Climate Policy Options

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Abstract

This paper provides an economics perspective on climate policy options that focus in particular on creating incentives to reduce greenhouse gas emissions. Questions are considered about what should be the objectives of climate policy, covering uses of the domestic and global social cost of carbon, and the target consistent approach that focuses on cost effectiveness rather than overall efficiency. The rest of the paper covers the conceptual basis of particular policy instruments with brief mention of real-world examples. There is treatment of the standard instruments of environmental policy with an emphasis on what is new and different with applications to climate change. These include command-and-control approaches, emissions taxes and subsidies, cap-and-trade programs, and comparisons across policies that can influence instrument choice. Further attention is paid to climate policy in an open economy setting, where "leakage" is an issue, and regulators can choose among production, consumption, or trade taxes (and combinations thereof), including the special case of carbon border adjustments. Additional topics include the role of green energy subsidies, performance based standards, and voluntary and information based approaches. Also covered are policy interactions that may arise because of overlapping policies, general equilibrium effects, and concerns about equity and distributional impacts.

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Contents

1 Introduction

Nearly every market activity is directly or indirectly associated with greenhouse gas (GHGs) emissions that accumulate in the atmosphere and contribute to a changing climate. Yet while individual agents fully benefit from the private consequences of their chosen activities, they experience only an infinitesimally small fraction of the damages their emissions cause worldwide, and to future generations. From an economics perspective, the problem of climate change is a problem of market failure. In particular, private market activities are associated with a global externality: the full social cost of emissions is generally not taken into account when individual agents make decisions, and the result is excessive emissions and growing challenges of climate change. Correcting externalities—especially one that arises on a global scale—provides an economic rationale for policy interventions.

The aim of this paper is to provide and overview of climate policy options that work towards this objective. Some boundaries on what to cover are nevertheless necessary given the broad scope of potential topics. The policies covered here are those focused in particular on climate change mitigation, that is, policies that seek to directly reduce GHG emissions. This, of course, immediately excludes a large number of climate policies that are important, including but not limited to those focused on adaptation, finance, industrial policy, innovation, research and development, and international agreements. But one needs to start somewhere, and consistent with the externality motivation in the opening paragraph, the focus here is on policies that seek to internalize at least some portion of the external costs of GHG emissions.

Not surprisingly, the particular policies discussed in this paper also have an economics bent. In other words, they tend to affect incentives rather than imposing direct controls on economic activity. And the discussion will emphasize economic efficiency. This will sometimes mean efficiency in the broad sense of maximizing social net benefits, but it will more frequently mean efficiency in the narrower sense of cost effectiveness. Indeed, an important question to consider when designing and evaluating climate policy is the policy objective itself: is the economic objective to maximize social net benefits, or is it to achieve a given emissions target at the lowest possible cost? Although well-established theories of environmental policy tend to focus on the former objective, a distinguishing feature of climate policy, which is emphasized in what follows, is the frequency with which the latter (and more modest) objective applies.

There are, of course, other criteria upon which to evaluate climate policy, including political feasibility and distributional outcomes. While these perspectives are critically important—and justifiably an increasing focus in climate economics—they are not the primary emphasis here, although the topics are discussed in various places. It is, however, worth mentioning why efficiency itself remains of the upmost importance too. The scale of climate challenges the world faces are immense and growing more severe, but the resources available to address them are limited. Hence there is an increasingly urgent need for policies that address climate change, and that do so in a way that is efficient and cost effective. Quite simply, the challenges are too big and important to promote measures that waste resources.

Recognizing there are topics missing in what follows, some intentional and some surely not, let us briefly consider what the paper actually does cover. Without providing anything close to a comprehensive literature review, the paper seeks to provide an overview of what might be termed the standard economics "toolkit" of climate policies. They are standard in the sense that literature exists to study them because of desirable properties, that they have attracted attention because of frequent or large scale implementation in the real world, or both.

Before turning to particular policy instruments, however, Section 2 provides some high-level perspectives on the aims of climate policy. Some of the issues arise because of the way that sovereign nations not only set domestic policy, they face a global collective action problem of nothing less than maintaining a stable planetary climate. This raises questions about whether countries should seek to internalize the global damages of climate change, or perhaps only the domestic damages that affect them. Topics covered include efficient shadow pricing and different geopolitical scopes of the social cost of carbon (SCC). These approaches to setting and evaluating climate policy are then contrasted with the alternative of a target consistent approach, where the policy objective is taken as given, and the job of an economist shifts from evaluating overall efficiency to evaluating cost effectiveness.

Subsequent sections focus on particular climate policy instruments. Section 3 begins with the proverbial straw man of command-and-control regulations. The aim is to show how the information requirements for a regulator to deploy this approach cost effectively are exceedingly difficult to satisfy. Section 4 pivots to the pricing instruments of emissions taxes and subsidies. Although the advantages of these instruments compared to command and control are well-established, the discussion emphasizes the unique challenges and opportunities when applied to climate change. Section 5 develops the basic theory of cap-and-trade programs, where the standard framework is generalized a bit to allow some degree over which carbon offsets can count towards compliance. Section 6 considers the question of how uncertainty affects when a regulator might prefer taxing emissions or establishing a cap-and-trade program. This is the classic question of prices *vs* quantities, although the discussion adds a novel result about how the analysis applies not only to expectationally efficient policies, but even more generally to those that are expectationally equivalent with respect to emissions.

Section 7 considers topics that arise in an open economy setting. This includes leakage, whereby policies to reduce emissions in one region have the side effect of increasing emissions elsewhere. There is also discussion of equivalence between between optimal policy packages that simultaneously include two of the three instruments among production taxes, consumption taxes, and trade taxes. The framework enables straightforward analysis of a carbon border adjustment mechanism, which is a topic of increasing interest among researchers and policymakers alike. Finally, there is discussion of how the open economy setting provides a unilateral welfare rationale for green subsidies, which are typically considered only a second-best policy instrument.

The next two sections focus on climate policy instruments that are of interest primarily because of traction they have obtained in real world settings. Section 8 covers production and investment subsidies in the renewable energy sector, with a discussion about when one approach might be preferred over the other, along with empirical evidence. Section 9 provides a basic theory of performance based standards, which may include credit trading, followed by examples of their application in a variety of climate policy settings, including electricity sector emissions rates, renewable portfolio standards, low carbon fuel standards, and vehicle fuel economy standards.

Section 10 provides a discussion of policy interactions that may arise because of overlapping policies, general equilibrium effects, and multiple objectives, including distributional and equity concerns. As the number of climate policies continue to grow and overlap, it is important to understand circumstances where policies can be mutually reinforcing or in conflict. What is more, climate policies that are big enough to have a meaningful impact are likely to affect a range of interacting markets and therefore require general equilibrium analysis to promote a complete understanding. And while economics has a long tradition of separating efficiency and distributional concerns when it comes to the design and evaluation of policy, recent changes in policy and guidance for official benefit-cost analysis, at least in the United States, are pushing economists to do more and opening new frontiers of analysis.

The final set of policies covered are those collectively referred to as voluntary and information based approaches. These policies seek to provide more complete information so that markets can adjust more efficiency and opportunities can emerge for voluntary actions to address climate change. The particular approaches discussed are information disclosure strategies, voluntary programs that offer certification or membership for meeting specific climate standards, and the strategic use of information to nudge behavior in ways that tap into social and psychological mechanisms. Finally, there is a brief discussion on the importance of understanding whether voluntary and information based approaches should serve a complements or substitutes for more centralized forms of climate policy.

Section 12 concludes with some final observations about how the economics of climate policy raises new challenges and opportunities that are not already central to environmental economics. The section also includes some modest predictions about promising directions for future research.

2 Climate policy objectives

What should be the normative aim of climate policy? Even among economists, and at a theoretical level, this basic question generates different answers and controversy. This section illustrates different perspectives within a simple graphical framework. Distinctions are made between the optimal shadow price of emissions, the social cost of carbon (SCC), with global versus domestic perspectives, and a target consistent approach to valuing emission reductions for purposes of setting and evaluating climate policy.

2.1 Efficient shadow pricing

We begin with the most basic way to motivate the theory of environmental policy applied to climate change. To keep things simple, while focusing on the key ideas,

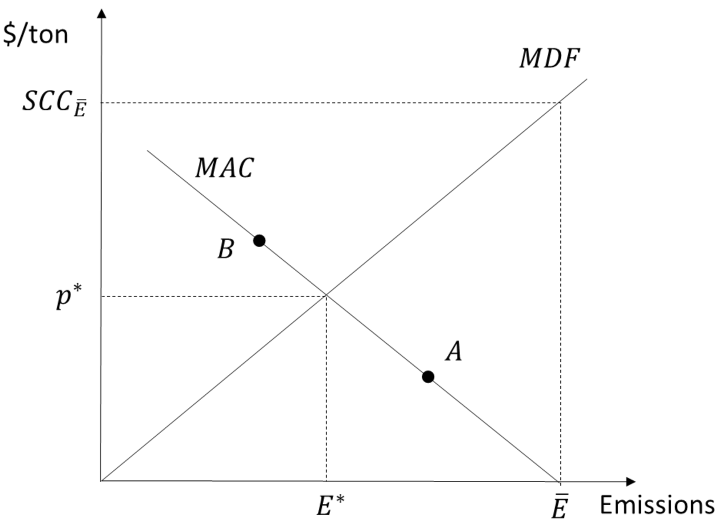

Figure 1: Comparison of the efficient carbon price, the global social cost of carbon, and different target consistent prices

consider the problem of climate change in a static setting. The horizontal axis of Figure 1 represents global GHG emissions, and $\bar{E}$ denotes the business as usual (BAU) level of emissions, that is, the level that would occur in the absence of a policy intervention. The curve labeled MAC represents the marginal abatement costs of reducing emissions below $\bar{E}$ (the next section derives the MAC more formally). The curve labeled MDF represents the social marginal damage function of emissions. The marginal damages are global, monetized, and assumed in the figure to be increasing.

