all in the design of climate solutions. While the physical sciences have alerted the world to the destructive potential of climate change and occupy a central role in developing the abatement technologies needed to mitigate climate damages, economically-motivated actors have largely been the perpetrators of the greenhouse gas emissions responsible for climate change. It seems reasonable then to question why economics deserves a place in designing climate solutions. There is a purported tension between mitigating climate change damages and protecting the economy—a tension that I discuss in greater detail later in this chapter. This belief that the economy and environment are fundamentally at odds might lead to the impression that elevating the environment must be done without regard to the economy. If nothing else, the cost-benefit analysis that underlies much of the economics discipline feels inappropriate when it comes to environmental issues. After all, why should we care about money when the fate of the planet is at risk?

The objective of this section is to address these concerns and motivate the use of economic analysis in climate policy design. First and foremost, it is important to establish that economic analysis should not and cannot hope to address climate change without other disciplines. There is a tremendous need for scientific research into technical solutions with the potential to reduce greenhouse gas emissions. In the International Energy Agency's plan to achieve net zero emissions by 2050, currently available technologies can only sustain abatement through 2030. By 2050 only half of the technology needed to reduce emissions is currently on the market. The agency estimates that governments worldwide will need to immediately invest over $90 billion into key areas of research and development like electrification and carbon capture technologies—areas that currently receive only about $25 billion in research funding (IEA, 2021). Not only does the world need to efforts of the physical sciences to address climate change, but economists do for their own work as well. As discussed in section 1.3.2, the damage functions economists use to estimate the costs of climate change necessarily rely on the physical sciences to build the underlying climate models. Clearly, economic analysis alone cannot guide climate policy design.

Still, physical science alone cannot hope to address climate change without the perspective of the social sciences.

As a discipline Amongst the social sciences,

First, economic tradeoffs exist whether or not we acknowledge them, and these tradeoffs are not always simple.

Consider an impoverished community with a coal-burning power plant. The plant emits sulfur dioxide into the air, which can lead to respiratory issues. But if the plant is to reduce its emissions and continue operating, the cost of electricity will likely rise and hurt the already poverty stricken community. Workers at the plant may lose their careers. Though troublesome, there is a tradeoff here between public health and poverty alleviation.

For the sake of example, consider a low-income, credit-constrained government. To keep this example simple, suppose the government can invest its publicly borrowed funds into either converting the nation's coal generation into clean, renewable generation or into expanding public education. Though troublesome, there is an apparent tradeoff in this scenario between improving the environment and improving access to education—both worthy goals with the potential to benefit future generations. Nordhaus (2019) makes this point more poignantly in his

Nobel lecture:

> "However attractive a temperature target may be as an aspirational goal, the target approach is questionable because it ignores the costs of attaining the goals. If, for example, attaining the 1.5°C goal would require deep reductions in living standards in poor nations, then the policy would be the equivalent of burning down the village to save it."

This isn't just some highly contrived example...

Economists generally try to quantify these competing interests and place them in terms of a common unit, the dollar.[11] The question of climate mitigation costs and benefits may seem irrelevant or even unethical to some observers, but assigning numeric costs to climate inaction provides a consistent and open framework to

Second, money is the primary concern of firms engaged in emissions producing activities. The economics discipline largely concerns itself with the incentives of both firms and consumers—incentives that if designed well, can lead to substantial emissions reductions. Money undoubtedly plays a role in determining whether or not people drive electric cars, manufacturers install smokestack scrubbers, and electric power producers build fossil fuel generators. Even if we concede that bringing the world down to net zero emissions is invaluable, public policy that does not systematically consider how firms and consumers will react risks failure. In a global crisis at the scale of climate change, the potential costs of this risk are substantial.

Lastly, despite what some political pundits might propagate, the economic consensus is remarkably clear: climate change is a major threat that warrants significant action. In a 2021 survey of climate economists, 74% said that climate change

[11] Expressing costs and benefits in terms of dollars is often convenient though not necessary. For instance, in Figure 9, Carleton et al. (2022) express climate change adaptation costs not in dollars, but in terms of "statistical lives."

necessitates "immediate and drastic action." Less than 3% answered that either "more research is needed before action is taken" or that climate change "is not a serious problem" (Howard and Sylvan, 2021).[12] Although it may seem trivial to some, economists largely agree that the benefits of bold climate policy outweigh the costs. The economic perspective adds further credibility to the case for climate policy, particularly when much of the criticism lodged at climate action focuses on its cost.

In summary, economics provides a quantitative and systematic approach to making potentially difficult decisions related to our relationship with the Earth's atmosphere and our environment. This is approach is not without its flaws, but it is one of many important perspectives. Not only does economic analysis allow us to consider the tradeoffs of specific policy proposals, but it provides theory and empirical techniques essential to identifying how firms and individuals will respond to policy. Climate economists predominantly agree that climate change urgently deserves bold public policy, a view that aligns with climate scientists and researchers at large. While physical scientific research can develop the technologies that permit emissions reductions, research in economics and other social sciences will be integral in the successful adoption of these technologies and related behavioral changes.

2.2 An Economic Motivation for Climate Policy

The first chapter established anthropogenic greenhouse gas emissions as the culprit behind climate change, but this still leaves open questions surrounding the social and economic motivations behind these emissions. Any public policy aimed at reducing greenhouse gas emissions must first reconcile with why those greenhouse gas emissions exist in the first place. Moreover, despite having established

[12] Another 24% said that "some action should be taken now" on climate change.

that economics as a discipline deserves a role in climate policy design, it is worth considering whether or not public policy is necessary to address climate change at all. The objective of this section is to fill in these holes and provide an economic interpretation for both why climate change happens and why climate change is not likely to improve in the absence of public policy. This section uses foundational elements of economic theory to answer two questions: (1) why do individuals and firms release greenhouse gases into the atmosphere, and (2) can we "solve" climate change without public policy?

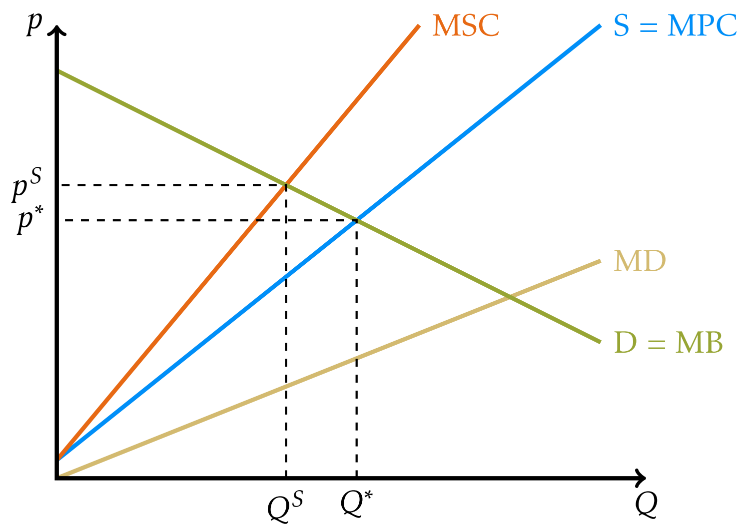
To the economist, climate change is the consequence of the *universal* nature of greenhouse gas emissions. Greenhouse gas emissions are a textbook example of an externality: a cost or benefit borne by an agent who is not involved in the economic transaction that creates the cost or benefit. Consider a driver with a gasoline-fueled car. Overall, burning gasoline creates greenhouse gas emissions that lead to anthropogenic climate change which would harm the average driver. The transaction between the driver and pump creates costs that are universal, borne by everyone on the planet, which are are externality by definition. When this driver buys and burns a gallon of gasoline in her car, she damages the climate by a non-negligible amount. In fact, a quick back-of-the-envelope calculation would suggest a central estimate for the cumulative damages associated with this gallon of gasoline of about \$1.64.[13] However, this cost is not borne by the driver alone, but distributed over the other eight billion people on the planet and even over the billions of people not yet born who will be affected by this decision in the future.

[13]The EPA (2022) finds that burning a gallon of gasoline in the average passenger vehicle creates 8887 grams of CO_2 emissions. Using a SCC of \$185 per tonne, as in Rennert et al. (2022), this implies the social cost of burning a gallon of gasoline of

$$\frac{8887\text{g } CO_2}{1\text{gallon gasoline}} \cdot \frac{1\text{tonne } CO_2}{10^6\text{g } CO_2} \cdot \frac{\$185}{1\text{tonne } CO_2} \approx \frac{\$1.64}{1\text{gallon gasoline}}.$$

Note also that this best thought of as a lower bound on true social damages, as this does not consider damages associated with the ambient air pollution emissions.

Figure 11: Market for an Emissions-Intensive Good



Note: Figure depicts a standard market for an emissions-intensive good, such as gasoline. In the figure, p denotes the price of the good, Q denotes the quantity of the good, D denotes demand, S denotes supply, MB denotes the marginal benefit associated with consumption, MPC denotes the marginal private cost associated with production, MD denotes the marginal damages stemming from the associated greenhouse gas emissions at a given quantity, and MSC denotes the marginal social cost—the sum of the marginal damages and the marginal private cost. In this case, we assume that marginal damages are increasing in Q, reflecting the accelerating disruptions caused by elevated greenhouse gas concentrations in the atmosphere.

Despite the additional or marginal damages from this gallon of gasoline of \$1.64, the climate damages that the driver faces herself for buying and burning this gallon of gasoline are effectively zero. If for instance, we simplified the situation to consider only damages that accrue to those eight billion people currently alive and assume that this driver experiences the average damages of all individuals, then her private cost of the associated emissions is approximately \$1.64/8 billion ≈ 0. As a result, the price this driver pays for a gallon of gasoline is just the price at the pump. Because the driver's costs do not reflect the universal costs of her emissions, she will end up consuming more of this good than what would be socially optimal.

Figure 11 depicts a generalized version of this situation diagrammatically through the market for an emissions-intensive good. As in any standard market, the market for an emissions-intensive good relates the quantity of this good (Q) to its price

(p). The effective components of the market are the downward-sloping demand curve (D), and the upward-sloping supply curve (S). Here, consumers demand the good such that the price they will be willing and able to pay for an additional unit of the good is equivalent to the additional or marginal benefit (MB) they receive from consuming it, hence why D = MB. Similarly, producers supply the good such that the price they will be willing and able to sell an additional unit of the good at is equivalent to its additional or marginal private cost (MPC), hence why S = MPC. Together, the demand and supply for the emissions-intensive good lead to an equilibrium price and quantity of p^* and Q^* respectively.

Outside of the market though, the production and consumption of the emissions-intensive good produces greenhouse gas emissions, which lead to climate change and associated damages to others. The upward-sloping marginal damages curve (MD) depicts the cost of these emissions for each additional unit of the good. As in the previous example, these damages accrue to society at large, but not to the individual involved in the transaction. The marginal social cost (MSC) considers the full scope of costs associated with the emissions-intensive good, summing the marginal private costs and the marginal (social) damages. Total welfare in the market is maximized when the marginal social cost is set equal to the marginal benefit, an unreached equilibrium at Q^S and p^S. Note that for an emissions-intensive good, the socially-optimal price is higher than the equilibrium price and the socially-optimal quantity is less than the equilibrium quantity. That is, the market will under-price and over-produce an emissions-intensive good. The concept of externalities provides an economic explanation for why society creates excessive greenhouse gas emissions that lead to climate change.

It is worth considering then why—if the atmosphere is in fact so valuable—there is no market for clean air. Modern economic theory classifies goods according to two criteria: rivalry and excludability.[14] A good is rival if one agent's consumption of the good inhibits another agent's consumption of the good, or is non-rival if one agent's consumption of the good does not inhibit the consumption of any other agents. Concert tickets, for example, are a rivalrous good—one person holding a ticket prevents another person from holding that same ticket. A good is excludable if it is reasonably easy to prevent someone from using it. Video subscription services are excludable, as a service can always prevent a person from accessing the service if, for instance, he stops paying his bill. If we accept the double dichotomies of a good being either rival or non-rival and excludable or non-excludable, then these criteria lead to four types of economic goods: private goods (excludable and rival), public goods (non-excludable and non-rival), open-access goods (non-excludable and rival), and club goods (excludable and non-rival).[15] These good matrix in Figure 12 summarizes these four types of goods.

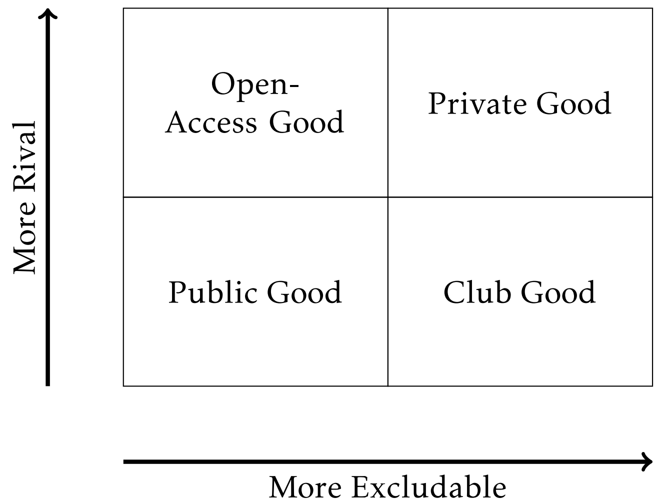
A clean atmosphere is firmly a public good. There is no way to prevent people from benefiting from a healthy atmosphere with greenhouse gases at a level that supports climate stability, and one person's benefit does not infringe on another's. By the same virtue, greenhouse gas emissions are a public bad. No individual can exclude herself from climate change, and one person's climate damages do not prevent someone else from also experiencing those same damages.

Defining a clean atmosphere as a public good provides a grounded explanation

[14] Ostrom (2010) reviews the historical development of the four goods commonly used today. The seminal paper Samuelson (1954) moved the discipline away from just private goods and described a public good, introducing the excludability criterion. Although Hardin (1968) popularized the concept of rivalrous goods, club goods were first formally introduced in Buchanan (1965) and open-access goods were first formally introduced in V. Ostrom and E. Ostrom (1977).

[15] Here I choose to use the term "open-access good" rather than "common-pool resource," a term more common in work such as Ostrom (1990). The intention of this choice is to clarify the non-excludability of this class of goods. A common-pool resource might be shared by a group of agents, but still excludable to others outside of this group. For instance, Ostrom (1990) considers a community forest in the Swiss Alps where the right to fell timber in the community forest was restricted to certain land owners who could prevent others from purchasing land that would grant them the timber rights. The term "open-access good" more clearly describes a good that is available to any interested actor but still rival (e.g., using the swing set at a public park).

Figure 12: A Taxonomy of Goods



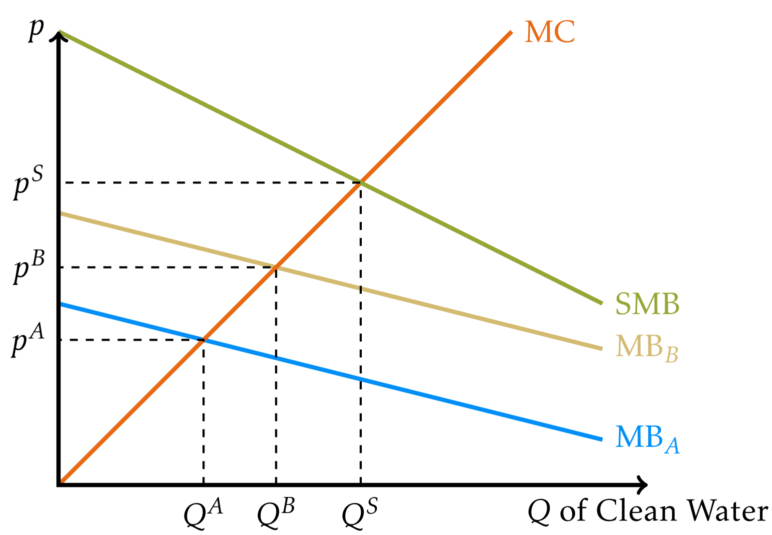
Note: The goods matrix depicts the four main types of goods: private goods (excludable and rival), public goods (non-excludable and non-rival), open-access goods (non-excludable and rival), and club goods (excludable and non-rival). Although these are cannonically presented in four categories, the excludability and rivalry of goods is best thought of as taking place on a continuum.

for why socially efficient greenhouse gas emissions abatement is unlikely to occur in the absence of public policy. All public goods struggle to find buyers. This lack of buyers is not necessarily because few people are willing and able to pay for the public good, but because these people do not have the proper incentives that would motivate them to actually buy into the public good. To see this, suppose there are two cities *A* and *B* on either side of a lake that is currently polluted and covered in algae blooms. Both cities benefit from the clean water in the lake through greater aesthetic appeal, higher property values, and increased ecotourism. As we have described it, clean water in the lake is a public good. Neither city can exclude the other from enjoying the clean water and one city's enjoyment of the clean water does not inhibit the other city from enjoying the clean water.

adapted from Keohane and Olmstead (2016)

With this discussion of public good provision in mind, consider again whether or not it is possible to "solve" climate change—in the sense limiting of limiting—in

Figure 13: Market for a Public Good



Note: Figure depicts a market for an emissions-intensive good, such as gasoline, based on Figure 5.4 in Keohane and Olmstead (2016). In the figure, p denotes the price of the good, Q denotes the quantity of clean water, MC denotes the marginal cost of clean water, MB_A denotes the marginal benefit of clean water to city A, MB_B denotes the marginal benefit of clean water to city B, SMB denotes the social marginal benefit which is the sum of MB_A and MB_B. The figure demonstrates that even in the smallest of public good provision situations, the equilibrium production of the public good be less than the socially efficient.

the absence of public policy.

Even with domestic climate policy, this of course still leaves room for free riding at the global level. However, with a public policy focus in mind, the relevant actors are no longer individuals but entire nations. This change drops the number of relevant actors from billions to just dozens, making the prospect of cooperation far more likely. Currently, international cooperation has been mostly limited to voluntary climate pledges like the defunct Kyoto Protocol or the Paris Climate Agreement, where the compliance and enforcement of commitments is ambiguous at best. There are however other, more enforceable options at the international level to promote cooperation and prevent nations from shirking on their climate obligations. The most prominent of these approaches is likely the idea of a "climate club," popularized by Nordhaus (2015). A climate club is a group of nations that imposes trade penalties on other nations that do not fulfil their climate obligations, providing some incentive for nations to create policy that reduces their emissions profiles. Climate clubs are already beginning to emerge informally through the implementation of the European Union's recently revised Carbon Border Adjustment Mechanism (CBAM), which levies trade restrictions in Europe against imports from nations with relatively emissions intensive production processes. I save a more through discussion of Border Carbon Adjustments (BCAs) for later in the chapter.

For the sake of simplicity, assume that all technology needed to attain net-zero emissions and stablize the concentration of greenhouse gases in the atmosphere was commercially available. Even if this was the case,

Overall, when a good is non-excludable, it is difficult to create an incentive structure that motivates individuals who value the public good to contribute to its provision. The field of mechanism design studies these incentive structures, as called "mechanisms," with the intent of motivating individuals to reveal their private value for a public good and contribute this value to its provision. [16] These mechanisms are mathematically complex, and ultimately always rely on a social planner to implement and enforce

Economists often use the classic prisoners' dilemma game to model a public good contribution game.

All agents have a strictly dominant strategy to not contribute towards the public good, provided that they would prefer to not contribute to the public good and not receive it than finance the public good individually. A coal-burning power plant wants to prevent climate change damages, but preventing these damages will require sweeping action from around the world. It could not successfully mitigate climate change damages by itself, and even if it could, the costs involved would far exceed its benefits. If other actors choose to take aggressive action on climate change, then making serious abatement efforts costs the coal plant but provides no benefit. In either case, the plant is better off doing nothing. The universal, non-excludable nature of the benefits of climate change mitigation fails to create the proper incentives for individual actors to take action.[17]

Absent any additional incentive, individual agents will fail to implement the necessary changes. In some instances, economic actors can in theory internalize the externality through bargaining, a result known as the Coase theorem (Coase, 1960). This implies that in certain circumstances, private agents can resolve externalities without public policy.

Climate change does For the Coase theorem to hold even theoretically, there must be enforceable property rights and transaction costs must be negligible. These

[16] See Chapter 7 of Fudenberg and Tirole (1991) for the authoritative treatment on the application of mechanism design to public good provision problems.

[17] The rivalry of goods tends to be less important than their excludability in environmental contexts. Hardin (1968) famously considered the example of an English pasture to show that agents will overexploit non-excludable but rival goods, leading to the collapse of the natural system, provided the agents have no institutions that can enforce cooperation. For this reason, the excludability is the primary concern in the environmental and climate settings.

transaction costs are often substantial, especially when dealing with many different actors and assessing compliance is difficult. Because climate change involves quite literally every person on the planet (and many more people not yet born), it suffices to say that serious efforts at curbing climate change cannot be made without government involvement. Further, Coasean bargaining may have potentially troubling distributional consequences. However, bargaining will likely play a pivotal role in any successful international climate agreements. In these contexts, we can consider how bargaining may be able to address climate change without an international government. Even this will require national governments to implement strong climate policy.

Putting these pieces together, individual firms and consumers will emit far too many greenhouse gas emissions as the costs they face do not reflect the greater societal costs of their actions. These same firms and consumers will fail to produce a cleaner atmosphere, a necessary public good, because they cannot exclude others from enjoying the benefit of a clean atmosphere. Without this ability to exclude, those willing to produce a cleaner atmosphere will not do so because individuals do not have an incentive to buy a cleaner atmosphere. Without buyers, there can be no market for a clean atmosphere. The market failure that leads to climate change is less of a market failure and much more of a market omission. The omission of the market for a clean atmosphere creates ragged, incomplete edges in adjacent emissions intensive markets. Finally, the scope of the problem is so large that resolution of climate change through private actors is not only impractical, but too costly to be increasing welfare.

Decades later, Elinor Ostrom critiqued this dichotomy in her landmark book *Governing the Commons*, in which she documents many cases from around the world where non-government institutions have successfully sustained resources including grazing land, forests, and groundwater aquifers. In each of these cases, individuals and firms organized themselves in “collective action” to protect natural resources.

Could similar approaches like those Ostrom studies succeed in creating climate action? It is highly unlikely. Ostroms focus on open-access resources, where a healthy atmosphere is firmly a public good (alternatively, greenhouse gas emissions are a public bad). Much of their analysis is based on the rivalry of the resources and consequently does not translate well for reducing emissions. More importantly, some of the key features that allow these self-governance approaches to succeed are not met in the context of climate change. The systems Ostrom studies are primarily local and rely on mutual-monitoring and enforcement. Given the global nature of climate change and the invisibility of greenhouse gas emissions, it would be a tremendous leap to say that climate action is achievable through self-governance and collective action alone.

In summary, economic theory posits that agents will produce excessive greenhouse gas emissions because they do not face the full social consequences of their economic activities. A safe and stable atmosphere is public good, and consequently, private agents do not have an incentive to abate their emissions. Without policy intervention, the resulting equilibrium outcome will

Although non-policy options exist to internalize the externality (e.g., Coasen strategies) or cooperate towards more socially desirable outcomes (e.g., collective action strategies), the number of relevant parties means these are not serious alternatives to public policy.

The next section briefly address the suite of policy available

2.3 The Structure & Scope of Environmental Policy

In Garrett Hardin’s classic work “The Tragedy of the Commons,” he proposes two approaches to managing open-access resources: privatization and nationalization.

The key in both cases is consolidating agents, who would otherwise experience the consequences of each others' actions but not their own, under one umbrella. That is, when there is only one party in charge, there is no room to free ride.[18] Today, many environmental policies still fall into a dichotomy that parallels the dichotomy Hardin discussed: market-based policies and command-and-control policies.

Just as privatization of the commons consolidates incentives by ,

market-based policies consolidate social

Just as nationalization of the commons places the state as in charge

Again, both market-based policies and command-and-control policies

It is not surprising that current climate policy in the US predominantly resembles the dichotomy espoused by Hardin. This same dichotomy appears in US environmental policy as well.

The inevitability of the incentive-induced failure of private management of the climate crisis forces public policy. Still, there is a wide variety of tools available to policymakers for addressing environmental and climate issues. Analogous to Hardin's dichotomy, environmental policy typically falls into one of two categories: *market-based policy* and *command-and-control policy*. Command-and-control policies create changes by enforcing directives, while market-based policies make use of primarily financial incentives.

Command-and-control policies are what we would typically think of as environmental regulation. Here, government creates specific prescriptions to firms and possibly consumers. For this reason, command-and-control policy is also often called *prescriptive policy*. Prohibition policies prevent actors from taking cer-

[18]It is worth noting that an N-player "Tragedy of the Commons" game is functionally identical to an N-player Cournot game. This highlights how the market behavior of a monopoly ($N = 1$), under-producing and over-pricing a good, can actually become socially desirable in the case of environmentally damaging goods, which are usually over-produced and under-priced. Privatization and nationalization of the commons both amount to granting a monopoly on a good.

tain actions, like purchasing a piece of public land or disposing of a hazardous chemical. These typically appear in the management of public lands, like National Parks, Wildlife Refuges, and Forests. Often alongside prohibition is permission, where government may for instance lease National Forests to the logging industry or grant rights to a firm to drill for oil on state-owned land. In a loose sense, we might also classify any policy enforcement as a part of this category. Regulators may prohibit certain activities with prescribed punishments for violators.

Another approach to regulating and protecting the environment is through standard setting. Standards are generally either *technology standards* or *performance standards*. Technology standards require firms to use specific technologies. Many coal-burning power plants must install smokestack scrubbers to prevent damaging chemicals from entering the lower atmosphere. Alternatively, performance standards do not specify specific technologies, but set bounds on the rate or total magnitude of an environmental impact. This could involve setting an emissions cap on an individual firm or car fuel economy standards, which indirectly govern the rate of carbon dioxide emissions per mile. The discipline lacks clear definitions for some of these classifications, and occasionally performance standards form a category between market-based and command-and-control policies. Technology standards provide the characteristic inflexibility of a command-and-control policy, but performance standards can provide somewhat more flexibility.

Information tools can use a combination of both command-and-control and market-based policies. For instance, a mandatory eco-labeling program might require firms to display the carbon footprint of a good they sell. This a specific reporting requirement without a direct financial incentive attached to the policy. Still, consumers, seeing this information might change what and how many products they purchase. This creates secondary financial incentives for firms, similar to a market-based policy. Sometimes these programs are not mandatory, and firms voluntary participate in labeling due to some financial incentive. Other times, there is no financial incentive for information disclosure, but regulators require disclosure regardless. This is the case in program's like the EPA's Greenhouse Gas Emissions Reporting Program. This program requires facilities that have potential high emissions to collect data and report on their greenhouse gas emissions.

Generally, market-based policies operate instead not by imposing specific rules, but instead by creating those essential but missing markets. Policymakers primarily do this through the two components of any market: price and quantity. Price instruments are the traditional Pigouvian solution. When there is a market failure due to some externalitiy, we can internalize the externality by taxing or subsidizing a good so individual incentives will align with social incentive. Carbon taxes are a clear example of this strategy. There are costs of carbon dioxide emissions that do not appear in the prices of goods and activities that rely on these emissions. A carbon tax creates a financial incentive for firms and consumers to reduce their emissions. It also it flexible—no individual has to change her behavior, but continued emissions will come at a cost. Analogous programs subsidize energy-efficient goods, providing a financial incentive to adopt durables that will use less energy and reduce emissions.

Alternatively, policymakers might also use quantity-based instruments to create financial incentives. The typical example here is a cap-and-trade program, where policymakers require certain actors to own emissions permits or emissions allowances for every ton of their greenhouse gas emissions. Policymakers create a fixed quantity of these permits and can sell these to regulated firms. If firms were only allowed to keep these emissions allowances, then this would be equivalent to a performance standard. The key piece of the differentiation is the tradeable nature of these allowances. Under a cap-and-trade program, firms can buy and sell these emissions allowances from each other. This creates a market for allowances, which puts a price on emissions. Just like a carbon tax, the price of an emissions allowance creates a financial incentive for emissions abatement. Other programs outside of the reduction of greenhouse gas emissions make use of quantity-based instruments. For instance, Wetland Mitigation Banking in the US fixes a quantity of land for wetland conservation. Firms and farmers that wish to develop on existing wetland must offset this development by building or conserving a tract of wetland equivalent to the wetland they displace through development.

So what policies are most effective? Economists tend to favor market-based over command-and-control approaches in many contexts for two primary reasons. First, market-based approaches are in a theoretical sense, cost-effective. That is, well-designed price and quantity tools can achieve environmental targets while minimizing the burden of regulation on firms and consumers. This seems somewhat ironic. Many environmental issues are fundamental examples of market failure, yet here the implication is that these same issues are best resolved inside of a market. Keohane and Olmstead (2016) perhaps say it best "the problem is not that markets are so pervasive but that they are not pervasive *enough*—that is, they are incomplete." Are economists naive to suspect that the same free-market principles that cause environmental issues can actually resolve them? The section that follows expands on this question by providing an example of why carbon taxes and cap-and-trade programs can be reasonably cost-minimizing, and some justification of why command-and-control policies are not. Later sections will address this empirically and show that market-based tools can be effective in resolving environmental and climate issues.

Second, market-based programs create incentives for firms to invest in research and development of new technologies with positive environmental impacts. Under a technology standard, firms have no interest in creating new technologies. Doing so would only impose additional and unnecessary costs on themselves. Additionally, if firms encountered technologies with the potential to reduce their environmental impact, they would have an incentive to hide it from public and particularly from regulators. Under a market-based approach, firms have a strong incentive to innovate new technologies. With a carbon tax, major innovations in abatement technology would allow firms to save on emissions costs, giving them a strong competitive advantage. If firms could anticipate future increases in the price of emissions, they might even make this investment even if the current emissions price was relatively low.

Despite the apparent merits of market-based approaches to environmental policy, price and quantity instruments are no panacea. One significant concern in many areas of environmental policy is enforcement. Natural resources are often incredibly large and it is difficult to monitor individual behaviors that relate to these resources. The earlier discussion on the cost-minimizing nature of these market-based approaches excludes any consideration of enforcement costs. What happens if we incorporate these costs into our analysis?

For instance, say we wanted to reduce bycatch on commercial fishing vessels. Bycatch is when fishers unintentionally catch sealife like dolphins or sea turtles instead of the fish they intended to catch. There are ways fisher can mitigate bycatch, like using specific kinds of nets that allow some species to escape. Consider a market-based strategy to reduce bycatch, like taxing fishers for the non-targeted sea life that they catch and kill. If fishers followed this rule, the tax would be enough for many of them to adopt the technologies that would reduce bycatch. This would minimize the total costs incurred by fishers. Fishers who face high costs from reducing bycatch will barely reduce their bycatch as they would rather pay the tax. Fishers who face low costs from reducing bycatch will greatly reduce their bycatch as they would rather adopt new technologies than pay a tax. Of course, this assumes that there is perfect compliance and enforcement is costless.

What kind of costs would be involved in enforcing a tax like this? Monitoring and taxing the bycatch of every commercial fisher in an area would be tremendously difficult and expensive. We do not have the technology to monitor every animal caught in every commercial fishing nets. Even there was a monitoring official on every large commercial vessel, there would be strong incentives for collusion.

In situations where enforcement is incredibly costly, it may be more cost-effective to take a command-and-control approach that prescribes uniform policies across actors. In this example, it would much less expensive to require that commercial fishers use bycatch-reducing nets. Policymakers could incorporate this into existing procedures for commercial fishing licensing and even prevent the production and sale of more harmful nets. This policy would not be cost-minimizing for the fishers, but if the difference in enforcement costs was large enough, it may be more cost-minimizing to society as a whole. A technology standard, a command-and-control approach, seems more appropriate in this case.

2.4 Environmental Markets: Carbon Taxes & Cap-and-Trade

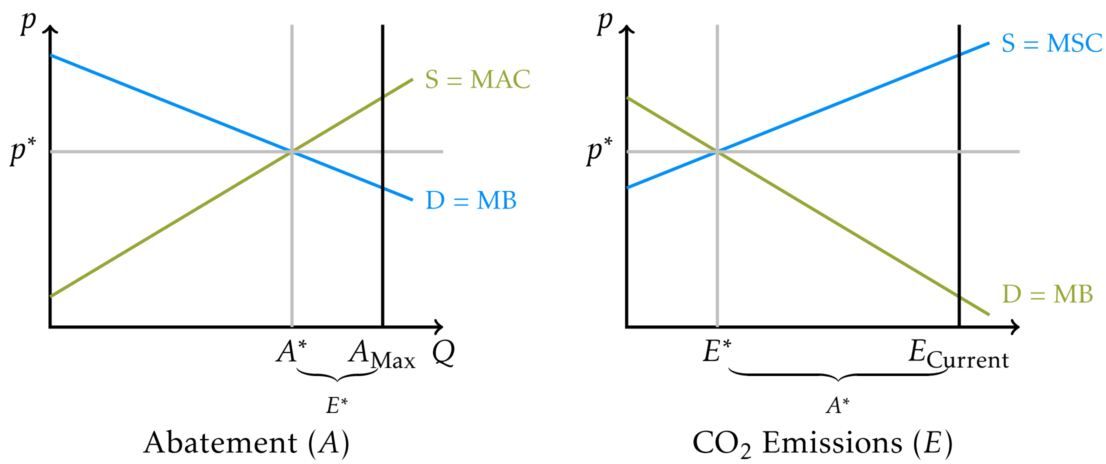
To illustrate the theory behind these polices, consider the example of carbon taxes and cap-and-trade programs. The market missing in climate change is a market for emissions abatement. Figure 14a displays this market. The supply of emissions abatement is equivalent to the marginal abatement costs (MAC). Towards the left of the MAC curve are the low hanging fruit of abatement options.[19] As more abatement occurs, the technologies involved in abatement become more costly, and many of these require new research investments into technologies that are not yet available.

Although there are private costs involved in emissions abatement, there are

[19] Some empirical estimates of this curve suggest that this far portion of the MAC may actually be negative. That is, initial emissions abatement is achievable at a negative cost, as firms and individuals can often save money through energy-efficiency improvements. This is related to the energy-efficiency gap (see Allcott and Greenstone, 2012; Gerarden et al., 2017).