The standard efficiency objective of environmental policy is to find ways to set the level of emissions to equate the marginal damages with the marginal abatement costs, which occurs at E^*. At this level, P^* represents the nonmarket shadow price of emissions. As we will see, different policy instruments can be used to internalize P^* and therefore implement E^* as the equilibrium level of emissions. But should E^* be the objective of climate policy? It clearly would be in the hypothetical world of a global planner that seeks to maximize global efficiency. However, motivations for, and discussions about, climate policy often take place from a different perspective, and we will see how alternative viewpoints relate to the standard framework just described.

2.2 The social cost of carbon

The SCC is a fundamental concept in climate economics. It represents the marginal damages of emitting an additional ton of carbon dioxide (CO_2), or the CO_2 equivalent of another GHG. The SCC is an "ambitious" parameter, as it seeks to capture the marginal external costs of emissions over all future time and all space across the planet. Integrated assessment models (IAMs) are typically used to produce estimates of the SCC (Tol 2023), though an expanding literature provides sector-specific estimates using observed data and econometric techniques (Rhode et al. 2021; Rhode et al. 2022; Carlton et al. 2022; Hultgren et al. 2022). The most recent estimate of the SCC for official use by the U.S. Environmental Protection Agency is \$190 per metric ton in 2020, and increasing to \$230 by 2030 (US EPA 2023). This estimate closely matches that in (Rennert et al. 2023), though a wide range of estimates can be found in recent reviews of the literature (Tol 2023; Moore et al. 2024).

Abstracting from the complexity of IAMs, we can ask how the SCC compares to the optimal shadow price of P^* in Figure 1? The distinction between the two concepts becomes clear when one recognizes that the SCC represents the marginal damages at a given baseline level of emissions. With use of IAMs, the baseline is often an assumption of BAU emissions now and into the future. Econometric approaches are also estimated on the observed BAU baseline. In Figure 1, the SCC therefore represents the shadow cost of emissions at the baseline of $\bar{E}$, shown as $SCC_{\bar{E}}$. It follows that with an increasing MDF, we have $P^* < SCC_{\bar{E}}$ because the later corresponds with a higher level of emissions, that is, $E^* < \bar{E}$.

Does the distinction matter empirically? Surprisingly few IAMs are able to produce estimates of both the optimal carbon price and the SCC, because they are typically built to estimate the marginal damages of emissions or the marginal costs of abatement, and not both. One exception is the DICE model developed over decades by William Nordhaus. In the most recent iteration, Barrage and Nordhaus (2023) report values of P^*, which is equivalent to the optimal carbon price, of \$50, \$59, and \$125 for the years 2020, 2030, and 2050, respectively. In contrast, their comparable estimates of the $SCC_{\bar{E}}$ are higher at \$66, \$78, and \$175. Beyond reinforcing the qualitative pattern in Figure 1, the important takeaway of these numbers is recognition that the optimal carbon price and the SCC are not in general the same, and this is often a point of confusion in the literature and in policy discussions. But as can be seen in Figure 1, they will be equal in the special cases where BAU is the efficient level of emissions, or where the MDF is constant, at least over the relevant domain.

What then is the use of the SCC, if it differs from the optimal shadow price? The answer is for benefit-cost analysis (BCA). Consider a policy that would reduce CO_2 emissions at a cost of $\$x$ per ton, and ask whether the benefits of the policy would exceed the costs? Assuming the policy is marginal relative to global emissions (or alternatively that the MDF is constant over the range of the emissions reduction), one need only compare the SCC to $\$x$. The global benefits of avoided climate damages exceed the policy costs if the SCC is greater than $\$x$. Indeed, this is precisely how the U.S. federal government currently uses the SCC for evaluating climate policy, along with many subnational levels of government and a handful of other countries, including Canada and Mexico. It is also how the SCC is used routinely among researchers in the academic literature to evaluate changes in emissions associated with climate policy.

2.3 The global *vs* domestic SCC

The conduct of BCA always requires a delineation between whose benefits and costs should count and whose should not. Typically, the jurisdiction of the regulatory agency for which the analysis is conducted determines the geographic scope of analysis. For example, a municipality considering investments in a local park will be concerned with the benefits and costs to those within its jurisdiction. The same logic does not apply, however, to conventional use of the SCC for evaluating climate policy.

Let's return to our example of a policy that would reduce GHG emissions at a cost of $\$x$ per ton. Assume the policy takes place in the United States. Standard practice for BCA is to compare this *domestic* cost per ton to the *global* SCC. Note how there is a mismatch between the geopolitical scope of the cost-benefit comparison: domestic costs to global benefits. Hence it is of both intellectual interest and policy relevance for us to examine this mismatch more carefully and to recognize how it is rationalized.

The fundamental issue can be understood with a simple prisoner's dilemma. Consider a setting with two identical countries that experience damages of $\alpha > 0$ per ton of emissions. This we can define as the domestic SCC. The global SCC with two identical countries is 2α. We can then ask, what marginal damages of emissions is individually rational for a country to internalize? The answer with this simple setup is of course α—the domestic SCC. The classic free-rider problem arises because both countries would be better off if they each internalized the global SCC of 2α. Put another way, it is individually rational for a country to only take account of its own MDF rather than the global MDF shown in Figure 1, with the result being less stringent climate policy due to under-provision of the global public good. One could of course also sketch the domestic MDF in Figure 1, as a downward shift (vertical subtraction), and show the domestic SCC, along with the domestically calibrated optimal level of emissions and shadow price.

How then does the United States, and other jurisdictions, rationalize use of global SCC as a normative benchmark for climate policy? There are at least two arguments that can be understood as potential ways out of the prisoner's dilemma. The first is that managing climate change is a repeated game, and the second is that international relations induce an element of reciprocity in how countries set their own climate policy. In these cases, it can be shown that a country's decision to internalize the global SCC can be individually rational (Kotchen 2018). Although this topic is occasionally discussed in the literature, it does receive the attention is deserves (Sunstein 2024). There appears to be an implicit assumption that countries should adopt cooperative behavior, because otherwise there appears to be is no way to solve the problem of global climate change.

The question of whether to use the global or domestic SCC is a topic that nevertheless generates controversy. There are legal questions that arise beyond the economic concerns (Gayer and Viscusi 2016; Howard and Schwartz 2019). Moreover, the official approach in the United States has flipped back and forth between the Obama, Trump, and Biden administrations (going from global to domestic and back to global), with significant consequences for how changes in GHG emissions are valued in federal policies. As of this writing, the U.S. approach is one that recognizes the importance of reciprocity on issues that affect global public goods, while emphasizing the importance of transparency and reporting results separately for global and domestic impacts (US OMB 2023; Sunstein 2024).

2.4 The target consistent approach

An alternative way to set the objectives of climate policy focuses on cost effectiveness rather than overall efficiency (Aldy et al. 2010). What has been referred to as the target consistent approach (TCA) begins with an intended target for reducing emissions, where the target is not necessarily chosen based on an efficiency criterion. An example is the internationally agreed upon target of keeping global average temperatures less the 2 degrees Celsius above preindustrial levels. This translates into an emissions reduction target that, while perhaps considered critical from a scientific perspective, is not necessarily the result of balancing benefits and costs. Other examples occur at the level of national, subnational, and private governance. Governments at many levels around the world have commitments to reduce emissions by specific amounts and dates, and many of these commitments are part of country-level Nationally Determined Contributions (NDCs) for emissions reductions within the framework of the Paris Climate Agreement.

The next part of a TCA is to model the minimized marginal costs on a path toward meeting the target. The result is a MAC curve that alone determines carbon prices for evaluating climate policy, and these prices are used in place of the SCC. The basic idea can be illustrated is a static framework with reference back to Figure 1. Consider a target that happens to be set at E^*. In this case, which also happens to be the efficient target, the marginal abatement costs are P^*. The TCA would use this price per ton to evaluate cost effectiveness of policies until the target is meet. A more lax target would set emissions to the right of E^* and have a lower price (consistent with point A), whereas a more stringent target to the left of E^* would have a higher price (consistent with point B). Kaufman et al. (2020) provide illustrative estimates. Assuming emissions pathways to net zero for the United States that would be accomplished in different years, 2040, 2050, or 2060, they find target consistent prices of \$93, \$52, and \$32, respectively, with lower prices reflecting the less ambitious target date. Given the corresponding targets, these estimates are intended to imply that policies with a cost per ton less than these amounts would be cost effective to implement.

It is important to emphasize how the TCA no longer entails a comparison of benefits and costs, but rather focuses on ensuring implementation of cost effective policies towards achieving a designated goal. The United Kingdom uses the TCA for evaluation of climate policy, which stands in contrast the U.S. approach based on the SCC (Aldy et al. 2021a). Economists have employed different arguments in support of the TCA, including alignment with international objectives, ethics, and uncertainty (Kaufman et al. 2020; Stern and Stiglitz 2021; Stern et al. 2020), and the approach is embedded in the way the Intergovernmental Panel on

Climate Change (IPCC) uses IAMs to inform climate policy. One might also interpret Weitzman's (2009, 2010) "dismal theorem"—whereby a fat-tailed distribution over climate damages blunts the ability for BCA to inform decision-making—as an argument in support of the TCA. Others nevertheless caution against abandoning efficiency when it comes to setting climate policy objectives (Aldy et al. 2021b), in large part because without an objective normative criterion, political expedience can unduly sway the targets of the TCA.

3 Command and control

This section begins a transition to discussion of actual policy instruments, starting with the command-and-control (CAC) approach to regulation. The CAC approach is somewhat of a "straw man" against which to compare more efficient approaches to climate policy. The first step, however, is to consider abatement costs a bit more formally.