Figure 14: Creating a Market for a Public Good (or Bad)

(a) The Market for Abatement (b) The Market for Emissions



also social gains. These gains are equivalent to avoided climate change damages. Marginal damages increase with the quantity of emissions; the more emissions are already in the atmosphere, the greater the impact of an extra ton of CO_2. For this reason, the marginal benefits of abatement are decreasing. The first ton of CO_2 abated is responsible for the largest reduction in climate change damages, and any subsequent abatement is less effective at reducing damages. Abatement is a public good though, so despite the social benefits, no private agents are willing to pay for abatement.

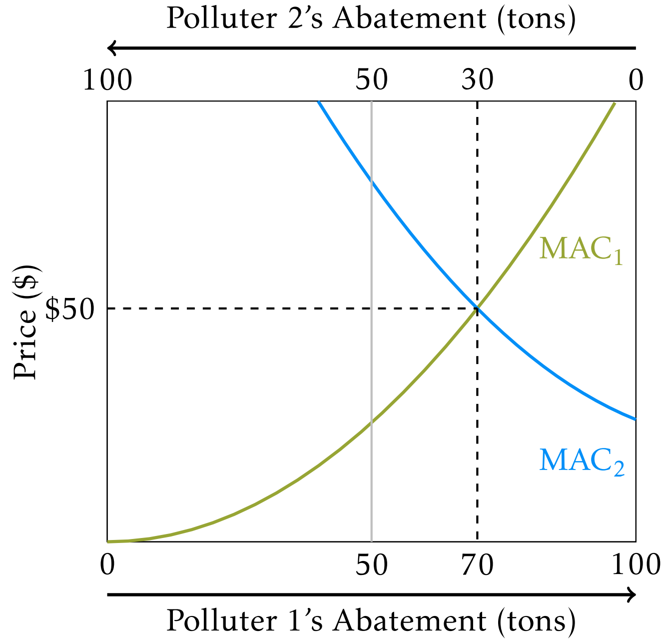
Market-based policies attempt to resolve this issue by using government to act as a "demander" of abatement. It is impractical for policymakers to set a full demand curve for abatement, so instead policymakers can set clearer demand curves that will still bring the market to its true equilibrium. Namely, a policymaker can set a horizontal demand curve for abatement at p^* or a vertical demand curve for abatement at A^*. These two options are identical in simple models of abatement as both lead to the socially optimal level of abatement.

The previous example framed market-based instruments from the perspective of creating a market for emissions abatement. Although this framing is important and one that is often more convenient, the interpretation and public policy implications can seem counterintuitive. With government on the demand side, this would imply a policy where government pays polluters to abate, either promising a fixed rebate on each ton of emissions abated or by purchasing abatement until it reaches A^*. In this system, polluters would earn more revenue by through abatement. Major climate policy proposals do not include such massive payoffs to polluters, and rightly so; in the long run these economic profits would attract more firms to enter high-polluting industries and diminish the efficacy of policy. There may also be additional social costs if government reduces other expenditures or raises taxes in order to finance these payouts.

The familiar policies focus on the inverse of the abatement market, the market for emissions. This market appears in Figure 14b. In this market, the government does not intervene to demand a public good, but to establish rights for and supply a public bad. The polluters derive their demand for emissions from their MAC curves—it represents the most polluters will be willing to pay for the right to send CO_2 emissions into the atmosphere rather than abate. The supply curve in this market is the marginal damage of emissions. This framing comes with a clearer interpretation. Here, policymakers impose a carbon tax—a charge of p^* on each ton of CO_2 emissions. In equilibrium, this tax will lead to total emissions E^*. A cap-and-trade program program instead sets a vertical supply curve of emissions allowances, permits that give polluters the right to emit one ton of CO_2, at E^*. A key feature of these allowances is that they are tradeable between polluters. Although it is not necessary for government to sell or auction off emissions allowances, if government did, their equilibrium price would be p^*.

The market for abatement and the market for emissions correspond. The difference between the maximum level of abatement and the equilibrium level of abatement is the equilibrium emissions, and the difference between the current

Figure 15: Distribution of Allowances



level of emissions and the equilibrium level of emissions is the equilibrium abatement. The market price for emissions is the same as the market price for abatement. Framing market-based policy through the market for emissions has a more convenient interpretation relative to standard policy. However, because the prices and quantities are identical in both markets, economists often choose to frame market-based polices through the market for abatement rather than the market for emissions. This approach can be clearer when considering the cost-minimizing nature of market-based instruments.

It turns out that in our simple theoretical model of a cap-and-trade program with tradeable allowances, the original distribution of allowances is irrelevant to whether or not the policy achieves the emissions reduction cost-effectively. Suppose that there are just two polluters in our system, Polluter 1 and Polluter 2, each of whom currently has 100 tons in emissions. The assumed benevolent policymaker wants to cut emissions in half by setting a cap of 100 tons of emissions. Polluter 1 and 2 have marginal cost of abatement curves depicted in Figure 15.

Consider two alternative scenarios: (1) the policymaker sells allowances to the polluters, and (2) the policymaker gifts 50 (tradeable) allowances to each polluter.

If the policymaker sells allowances to the polluters, then both polluters will purchase allowances up until the price of an allowance equals the cost of an additional ton of abatement. That is, each polluter will purchase the quantity of emissions allowances where the price of an allowance is equal to its marginal abatement cost. The demand for abatement is perfectly inelastic, so the equilibrium price will be where the sum of the quantities of abatement supplied by the polluters is 100 tons. Graphically, the total marginal abatement cost curve for the two polluters together is a horizontal summation of each individual marginal abatement cost curve. Figure 15 shows that at a price of \$50, the sum of the Polluter 1 and 2's abatement is 100 tons, the desired level of abatement. Total abatement costs are equal to the area under each abatement curve from 0 to its level of abatement. Figure 15 shows that this allocation minimizes this area.

Suppose instead each polluter begins with 50 allowances. If both have 50 allowances, Polluter 2 would have a far higher marginal cost of abatement than Polluter 1. Knowing this, Polluter 1 might sell some of its allowances to Polluter 2. Polluter 1 will sell its allowances as long as the price it receives is at least as high as its marginal abatement cost. Polluter 2 will buy allowances as long as the price it pays is weakly less than its marginal abatement cost. These dynamics bring the market to equilibrium where Polluter 1 sells 20 of its allowances to Polluter 2 at a price of \$50 per allowance. As before, this allocation of emissions and abatement minimizes total abatement costs. This shows that even if the two allowances are distributed uniformly and freely to polluters with heterogeneous marginal abatement costs, we still reach the cost-minimizing allocation of emissions abatement.

The major difference is not in the total costs, but in the distribution of these costs. If the policymaker uses an auction to allocate the allowances, then Polluter

1 will pay less (total) than Polluter 2, but both will bear the cost of purchasing emissions allowances and abatement costs; the cost of these allowances becomes government revenue. If the policymaker uniformly distributes the allowances between polluters, then Polluter 1 will collect additional revenues from selling 20 allowances, Polluter 2 will bear additional costs from buying another 20 allowances, and both bear their abatement costs.

Although the optimal distribution of allowances is highly normative, conventional economic thought suggests that the auction method may have a slight welfare advantage over the gifting of allowances. Selling the emissions rights is considered *non-distortionary*, as it corrects an existing market failure. If government used these additional revenue to reduce distortionary taxes, then this could lead to welfare gains in other pieces of the economy. We return to the question of how policymakers might choose to allocate allowances when we consider the European Union's Emission Trading System and the approach its policymakers had used up until recently to address emissions leakage risk.

Conventional economic theory suggests that carbon pricing is the most cost-effective option for emissions abatement. While the simple models discussed earlier in this section embody many of the ideas at the core of emissions pricing, these models also lack much of the nuance involved in the practical implementation of carbon pricing. We turn now to focus on carbon pricing policies in practice.

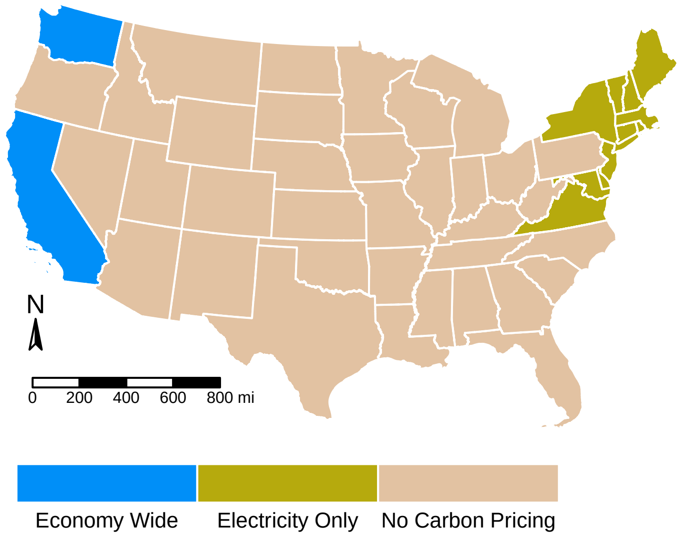
Before delving too far into an empirical review of carbon pricing, it is worth considering whether or not carbon pricing is even worth discussing in the US. It is also worth noting that although it seems unlikely that the US would implement a nationwide carbon pricing program anytime in the relevant future, this has not always been the case. The Clean Air Act amendments of 1990—legislation championed by then President George H.W. Bush—established a nationwide cap-and-trade program on sulfur dioxide emissions through the Acid Rain Program.

The broad bipartisan support of the legislation and overall success of the Acid Rain Program is at a minimum suggestive that similar policy for greenhouse gases might have been politically feasible. The prospects for such a policy became palpable when the House of Representatives passed the American Clean Energy and Security Act of 2009, more commonly known as the Waxman-Markey bill. The Waxman-Markey bill called for a nationwide cap-and-trade program for greenhouse gas emissions highly analogous to the Acid Rain Program's cap-and-trade program on sulfur dioxide emissions. Meng (2017) reviews data from the online trading exchange "Intrade," which ran a contract allowing investors to, in essence, bet on whether or not the Waxman-Markey bill would be signed into law and the US would have a nationwide cap-and-trade program for greenhouse gas emissions. These data suggest that one point investors perceived the probability that the US would adopt a cap-and-trade program on greenhouse gases by the end of 2010 at 55%. Ultimately the bill failed in the Senate, gaining some support from Republicans, but never enough to overcome the filibuster. It remains the only legislation that would price greenhouse gas emissions to pass a chamber of Congress.

Today, a nationwide cap-and-trade program for greenhouse gas emissions in the US is generally understood to be politically infeasible. Still, several state and city governments across the country have taken up these policies as a part of their decarbonization strategy. Figure 16 displays the states with some form of carbon pricing. Currently, there at are thirteen states with carbon pricing programs, the most recent being Washington state which began its cap-and-trade program at the beginning of 2023. These states are among some of the most populous in the country, and the nearly a third (32.4%) of the US population lives in a state with some form of carbon pricing.

FORTHCOMING: Brief review of the empirical literature on emissions pricing

Figure 16: Statewide Carbon Pricing in the US



Note: Figure displays statewide carbon pricing policies as of January 1, 2023 for the contiguous 48 states. Economy-wide cap-and-trade programs price emission from electricity, as well as other sectors, like industrial processes and transportation fuel distributors. Electricity-only cap-and-trade programs only pricing emissions from the electric power industry. Together, there are thritheen states with carbon tax or cap-and-trade programs at the state level in the US. The remaining 37 states do not have carbon pricing programs. Records from C2ES (2023).

- Borenstein and Kellogg (2022)
- Green (2021)
- Burtraw et al. (2022)
- Burtraw and Hayes (2022)
- Need to talk briefly about emissions offsets: John Oliver?

2.5 Incomplete Carbon Markets

Previously, we have looked at the ability of carbon pricing schemes (either an emissions tax or an emissions trading program) to reduce greenhouse gas emissions within a closed economy. Although this is a standard example of Pigouvian approaches to tackling externalities, the story is more complex when we instead consider an open economy.

When an individual country/state/city takes up a carbon pricing scheme, we call this a *unilateral* carbon pricing scheme, meaning that this jurisdiction adopts the policy without coordinated carbon pricing schemes across all or most all other jurisdictions. This is the current state of carbon pricing schemes. According to the The World Bank (2022), 21% of all anthropogenic greenhouse gas emissions faced an emissions price in 2021. Even if Country A has a price on its carbon, it will not be able to put a price on the emissions from Country B, even though Country B's emissions are just as damaging to Country A as its own emissions. That is not to say that unilateral carbon pricing schemes are not worth it, but to acknowledge that there is something missing. This is an example of an *incomplete regulation*: a situation where not all relevant actors in the market face regulation. In the case of greenhouse gas emissions, everyone is a relevant actor, meaning that without a global carbon pricing scheme, any unilateral carbon pricing scheme will always be incomplete. In this section, we begin to explore the implications of the incompleteness of unilateral emissions pricing and analyze possible solutions.

A frequent claim of those opposing aggressive climate policy is that it will make the country less economically competitive relative to other countries. Here, I will use the term "competitive" in the sense that foreign firms will gain a greater global market share, usually as a result of lower costs. Understandably, the effect of climate and environmental policy on economic activity (both domestic and foreign) is of considerable interest to not just economists, but policymakers and the general public.

The contemporary literature on the relationship between economic standard of living and environmental decay begins with Simon Kuznets, and his work related not to the environment, but inequality. Kuznets (1955) laid out a empirical relationship between economic development and inequality. Kuznets findings suggest that income inequality rises as countries move from low-income to middle-income, and income inequality falls as countries move from middle-income to high-income. Diagrammatically, this creates an inverted U-shaped path called the Kuznets Curve with GDP per capita on the horizontal axis and measures of inequality (usually the income ratio between the top quintile and bottom quintile of earners) on the vertical axis. Realizing that economic development and environmental degradation follow a similar relationship, Grossman and Krueger (1991) were the first to formulate the *Environmental* Kuznets Curve (EKC) in an analysis of NAFTA. While the model was not the primary focus of the original paper, it later led to its own published paper, Grossman and Krueger (1995) and is now a standard in environmental economics.

Figure 17 displays the Environmental Kuznets Curve. The EKC hypothesizes that low-income economies will have relatively high environmental quality, as these economies may be more agrarian or pastoral. Countries often move from low-income to middle-income through industrialization, and as countries industrialize, their environmental degradation increases. Eventually though, economic development requires countries to move away from manufacturing and into higher human capital industries. When this happens, sectors dependent on high human capital (e.g., finance, engineering, education) tend to be less harsh on the environment. Past the turning point, economic development will decrease environmental degradation.

Despite its quick adoption in the discipline and its continued use, the EKC has largely been discredited (Stern, 2004). Arrow et al. (1995) importantly note that the usual form of the EKC does not allow for any feedback between the environment and development, implicitly assuming that pollution and other forms of environmental degradation do not hinder economic development.

The claim from the EKC that economic development itself will lead to improve-

Figure 17: The EKC

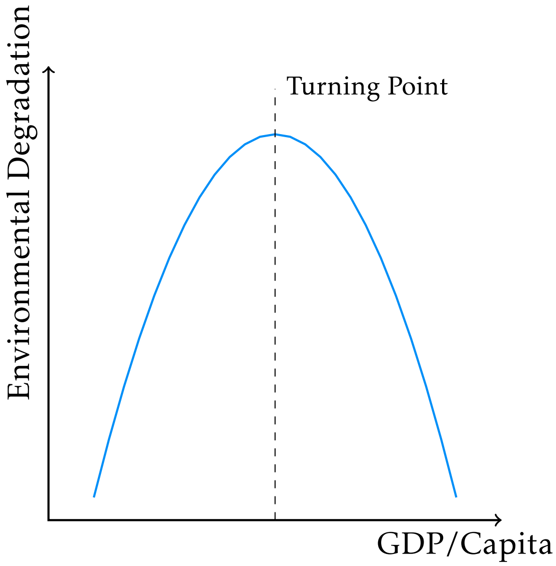
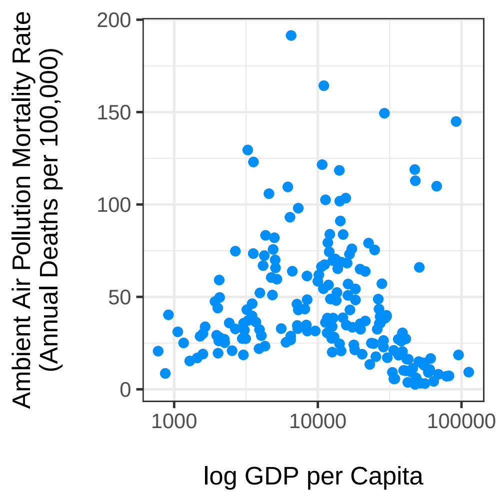


Figure 18: Application of the EKC



Data from Ritchie and Roser (2019)

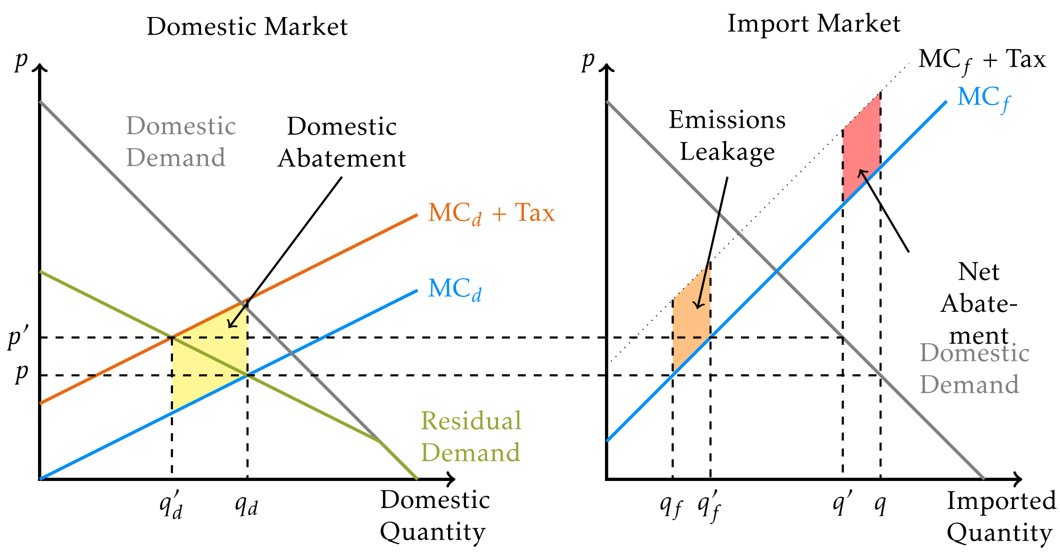
ments in environmental quality make dubious assumptions. The EKC correctly captures the tendency for rich nations to substitute dirty economic activities for relatively cleaner activities. Ultimately though, the world is finite, and some countries must house the high-pollution industries. This leads to what is known as the *pollution haven hypothesis*. Stringent environmental regulation will raise the costs of firms in high-pollution industries, making firms in less-regulated economies relatively cheaper and more competitive. This means that some economies with relaxed environmental regulation might end up specializing in only high-pollution industries, becoming pollution havens. Thus, one consequence of environmental regulation may be that it shifts the burden of damaging economic activities elsewhere, usually to low- and middle-income countries.