3.1 Abatement costs

Consider a setting with $i = 1, ..., n$ sources of emissions e_i. All are subject to the same regulatory authority. Each source benefits from emissions according to $b_i(e_i)$, measured in monetary units, where $b_i(0) = 0$, $b_i^{'} > 0$, and $b_i^{''} < 0$. The unregulated level of emissions at each source satisfies $b_i^{'}(\bar{e}_i) = 0$, and aggregate emissions without regulation are $\bar{E} = \sum_{i=1}^{n} \bar{e}_i$. This level of emissions corresponds with the unregulated, BAU level of emissions $\bar{E}$ in Figure 1. Reducing emissions through abatement a_i means foregone benefits, and abatement costs can be written as $c_i(a_i) = b_i(\bar{e}_i) - b_i(\bar{e}_i - a_i)$ for any level of abatement $0 \leq a_i \leq \bar{e}_i$. It follows that $c_i(0) = 0$, $c_i^{'} > 0$, and $c_i^{''} > 0$ for all i.

Let us now define the minimum costs for achieving any aggregate level of abatement A:

$$C(A) = \left\{ \min_{\{a_i\}_{i=1}^{n}} \sum_{i=1}^{n} c_i(a_i) : A = \sum_{i=1}^{n} a_i \right\}. \tag{1}$$

A consequence of this definition is that minimizing the cost of reaching any level of abatement (or equivalently a level of emissions $E = \bar{E} - A$) requires $c_i^{'}(a_i) = c_j^{'}(a_j)$ for all $a_i, a_j > 0$. In other words, the marginal abatement costs must be equalized across all sources with positive levels of abatement. What is more, the aggregate marginal abatement costs are equal to the individual marginal abatement costs such that $C^{'}(A) = c_i^{'}(a_i)$ for all $a_i > 0$. The function $C^{'}(A)$ is simply a more formal statement of the MAC curve illustrated in Figure 1.

3.2 Direct regulation

Now consider a regulator that seeks to reduce emissions to some level below $\bar{E}$, and this requires a level of aggregate abatement $A > 0$. Using a CAC approach, we can ask, how should the regulator assign required abatement levels across the different entities? One seemingly reasonably possibility is that a_i should be set equally across all i. Another is that abatement levels should be proportional to baseline emissions $\bar{e}_i$. In fact, there are an infinite number of possibilities, assuming there is more than one emitter. But there is only one distribution of abatement levels that achieves the overall objective at the least cost, and it is the one that satisfies equation (1).

Using direct regulation and minimizing compliance costs is nevertheless exceedingly difficult to achieve in practice because of the information requirements. The regulator would need to know the abatement cost function for all i sources of emissions, yet obtaining such information is challenging and unlikely to occur in a complete and unbiased way, due to information asymmetries and incentive compatibility issues with truthful reporting. The difficulty of having enough information to implement direct regulation in a cost effective way is one reason why economists tend to disfavor CAC approaches. The concern applies regardless of whether the level of aggregate abatement is set to maximize overall efficiency or some other criterion, though with efficiency additional information is needed about the marginal damages of emissions, that is, the MDF in Figure 1.

Two additional question are worth considering at this point. First, are there policy instruments that can implement least-cost abatement without having complete information? The short answer is yes, as we will begin to see in the next section. Second, although economists often take it for granted, it is worth pausing for a moment to ask, why should we care so much about cost minimization? There are certainly other objectives of climate policy that people might care about, including different notations of equity, which might, for example, include forcing larger emitters pay more. But even in these cases the cost minimizing approach is a useful benchmark. As mentioned in the paper's introduction, resources are limited for addressing the growing challenges of climate change, so we should be cautious about pursuing GHG emissions reductions at higher costs than necessary. Moreover, to the extent that distributional concerns can be addressed separately through redistribution policy, all objectives can be accomplished to an even greater extent with cost minimization. For example, rather than forcing a large emitter with high marginal abatement costs to reduce emissions, a small emitter with lower marginal abatement costs can do it and receive a compensation payment from the high emitter. The result in this case will be lower costs of abatement and the potential for both emitters to be better off, that is, a Pareto improvement. Indeed, this is precisely the mechanism at work in cap-and-trade programs, as we will see in Section 5.

A final observation is that CAC approaches in practice are typically not as prescriptive as just described, although discussion of a regulator choosing abatement levels for all emitters is a useful way to illustrate the key ideas. Alternative CAC approaches might require firms to adopt a specific technology or to comply with a specified emissions rate, variants of which are discussed in Section 9. But the same general critique applies even in these cases. With a technology requirement, firms are not afforded the flexibility to choose their own way of reducing emissions, which in all likelihood would be lower cost. And emission rates applied uniformly across firms does not leverage the possibility that some firms can reduce emissions at a lower cost than others. Emission rates combined with tradable credits, however, does help somewhat, as will be discussed in Section 9.

4 Emissions taxes and subsides

We now turn to instruments of climate policy that directly target prices. These include emissions taxes, also referred to a carbon taxes, and subsidies. The discussion of subsidies will cover some of the potential benefits and challenges of carbon offsets, and the perverse incentives of inefficient fossil fuel subsidies.

4.1 Carbon taxes

When economists hear the word externality, it is almost a knee-jerk reaction to immediately recommend a Pigouvian tax. In the standard introductory setting, a Pigouvian tax is levied on a good in the amount equal the marginal external costs at the efficient quantity. The consequent internalization of the externality implements the efficient quantity of exchange as an equilibrium, and by assumption the tax revenue is returned lump sum. The standard way of modeling an emissions tax follows much the same logic if we think of emissions as an input for which there is demand and an associated externality. The reason for clarifying this point is that Pigouvian taxes are typically applied to a good, the production or consumption of which generates the externality, possibly through emissions. But emissions taxes are levied on the source of the externality itself, rather than indirectly on a good. One advantage of targeting the tax on emissions, rather than on the associated good, is that emissions taxes create incentives to find ways for reducing emissions beyond reducing exchange of the good itself.

Consider a carbon tax τ per unit of emissions, which we assume can be measured at each of the i emission sources. Let's remain agnostic for the moment about whether the tax is intended to maximize overall efficiency or is set at some other level, noting that only the former corresponds precisely with a Pigouvian tax. Each emitting entity will choose e_i to maximize $b_i(e_i) - \tau e_i$, with the first-order condition $b_i^{'}(e_i) = \tau$ defining emissions as a function of the tax. In effect, $b_i^{'}(e_i)$ is an inverse demand function for emissions, where τ is the price. We can equivalently write each entity's cost minimization problem as choosing a_i to minimize $c_i(a_i) + \tau(\bar{e}_i - a_i)$, with the first-order condition $c_i^{'}(a_i) = \tau$. This defines the function $a_i(\tau)$ that is effectively each entity's supply function for abatement.

Aggregate abatement for a given tax is then $A(\tau) = \sum_{i=1}^{n} a_i(\tau)$, and it follows that $c_i^{'}(a_i(\tau)) = c_j^{'}(a_j(\tau))$ for all i and j. Hence the level of abatement is increasing in the level of the tax, and referring back to the conditions implied by the definition of $C(A)$ in (1), we find that aggregate abatement at any level of τ is implemented at the minimum cost. What is more, and important, the regulator need not know anything about the cost curves of each emitting entity.

There are nevertheless limitations. Without knowing anything about the aggregate abatement cost function, a regulator will have little sense about how much abatement will occur at a given tax rate. Thus far we have also said nothing about the regulator's objective function. Information about abatement costs is clearly needed if the aim is to use a carbon tax to meet some emissions reduction target. And if the objective is to set the target efficiently, additional information is needed about the marginal damages of emissions (i.e., the *MDF*), which as discussed previously could be calibrated to global or domestic damages.

Another important feature of carbon taxes is their potential to raise revenue. With our simple setup, the tax revenue is equal to $\tau\left(\bar{E} - A(\tau)\right)$ and assumed to be returned lump sum. Estimates of the revenue from carbon taxes are large because of the broad base upon which they can be levied. In the United States, for example, a meta-analysis of 11 different energy and economy models finds that carbon taxes of \$25 and \$50 per ton would generate revenue of roughly \$103 and \$170 billion per year (Barron et al. 2018). Some have argued that the potential for raising revenue can make carbon taxes an attractive policy option (Bistline et al. 2025), whereas others point out that the comparison between tax revenue and welfare gains can affect political feasibility (Kotchen 2025). Surveys suggest that how revenue is spent can have a significant affect on public support, showing greater support for carbon taxes when revenue is used to subsidize clean energy and to make direct transfers to those most adversely affected by climate change or the tax burden (Kotchen et al. 2017; Klennert et al. 2018; Dechezlepretre et al. 2022). To the extent that raising large amounts of revenue is a concern, nonlinear taxes are also possible, which can include exemptions over a range of emissions and for specific sectors. Such modifications to the tax policy can lower revenue while still creating the same incentives to reduce emissions.

The World Bank (2024a) maintains a comprehensive and updated list of carbon tax policies around the world, including those at the national and subnational levels. Nearly 30 countries currently have some form of a carbon tax in place, covering an estimated 6 percent of global emissions. The prices per ton range widely, from less than \$1 in Ukraine to \$167 in Uruguay. Countries with carbon taxes over \$60 per ton are Ireland, Netherlands, Finland, Norway, Sweden, and Switzerland. Across these and others, however, there is a wide range in the share of GHG emissions covered. A review of studies that evaluate the impacts of implemented carbon taxes can be found in Metcalf (2021) and Timilsina (2022), although given the emphasis that economists place on carbon taxes, this is an area in need of more research.

4.2 Subsidies and carbon offsets

Now consider an abatement subsidy s that is paid to each polluting entity for every ton of emissions reductions below $\bar{e}_i$. We can again think of each polluting entity's decision problem in two ways. The first is to chose emissions to maximize benefits

$b_i(e_i) + s(\bar{e}_i - e_i)$. The second is to chose abatement to minimize costs $c_i(a_i) - sa_i$. Focusing on the later, the first-order condition, $c_i^{'}(a_i) = s$, defines abatement as a function of the subsidy, $a_i(s)$. It is immediately clear that the solution for all i is the same as that for the tax when $s = \tau$. Hence, like the emissions tax, an abatement subsidy can reduce aggregate emissions at the minimum abatement costs.

The potential for Coasian bargaining provides an intuitive way to understand why an abatement subsidy and an emissions tax, with $s = \tau$, induces the same equilibrium. Coase's (1960) fundamental insight is that bargaining between parties can result in the efficient resolution of an externality if property rights are well-established and there are zero transaction costs. Implementing a tax or subsidy effectively satisfies both conditions. Property rights are established by delineating who pays (the emitters or the public), and the level of the tax or subsidy eliminates transaction costs associated with how much to pay (i.e., there is no need to bargain). If the tax or subsidy is set at the efficient level, then both instruments will implement the efficient equilibrium. Although Coasian bargaining is typically invoked in cases where policy interventions are unnecessary to resolve externalities (Deryugina et al. 2021), we can see here that the same logic applies to the symmetry between emissions taxes and abatement subsides. Distributional implications are the primary difference between the two instruments, as the assignment of property rights determines whether emitters must pay or get paid.

There are other differences between emissions taxes and abatement subsidies. The payment of subsidies requires raising revenue through other means, likely taxes, and these can be distortionary. The analysis of subsidies might therefore need to account for the marginal cost of public funds. The two instruments can also differ in the long run because of differential effects on entry and exit. Another important way the policies differ is the information required for implementation. The tax applies to emissions, which we have assumed is observable. In contrast, the subsidy applies to emissions reductions, and implementation requires observation not only e_i, but also $\bar{e}_i$ for all i.

There are nevertheless difficulties identifying the baseline because it is inherently an unobservable counterfactual, and this contributes to the "additionality" problem in markets for carbon offsets, which are effectively abatement subsidies. Recent studies in the energy and forestry sectors highlight how additionality is a growing concern (Calel et al. 2024; West et al. 2023). Full additionality would occur if none of the emissions reductions below $\bar{e}_i$ would occur for entity i without the subsidy payment. But upon observing e_i, there is asymmetric information about what $\bar{e}_i$ would have been, and truthful reporting about baselines is generally not incentive compatible.

4.2.1 Baselines and additionality

There is something that can be done to help allay concerns about additionality. By adjusting the baseline, a regulator can decrease the subsidy cost per ton and stretch a fixed budget to induce greater emissions reductions. Assume the subsidy per ton must remain constant, the regulator does not observe $\bar{e}_i$, but can choose a baseline to which the subsidy applies, denoted $\tilde{e}_i$. Regardless of what baseline the regulator chooses, conditional on accepting the subsidy s, the emitter will chose a level of emissions $e_i(s) = \bar{e}_i - a_i(s)$. The question is then, how low can the baseline be set to still induce uptake? The answer is the lowest $\tilde{e}_i$ that satisfies $s(\tilde{e}_i - e_i(s)) \geq b(\bar{e}_i) - b_i(e_i(s))$. That is, the total subsidy payment must be greater than the foregone private benefit of reducing emissions optimally conditional on uptake, and the solution will be some baseline greater than $e_i(s)$ and less than $\bar{e}_i$.

While lowering the baseline is appealing and potentially useful, it is unfortunately not a "free pass" for eliminating non-additionality or extracting all rents, as accomplishing both requires knowing $\bar{e}_i$ and the marginal abatement cost curve. Another approach to help address additionality that has gained traction in practice, particularly with international forest offsets, is to assign group-level baselines (van Benthem and Kerr 2013). This is an application of group-level approaches to environmental policy that have been employed in a range of other settings (Kotchen and Segerson 2019, 2020).

4.2.2 Accounting for transfers

That a portion of subsidy payments are likely to represent a transfer from the government's budget to the emitting entities raises an additional topic about how to evaluate efficiency or cost effectiveness. When evaluating subsidy programs, it is typical for analysts to estimate the subsidy cost per ton of emissions reductions. While that is how the subsidy is set in the simple model here, subsidies in practice often target actions that subsequently affect emissions. Examples include subsidies for home weatherization to improve efficiency, the installation of heat pumps or solar panels, and the purchase of electric vehicles.

When evaluation of such programs entails estimates of a subsidy cost per ton, whether or not the transfer portion of the subsidy should be included in the ratio depends on the question the analysis intends to answer. If the benchmark is efficiency, whereby the subsidy cost per ton is compared to an estimate of the SCC, then the relevant comparison is the cost per ton *net* of the transfer—that is, the transfer portion of the subsidy should not be included as part of the cost. If, however, the analysis is intended to inform cost effectiveness—as would be the case for a government seeking to maximize emissions reductions with a given budget—then the transfer portion of the subsidy payment should be included in the subsidy cost per ton ratio. But in this case, the ratio should be used to make comparisons across potential subsidy alternatives, rather than be compared to the SCC. Finally, an alternative approach that nests both comparisons is to evaluate subsidy programs based on the marginal value of public funds (MVPF) (Hahn et al. 2024). The MVPF for a particular policy is the ratio of beneficiaries' willingness to pay for the policy to the net cost to the government. In this case, transfers are included in both the numerator and denominator, so MVPF ratios greater than unity pass a benefit-cost test, and the magnitude of ratios can be used to compare cost effectiveness.

4.3 Fossil fuel subsidies

The elimination of fossil fuel subsidies warrants consideration as a climate policy option because of their global scale and the way they are precisely counter productive to the emissions taxes and abatement subsidies just discussed. They lower the price of emitting GHGs and make it more difficult for clean energy substitutes to compete. Back in 2009, the Group of 20 (G-20) nations, comprising the largest developed and developing countries, agreed to the phase-out of inefficient fossil fuel subsides (G-20 Leaders 2009). While the commitment has been repeated in multiple international fora every year since, there has been very little (if any) progress. The International Energy Agency (IEA 2023) estimates explicit, global fossil fuel subsidies at nearly $1.1 trillion in 2022, almost double the estimate in 2010.

The International Monetary Fund (IMF) has advanced an influential research program to broaden thinking about about fossil fuel subsides. The IMF work begins with the distinction between explicit and implicit subsidies. Explicit subsides are the familiar notion of a subsidy, based on fiscal costs that lower prices. The IEA estimates just mentioned are an example. In contrast, implicit subsidies arise because of the absence of efficient pricing, which gives rise to social costs not reflected in the market for fossil fuels. The IMF has drawn attention to implicit subsidies, and one way to think about them is a Coasian reframing of missing Pigouvian taxes: if the public has a property right to an emissions-free environment, than the absence of efficient pricing is an implicit subsidy to the fossil fuel sector. The IMF considers externalities associated with climate change, local air pollution, and road use, along with foregone tax revenue. The most recent estimates put the total fossil fuel subsidies at roughly $7 trillion in 2022, equivalent to about 7 percent of global GDP (Black et al. 2023), and implicit subsidies due to climate damages account for 30 percent of this amount, assuming a global SCC of $60 per ton.

To promote progress on phasing-out fossil fuel subsides, arguments are made about the importance of considering the distributional consequences (Rentschler and Bazilian 2017) and instituting mechanisms for monitoring and review (Aldy 2015). Political economy also plays a role: the fossil fuel sector has a lot at stake and wields significant political influence. Expanding on the IMF approach, Kotchen (2021) illustrates the importance of considering the incidence of implicit fossil fuel subsidies. In particular, the producer incidence indicates how much the fossil fuel sector stands to lose with the phase-out of implicit subsidies. In 2018, for example, the direct benefit to fossil fuel producers in the United States was estimated at $62 billion (Kotchen 2021), helping to explain lobbying on the part of fossil fuel suppliers and one reason why reform is difficult.

5 Cap-and-trade programs

The cap-and-trade mechanism is a central instrument of environmental policy. Dales (1968) is given credit for first developing the idea. The academic literature on cap-and-trade is expansive, and the approach to reducing emissions has take hold in practice. The United States has a history of using cap-and-trade to regulate air pollution under the Clean Air Act. There are cap-and-trade programs to regulate CO_2 emissions in California and among states in the northeastern United States. The largest program is the European Union's Emissions Trading System (EU ETS), accounting for 2.6 percent of global GHG emissions. While China's emissions trading system is sometimes referred to as a cap-and-trade, it is actually a tradable performance standard, which will be discussed in Section 9. The World Bank (2024a) dashboard on carbon pricing around the world provides details on all cap-and-trade programs, and the accompanying report includes additional country-specific information (World Bank 2024b).

5.1 The basic mechanism

Consider a regulator that seeks to limit aggregate emissions at level $\hat{E}$. The cap-and-trade mechanism begins with issuance of tradable emissions permits totaling this amount, which we assume is a binding constraint. There is the question of how the permits are initially allocated, and assume for the moment they are auctioned off to the n emitting entities. Assume further that an auction mechanism is employed such that the resulting price, denoted p, exactly clears the market for permits. Before turning to the price that emerges, consider the optimization problem of each emitting entity for a given p. Each entity chooses its level of emissions to maximize $b_i(e_i) - pe_i$, with the the first-order condition, $b_i^{'}(e_i) = p$, defining demand for emissions, $e_i(p)$. Notice how this problem has an identical structure to that for the emissions tax, with the only difference being replacement of τ with p. Aggregate demand for emissions, for a given p, can be written as $E(p) = \sum_{i=1}^{n} e_i(p)$. The market clearing price must then satisfy $\hat{E} = E(\hat{p})$. Assuming an interior solution for all emitting entities, it follows that $\hat{p} = b_i^{'}(\hat{e}_i) = c_i^{'}(\hat{a}_i)$ for all i. Hence, referring again back to the implications of (1), we find that the cap-and-trade mechanism implements the cost minimizing solution for reducing emissions down to the regulator's chosen level. Importantly, this solution is obtained without the regulator having any information about marginal abatement costs. This is similar to the result we found for the emissions tax, but now the regulator is choosing a quantity of emissions at $\hat{E}$ rather than a price on emissions at τ.

Let us now revisit the initial allocation mechanism with an alternative. The "grandfathering" of permits occurs when they are allocated based on some predetermined, entity-specific characteristics, such as previous levels of emissions. Although the precise way that permits are grandfathered can create inefficient incentives in a dynamic setting, it has long been established that grandfathering and auctioning have the same efficiency consequences in the short-run, assuming no other market failures (Montgomery 1974). To see why, let $\check{e}_i$ denote any initial allocation to entity i where it continues to hold that $\hat{E} = \sum_{i=1}^{n} \check{e}_i$. For a given permit price, each entity chooses emissions to maximize $b_i(e_i) - p(e_i - \check{e}_i)$, and the first-order condition is identical to that shown previously. Hence the conditions identifying an equilibrium—all i first-order conditions and the market clearing condition—remain unchanged.