Contemporary empirical evidence on the pollution haven hypothesis leads to a few key conclusions: (1) environmental regulation does not have an economically significant effect overall trade flows, and (2) environmental regulation can have an economically significant effect on the trade flows of specific industries. A common technique for assessing differences in climate policies is considering differences in energy prices (see for example Fowlie and Reguant, 2022). The idea is that carbon prices function in the short-run by raising the price of energy that a firm's technology limits them to use. Using differences in energy prices as a proxy, Sato and Dechezleprêtre (2015) show that an increase in the energy price gap between trading countries only increases bilateral manufacturing trades by 0.2%. Further these same energy price differences only explain 0.01% of the variation in trade flows. Aldy and Pizer (2015) find a null result in a similar study looking at energy price differences between US states—the effect of energy price differences on total manufacturing imports between states was statistically insignificant, even with their over thirty years of panel data. However, they do find pronounced effects in certain, energy intensive sectors including steel, industrial chemicals, and cement. In their survey of the literature, Dechezleprêtre and Sato (2020) come to the conclusion that there is likely a pollution haven effect, but that it is confined to a select number of industries.

If empirical evidence seems to suggest that climate policy only leads to significant competitive effects in a few industries, where is the problem? Unfortunately, even if the transfer of economic activity is small overall, the transfer of emissions can be quite large.

Emissions leakage occurs when the implementation of stringent regulation (almost always meaning a carbon pricing scheme) on GHG emissions in one place leads to increased GHG emissions in another place with looser regulations. Emissions leakage is closely related to the pollution haven hypothesis, but differs in a few ways. First, emissions leakage refers exclusively to GHG emissions, not pollution in general. This distinction is important as most GHG emissions have a negligible effect on the areas downwind from their source of emissions, but ambient air pollutants do not. Thus, the consequences of increased GHGs from emissions leakage is global rather than local. Second, the pollution haven hypothesis

Figure 19: Competitive Emissions Leakage



is much more concerned with international trade flows and the changing composition of economies, whereas emissions leakage is concerned more with changing the distribution of emissions. That is, the pollution haven hypothesis focuses on the implications of displaced economic activity, and emissions leakage focuses on the implications of displaced emissions.

Figure 19 displays how competitive effects can drive emissions leakage in an example market. In the left panel of figure 19 is the domestic market for an emissions creating good. In the right panel of figure 19 is the import market for the same good. Domestic producers do not face the full domestic demand curve, as foreign producers will also be willing to supply the domestic market. Instead, domestic producers face the residual demand curve, the difference between the domestic quantity demanded and the import supply at each price. Domestic firms will produce where their marginal cost curve MC_d intersects residual demand. This price then caries into the import market, and foreign firms will produce where the domestic market price intersects their marginal cost curve MC_f. Absent any carbon pricing scheme, domestic firms produce q_d, foreign firms import q_f, and the total market quantity is q.

Now suppose that domestic policymakers implement a carbon pricing scheme. For ease, assume that this takes the form of a per ton emissions tax and that marginal emissions and marginal damages from emissions are both constant. The carbon pricing scheme is unilateral, meaning that it applies to all domestic producers, but not any foreign producers. The constant marginal emissions rate and per unit carbon tax imply that domestic firms pay a constant per unit tax on their output, creating a parallel shift up in from MC_d to MC_d + Tax. Again, firms produce where the marginal cost they face equals residual demand. This causes the domestic price of the good to rise to p' and the domestic production of the good to fall to q'_d. The yellow region of left panel in figure 19 represents a monetary measure of domestic abatement. If the tax on emissions is set to the social cost of a ton of emissions, then this area is the monetary value of all domestic emissions abatement τE_d, where E_d is the sum of domestic emissions in the market. Like we should expect, the carbon pricing scheme induces domestic reductions in GHG emissions.

Unfortunately, this is not the case in the import market. Unlike firms in the domestic market, foreign firms do not face this same emissions price. Higher prices in the domestic market without the counteracting increase in costs induce foreign firms to expand their production from q_f to q'_f. Analogous to the yellow area, the orange area in the right panel of figure 19 represents the social cost of the additional emissions in the import market. This is emissions leakage: an increase foreign emissions as a result of unilateral carbon pricing. Still, unilateral carbon pricing manages to reduce total emissions despite the leakage. Total quantity in the domestic market falls from q to q', with the area of the red region representing the social value of the net abatement. We see that when we take leakage into account, the emissions reductions are much more modest than what they appeared to from domestic production alone.

There are a certain class of goods that are particularly susceptible to emissions leakage known as *emissions-intensive and trade-exposed* (EITE) goods. A good is emissions intensive if its production creates a lot of emissions per unit (tons of $CO_2e/\$$). We measure the trade exposure of a good with the ratio of the volume traded domestically (value of imports + value of exports) to the total volume of good that passes through the domestic economy (value of domestic production + value of imports). Fowlie and Reguant (2022) and Fowlie et al. (2016) show that it is not enough to be only emissions intensive or only trade exposed to have a high risk of leakage. Both conditions are necessary to have a substantial risk of emissions leakage. EITE goods include cement, steel, and many industrial chemicals.

The bad news of emissions leakage does not end there. There are many ways that emissions leakage can occur. Using the language of Cosbey et al. (2020), we have so far discussed the *competitiveness channel*, where emissions increase outside of the regulated jurisdiction as unregulated producers become more competitive. Another important form of leakage occurs through the *energy market channel*. If the US implemented a stringent tax on GHG from cars, we can expect that the domestic demand of gasoline will fall dramatically as US commuters opt for modes of transportation other than gas-fueled vehicles (e.g., electric vehicles, bikes, public transit). The US is large enough though that this will cause prices to fall in global energy markets, and when fuels like petroleum-based fuels become cheaper, more firms will begin using petroleum-based fuels and creating more emissions elsewhere. These general equilibrium effects that move in and around global energy markets are difficult to address without globally coordinated efforts to ditch fossil fuels. These two channels are thought to be the primary drivers of leakage (Branger and Quirion, 2014)

There are also a few ways where we might see negative emissions leakage. That is, situations where ambitious steps towards abatement in one location spillover into abatement somewhere else. The *income channel* provides another opportunity for negative leakage. If a carbon tax makes people poorer in less-regulated jurisdictions, then this could decrease foreign consumption and production of emissions intensive goods and lower emissions. Of course, this is not a favorable way to reduce emissions. The income channel could operate in the opposite direction as well, raising emissions in places where incomes increase as a result of the incomplete regulation. The more likely form of negative leakage occurs through the *technology channel*. Carbon pricing schemes reduce emissions not just by internalizing the externality, but by providing incentives for the creation of new, cleaner technologies. Producers facing emissions pricing certainly have an incentive to adopt cleaner technologies, but producers outside of the regulated region do not have this same carrot and stick. If these new technologies happen to be more cost-effective than existing technologies, then it is possible that producers would adopt these cleaner technologies and reduce emissions this way. The prospect of negative emissions leakage is overly optimistic as a whole, and empirical evidence to date suggests that negative leakage is negligible compared to the other channels of leakage (Winchester and Rausch, 2013).

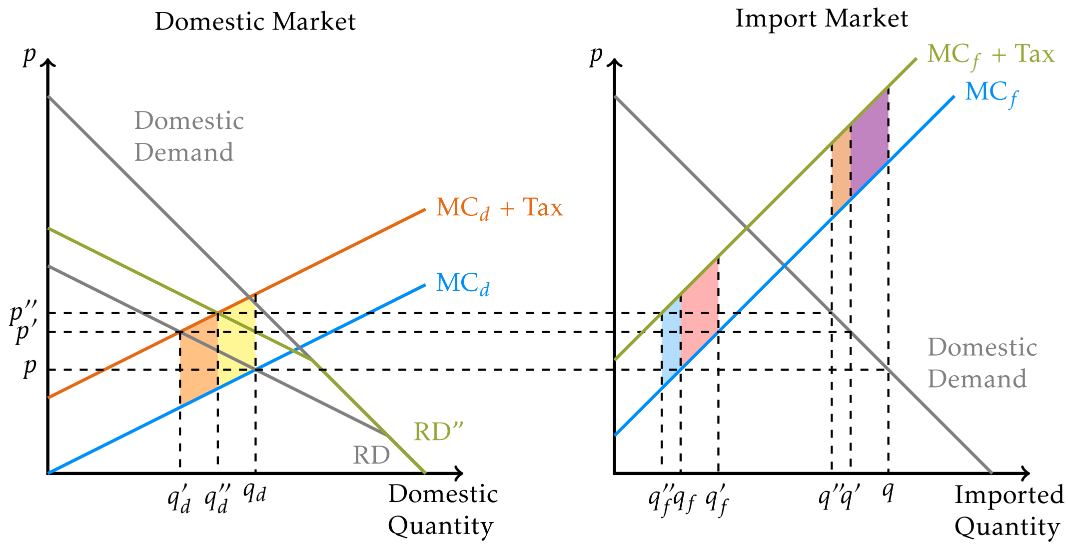
An important approach to completing emissions regulations is through border carbon adjustments. Border carbon adjustments (BCAs) are policies that manipulate the price of goods as they move between jurisdictions with different emissions prices, usually between one place with a carbon price and another without a carbon price. That is, these policies adjust the price of goods based on their carbon emissions (or carbon equivalent emissions) at the border. They come in two major varieties: import taxes (charges) and export (output) rebates

Import taxes or *import charges* attempt to complete the regulation of domestic markets by subjecting foreign imports to carbon taxes similar to the carbon taxes domestic producers pay. Import charges are the more relevant of the two major varieties of BCAs, and often we use the term BCA when we just mean import charges. This is largely because we import more EITE goods than we export.

Figure 20 displays how an emissions charge on imports can reduce leakage. Like in figure 19, suppose that domestic firms pay a constant tax for each ton of their GHG emissions. For simplicity, assume that all producers, domestic and foreign, have a constant, identical emissions intensity. With the unilateral emissions tax and without an import charge, there is substantial domestic abatement—represented by the orange and yellow regions in the domestic market—and there is substantial leakage—represented by the red region in the import market. The total emissions reductions are represented by the violet region in the import market.

Consider now when policymakers impose an import charge analogous to the domestic emissions tax. Now foreign producers face $\mathrm{MC}_f + \mathrm{Tax}$, a parallel shift of their previous marginal cost curve. With the marginal cost curve shifting back in the import market, the difference between the domestic quantity demanded and the quantity of imports supplied increases at every price level. As a result, residual demand in the domestic market shifts up. Setting this new residual demand curve RD″ equal to the marginal cost $\mathrm{MC}_d + \mathrm{Tax}$, increases the domestic quantity from q'_d to q''_d. This means that the value of domestic abatement decreases from the sum of areas of the orange and yellow regions in domestic market to just the area of the yellow region. Although there is modest increase in domestic emissions due to the import charge, there is larger reduction in foreign emissions. The import charge moves foreign production from q'_f to q''_f. Previous to the imposition of the import charge, the unilateral emissions tax increased the costs of foreign emissions by the area of the red region in the import market. With the imposition of the import charge though, we see that foreign emissions are actually less than they were in the baseline (no domestic emissions tax and no import charge). The social value of

Figure 20: Leakage with an Import Charge



Adapted from Fowlie et al. (2016).

this foreign abatement is give by the area of the region in blue. The total quantity of the good in the domestic market decreases from q_d' to q_d''. The additional social value of emissions abatement due to the import charge is given by the area of the green region in the import market.

Import charges bring with them a host of technical challenges that for the most part tie back to one central question: how do we assess the emissions of imported goods?

Before we determine how to assess the emissions of imported goods, it is useful to know how we assess the emissions of domestically produced goods. The GHG Protocol, the internationally recognized leader in GHG emissions accounting standards, sets out three emissions scopes. Scope 1 looks at just an organization's direct emissions, like the GHGs that the organization emits on site. Scope 2 includes all these direct emissions from Scope 1, but also includes indirect emissions associated with energy inputs. For instance, a database center might have relatively low Scope 1 emissions, but if all electric power needed for the database center comes from a coal-fueled plant, Scope 2 emissions would be high. Scope 3 takes this a step further to look at the lifecycle emissions associated with an organization. This includes all the emissions captured by Scope 2, and includes emissions embodied in non-energy inputs and downstream emissions from distribution, processing, use, and disposal of its output. Any domestic emissions pricing program first needs to determine what emissions it will use to assess emissions to firms. It is best practice to assess foreign emissions with the same scope as domestic emissions, and likely violates international trade law to assess emissions using a higher scope for foreign producers (Cosbey et al., 2020).

In their most complete form, border carbon adjustments cover all goods that cross the border, not just imports. Just like highly-regulated domestic production will likely have a cost disadvantage in the domestic market, highly-regulated exports will likely have a cost disadvantage in foreign markets. To prevent jurisdictions with ambitious climate policy from losing their exports requires some way to adjust the price of exports. This is the purpose of an *export rebate*, often just called an *output rebate*.

An output rebate pays back a flat rate to domestic producers for every unit they export. While carbon taxes on imports try to even the playing field between highly regulated and less regulated producers in domestic markets, output rebates try to even the playing field between highly regulated and less regulated producers on foreign markets. For instance, if US fertilizer manufacturers export much of their product, imposing a domestic carbon tax raises these manufacturers' costs relative to their competitors overseas. This cost differential may allow foreign fertilizer manufacturers to retake some of the (foreign) market share from US fertilizer manufacturers. This increased foreign production will lead to greater GHG emissions associated with the foreign fertilizer market, a problem that may be exacerbated if foreign manufacturers were already more emissions intensive than US manufacturers.

Output rebates lack the same intuitive appeal that an emissions tax on imports have. After all, why should we tax manufacturers only to pay them back? Why not just tax manufacturers the difference between the original emissions tax and the output rebate? The first reason is a matter of accounting. Output rebates only apply to exports, so reducing the tax on all goods would not differentiate between the goods that should and should not receive a subsidy to avoid leakage. The second reason is a matter of incentives. Output rebates are not refunds on emissions taxes, as the government pays these out for every unit of output rather than for every ton of GHG emissions. In a world where goods had a fixed emissions intensity, this difference would not matter. Thankfully though, there are ways to reduce emissions without reducing output (e.g., switching to cleaner inputs or installing smokestack scrubbers). Thus, an output rebate will maintain the same abatement incentive on exports, while also allowing domestic producers to maintain their ability to compete in foreign markets. The low volume of US manufacturing exports relative to imports means that these are not typically the primary concern in anti-leakage policy.

3 Ambient Air Pollution & Electricity Generation

The previous two chapters have focused on preparing a broad base of knowledge on climate economics—the first chapter by reviewing the physical science of climate change and the second chapter by reviewing the economics of climate policy design. This chapter continues to build background, but focuses instead on providing context specific to the modeling and empirical work done in the two chapters that follow it.