This establishes an important result about cap-and-trade programs: they implement emission reductions at least cost, and the result does not depend on how permits are initially allocated. The result does, however, rely on the assumption that b_i does not depend on the allocation of allowances, and that all i are price takers in the permit market. Numerous papers in the literature have considered various implications of market power, with an early and influential contribution by Hahn (1984).

It is nevertheless important to recognize that the allocation mechanism does have distributional consequences, as it effectively assigns valuable property rights. With the auction mechanism, no entity has the right to pollute, so they all must purchase permits for each unit of emissions. In contrast, with grandfathering of freely allocated permits, entities are given a property right for emissions, and each unit has value $\hat{p}$. Clearly an entity would prefer to have a free allocation, or a higher $\check{e}_i$, where it can sell any excess permits. Accordingly, with the static basic setup and through the allocation of permits, cap-and-trade programs are able to separate efficiency and distributional concerns, and this has a potential advantage when it comes to political economy. The use of grandfathering is more widely adopted in practice compared to auctions, presumably because regulators can build political support through concessions to influential stakeholders, adversely impacted entities, or both. When accounting for dynamic settings, however, allocation mechanisms can induce strategic behavior that is distortionary, and this should be taken into account as part of program design (Harstad and Eskeland 2010).

We have thus far been silent about how the regular chooses the emissions cap $\hat{E}$. The mechanism will be cost effective for any chosen target. But additional information is required if the regulator seeks to set the target with an efficiency goal in mind. Recall that the efficient level of emissions E^* is shown in Figure 1 at the intersection of the MAC and MDF curves. Information about both curves is necessary to set an efficient emissions cap, and with respect to climate change, there is also the question of which MDF a regulator might seek to internalize (e.g., global or domestic damages).

A further nuance that can affect the efficiency of cap-and-trade programs in general is whether the pollutant is uniformly mixing or whether the marginal damages differ by the source of emissions. GHG emissions ultimately have the same impact on climate change regardless of where they are emitted, but the same does not apply for local pollutants. With local pollutants, the cap-and-trade approach may be subject to “hot spots”—i.e., locations where emissions are more highly concentrated—that can affect overall efficiency of the instrument, in addition to it distributional consequences.

5.2 Empirical research

There is a literature focused on program evaluation of cap-and-trade programs. Schmalensee and Stavins (2017) and Haites et al. (2018) provide reviews. Studies have evaluated various aspects of the European Union ETS that was adopted in 2003 and covers about half of EU CO_2 emissions in 31 countries. Others examine California’s cap-and-trade system (AB-32) that began in 2013 and covers all electricity generating units and large scale manufacturing, and the Regional Greenhouse Gas Initiative (RGGI) that focuses on emissions of the electric power sector in northeastern states of the United States. Finally, while hotspots are not a concern for cap-and-trade programs focused on CO_2 emissions—at least with respect to the regulated pollutant—studies have begun to examine the distributional consequences of changes in the levels and distribution of co-pollutants that have local effects on public health (Hernandez-Cortes and Meng 2023; Sheriff 2024).

5.3 The allowance of offsets

Many cap-and-trade programs for reducing GHG emissions have provisions that allow emitting entities to use offsets in place of permits for compliance. Examples include the Clean Development Mechanism (CDM) as part of the EU ETS, and the Compliance Offset portion of California’s cap-and-trade program. Allowing offsets is not without controversy, however. Advocates argue in favor of lower costs of compliance, whereas detractors question whether offsets actually deliver equivalent emission reductions, pointing to concerns about additionality, impermanence, uncertainty, and measurement.

We can see the basic issues at play with a simple graphical illustration. Figure 2 includes an aggregate marginal abatement cost curve, MAC as previously discussed, with the unregulated level of emissions at $\bar{E}$. Without the use of offsets for compliance, a cap on emissions $\hat{E}$ induces the market clearing price of permits at $\hat{p}$. Total abatement costs are given by the area $\bar{E}\hat{E}A$.

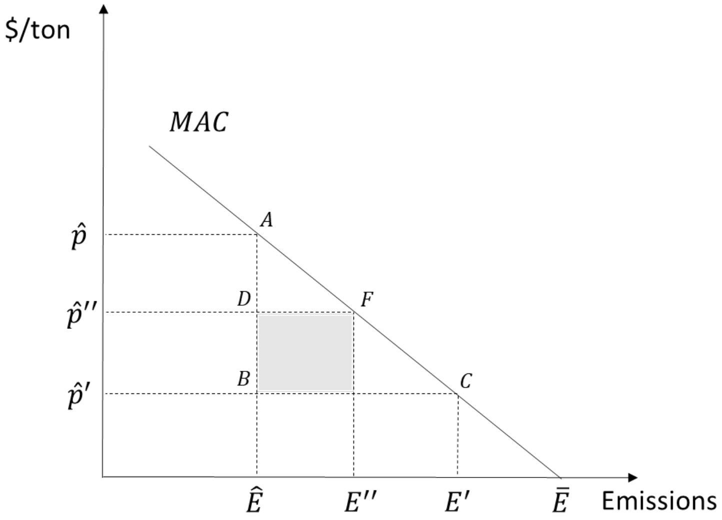

Figure 2: Total abatement costs with a cap-and-trade program and the possibility of using offsets for compliance

Now consider what happens if offsets are allowed for compliance in place of permits. Assume offsets are available at constant marginal cost $c_o > 0$. Begin with the case where there is no limit to the number offsets that can be used. The maximum willingness to pay for an offset is $\hat{p}$, and the MAC to the right of $\hat{E}$ represents the demand for offsets. Emissions in the regulated sector will increase up to E', where the marginal willingness to pay for offsets equals their marginal cost, and the permit price decreases to $\hat{p}^{'} = c_o$. In principle, the increase in emissions in the regulated sector, $\hat{E}$ to $E^{'}$, is offset by an equal amount of emissions reductions in the offset sector. A further consequence is the total abatement costs decline to area $\bar{E}\hat{E}BC$. In practice, however, cap-and-trade programs limit the amount of offsets that can be used for compliance. With a binding constraint, the market clearing permit price $\hat{p}''$ will remain higher than c_o, and assuming rents denoted by the shaded areas accrue to the offset providers, total abatement costs will be area $\bar{E}\hat{E}DF$, which is lower than without the offset option but greater than with unlimited offsets. This is the argument is favor of allowing offsets: the same emissions reduction target can be achieved at a lower cost.

Two other observations are worth making. First, if offsets are available, each permit has less value. This may be important because it lowers the potential revenue a regulator can raise through the auctioning of permits. Second, and important, there are concerns about the validity of offsets, which have been questioned in both the CDM and California's program (Calel et al., 2024; Stapp et al. 2023). In the extreme case where offsets are fully "hot air," emissions will increase by the full amount of offset purchases. But interestingly, even if offsets are not perfect, they can still play a role if we have an estimate of their success probability η. A regulator can make adjustments based on the expected tons. The key ratio is $1/\eta$ so that if, for example, the offset has a success probability of $\eta = .5$, it takes two offsets to count towards a single permit. As a consequence, the price of an offset effectively doubles (and appropriately so), which means that the permit price would not be as low, emissions in the regulated sector would not increase by as much, and the total abatement costs would be higher, though more realistic. Recent work on the social value of offsets (Groom and Venmans 2023) can help provide guidance on potential success probabilities.

6 Prices *vs* quantities

Should climate policy take the form of an emissions tax or a cap-and-trade program? Arguments often center on political feasibility, seeking to advance whichever instrument is more likely for actual implementation. But there are cases where one policy can be more economically efficient than the other, and when they are equivalent. We have already seen a circumstance where they are equivalent. The previous sections show how setting a cap on emissions at $\hat{E}$ is associated with a permit price of $\hat{p}$, and the same level of emissions would arise if instead an emission tax were set at $\tau = \hat{p}$. Both instruments also generate the same revenue assuming the permits are auctioned rather than freely allocated. The two instruments can nevertheless differ when taking account of uncertainty.

6.1 Weitzman's central result

Let us begin with Wetizman's (1974) seminal analysis, framed as prices *vs* quantities. The regulator seeks to maximize overall welfare and must choose between and emissions tax or a cap-and-trade, where each is set optimally in expectation. The tax sets the emissions price with certainty, whereas the cap-and-trade sets the emissions quantity with certainty. There is uncertainty about the marginal abatement costs, perhaps because of asymmetric information, and the question is which instrument can take better account of the different possible outcomes.

Clear and direct results emerge with assumed linearity of the MAC and MDF curves, as shown in Figure 1. In this setting, it is helpful (and with no consequence) to redefine the MAC as the marginal benefit of emissions. Noting that $E = \bar{E} - A$, we can write the expected marginal benefits of emissions as $MB(E) = \varphi - \kappa E$, and the realized marginal benefits are $MB(E) \pm \delta$, where δ captures the uncertainty. In the high-benefit state of the world, the marginal benefit shifts up by δ, which we assume occurs with probability .5, and in the low-benefit state of the world, it shifts down by δ with probability .5. The marginal damages of emissions are given by $MD = \phi + \gamma E$, which are known with certainty. Although unrealistic, this assumption is justified in the basic setup because of a welfare invariance between policy instruments with uncertainty about marginal damages, which does not (on its own) affect the level of pollution with either the tax or cap. Indeed, Weitzman (1974) pays little attention to uncertainty about the marginal damages of emissions because it "affects price and quantity modes equally adversely" (p. 485).

The central result of Weitzman (1974) is that when choosing each instrument optimally ex ante, the welfare advantage of the tax compared to the cap is

$$\Delta^{\tau} = \frac{\delta^2(\kappa - \gamma)}{2\kappa^2}. \tag{2}$$

This expression is based on a comparison between the expected, deadweight loss of each instrument, assuming the uncertainty is not large enough to cause corner solutions. It makes clear that taxes and caps deliver equivalent welfare in the absence of uncertainty ($\delta = 0$), or if the slopes of the marginal benefit and damage functions are the same ($\kappa = \gamma$). More generally, the preferred instrument depends on the relative slopes of the marginal benefit and damage functions. The tax is preferred, for example, if the marginal damage function is flatter than the marginal benefit function, that is, if $\kappa - \gamma > 0$.

There are many ways to gain intuition for the result in equation (2), though perhaps the simplest is to focus on the the slope of the marginal damages. If marginal damages are nearly constant ($\gamma \to 0$), an emissions tax can set nearly the right incentive regardless of the marginal benefits of emissions. If, however, the marginal damages are very step ($\gamma \to \infty$), the efficient quantity of emissions is relatively constant, so a cap that ensures this result is preferred to a tax. Figure 3 illustrates a case where the tax is preferred, as the expected deadweight loss with the tax (the

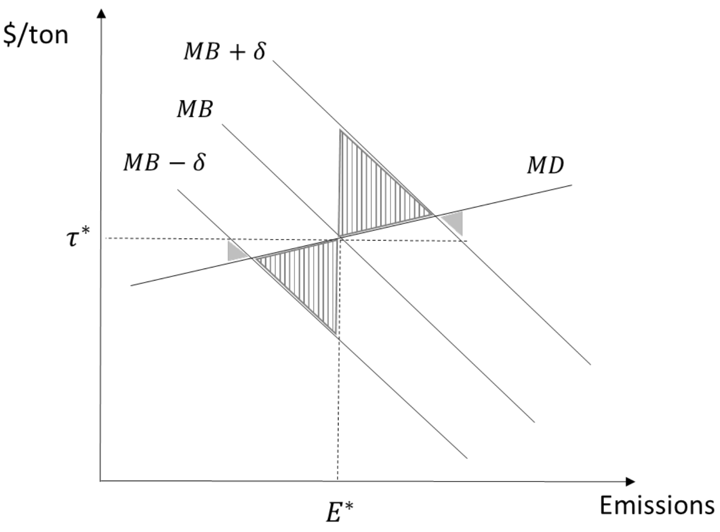

Figure 3: Example of the Weitzman result favoring an emissions tax over a cap-and-trade program

sum of the shaded areas) is smaller than that for the cap (the sum of the hashed areas).

When applied to climate change, many have argued that the framework favors taxes. The argument is based on the way that GHGs are a stock (rather than flow) pollutant, and hence marginal damages are relatively less responsive than marginal abatement costs to changes in emissions over what is considered the policy-relevant range and duration (Metcalf 2023). Others have nevertheless argued recently in favor of cap-and-trade programs, based on extensions of the setup that accounts for technology and pollution shocks that are persistent over time (Karp and Traeger 2024).

6.2 Extensions and hybrid approaches

Weitzman's analysis has given rise to an expansive literature that investigates whether or not the basic result holds up with modifications to the original setup. Although not the focus of their paper, Pizer and Prest (2020) provide a nice review of the literature. Some papers explore how regulators can seek better information from firms to address information asymmetries. Other papers examine different forms of uncertainty, including correlated uncertainty between marginal benefits and damages, market power, non-linearities, and how the choice of policy instrument affects other outcomes. Pizer and Prest (2020) also contribute to a literature that considers Weitzman-type results with policy updating in a multi-period setting. They categorize papers on this topic by the way they differentially account for uncertainty, intertemporal trading of permits, policy updating, and welfare analysis.

The framework has also given rise a number of papers that examine the design of hybrid instruments. For cap-and-trade programs, these include price containment mechanisms that may, for example, include a price ceiling on allowances or an additional reserve that can be released if permit prices get too high (Roberts and Spence 1976; Pizer 2002; Newell et al. 2005; Murray et al. 2009). It turns out that in practice, most cap-and-trade programs include some form of a price containment mechanism to help alleviate political concerns about significant price uncertainty (Brooks and Keohane 2020). In many cases, however, allowance prices that are too low, meaning the cap is less binding, is a greater concern than ones that are too high (Burtraw and Keyes 2018). More recently, research and specific policy proposals have focused on ways to employ emissions taxes with additional mechanisms to reduce uncertainty about the associated level of emissions (Aldy 2017; Hafstead and Williams 2020; Metcalf 2020). An example, consistent with the design of Switzerland's carbon tax, is a case where the tax rate is designed to increase over time, but the rate of increase is faster if emissions reductions fall short of intended annual targets.

6.3 A generalization

The Weitzman result in equation (2) captures the expected welfare benefit (or cost) of an emissions tax compared to an emissions cap-and-trade when both instruments are chosen optimally ex ante. That is, both instruments are chosen at levels that maximize the expected welfare gain. But what if the instruments are not chosen with the objective of maximizing efficiency? We have considered in this paper how the efficiency criterion is not always the objective of climate policy. It turns out that the result in equation (2) is even more general and can inform policy instrument choice under a broader set of circumstances: it shows the welfare advantage of the tax for any pair of price-quantity instruments where both are set to implement the same level of emissions in expectation. While a potentially useful result in the context of climate policy, it is one that appears to have not been shown in the

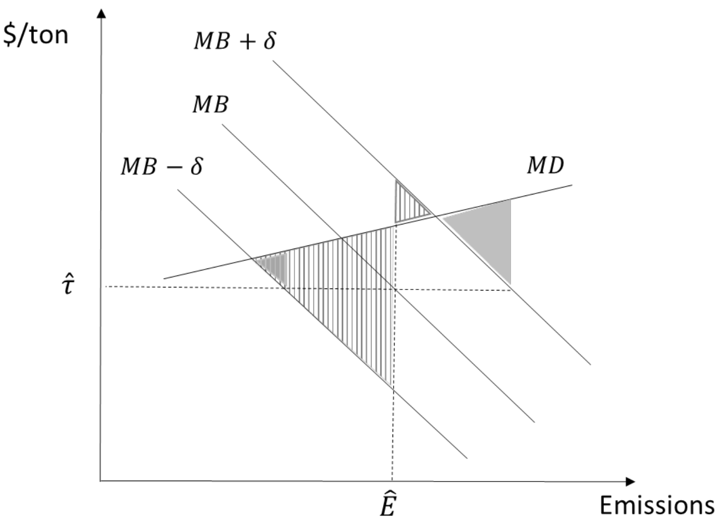

Figure 4: Generalization of the prices *vs* quantities result to emissions equivalent instruments in expectation, which need not be efficient in expectation

existing literature.

Figure 4 provides a graphical illustration. Recall that the tax and cap in Figure 3 where selected optimally in expectation, that is, the levels of each policy satisfy $MB(E^*) = MD(E^*) = \tau^*$. In contrast, the policy levels in Figure 4 need only satisfy the same level of emissions in expectation, that is, $MB(\hat{E}) = \hat{\tau}$. All other assumptions of the setup remain the same. The sum of the shaded areas still represents the expected deadweight loss with the tax, and the sum of the hashed areas still represents the expected deadweight loss with the cap. Here again, with the same curves, we find that the expected deadweight loss is lower with the tax. In fact, a few lines of algebra comparing the magnitudes will show that the welfare advantage of the tax is precisely equation (2). What is more, assuming the deadweight loss triangles do not hit a corner, the result holds when comparing any pair of policies with the same level of emissions in expectation. Figure 4 shows just a single example, where the policies are less stringent than the ex ante efficient levels.

We find, therefore, that the prices *vs* quantities logic can inform policy instrument choice in what might be a more realistic setting for climate policy: when the primary objective is to reach what can be an arbitrarily set emissions target, the preferred instrument still depends on the relative slopes of the marginal damages and benefits of emissions. And it does so in precisely the same way as the standard result.

7 Climate policy in an open economy

Let us now turn to climate policy in an open economy setting. The perspective is important at a high level because of the way GHG emissions create a global externality, and economies are linked through trade. This gives rise to several topics covered here. The first is "leakage," which occurs when policies to reduce emissions in one region (or sector) have the side effect of increasing emissions elsewhere. The second is how climate policy can include a broad set of potential tax policy instruments, including production, consumption, and trade taxes. Third is how carbon border adjustments are a special case of trade taxes. The final set of observations relate to the different role green subsidies can play in open and closed economies.

7.1 Basic setup

The model used here is a simplified version of that in Kotchen and Maggi (2024), and it is closely related to the basic setup in Weisbach et al. (2023). Begin with the closed economy to establish a baseline. There are two final goods sectors: A is energy, and B is a numeraire. The numeraire is produced one-for-one with labor, which is in fixed supply. In this simple setup, energy is assumed to come from only one source that generates GHG emissions (the possibility for zero-emissions energy is discussed below). Energy is produced with a specific factor and labor, with constant returns to scale. Let y denote the production of energy, which causes marginal damages $\alpha > 0$, with a climate externality denoted $D = \alpha y$. We can think of energy as measured in units of its CO_2 emissions, in which case α is the domestic social cost of carbon. Preferences are quasilinear of the form $U(c^A) + c^B - D$, where $U^{'} > 0$, $U^{''} < 0$, and c^j is consumption of good $j = A, B$.

Now consider demand, supply, and the market clearing condition for energy at price p. Demand, denoted $d(p)$, is defined implicitly from $U^{'}(c^A) = p$. Consumer surplus is $CS(p)$, and it follows that $\frac{dCS(p)}{dp} = -d(p)$. On the supply side, total returns to the energy sector will depend only on p and the fixed wage $w = 1$. We can therefore write these returns as $\pi(p)$ and interpret the expression as producer surplus. The supply of energy can be written as $y(p) = \frac{d\pi}{dp}$, where the equality follows by Hotelling's lemma. Finally, market clearing requires $d(p) = y(p)$.