To motivate these proceeding chapters, this chapter begins by discussing ambient air pollution with particular emphasis on the impacts of ambient air pollution and air pollution disparities. As alluded to earlier, the ultimate goal is to model and simulate these air pollution disparities that result from the implementation of a carbon tax on the electric power industry in California. Keeping this in mind, the discussion on air pollution is followed by an overview of wholesale electricity markets and Assembly Bill 32 (AB-32), the California statute that creates an emissions trading program across the state. Finally, I review the body of literature immediately adjacent to this research. The related literature serves both to establish what we already know about the implications of carbon pricing for environmental inequality and to motivate the specific goals of the research in this paper. This chapter concludes by describing the overall research design that unfolds in the next two chapters. The description of this design is outlines both the research design choices I make in these later chapters and the motivation for these design choices.

3.1 Primer on Ambient Air Pollution

Introduction

- What is ambient air pollution?

- What are the most common air pollutants?

Ambient air pollution exposure comes with many negative consequences, but the most striking of these is the effect of ambient air pollution on human health and mortality. **Talk about the mechanisms using Aguilar-Gomez et al. (2022)**.

The World Health Organization (WHO) estimates that ambient air pollution caused over 4.2 million premature deaths in 2019, making ambient air pollution one of the leading global health stressors (WHO, 2022). Around the world, 99% of people live in environments that do not meet the WHO's air quality guidelines. Understandably, the vast majority (89%) of these premature deaths are in low- and middle-income countries, but ambient air pollution remains a serious health threat even in wealthy nations, including the US. Lelieveld et al. (2019) uses atmospheric models alongside a global exposure mortality model—a model that maps air pollutant concentrations into mortalities—to study excess mortalities attributable to anthropogenic air pollution emissions. They find that ambient air pollutants from anthropogenic sources (primarily the burning od fossil fuels) result in 230,000 excess deaths annually in the US.[20]

Apart from the devastating effects of air pollution on human health, the other primary effect of air pollution exposure is reduced cognitive performance and decision making. Fonken et al. (2011) find physical changes in the brains of mice who have been exposed to fine particulate matter at concentrations and durations comparable to Beijing. Namely, they find that neurons in the hippocampus—an area of the brain devoted to memory and learning—have shorter and less dense dendrites. These dendrites are responsible for receiving signals from other neurons, and the reduced length and density of these neurons is correlated with poorer memory (Weir, 2012).Additionally, the mice exposed to particulate matter display depressive-like symptoms, giving up earlier in forced swimming tests and eating

[20]The 95% confidence interval around these estimates is 184,000–276,000 excess deaths—a wide interval, but an interval where even the minimum of the interval warrants serious concern.

less.

These physiological findings in mice correspond with a wealth of evidence on the effects of air pollution on human learning and cognition. Aguilar-Gomez et al. (2022) provides the best review of these effects and their implications for human capital formation and labor economics more broadly.

Education/Human Capital Development & Labor Implications

- Zhang et al. (2018b)
- Currie et al. (2014)
- Aguilar-Gomez et al. (2022)
- Currie et al. (2009)
- Ebenstein et al. (2016)
- Chang et al. (2016)

Crime

- Bondy et al. (2020)
- Burkhardt et al. (2019)

Happiness

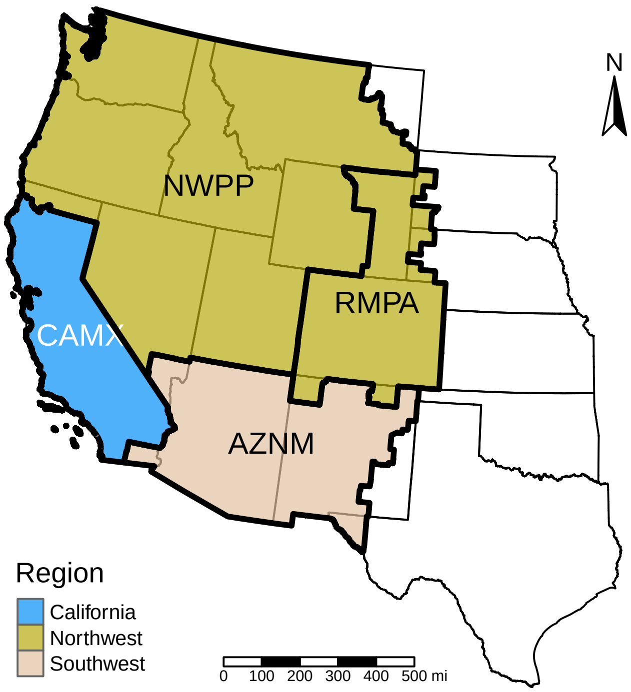
- Zheng et al. (2019)

Together, the many effects of air pollution add to the popular

Justice/Inequality/Distributional perspectives

- Colmer et al. (2020)
- Hernández-Cortés et al. (2022)
- Currie et al. (2023)

Figure 21: Western Interconnection Subregions



Note: Figure displays the subregions of the Western Interconnection. These subregions are a unit of geography set by the North American Electric Reliability Council (NERC). NERC determines these regions based off of the connections/boundaries between balancing authorities, the administrative unit of the US power grid. These regions are the California-Mexico Power Area (CAMX), the Northwest Power Pool Area (NWPP), the Rocky Mountain Power Area (RMPA), and the Arizona-New Mexico-Southern Nevada Power Area (AZNM). The EPA reports data for each of the four NERC regions, but the EIA only provides electricity demand data for the NWPP and RMPA together. These two subregions are treated as one throughout the paper, and future chapters will model just the three regional markets displayed: the California market, the Southwest market, and the Northwest market. Shapefiles for the regions come from HIFLD (2023).

- Banzhaf et al. (2019)

- Voorheis (2017)

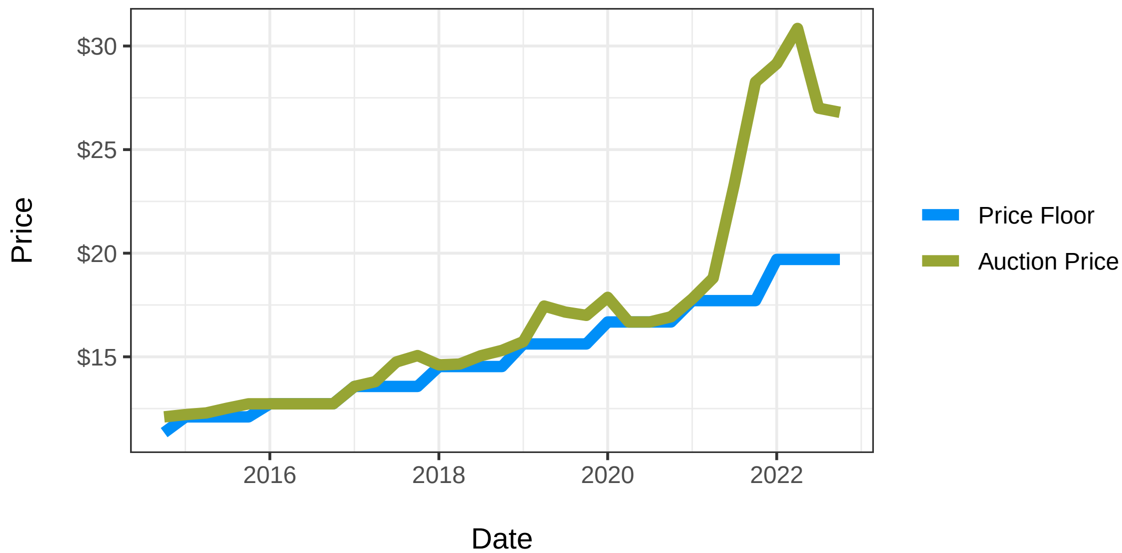
3.2 The Case of California: Electricity & AB-32

Wholesale electricity markets: How they work and their "competitiveness"

- FERC (2020)

Short history of CAISO

Figure 22: California Emissions Allowance Price



Note: Figure displays the auction price and price floor for emissions allowances in California from Q4 2015 through Q4 2022. Each emissions allowance covers one tonne of CO_2e emissions. Data on emissions allowances come from the California Air Resources Board, CARB (2023a).

- Sweeney (2013)
- Knittel and Roberts (2005)
- Borenstein et al. (2000)
- Borenstein and Bushnell (2015)

Leakage

- Burtraw et al. (2022)
- Fowlie (2009)
- Fowlie et al. (2021)

Effect of AB-32 on Electricity

- https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/cap-and-trade-regu

3.3 Carbon Pricing & Environmental Inequality

Carbon pricing policies are highly popular among economists. In what is likely the greatest display of consensus on climate policy from the economics discipline, most all of the nation's leading economists endorsed a series of policy recommendations published in the Wall Street Journal in 2019. The statement titled "Economists' Statement on Carbon Dividends" calls for the implementation of a nationwide tax on greenhouse gas emissions, border carbon adjustments, and carbon dividends to redistribute the collected tax revenue. Original signatories of the statement include twenty-eight Nobel Laureates, four former Chairs of the Federal Reserve, and fifteen former Chairs of the Council of Economic Advisors. Since its initial release, the statement has earned the signature of thousands of other economists.[21]

As discussed in Chapter 2, the primary appeal of carbon pricing for economists is the cost-minimizing nature of these policies. The consensus statement's first policy recommendation states this unambiguously:

> "A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary. By correcting a well-known market failure, a carbon tax will send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors towards a low-carbon future."

It is also relevant to note that the signing economists address how the revenue generated from the carbon price should be distributed—an aspect that if done poorly could create major inequality concerns. The statement's fifth and final policy recommendation reads:

[21] This includes many other well-known economists, like Susan Athey, Daron Acemoglu, and Rick Eichhorn.

> "To maximize the fairness and political viability of a rising carbon tax, all the revenue should be returned directly to U.S. citizens through equal lump-sum rebates. The majority of American families, including the most vulnerable, will benefit financially by receiving more in 'carbon dividends' than they pay in increased energy prices."

Together the policy recommendations in the statement provide a brief but clear strategy for reducing greenhouse gas emissions in a manner that is both efficient and progressive in the sense that tax revenue would flow towards those at the bottom end of the income distribution.

Despite the carbon-pricing fervor of economists, many in the climate policy community remain skepitcal of proposals that rely heavily on carbon pricing for decarbonization. There are a number of arguments against carbon pricing that critique the efficacy of these programs relative to their alternatives, but these concerns are not new and generally struggle to make a strong case.[22] Instead, more recent criticism of these policies has centered around their potential to perpetuate environmental inequality. Because global air pollutants (i.e., greenhouse gases) are often released at the same time as local air pollutants (i.e., criteria air pollutants, including PM, NO_x, SO_2), carbon pricing has the potential to shift the distribution of ambient air pollution. In this context, the less-regulated local air pollutants are often called copollutants. The concern is that even if environmental markets

[22]Chapter 2 describes arguments against carbon pricing that critique the efficacy of these programs. This discussion comes to four primary conclusions. First, there is a need for additional research that measures the ex-post effect of carbon pricing on emissions reductions. Second, many jurisdictions with carbon pricing programs have chosen to rely on other regulations to attain emissions targets. That is, the implicit price on emissions from other regulations is often higher than the market price of emissions, which can make the effect of emissions pricing appear weak relative to other regulations. Third, in situations where policymakers rely primarily on carbon pricing more so than other regulations, carbon pricing does appear to be the more cost-effective policy. This difference appears to be small though, especially in the electricity market where the strong correlation between the merit order of generation and emissions intensity mean that clean energy standards perform only negligibly worse carbon pricing. Fourth, there are likely tangible improvements to emissions trading programs that can be made, such as reforming or eliminating the use of emissions offsets.

can induce abatement efficiently, the "invisible hand" economists celebrate might just shift the burden of air pollution towards already disadvantaged communities. Raising this possibility is entirely fair. After all, the decentralized nature of market means there is no specific mechanism to prevent this from happening. The most vulnerable in society may already feel disenfranchised by market-systems, so the resistance to a cap-and-trade program—a market-based policy instrument—is not entirely surprising.

Many Californians have expressed concerns about the potential for California's cap-and-trade program to redistribute the air pollution burden towards communities with already poor environmental quality and economic status. In fact, the first question on the "Frequently Asked Questions" page of California's cap-and-trade program's website reads: "Does the cap-and-trade program lead to increases of air pollution in environmental justice communities burdened with air pollution?" (CARB, 2023b). This was not a major concern when AB-32 was originally passed in 2006, but nearly ended California's cap-and-trade program when it needed to be reauthorized ten years later in 2016 (Johnson, 2020).

These concerns were intensified following the release of several descriptive analyses that seemed to indicate that California's cap-and-trade program had done exactly that: redistributed air pollution towards disadvantaged communities. Cushing et al. (2018), circulated at the time as Cushing et al. (2016), notes that even though total emissions from regulated facilities decreased in the three years after the implementation of California's cap-and-trade program, 52% of facilities actually increased their emissions. Further, Cushing et al. (2018) finds that the communities with increases in co-pollutant emissions are on average poorer, less educated, and have a higher proportion of non-white residents than communities with decreases in co-pollutant emissions. In a follow-up study with a few additional years worth of data, Pastor et al. (2022) found similar results. The median facility covered by the cap-and-trade program in a disadvantaged community increased its PM10 emissions by 3.1%, while the median facility covered by the cap-and-trade program in a non-disadvantaged community decreased its PM10 emissions by 6.9%—a 10 percentage point difference in changes of PM10 emissions. Other air pollutants show similar disparities in pollution changes, though these differences are only statistically significant at the 5% level for PM10 and SO_x, not for PM2.5, NO_x, or greenhouse gas emissions themselves.

While these two studies help establish important descriptions of environmental justice outcomes in California, as Hernández-Cortés and Meng (2022) note, these do little to speak to the actual effect of the cap-and-trade program. First, their results cannot disentangle the effects of the cap-and-trade program from contemporaneous events that may cause the redistribution of co-pollutants. Pollution intensive activities are highly responsive to macroeconomic trends, and it is entirely possible that the redistribution of co-pollutants towards disadvantaged communities is a consequence of these macroeconomic trends rather than the effects of the cap-and-trade program. Second, co-pollutants are often not stagnant, but move into neighboring communities based on geography and atmospheric conditions. This means that even if the emissions of co-pollutants increases in a community, this is not sufficient information to suggest that the air pollution exposure in that community increases as well.

Hernández-Cortés and Meng (2023) is the first study to provide credible causal measurements of the impact of the cap-and-trade program on air pollution exposure. The authors define and measure changes in the "environmental justice gap," the average difference in air pollution concentrations between disadvantaged and other communities.[23] In contrast to Cushing et al. (2018) and Pastor et al. (2022), Hernández-Cortés and Meng find evidence that California's cap-and-

[23] California designates certain census tracts as "disadvantaged" as a part of the CalEnviroScreen.

trade program actually reduced the environmental justice gap, by 6-10% annually. Hernández-Cortés and Meng address the two limitations of earlier descriptive analysis by (1) using a difference-in-differences model that makes use of the staggered implementation of the cap-and-trade program to disentangle the effects of the cap-and-trade program from other contemporaneous events, and (2) embedding the predicted facility-level co-pollutant emissions within a chemical transport model that allows them to accurately measure air pollution exposure. Although Hernández-Cortés and Meng find evidence the cap-and-trade program has reduced disparities in air pollution exposure, they are also careful to emphasize that a cap-and-trade is not necessarily the sufficient to reduce these disparities. Nonetheless, their results suggest that Californians need not worry that the State's cap-and-trade program will exacerbate existing disparities in air pollution exposure.

The previously mentioned literature studying the effects of carbon pricing on air pollution disparities has all focused on ex-post analysis of such policies. While retrospective research is vital to ensuring the success of California's cap-and-trade program going forward, the highly contextualized nature of the analysis makes the external validity of these results questionable. The econometric analysis cannot describe any underlying mechanisms that produce the measured causal effects, and without a clear understanding of *how* California's cap-and-trade program helped to close disparities in air pollution exposure, we cannot anticipate the effects of similar policies applied elsewhere.

Weber (2021) offers, to my knowledge, the first and only ex-ante model that studies how carbon pricing in California affects the spatial redistribution of co-pollutants. The model focuses on the State's electric power industry and follows in the spirit of related structural, industrial-organization models (e.g., Gowrisankaran et al., 2022; Abito et al., 2022). Although Weber focuses primarily on the total welfare effects of the redistribution of co-pollutants, her results suggest that counties with more "disadvantaged" communities appear to also see greater reductions in co-pollutant emissions. These findings pair well with those in Hernández-Cortés and Meng (2023), although Weber focuses on only power plants and Hernández-Cortés and Meng focus on all regulated facilities except power plants.

3.4 Research Design

4 A Model of Emissions Pricing & Environmental Inequality

4.1 Model Summary

The purpose of this chapter is to build an economic model of electric power generation that connects carbon pricing to the distribution of air pollution. I do this by expanding on the model in Weber (2021).

The model follows a set of generators spread across several regions as they decide whether or not to invest in efficiency improvements and whether or not to operate in each hour. These generators in the model are all fossil fuel generators—either coal, natural gas, or oil—meaning that we consider the generation of renewable and nuclear to largely be determined outside of the model. Generators operate on wholesale electricity markets, which we assume are competitive. The chapter describes the profit-maximizing investment and operating decisions for each generator, and then uses these decisions to model the associated change in air pollution exposure for disadvantaged and non-disadvantaged communities. The model explicitly incorporates a measure we call the *Environmental Inequality Gap* that is analogous to the *Environmental Justice Gap* in Hernández-Cortés and Meng (2023) and is defined as the difference in the average air pollution concentration between disadvantaged and non-disadvantaged communities associated with electric power generation.