We begin with climate policy in the form of a production tax t on energy. As noted previously, there can be an equivalence between price and quantity instruments, so much of what follows can be translated into other forms of climate policy (e.g., a cap-and-trade program with auctioned permits), although the discussion focuses on taxes. Letting p and q denote consumer and producer prices, respectively, we have the price wedge $q = p - t$, and market clearing must satisfy $d(p) = y(p - t)$. Solving the welfare maximization problem—a special case of maximizing equation (3) below—one finds the intuitive solution of $t = \alpha$ in a closed economy. This is simply the benchmark Pigouvian tax.

7.2 A unilateral tax with leakage

Now assume there are two countries, Home and Foreign, and both have economies structured as just described. There is trade in energy with no trade costs. To illustrate the basic ideas, let's focus on Home's unilaterally optimal policies, assuming Foreign is passive with no policies of its own in place. The welfare of Home can be defined as aggregate indirect utility: $CS + \pi + R - D$, where R is government revenue, and we can ignore labor income because it is fixed. Letting ρ denote the world price of energy, Home's welfare function can be written as

$$W = CS(p) + \pi(q) + R - \alpha \left[y(q) + y^{*}(\rho) \right], \tag{3}$$

where $R = ty(q)$ is the production tax revenue, and asterisks are used to denote Foreign, so y^{*} is Foreign's production of energy, which depends on the world price. Note that the externality Home experiences depends on energy production in both countries, and we have assumed Home cares only about its own domestic SCC. Home's problem is to choose t to maximize W, where the market clearing condition is now $d(p) + d^{*}(\rho) = y(q) + y^{*}(\rho)$ with $p = \rho$ and $q = p - t$.

The first-order condition for the solution to Home's problem can be written as

$$\frac{\partial W}{\partial t} = -m \frac{\partial p}{\partial t} + (t - \alpha)\, y^{'} \frac{\partial q}{\partial t} - \alpha y^{*'} \frac{\partial p}{\partial t} = 0, \tag{4}$$

where $m = d - y$ denotes Home's imports or exports of energy, and the primes denote derivatives. Totally differentiating the market clearing condition, we can substitute out the price changes and solve for Home's unilaterally optimal production tax:

$$t = \alpha - \frac{m + \alpha y^{*'}}{y^{*'} - d^{*'} - d'}. \tag{5}$$

It is immediately clear that without trade ($m = 0$) and no Foreign supply response ($y^{*'} = 0$), the solution is $t = \alpha$, which is the closed economy solution. More generally, the open economy introduces two additional effects that alter the level of the tax, both of which can be seen in the first-order condition and (5). First is the terms of trade (TOT) effect, which pushes down the tax if Home is an importer of energy. Second is leakage, whereby the increase in the world price of energy caused by the tax increases the Foreign supply of energy, and this in turn causes Home to choose a lower tax because of the climate damages it experiences as a consequence. In order to focus on the climate externality, it is helpful to assume that if $m > 0$, it is not large enough to turn the tax into a subsidy.

Leakage is a potentially important side effect of climate policy, and the type of leakage just described is often referred to as leakage through the "competitiveness channel." It occurs because regulation at Home increases costs, so production shifts abroad where regulation is more lax. Markusen (1975) is an early paper that identifies the leakage effect in the context of transboundary pollution, Hoel (1994) considers the issue specifically in the context of climate change, and other papers examine various aspects of leakage (Hoel 1996; Fowlie 2009; Böhringer et al. 2014; Holliday et al. 2018; Fowlie and Reguant 2022; Weisbach et al. 2023). Branger and Quiron (2014) review studies with international estimates, primarily based on computational general equilibrium models, and find leakage ranges between 5 and 20 percent. See also Yu et al. (2021) for a meta-analysis with estimates of the same magnitude or greater. Finally, it is worth noting that the mechanism underlying leakage is related to another concept known as the pollution haven hypothesis, based on the idea that more lax environmental regulations within a region promotes comparative advantage for more pollution-intensive production in that region (Copeland et al. 2022).

7.3 Combining multiple tax instruments

Let us now examine what happens if we allow Home to deploy a fuller set of tax policies. Begin with the possibility for a consumption tax, in addition to the production tax. Recall that in a closed economy, production and consumption taxes are equivalent, but the equivalence no longer holds in an open economy setting, as the instruments have different effects on the world price. We have already discussed how the production tax increases the world price of energy, and this increases Foreign's supply, which causes leakage through the competitiveness channel. In contrast, a consumption tax at Home will decrease the world price of energy and therefore stimulate Foreign's demand. This effect is another unintended consequence also referred to as leakage in the literature, but this time through the "fuel price channel." Hence, while both instruments decrease the externality at Home, neither is without leakage effects in an open economy setting. A question worth considering, therefore, is how Home might choose the optimal balance between instruments, taking account of the different leakage effects, when setting its own unilateral policies (Weisbach et al. 2023).

Let θ denote Home's consumption tax on energy. The market clearing condition remains identical to that specified previously, but prices are now related according to $p = \rho + \theta$ and $q = \rho - t$. There is also an additional source of government revenue, so in this case $R = ty(q) + \theta d(p)$ in (3). Solving Home's maximization problem yields two first-order conditions, $\frac{\partial W}{\partial t} = \frac{\partial W}{\partial \theta} = 0$, which together define the optimal, unilateral policy package. Using the market clearing condition and the price identities, we can once again substitute the price changes out of the first order conditions (not shown) and solve for the optimal production and consumption taxes:

$$t = \alpha - \theta \quad \text{and} \quad \theta = \frac{m + \alpha y^{*'}}{y^{*'} - d^{*'}}. \tag{6}$$

In general, both instruments will be used, and the sum of the production and consumption tax equals α. This means that the climate externality is fully internalized from Home's perspective. Assuming m is sufficiently small also ensures that both taxes are positive.

How does Home split the incentive between the two instruments? Using the expressions in (6), we can write the ratio of the production tax to consumption tax as

$$\frac{t}{\theta} = -\frac{m + \alpha d^{*'}}{m + \alpha y^{*'}}. \tag{7}$$

It is clear from (7) that the ratio depends on the relative slope of Foreign's demand and supply for energy. The intuition is that Home seeks to avoid taxing in ways that provoke greater Foreign responsiveness, which causes leakage. To see this clearly, let's assume for the moment that $m = 0$. Then, to the extent that Foreign's demand for energy is more responsive than its supply, Home will favor the production tax, as leakage through the competitiveness channel (which depends on Foreign supply) is less of a concern than through the fuel price channel (which depends on Foreign demand). On the other hand, Home will favor a consumption tax when Foreign's demand is less responsive than its supply. Weisbach et al. (2023) describe the optimal ratio between the taxes as balancing these concerns, although their result differs from equation (7) because they restrict Home's policies to Pareto improvements, and this eliminates TOT effects by construction.

What about other combinations of tax instruments? There is a general equivalence in trade theory between the equilibria implied by the optimally chosen policy packages of (*i*) production and consumption taxes, (*ii*) production and trade taxes, and (*iii*) consumption and trade taxes. We just considered (*i*) and now turn to (*ii*), as trade taxes in various ways are increasingly a focal point in climate policy.

Letting μ denote the trade tax, the price relationships are now $p = \rho + \mu$ and $q = \rho - t + \mu$. What differs between this scenario and the one considered previously is that while $q = p - t$ continues to hold, the trade tax can be used to regulate the level of the world price ρ, because it directly shifts both p and q. Choosing t and μ to maximize (3), where in this case $R = ty(q) + \mu\left[d(p) - y(q)\right]$, yields two first-order conditions that, following the same steps outlined above, can be used to solve for the optimal, unilateral policies:

$$t = \alpha \quad \text{and} \quad \mu = \frac{m + \alpha y^{*'}}{y^{*'} - d^{*'}}. \tag{8}$$

In this case, the production tax is equal to the full marginal climate damages α, and the trade tax is equal in magnitude to the consumption tax in equation (6). Equivalence between the two optimally chosen policy packages, cases (*i*) and (*ii*), means they implement the same allocations, and generate the same level of government revenue. Although not a focus here, it is worth noting for completeness that case (*iii*), involving consumption and trade taxes, also implements the same allocation with $\theta = \alpha$, and $\mu = \frac{m+\alpha d^{*'}}{y^{*'} - d^{*'}}$. In effect, trade taxes are used to affect the world price, while the production or consumption taxes are used to internalize the externality at Home.

Many papers in the literature explore these relationships in far greater detail, allowing for a blend of different instruments, more comprehensive setups with goods that vary in their emissions intensities, and calibrated simulations. Examples that cover these topics in various ways include Markenson (1978), Hoel (1994, 1996), Jakob et al. (2013), Böhringer et al. (2014, 2017), Kortom and Weisbach (2022), and Weisbach et al. (2023).

7.4 Carbon border adjustments

There are, of course, limits to the policy instruments available to regulators in practice. Constraints may arise because of challenges due technical feasibly (perhaps because of measurement), political economy, or as a matter of law. For example, the World Trade Organization (WTO) imposes limits on trade taxes. Seeking to find ways to implement trade taxes that are WTO compliant, economists and policymakers are increasingly focused on carbon border adjustments (Bohringer et al., 2022; Jakob et al. 2022). The most prominent example is the European Commission's Carbon Border Adjustment Mechanism (CBAM) that entered transitional implementation in 2023. Border adjustments are trade taxes that take the form of an import tariff (or possibly an export subsidy) calibrated specifically to the difference in the climate policy costs borne by domestic- and foreign-produced products. The rationale is to not disadvantage domestic producers and ultimately seek to leverage other countries into adopting more stringent climate policies.

Added to the basic setting here—with a production tax at Home and no Foreign climate policy (Section 7.2)—a border adjustment would entail a tariff on energy imports equal to the production tax t, or a subsidy on exports of the same magnitude. To keep things simple, assume Home is an importer, so the border adjustment would be a trade tax satisfying $\mu = t$. But of course the solution in (8) does not in general satisfy this condition. Indeed, it is important to recognize that in the previous section, we solved for the optimal unilateral production and trade tax, without any constraint on their relative magnitudes. A carbon border adjustment is therefore a constrained special case of a trade tax.