Many of the fundamentals of the model come from Weber (2021), though the model in this chapter and Weber's model differ in several substantive dimensions. First, this model generalizes the geographic scope of Weber's model such that it includes other regions which do not face the same carbon price. This modeling decision allows us to consider the environmental implications of unilateral carbon pricing schemes and the incompleteness of these regulations. Second, this model explicitly measures disparities in air pollution concentrations between disadvantaged and non-disadvantaged communities. By incorporating these disparities into the model, we are able to better characterize the contextual factors that might allow carbon pricing to widen disparities. Third, this model omits several of the more intricate details of generation, namely the ramping costs that generators incur when turning "on" and "off."

On the whole, this model is more computational than analytical in the sense that it does not yield a clear relationship between the carbon price and environmental inequality in the absence of data. Given the complexities in both the dispersion of air pollution and the distribution of generators across low- and high-SES communities, a purely analytical model would likely abstract too far away from the context to be instructive. Although, this chapter does not produce a clear analytical solution, the model still provides some intuition that connects the policy context to the effect of carbon pricing on the distribution of air pollution.

The model highlights two channels through which carbon pricing could potentially exacerbate environmental inequalities. First, the model suggests that if generators in and around disadvantaged communities have lower investment costs relative to the generators in and around non-disadvantaged communities, then carbon pricing has the potential to redistribute the air pollution burden towards disadvantaged communities (the *investment channel*). Second, the model suggest that if generators in and around disadvantaged communities are relatively less regulated (i.e., a lower average carbon tax) than generators in and around non-disadvantaged communities, then again, carbon pricing has the potential to redistribute the air pollution burden towards disadvantaged communities (the *leakage channel*).

The remainder of the chapter proceeds by first establishing key features of each generator setting up the model environment they exist in. With the necessary context and nomenclature built, we then describe the behavior of equilibrium outcomes of generators in the generation phase, followed by the the behavior of equilibrium outcomes of generators in the initial investment phase. The final sections pull these generator-level decisions back to model air pollution disparities and characterize the pathways through which air pollution disparities could be widened by carbon pricing. For easy reference throughout, Table 3 in Appendix A.4 contains a full glossary of all the mathematical notation that appears in the model.

4.2 Model Environment

Suppose there are N generators in a set of generators $\mathcal{N} = \{1, \ldots, N\}$ spread across R contiguous regions. Let $\mathcal{N}_r$ denote the set of generators in region r such that the set of all $\mathcal{N}_r$ forms a partition of $\mathcal{N}$.[24] Each generator has a primary fuel, f_i where $f_i \in$ {Coal, Natural Gas, Oil}. All generators operate within the hourly wholesale market for electricity, where generators sell electricity to utilities, distributors, and commodity traders. The model considers the implications of decisions made in the wholesale electricity market in the short- and medium-run.

Assume that hourly demand in the wholesale market for electricity is perfectly inelastic. This assumption is primarily motivated by the lack of dynamic pricing for end users. Demand in the wholesale market is derived from the retail market for electricity, where distributors (e.g., utilities) purchase generation in the wholesale market to sell to end users. Because end users pay a price for electricity that they observe only at the end of the month, they cannot respond to variation in prices over a single hour. Distributors ultimately must purchase just enough electricity to cover the demand of end users for each hour, meaning that the buyers in the wholesale market for electricity are not able to respond to hourly price changes. Over longer spans of time, we can reasonably expect that end users will

[24]Formally, $\bigcup_{r \in \mathcal{R}} \mathcal{N}_r = \mathcal{N}$ and there does not exist a generator i and distinct regions a and b such that $i \in \mathcal{N}_a$ and $i \in \mathcal{N}_b$.

eventually respond to wholesale electricity prices passed through by distributors, but difficulties substituting away from electricity will mean that this response will be muted. For instance, Burke and Abayasekara (2018) find that US end users do respond to prices in the retail market for electricity, with a price elasticity of electricity demand of -0.1 within the year, implying a highly inelastic demand in the short-run though not perfectly inelastic.

Each region has a distinct market with its own price, although these regional markets are integrated to an extent. Maximum transmission constraints restrict the volume of electricity that any one region can import or export to a neighboring region.

The model sequence begins with an initial investment phase, followed by a generation phase. The investment phase takes place prior to the first period, and is an opportunity for generators to make efficiency improvements. These efficiency improvements come through the generator's *heat rate*—the amount of heat energy input measured in British thermal units (BTUs) required to generate one kilowatt-hour (kWh) of electricity. Assuming that generators use fuels with an unchanging fuel content, the heat rate measures how efficiently a generator can convert fossil fuels into electricity. A generator with a high heat rate will require more fuel inputs to produce the same amount of electricity as a generator with a low heat rate, meaning more efficient generators will have lower heat rates. In practice, heat rate improvements primarily involve the installation of new equipment, though additional training and maintenance work can reduce the heat rate of a generator as well (EIA, 2015).

Let ρ_i^0 denote the initial heat rate of generator i. Each generator i faces a discrete set of investment options $\mathcal{J}$, where $0 \in \mathcal{J}$ and represents the decision not to invest in any heat rate improvements. Then given i's chosen investment j_i, its heat rate throughout the generation phase is

$$\rho_i = \rho_i^0(1+\tilde{\delta}) - j_i \tag{1}$$

where ρ_i is generator i's heat rate and $\tilde{\delta} \in (0,1)$ is an exogenous depreciation rate that models reductions in efficiency (i.e., increases in the heat rate) over time. Reducing the heat rate comes at a cost that varies from generator to generator. Let Γ be the investment cost function, mapping generator i's potential heat rate reductions j_i to costs, through the specification

$$\Gamma(j_i, v_i) = \gamma j_i^{1/\alpha} + v_i. \tag{2}$$

In this cost function, $\gamma > 0$ and $\alpha > 0$ are fixed parameters that are common to all generators, while v_i is an exogenously determined stochastic shock to investment costs unique to generator i. Note that γ determines the scale of investment costs and α determines whether or not the marginal cost of investment is increasing or decreasing in the investment level j.[25]

During the investment phase, generators cannot directly observe the future demand of electricity and instead must form expectations about future electricity demand. First assume that all generators have identical expectations for future electricity demand. Let Q_t^e denote the R-dimensional vector with the expected quantity demanded of electricity in each region in period t. For the sake of simplicity, assume that the common expectations of future electricity demand in all regions match the actual quantity of electricity demanded in each region.

After the investment phase is the generation phase. In this phase, each gener-

[25]To see this, note that if j were a continuous variable, then $\frac{d^2\Gamma}{dj^2} = \gamma\left(\frac{1}{\alpha}\right)\left(\frac{1}{\alpha}-1\right)j^{(1/\alpha)-2}$. This implies that the marginal cost of investment is strictly increasing if and only if $\alpha < 1$, the marginal cost of investment is strictly decreasing if and only if $\alpha > 1$, and the marginal cost of investment is constant if and only if $\alpha = 1$.

ator decides whether or not to produce electricity in each period. In practice, the production of an individual generator is usually tightly distributed around just a few discrete levels, with the most common level near the generator's nameplate capacity—the maximum rated generation level. **APPENDIX WITH SOME OBSERVATIONAL EVIDENCE OF THIS.** To simplify the model, assume that each generator i makes a discrete choice a_{it} of whether or not to generate power in the period. Connected to this decision, each generator must choose what regional wholesale market to sell its electricity in. Let a_{it} come from the set $\{0, 1, \ldots, R\}$, such that $a_{it} = 0$ indicates that generator i does not operate in period t, and $a_{it} = r$ indicates that generator i operates and sells its generation to a distributor in region r at time t. Assume that if a generator chooses to operate, that it always operates at its full capacity such that generator i's production in period t for a distributor in region r, q_{itr}, is

$$q_{itr} = \overline{q}_i \cdot \mathbb{1}(r = a_{it}) \tag{3}$$

where $\overline{q}_i$ is generator i's nameplate capacity and $\mathbb{1}(r = a_{it})$ is an indicator function that evaluates to one when $r = a_{it}$ and zero otherwise. Reinterpreting the generator's operating decision within this production function, $a_{it} = 0$ implies that there is no region r such that $q_{itr} > 0$ and $a_{it} \neq 0$ implies that there is exactly one region r such that $q_{itr} = \overline{q}_i$.

To produce an additional kilowatt-hour of electricity, each generator i incurs a constant regionally dependent marginal cost mc_{ir}. Generator i's marginal cost when operating in region r is

$$mc_{ir} = \rho_i (u_{f_i} + e_{f_i} \tau_r) = \underbrace{\rho_i u_{f_i}}_{\text{Fuel Cost}} + \underbrace{\rho_i e_{f_i} \tau_r}_{\text{Emissions Cost}} \tag{4}$$

where u_{f_i} is the unit cost of fuel f_i in dollars per BTU, e_{f_i} is the greenhouse gas emissions intensity of fuel f_i in tonnes CO_2e per BTU, and τ_r is the tax on greenhouse gas emissions in region r in dollars per tonne CO_2e.[26] This specification of the marginal cost clearly displays the two motivations for heat rate improvements. Investing to reduce the heat rate both lowers fuel costs and lowers the costs incurred through emissions pricing, provided that $\tau_r > 0$.

Given generator i's production process and marginal costs, we can define the period profits of generator i, as

$$\pi_{it} = \sum_{r=1}^{R} q_{itr}(P_{tr} - mc_{ir}) \tag{5}$$

where π_{it} is generator i's profit in period t and P_{tr} is the wholesale price of electricity in region r in period t. Because we have assumed the wholesale market for electricity is perfectly competitive, each generator i takes P_{tr} as given. Then generators can change their profits in period t through their marginal costs (the investment channel) or their generation (the operating channel).

4.3 Equilibrium Behavior in the Generation Phase

Now we turn our attention to the individual behavior of an arbitrary generator and the corresponding aggregate behavior of all generators through equilibria in regional wholesale markets for electricity. In the spirit of backward induction, we proceed by first considering what takes place during the generation phase for given investment decisions and then move to consider equilibrium behavior in the investment phase with the equilibrium generation outcomes known for each level of investment.

[26]This specification follows from the unit conversions:

$$\frac{\$}{\text{kWh}} = \frac{\text{BTU}}{\text{kWh}}\left(\frac{\$}{\text{BTU}} + \frac{\text{CO}_2\text{e}}{\text{BTU}}\frac{\$}{\text{CO}_2\text{e}}\right).$$

Throughout the generation phase, each generator's goal is to maximize its profits in each period.[27] A generator accomplishes this by choosing whether or not to operate in each period, and if it does operate, what regional wholesale electricity market to sell its electricity on. Let a_{it}^* denote the equilibrium operating decision of generator i at time t, where

$$a_{it}^* = \arg\max_{a_{it}} \left\{ \sum_{r=1}^{R} \underbrace{\overline{q}_i \mathbb{1}(r = a_{it})}_{q_{itr}} \underbrace{(P_{tr} - mc_{ir})}_{\pi \text{ per unit}} \right\}. \tag{6}$$

Equation (6) states that the equilibrium operating decision for any generator will maximize profits earned in the current period, using the expanded version of i's period profits from equation (5). Note that this is a deterministic decision function, as we assume wholesale electricity markets operate competitively, such that any individual generator will take P_{tr} as given.

Ultimately, the model is not focused on the equilibrium operating decision for any individual generator, but is instead focused on the equilibrium operating decision of all generators. Let a_t denote the profile (or vector) of operating decisions for all N generators at time t. The equilibrium profile of operating decisions a_t^* contains the individually profit maximizing decisions of each generators given the decisions of all other generators such that $a_t^* = (a_{1t}^*, a_{2t}^*, \ldots, a_{Nt}^*)$. This profile of operating decisions defines an equilibrium in period t of the generation phase. Solving for this equilibrium is difficult in its current form, both analytically and numerically. With N generators, finding the equilibrium in the problem's current formation would require simultaneously solving each of the N optimization problems implied by equation (6), subject to a set of constraints.

[27]Note that this is not usually the case. Typically we would instead make it the goal of each generator to maximize the discounted sum of its future profits in the generation phase. However, in this case, future payoff streams are not dependent on operating decisions in the current period. There is no strategic link between periods in the generation phase, so maximizing the discounted sum of its future profits corresponds with maximizing profits in each period.

To simplify the characterization of the equilibrium profile of operating decisions, we leverage the assumed perfectly competitive nature of the regional wholesale electricity markets. It is a well-known result across economics that, in perfectly competitive markets, the equilibrium that emerges from individual profit maximizing firms corresponds with the cost-minimizing behavior of the entire market. Recall from Chapter 2 that this is the primary appeal of emissions pricing schemes—creating a perfectly competitive market for emissions allowances leads to the cost-minimizing levels of abatement. Though in this context there is the added challenge of transmission constraints across regions, for now, we take it on faith (and some familiar intuition) that the cost-minimizing profile of operating decisions corresponds is the same as a_t^*. By making use of this correspondence, we can optimize over one objective function (total costs) rather than optimizing over N objective functions (generator-level profits).

It follows then that the equilibrium profile of operating decisions in period t is

$$a_t^* = \arg \min_{a_t \in \mathbb{Z}_{R+1}^N} \sum_{i=1}^{N} \sum_{r=1}^{R} mc_{ir} q_{itr}. \tag{7}$$

In this equation, we sum over all the total costs $mc_{ir}q_{itr}$ each generator incurs for generation in any region—yielding the total costs for generation in period t. The notation around the minimization $a_t \in \mathbb{Z}_{R+1}^N$, indicates that the profile of operating decisions comes from an N-dimensional vector space over the integers modulo $R+1$. That is, the all operating profiles take the form $a = (a_1, a_2, \ldots, a_N)$ where $a_i \in \{0, 1, \ldots, R\}$ for all i, 1 to N. This also illustrates that even though each generator has a discrete choice set, the number of potential solutions can easily become quite large, specifically $(R+1)^N$. Beyond this, equation (7) is hardly functional. Note that although the optimization occurs over the set of possible operating profiles, nothing in the total cost function in equation (7) is an explicit function of a_t.

To make the equilibrium objective function optimization operational—such that we can "plug in" the two relevant decision profiles, a_t and j—we opt for a matrix specification of total costs. Let $C(a_t \mid j)$ denote the total generation costs incurred in period t that correspond with the profile of operating decisions a_t given the profile of investment decisions $j = (j_1, j_2, \ldots, j_N)$. The matrix form of the total cost function in equation (7) is the trace of a marginal cost matrix and the transpose of a generation matrix:[28]

$$C(a_t \mid j) = \operatorname{tr}\left[\overbrace{\mathrm{MC}(j)}^{N\times R} \times \overbrace{G(a_t)'}^{R\times N}\right] \tag{8}$$

where $\mathrm{MC}(j)$ is a matrix of the marginal costs such that $\mathrm{MC}(j)_{(i,r)} = mc_{ir}$ and $G(a_t)$ is a matrix of generation decisions such that $G(a_t)_{(i,r)} = q_{itr} = \overline{q}_i \cdot \mathbb{1}(a_{it} = r)$.[29] That is, the total generation costs in period t are given by

$$\operatorname{tr}\left(\begin{bmatrix} mc_{11} & mc_{12} & \cdots & mc_{1R} \\ mc_{21} & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ mc_{N1} & \cdots & \cdots & mc_{NR} \end{bmatrix} \times \begin{bmatrix} \overline{q}_1 \mathbb{1}(a_{1t} = 1) & \overline{q}_1 \mathbb{1}(a_{1t} = 2) & \cdots & \overline{q}_1 \mathbb{1}(a_{1t} = R) \\ \overline{q}_2 \mathbb{1}(a_{2t} = 1) & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ \overline{q}_N \mathbb{1}(a_{Nt} = 1) & \cdots & \cdots & \overline{q}_N \mathbb{1}(a_{Nt} = R) \end{bmatrix}'\right).$$

In the resulting $N \times N$ matrix product, the element in row m and column n is the dot product of generator m's marginal cost vector with generator n's generation vector, or the sum of costs that would result if generator m produced electricity with the marginal costs of generator n. Off diagonal elements in this matrix are not meaningful, but entries along the main diagonal represent the total costs of each generator in period t. The trace of the matrix then sums the period t costs for each generator to give the total costs of all generators.

[28]The trace of a matrix A, denoted $\operatorname{tr}(A)$, is the sum of the entries along the main diagonal of A.

[29]For a matrix A, we denote the element in the ith row and rth column as $A_{(i,r)}$.

Although the marginal cost matrix and the generation matrix in equation (8) are in fact functions of the decision profiles j and a_t respectively, the previous forms are not clear how these decision profiles are translated into the matrices that we use to compute total costs. For clarity, we specify the marginal cost matrix as a function of the investment profile as

$$MC(j) = D_{\rho^0 - j} \times U \tag{9}$$

where ρ^0 is the N-dimensional vector of heat rates in the absence of investment such that the ith element of ρ^0 is $\rho_i^0(1+\tilde{\delta})$, j is the given N-dimensional profile of investment decisions, D_{ρ^0-j} is the $N \times N$ diagonalized matrix that corresponds with the heat rates given by $\rho^0 - j$, and U is the $N \times R$ unit cost matrix such that $U_{(i,r)} = u_{f_i} + e_{f_i}\tau_r$ (the cost per BTU). Similarly, define the generation matrix as the product of the two matrices

$$G(a_t) = D_{\overline{q}} \times \mathbb{1}(a_t) \tag{10}$$

where $\overline{q}$ is the N-dimensional vector of each generator's nameplate capacity and $D_{\overline{q}}$ is the diagonalized matrix that corresponds with $\overline{q}$. In a slight abuse of notation, let $\mathbb{1}(a_t)$ denote the $N \times R$ matrix of operating decisions such that $\mathbb{1}(a_t)_{(i,r)} = \mathbb{1}(a_{it} = r)$. Together, this specification of total costs in period t using the marginal cost and generation matrix make the optimization presented in equation (7) much more functional by allowing us to compute total costs by simply substituting in a_t and j, the two relevant decision vectors at time t.

As alluded to earlier, this optimization comes with several constraints. First and most obvious is the requirement that each of the R wholesale electricity markets must clear. That is, for all $r \in \{1, \ldots, R\}$ at time t

$$\sum_{i=1}^{N} q_{itr} \geq Q_{tr}. \tag{11}$$

That is, the generators must produce at least as much power for each region as demanded by distributors on the wholesale market for electricity. Because generation will always have a positive marginal cost, then this constraint will always hold. The wholesale markets will not produce a surplus of electricity.

Less obvious, but important nonetheless, are the transmission constraints. Empirically, we see that wholesale electricity prices are often close to each other within regions, but quite different between regions. Incorporating regional transmission constraints allows the model to capture these price differences between regions. These transmission constraints are also a salient aspect of the interregional electricity exchanges, and because this model considers how these interregional electricity exchanges lead to the redistribution of local air pollution, they are also a salient aspect of this model. More so than any other part of the model though, modeling the transmission constraints relies on intuition specific to power grid operation. To do so, we use the approach used by Bushnell et al. (2017) and more recently by Fowlie et al. (2021). This approach starts by defining a "swing hub," a reference point for transmission activity. Let the first region $r = 1$ be the swing hub. Between the regions there exist a set of transmission lines $\mathcal{L}$ that allow power to move from one region to another. A transmission line ℓ runs between exactly two region, say a and b, where the order of these regions is not important. For instance, there is not one transmission line that runs from region a to region b and another line that runs from region b to region a, but a single transmission line between a and b. Each line ℓ has a maximum capacity denoted Cap_ℓ measured in kilowatts.

The transmission constraints constrain interregional electricity exchanges by limiting the net electricity exports. Let y_{tr} denote the net electricity exports from region r in period t. All these net exports are relative to the swing hub, region $r = 1$, such that we assume any exports from region $r \neq 1$ eventually flow to region

$r = 1$. For this reason, we do not define y_{tr} for the swing hub. The net electricity exports (also known as marginal power injections) for all $r \neq 1$ in period t are

$$y_{tr} = \underbrace{\left(\sum_{i \in \mathcal{N}_r} \overline{q}_i \cdot \mathbb{1}(a_{it} \neq 0, a_{it} \neq r)\right)}_{\text{Total Exports}} - \underbrace{\left(\sum_{i \notin \mathcal{N}_r} \overline{q}_i \cdot \mathbb{1}(a_{it} = r)\right)}_{\text{Total Imports}}. \tag{12}$$

When a generator produces electricity, the flow of this electricity is governed by the transmission lines it is connected to. This means that interregional electricity exchanges are not fully controlled in the sense that generator i cannot truly produce electricity that will go directly to another region r, but that generator i can produce more electricity which will then allow region r to pull more electricity from the grid generator i is on. These flows are governed by power transfer distribution factors, a constant that measures the change in real power along a transmission line attributable to a marginal power injection in one region. Let $PTDF_{r\ell}$ denote the power transfer distribution factor for region r along transmission line ℓ.

Each transmission constraint is associated with a particular transmission line between two regions. Then each transmission line ℓ in $\mathcal{L}$, faces the constraint

$$-\text{Cap}_\ell \leq \sum_{r=2}^{R} PTDF_{r\ell} \cdot y_{tr} \leq \text{Cap}_\ell. \tag{13}$$

Note that we sum over the changes in real power $PTDF_{r\ell} \cdot y_{tr}$ for all regions except the region of the swing node, $r = 1$. If this sum included the swing hub, then the sum would always evaluate to zero as the sum of net exports across all regions must be zero. Implicitly, this groups all regions into two groups: the region with the swing hub ($r = 1$) and the regions without the swing hub ($r \neq 1$). The constraint makes sure that transmission lines will not be overwhelmed by a large volume of electricity imports or electricity exports by either of these two groups.

With the total cost function in period t defined and the constraints set, we can now fully describe the equilibrium outcomes in period t. In equilibrium,

$$
\begin{aligned}
C^*(j \mid Q_t) = &\min_{a_t} \{C(a_t \mid j)\} \\
\text{s.t.} &\left\{ \begin{array}{l} \displaystyle\sum_{i=1}^{N} q_{itr} \geq Q_{tr}, \forall r \in \{1, \ldots, R\} \\ \displaystyle -\text{Cap}_\ell \leq \sum_{r=2}^{R} PTDF_{r\ell} \cdot y_{tr} \leq \text{Cap}_\ell, \forall \ell \in \mathcal{L} \end{array} \right.
\end{aligned}
\tag{14}
$$

where $C^*(j \mid Q_t)$ denotes the total cost of generation in equilibrium with investment profile j and given the period regional quantities demanded Q_t. Note that the state variable Q_t is fixed, but j is still endogenous. By solving for equilibrium costs in an arbitrary period of the generation phase as just a function of j, we can now directly consider the future costs associated with investment decisions made prior to the first period.

4.4 Equilibrium Behavior in the Investment Phase

Just as we began with the objective of an individual generator in the generation phase, here we begin with the objective of an individual generator in the investment phase. The goal of a generator i in the investment phase is to choose the investment j_i that will maximize its profits over both the investment and generation phases:

$$
j_i^* = \arg\max_{j_i \in \mathcal{J}} \left\{ \underbrace{\left(\sum_{t=0}^{T} \delta^t \pi_i(a_{it}^*, j_i \mid Q_t^e) \right)}_{\substack{\text{Discounted Sum} \\ \text{of Future Profits}}} - \underbrace{\Gamma(j_i, v_i)}_{\substack{\text{Investment} \\ \text{Costs}}} \right\} \tag{15}
$$

Here we assume that generators only consider a finite generation period lasting T periods and use an hourly discount factor $\delta \in (0,1)$. The lifetime profits for a generator are the discounted sum of future profits from generation less the cost of investment.[30] Generator i's profits in any period of the generation stage are a function of both is investment decision j_i and its operating decision a_{it}. However, equation (6) allows us to implicitly write a_{it}^* as a function of the investment decision, so lifetime profits are in effect just a function of j_i.

Again though, we are not particularly interested in the investment decision of just a single generator but the investment decisions of all generators. Previously we leveraged the equivalence of the operating decisions that maximize individual generators' profits and operating decisions that minimize total costs, all in an arbitrary period of the generation phase. This equivalence comes from the perfectly competitive nature of the wholesale electricity markets. To solve for equilibrium behavior in the investment phase, assume analogously that investment is efficient such that the profile of investment decisions will minimize the sum of all (expected) lifetime costs for generators. That is, the equilibrium investment profile j^* is

$$j^* = \arg\min_{j \in \mathcal{J}^N} \Bigg\{ \underbrace{\Gamma(j \mid v)}_{\substack{\text{Investment} \\ \text{Phase Costs}}} + \underbrace{\sum_{t=0}^{T} \delta^t C^*(j \mid Q_t^e)}_{\text{Generation Phase Costs}} \Bigg\} \tag{16}$$

where, in a slight abuse of notation, we let $\Gamma(j \mid v)$ be the sum of investment costs for all generators.[31] This equation describes the equilibrium investment decisions of all generators. Given the efficient investment profile, we can identify the corresponding equilibrium profiles of operating and generation decisions through the arguments that solve equation (14).

[30]Technically this is the expected sum of discounted future profits as the generator still only knows future demand in expectation, but this is a minor detail as we have assumed that all generators will have expectations of regional demand in time t that perfectly match the actual regional demand in time t.

[31]As before, we can use a matrix form for $\Gamma(j \mid v)$ so we can compute the sum directly from the investment profile. Let $\Gamma(j \mid v) = \left(\gamma j^{1/\alpha} + v\right) \cdot \mathbf{1}$, where $j^{1/\alpha}$ is the vector of investment decisions where each element has been raised to the $1/\alpha$ power and v is the vector of investment cost shocks.

4.5 Incorporating Air Pollution & Environmental Inequality

Thus far, the model has focused exclusively on the investment and operating decisions of electric power generators in response to a carbon pricing scheme. In this section, we build on this model to develop a measure we call the *environmental inequality gap*. This measure is analogous to the environmental justice gap in Hernández-Cortés and Meng (2023). To develop this measure, we start by classifying communities as either "disadvantaged" or "non-disadvantaged." Then, using the generation predictions from the previous part of the model, we describe a generic mapping that translates generator-level air pollution into concentrations of air pollutants in nearby communities. The resulting model allows us to connect carbon pricing to disparities in air pollution.

Divide each of the R regions into subregions or communities, such that there are M communities where $M > R$. Each community is labelled as either "disadvantaged" or "non-disadvantaged." This is clearly a crude dichotomization of the many dimensions of inequality, but it is dichotomization that both simplifies the model and allows for an easier application to the data. I discuss in greater detail what criteria qualify a community for disadvantaged-status in a later section. Define an M-dimensional vector d such that $d_m = 1$ if subregion m has the label "disadvantaged" and let $d_m = 0$ otherwise. Each generator belongs to exactly one subregion such that the subregions form a partition on the set of generators. Denote the subregion that generator i belongs to m_i.

Consider an arbitrary air pollutant w. In this context, w could be any air pollutant from a power generator, mostly likely NO_2 or SO_2, but for now we use w to denote a generic air pollutant of interest. Following Weber (2021), assume that heat rate improvements do not affect on emissions of local air pollutants, such that each generator i has a fixed emissions intensity for local air pollutants. Assume generator i releases e_i^w pounds of w per kilowatt-hour. Let w_{it} denote generator

i's emissions of pollutant w in period t. Given the equilibrium generation of i in period t, then i's equilibrium emissions of w in period t is just $w_{it}^{*} = e_i^w q_{it}^{*}$. Equilibrium emissions of w follow directly from equilibrium generation.

The environmental inequality gap does not measure disparities in emissions but disparities in concentrations of local air pollutants. To help translate air pollutant emissions into air pollution concentrations, let $\phi_w(w_{it} \mid i, t)$ be a function that maps the emissions of air pollutant w from generator i at time t to an M-dimensional vector containing the corresponding changes in the concentration of air pollutant w in each of the M subregions, given plant i (its location) and the period t. For now, we remain agnostic about the functional form of ϕ_w. Ideally ϕ_w would be a function defined by a chemical air transport model, which uses meterological data to simulate the trajectories of particle emissions in the atmosphere and the resulting changes in the concentration of air pollutants. However these models are computational in nature more so than functional, and computationally intensive at that.

Let $\Phi_w^1(T)$ denote the average change in the concentration of pollutant w for disadvantaged communities after T periods. We specify this function with the following equation:

$$\Phi_w^1(T) = \underbrace{\left(\frac{1}{d \cdot \mathbf{1}}\right)}_{\frac{1}{\text{\# Disadvantaged}}} \overbrace{d \cdot \underbrace{\sum_{t=1}^{T} \sum_{i=1}^{N} \phi_w(w_{it} \mid i, t)}_{\text{Total } \Delta\phi_w \text{ for all communities}}}^{\text{Total } \Delta\phi_w \text{ for disadvantaged communities}} \tag{17}$$

The far right side of the formula calculates the total change in the concentration of w by summing the contributions to changes in w from all generators in all periods. The result of this summation is an M-dimensional vector of the total change in the concentration of w after T periods in each of the M communities. Taking the dot product of this vector with d, the vector that indicates a community's disadvantaged status, yields the sum of the changes in the concentration of w across all disadvantaged communities. The dot product $d \cdot \mathbf{1}$ evaluates to the number of disadvantaged communities, so dividing the sum of w concentration changes across all disadvantaged communities by the number of disadvantaged communities produces the average change in the w concentration across disadvantaged communities.

Now let $\Phi_W^0(T)$ denote the average change in the concentration of pollutant w for non-disadvantaged subregions after T periods. This uses the analogous specification:

$$\Phi_w^0(T) \;=\; \underbrace{\left(\frac{1}{(\mathbf{1}-d)\cdot\mathbf{1}}\right)}_{\frac{1}{\text{\# Non-disadvantaged}}} \quad \overbrace{(\mathbf{1}-d)\cdot \quad \underbrace{\sum_{t=1}^{T}\sum_{i=1}^{N}\phi_w(w_{it} \mid i,t)}_{\text{Total } \Delta\phi_w \text{ for all subregions}}}^{\text{Total } \Delta\phi_w \text{ for non-disadvantaged subregions}} \tag{18}$$

The only difference between the specification in equation (17) and the specification in equation (18), is that the latter replaces all instances of d with $\mathbf{1}-d$, swapping the indicator to represent non-disadvantaged communities.

The Environmental Inequality Gap, hereafter the EI Gap, is the difference in the average concentration of local air pollutant w in disadvantaged communities and non-disadvantaged communities. Denote the environmental inequality gap for air pollutant w after T periods with $\text{EIGap}_w(T)$. The specification for the EI

Gap follows closely from equations (17) and (18):

$$\text{EIGap}_w(T) = \Phi_w^1(T) - \Phi_w^0(T) \tag{19}$$

$$= \underbrace{\left[\left(\frac{1}{d \cdot \mathbf{1}}\right) d - \left(\frac{1}{(\mathbf{1}-d)\cdot \mathbf{1}}\right)(\mathbf{1}-d)\right]}_{\substack{\text{Subregion weights} \\ M\times 1}} \cdot \underbrace{\sum_{t=1}^{T}\sum_{i=1}^{N} \Phi_w(w_{it} \mid i, t)}_{\substack{\text{Total } \Delta\phi_w \text{ for all subregions} \\ M\times 1}} \tag{20}$$

The factored version of this equation shows that we can write the EI Gap as the dot product of community-level weights and the vector of the total changes in w concentrations.

4.6 Pathways from Carbon Pricing to Environmental Inequality

- Homogenous regulation investment differences: Investment cost disparities $\rightarrow$ heat rate improvement differences $\rightarrow$ marginal cost differences $\rightarrow$ reordering along the supply curve $\rightarrow$ disparities in generation $\rightarrow$ disparities in air pollution $\rightarrow$ EI Gap

- Direct generation effect of regulation: Regulation (τ) differences $\rightarrow$ marginal cost differences $\rightarrow$ reordering along the supply curve $\rightarrow$ disparities in generation $\rightarrow$ disparities in air pollution $\rightarrow$ EI Gap

- Indirect investment effect of regulation: Regulation (τ) differences $\rightarrow$ heat rate improvement differences $\rightarrow$ marginal cost differences $\rightarrow$ reordering along the supply curve $\rightarrow$ disparities in generation $\rightarrow$ disparities in air pollution $\rightarrow$ EI Gap

Cool flow chart made in TikZ with this all laid out and all the equations and that kind of jazz

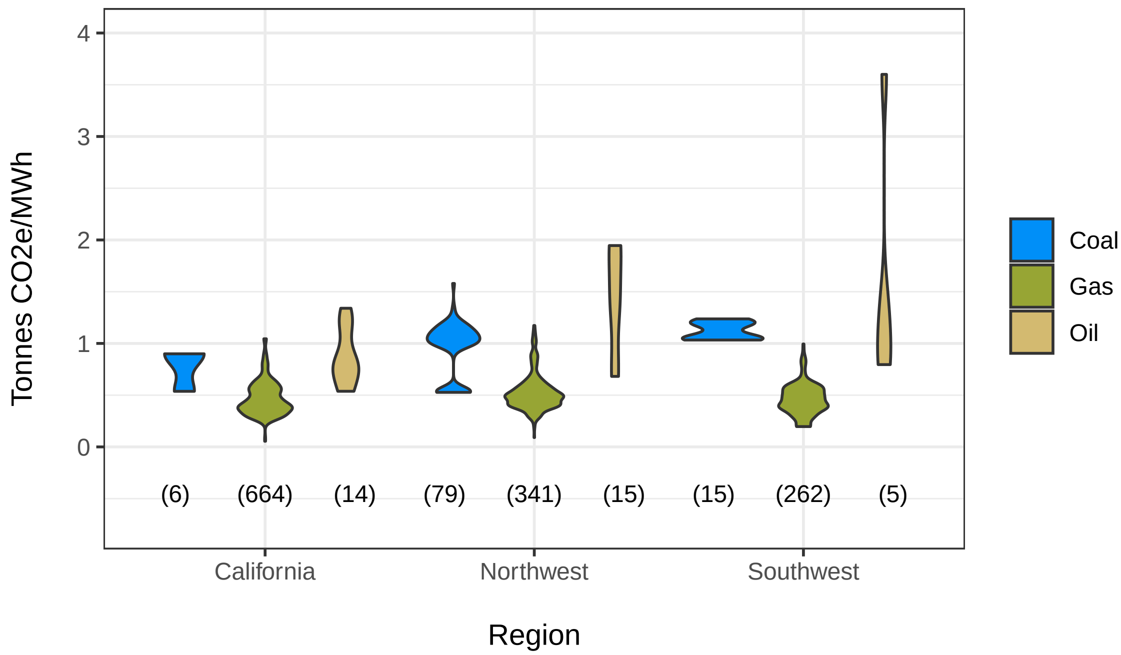
5 Model Application: Electricity & Air Pollution in California

5.1 Data

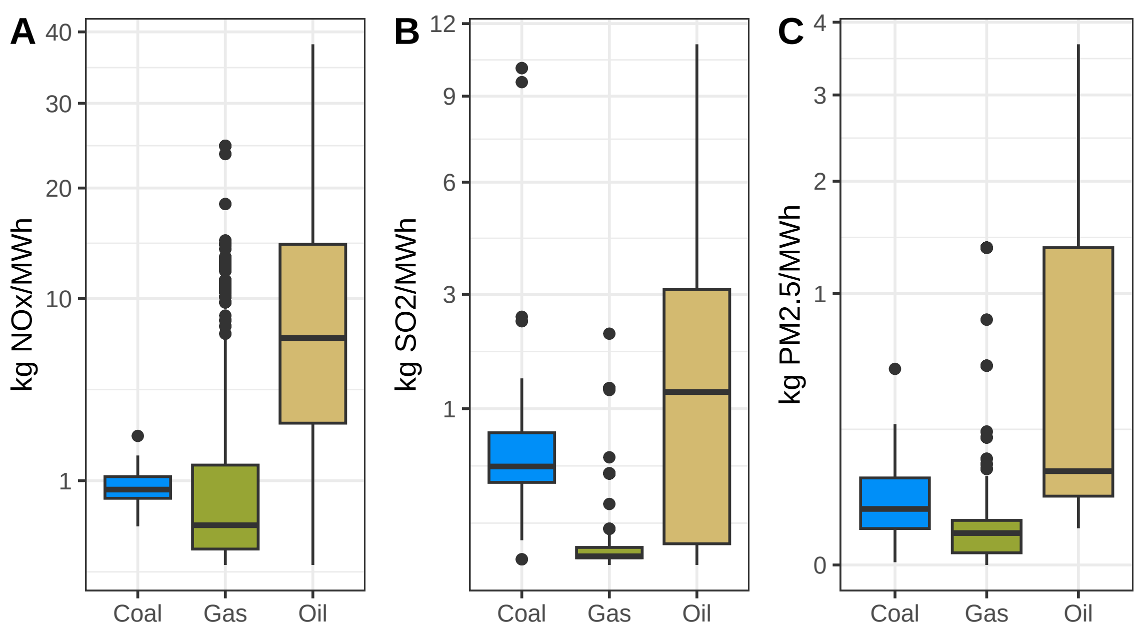
5.2 Empirical Strategy

5.3 Results

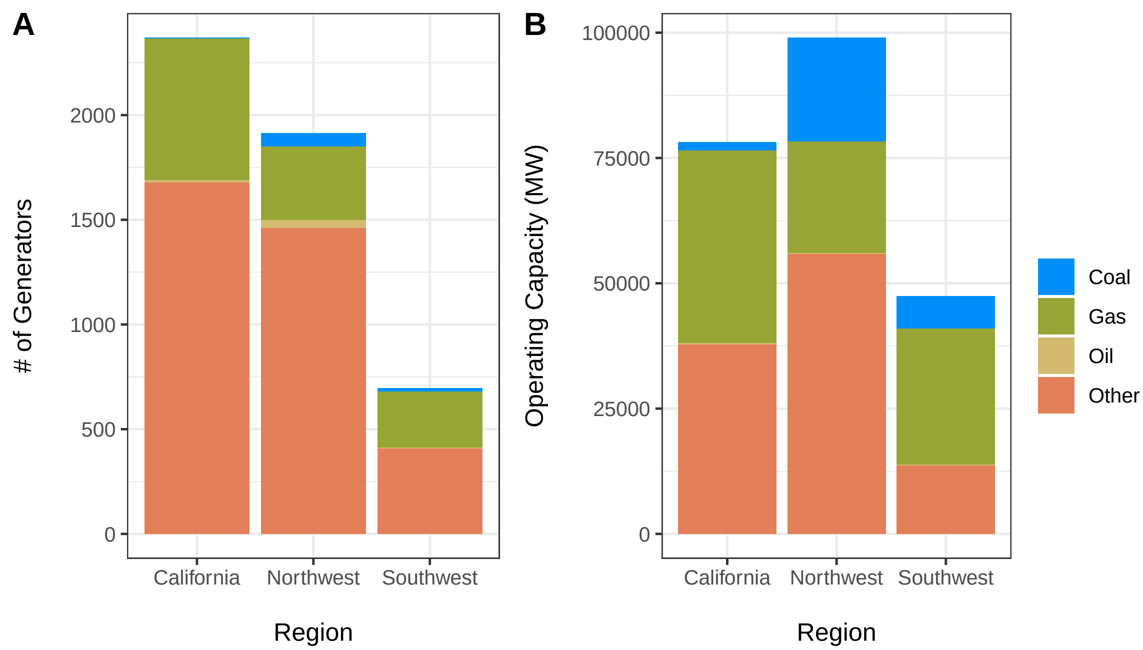
5.4 Diagnostics



Tonnes CO2e/MWh
4
3
2
1
0
(6)
(664)
(14)
(79)
(341)
(15)
(15)
(262)
(5)
California
Northwest
Southwest
Region
Coal
Gas
Oil



A
kg NOx/MWh
40
30
20
10
1
Coal
Gas
Oil
B
kg SO2/MWh
12
9
6
3
1
Coal
Gas
Oil
C
kg PM2.5/MWh
4
3
2
1
0
Coal
Gas
Oil


A
B
# of Generators
Operating Capacity (MW)
2000
1500
1000
500
0
100000
75000
50000
25000
0
California
Northwest
Southwest
Region
Coal
Gas
Oil
Other

Conclusion

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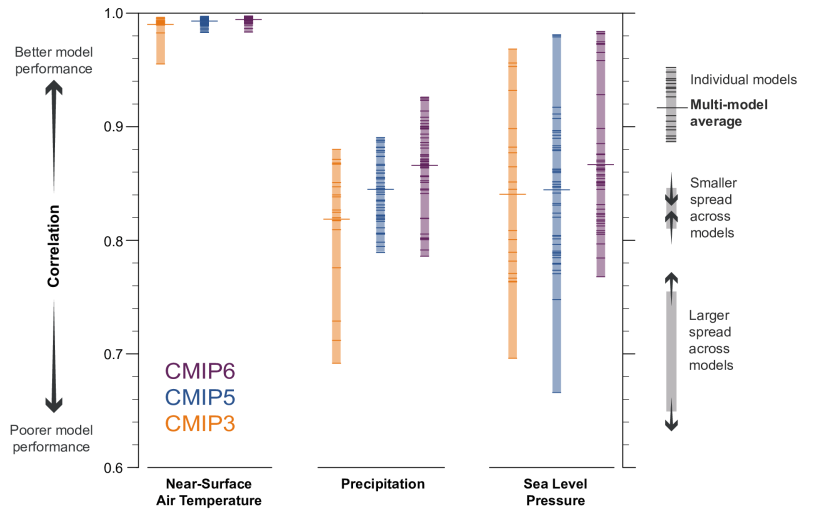
Appendix

A.1 Background an Climate Change & Ambient Air Pollution

Figure 23: Contemporary Climate Models are Highly Accurate



Note: Figure from IPCC (2021a). The figure displays predictions for three common climate variables, near-surface air temperature, precipitation, and sea level pressure, under three different climate models. These three models are the Coupled Model Intercomparison Project Phases 3, 5, and 6. These are the three climate models used in the IPCC's fourth, fifth, and sixth assessment reports. There is no CMIP4 due to re-numbering. The vertical axis is the correlation between the model predicted outcomes the actual, observed outcomes. Clearly these models can predict near-surface air temperatures with near perfect accuracy. Other climate variables, like precipitation and sea levels rise have been more difficult to predict, but are still reasonably accurate. Climate scientists continue to learn more about the physical processes underlying climate, and consequently, these models continue to improve.

A.4 A Model of Emissions Pricing & Environmental Inequality

Table 3: Overview of Notation

Variable	Description	Determined	Source
Indices & Model Environment			
i	Generator identifier	–	–
r	Region identifier	–	–
ℓ	Transmission line identifier	–	–
m	Subregion or community identifier	–	–
N	The number of generators	Exogenous	(1)
$\mathcal{N}$	Set of all generators; $\mathcal{N} = \{1, \ldots, N\}$	Exogenous	(1)
$\mathcal{N}_r$	Set of all generators in region r	Exogenous	(1)
R	The number of regions	Exogenous	(1)
$\mathcal{L}$	Set of all transmission lines	Exogenous	(5)
M	Number of subregions or communities	Exogenous	(3), (4)
T	Final period of the generation phase	Exogenous	Chosen
Investment Phase			
$\mathcal{J}$	Set of all investment options	Exogenous	Chosen
j_i	Generator i's investment decision; $j_i \in \mathcal{J}$	Endogenous	–
j	Investment profile, $j = (j_1, j_2, \ldots, j_N)$	Endogenous	–
ρ_i^0	Generator i's initial heat rate (BTU/kWh)	Exogenous	(1)
ρ_i	Generator i's heat rate (BTU/kwh)	Endogenous	–
$\tilde{\delta}$	Heat rate depreciation rate from the investment phase to the generation phase; $\tilde{\delta} \in (0,1)$	Exogenous	(10)
v_i	Generator i's stochastic investment cost shock; $v_i > 0$ for all $i \in \mathcal{N}$	Exogenous	Chosen
γ	Constant scalar in the investment cost function; $\gamma > 0$	Exogenous	
α	Scale parameter in the investment cost function; $\alpha > 0$	Exogenous	

$\Gamma(j_i, v_i)$	Investment costs for generator i; a function of generator i's investment choice j_i and i' stochastic investment cost shock v_i	Endogenous	–
$\Gamma(j \mid v)$	Total investment costs for all generators; a function of the investment profile j given a vector of all generator's stochastic investment cost shocks v	Endogenous	–
Q_t^e	R-dimensional vector of expected quantities demanded of electricity at time t for each region (kWh)	Exogenous	(2)
Generation Phase			
a_{it}	Operating decision of generator i in period t; $a_{it} \in \{0, 1, \ldots, R\}$ where $a_{it} = r$ indicates that generator i operates in period t to sell its generation in region r and $a_{it} = 0$ indicates that generator i does not operate in period t	Endogenous	–
a_t	Profile of operating decisions in period t; $a_t = (a_{1t}, a_{2t}, \ldots, a_{Nt})$	Endogenous	–
$\overline{q}_i$	Generator i's nameplate capacity (kW); the maximum rated generation of generator i in an hour	Exogenous	(1)
q_{itr}	Generator i's generation to be sold in region r's wholesale electricity market at time t (kWh)	Endogenous	–
f_i	The primary fuel type of generator i; $f_i \in \{\text{Coal}, \text{Natural Gas}, \text{Oil}\}$	Exogenous	(1)
u_{f_i}	Unit cost of generator i's fuel f_i (\$/BTU)	Exogenous	(6), (7), (8)
e_{f_i}	Greenhouse gas emissions intensity of generator i's fuel f_i (tonnes CO_2e/BTU)	Exogenous	
τ_r	Greenhouse gas emissions tax in region r (\$/tonnes CO_2e)	Exogenous	(9)
P_{tr}	Price of electricity in region r's wholesale market at time t	Endogenous	–
Q_{tr}	Quantity of electricity demanded in region r's wholesale market at time t	Exogenous	(2)
$C(a_t \mid j)$	Total cost of generation in period t; a function of the profile if operating decisions a_t given the profile of investment decisions j	Endogenous	–

$MC(j)$	Marginal cost matrix, $N \times R$; a function of the investment profile (vector) j; element in the ith row and rth column is mc_{ir}	Endogenous	–
$G(a_t)$	Generation matrix, $N \times R$; a function of the operating decision profile (vector) a_t; element in the ith row and rth column is q_{itr} or $\overline{q}_i \mathbb{1}(a_{it} = r)$	Endogenous	–
ρ^0	N-dimensional vector of heat rates in the absence of investment; the ith element is $\rho_i^0(1+\tilde{\delta})$	Endogenous	–
$D_{\rho^0 - j}$	Diagonalized $N \times N$ matrix corresponding with the vector $\rho^0 - j$; for elements along the diagonal, the element in the ith row and i column is $\rho_i = \rho_i^0(1+\tilde{\delta}) - j_i$, all elements not along the diagonal are 0	Endogenous	–
U	Unit cost matrix, $N \times R$; the element in the ith row and rth column is generator i's cost in region r per BTU, $u_{f_i} + e_{f_i}\tau_r$	Derived	–
$\overline{q}$	N-dimensional vector of nameplate capacities; $\overline{q} = (\overline{q}_1, \overline{q}_2, \ldots, \overline{q}_N)$	Derived	–
$D_{\overline{q}}$	Diagonalized $N \times N$ matrix corresponding with the vector $\overline{q}$; for elements along the diagonal, the element in the ith row and ith column is $\overline{q}_i$, all elements not along the diagonal are 0	Derived	–
$\mathbb{1}(a_t)$	Operating decisions matrix, $N \times R$; the element in the ith row and rth column is $\mathbb{1}(a_{it} = r)$	Endogenous	–
δ	Hourly discount factor, $\delta \in (0,1)$	Exogenous	(10)
y_{tr}	Net electricity exports for region r at time t; alternatively, understood as a marginal power injection out of region r at time t	Endogenous	–
$PTDF_{r\ell}$	Power transfer distribution factor on transmission line ℓ out of region r	Exogenous	(5)
Cap_ℓ	Maximum capacity of transmission line ℓ (kW)	Exogenous	(5)

The EI Gap

d	M-dimensional vector of communities' disadvantaged status; the mth element is 1 is m is a disadvantaged community and 0 otherwise	Exogenous	(3), (4)
w	Local air pollutant identifier	–	–
e_i^w	Generator i's emissions intensity of air pollutant w (pounds/kWh)	Exogenous	(1)

w_{it}	Generator i's emissions of air pollutant w (lbs)	Endogenous	–
$\phi_w(w_{it} \mid i, t)$	M-dimensional vector of the changes in the concentration of air pollutant w across all M communities resulting from w_{it}, the emissions of air pollutant w from generator i in time t	Endogenous	–
$\Phi_w^1(T)$	Average change in the concentration of pollutant w for disadvantaged communities (elements of d equal to 1) after T periods	Endogenous	–
$\Phi_w^0(T)$	Average change in the concentration of pollutant w for non-disadvantaged communities (elements of d equal to 0) after T periods	Endogenous	–
$\text{EIGap}_w(T)$	The environmental inequality gap after T periods	Endogenous	–

Note: Table summarizes the notation used in Chapter 4. In general, lowercase letters without an index are profiles/vectors, plain-text uppercase letters denote matrices or the size of a set, and uppercase letters in the `mathcal` font are sets (e.g., $\mathcal{N}$). We denote the equilibrium of any variable as the variable with an asterisk. Derived variables are those that are a deterministic function of entirely exogenous variables. The source key for exogenous variables correspond with the data sources in Table 5.

Table 5: Data Sources Key

Source Key	Source Citation
(1)	United States Environmental Protection Agency (EPA). 2021. "Emissions & Generation Resource Integrated Database (eGRID), 2019" Washington, DC: Office of Atmospheric Protection, Clean Air Markets Division. Available from EPA's eGRID web site: https://www.epa.gov/egrid.
(2)	United States Energy Information Administration (EIA). 2023. "Hourly Electric Good Monitor" Region Files. Available at: https://www.eia.gov/electricity/gridmonitor/dashboard/electric_overview/US48/US48
(3)	United States Environmental Protection Agency. 2021 version. EJScreen. Census Tract-Level US Percentiles. Retrieved: 2023-03-03. Available at: https://gaftp.epa.gov/EJSCREEN/2021/

(4)	California Office of Environmental Health & Hazard Assessment (OEHHA). 2022. SB 535 Disadvantaged Communities. Retrieved: 2023-03-03. Available at: https://oehha.ca.gov/calenviroscreen/sb535
(5)	Fowlie, Meredith, Petersen, Claire, and Reguant, Mar. Data and Code for: Border Carbon Adjustments When Carbon Intensity Varies Across Producers: Evidence from California. Nashville, TN: American Economic Association [publisher], 2022. Ann Arbor, MI: Inter-university Consortium for Political and Social Research [distributor], 2021-05-13. https://doi.org/10.3886/E131024V1
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Still missing:

- Investment stuff...