This distinction raises an interesting question: If Home knows the trade tax must satisfy the border adjustment constraint ($\mu = t$), what is Home's optimal unilateral choice of the production tax? In this case, we have the same price relationships as in the previous section, but the added constraint implies $q = \rho$, so the price wedge occurs only between the consumer price at Home and the world price. Interestingly, this setup is isomorphic to a problem where Home is solving for the optimal consumption tax, when a consumption tax is the only available instrument. Let us therefore use the notation for a consumption tax θ and write the price wedge as $p = \rho + \theta$. Solving this problem by choosing θ to maximize (3), with $R = \theta d(p)$, yields a single first-order condition that we can use to solve for

$$\theta = t|_{\mu=t} = \alpha + \frac{m + \alpha d^{*'}}{y^{*'} - d^{*'} + y'}. \tag{9}$$

It is straightforward to see that without the TOT effect, the tax is less than α. This reflects the way that leakage still occurs, but this time through the fuel price channel, rather than the competitiveness channel.

Many of the papers cited previously examine various aspects of carbon border adjustment mechanisms. Another to mention is Kortum and Weisbach (2017) because they provide a nice discussion about how a border tax adjustment effectively shifts the tax from production to consumption at Home, which is the insight of equation (9). In effect, the production tax, without a border adjustment, taxes production at Home regardless of where energy is consumed, whereas adding the border adjustment taxes consumption at home regardless of where energy is produced. It follows that the question of whether Home would want to use a border adjustment, along with a production tax, is equivalent to asking whether Home would prefer a consumption tax to a production tax.

7.5 Green subsidies

What happens if a zero-emissions source of energy (i.e., green energy) is also available? This is the more general setting that Kotchen and Maggi (2024) consider. They find that if production instruments are available, the regulator will choose to subsidize green energy, while taxing the emitting source of energy, albeit at a lower level than when green energy is not available. The underlying mechanism is that green subsidies provide an additional channel through which a country can lower the world price of GHG emitting sources of energy. Green subsidies are also associated with a "reverse leakage" effect: subsidizing green energy at Home lowers its world price, and this causes a decrease in demand for conventional energy for both Home and Foreign. But it is the effect on Foreign that motivates the green subsidy, as the tax on conventional energy is a more targeted instrument for reducing the quantity demanded and supplied at Home. Indeed, focusing on only the climate externality, Kotchen and Maggi (2924) find a unilateral welfare rationale for a green subsidies in an open economy setting. This result stands in contrast to that in a closed economy, where green subsidies serve only as second-best instruments.

8 Renewable energy subsidies

World leaders agreed to triple global renewable energy capacity by 2030 (UNFCCC 2023), and in line with this goal, renewable energy subsidies are among the favored instruments of climate policy. There are different rationales for green subsidies based on different market failures (Armitage et al. 2024; Gillingham and Stock 2018), including the open economy scenario covered in the the previous section. But regardless of the motivation, green subsidies are substantial, often comprising a central part of the recent trend toward green industrial policy. Direct subsidies to renewable sources of energy were estimated at $166 billion worldwide in 2017, and forecasts for 2030 reach $192 billion (Taylor 2020). Not included in this estimate, however, is the U.S. Inflation Reduction Act (IRA) of 2022, which includes provisions initially estimated at $271 billion for renewable energy subsides over 10 years, with more recent estimates putting the magnitudes at $700 billion or more (Bistline et al. 2023).

8.1 Investment *vs* production subsidies

Renewable energy subsides often take the form of either decreasing the costs of investment or increasing the benefits of production. Examples include the investment and production tax credits (the ITC and PTC, respectively) in the United States and the European Union's Renewable Energy Financing Mechanism. Given the scale of these different approaches, it is worth considering the circumstances under which subsidies should target investment or production.

One consideration is the precise market failure the subsidy seeks to address. In some settings, there might be barriers to getting renewable energy projects up and running. These can range from a lack of well-developed capital markets to provide financing, political and institutional risk, and a shortage of technical experience and expertise. These barriers often provide the rational for multilateral financing of renewable energy projects that focus on lowering investment costs, along with that for green banks at the international, national, and subnational levels. The idea is that by demonstrating successful projects and promoting learning-by-doing, the implicit and explicit costs of future projects will be lower.

In other cases, the market failure is more generally the under-provision of clean energy, which does not generate a negative climate externality. Hence the objective is to scale up generation. While intuition might suggest a production subsidy would be preferred to an investment subsidy, there are additional factors to consider. Parish and McLaren (1982) consider a static setup with perfect competition and ask how much of an input or output subsidy would be needed to induce the same increase in output. The answer depends on whether the inputs are used more intensively on average or on the margin. They focus on how an investment subsidy is more cost effective at increasing output when production has decreasing returns to scale. But it turns out that their static setup misses some important features that can affect the preference between investment or production subsides. Consumers and investors may discount future payments too much, thereby providing a reason to favor the up-front investment subsidy (De Groot et al 2019; Bartlett 2023). One the other hand, conditional on project construction, production subsides create continuing incentives to maintain and improve operations and management that can boost production (Aldy et al. 2023). Finally, the efficiency of a production subsidy will also depend on its duration, and when limited, a combination of investment and production subsides can be optimal (Ricks and Kay 2024).

Aldy et al. (2023) provide empirical evidence comparing the ITC and PTC for wind energy in the United States. They find that installations claiming the investment subsidy were between 10 and 12 percent less productive than they would have been under the production subsidy. Moreover, they estimate that the amount of wind power attributed to the investment subsidy could have be achieved with a cost reduction of 29 percent if an output subsidy were used instead.

There are also efficiency concerns to consider beyond cost effectiveness when doing a full comparison between investment and production subsides. The subsidies will affect the production costs and value of electricity generation is ways that are distortionary (Bartlett 2023), and future research that takes these effects into account would be useful. Investment subsidies can raise the costs of electricity production by encouraging excessive spending on capital costs or by inadequately incentivizing operations and maintenance. In contrast, production subsidies that are set irrespective of prices, can incentivize lower valued electricity production. This arises because the subsidy takes no account of how the value of electricity can differ with the timing of generation and the location. For example, production subsidies can encourage greater electricity generation when prices are negative (Aldy et al. 2023). Furthermore, subsidies, when set at fixed and uniform rates, are not calibrated to the way that displaced marginal emissions from fossil sources of electricity generation differ by location, time of day, and therefore social value (Graff Zivin et al. 2014; Holland et al., 2022).

8.2 Feed-in tariffs

Another form of production subsidies for electricity generated from renewable source of energy is a feed-in tariff (FIT). FITs are long-term contracts that guarantee an above market price for electricity generation form renewable sources of generation. The guaranteed price can differ by source, depending on the costs of generation, and FITs differ from the type of production subsidies previously discussed because they establish a price rather than a fixed subsidy amount. FITs promote renewable generation because they not only provide a subsidy, they protect producers from price uncertainty. As with any production subsidy, FITs can result in inefficiencies because the incentives are not calibrated to the socially optimal timing and location of generation. They may also raise concerns politically because the potential costs to the regulator can be unbounded, though the same concern potentially applies to all subsidies unless limits are set.

FITs have been implemented around the world in developed and developing countries, at both the national and subnational levels. Jenner et al. (2013) provide an evaluation of program effectiveness among Eurpean Union countries along with a literature review. Germany is often pointed to as having the most impactful FIT program, contributing to the country's significant increase in the share of renewable sources of energy for electricity generation, from roughly 8 percent in 2000 to 46 percent in 2020 (EIA 2024). Despite the significant shift in Germany's generation profile, there are critics of Germany's FIT design and cost effectiveness (Frondel et al. 2010).

9 Performance based standards

A common form of climate policy, and environmental policy more generally, is a performance based standard. Performance based standards apply a benchmark for compliance at a per unit level of output for a regulated entity, or perhaps an entity's average across units of output. Examples include limits on the emissions per megawatt of electricity generation, and the average fuel economy of vehicles sold. Two features of many performance based standards contribute to their ability to lower compliance costs. First is how regulated entities have flexibility about how to comply, and second is the allowance of tradable credits for compliance. Nevertheless, performance based standards are generally not efficient or cost effective compared to other instruments. This section briefly illustrates why, followed by specific examples of how of performance based standards have been applied in different climate policy settings.

9.1 Basic theory

The potential inefficiency of performance (or sometimes intensity) standards has been well established for quite some time (Helfand 1991). To convey the basic issues that arise, let's consider a simplified version of the setup in Holland et al. (2009). Focus on electricity generation, and assume there are two sources of fuel for generation: q_l and q_h are associated with low and high emissions rates, respectively. Specifically, the marginal CO_2 emissions rates are β_l and β_h, with $0 < \beta_l < \beta_h$. Consider a single, representative price taking firm with strictly increasing and strictly convex costs of generation from each fuel of $c_l(q_l)$ and $c_h(q_h)$. We can think of q_i in units of embodied energy that maps into different emissions rates, and the cost functions represent the respective costs of generating perfectly substitutable electricity that sells at a fixed price p. Finally, let α denote the marginal social damages of emissions.

Without any regulatory intervention, electricity producing firms will choose q_i to maximize $pq_i - c_i(q_i)$ for both fuels, where the solution (assuming it is interior) will satisfy $p - c_i^{'}(q_i) = 0$ for both i. A welfare maximizing regulator, however, will account for the marginal external external costs associated with each fuel, $\alpha\beta_i$, and the socially optimal levels of each will satisfy $p - c_i^{'}(q_i) = \alpha\beta_i$. As discussed in Section 4.1, one way to implement the efficient quantity of each fuel is for the regulator to impose a carbon tax equal to α, which results is a differential tax for each fuel depending on its emission rate.

But we can also consider a more general set of tax levels that need not be set to maximize social welfare. The total emissions will be decreasing in the carbon tax level, and we know from our previous discussion that the emissions reductions associated with each are implemented at least cost. Taking the ratio of the first-order conditions with any tax yields the following useful condition:

$$\frac{p - c_l'(q_l)}{p - c_h'(q_h)} = \frac{\beta_l}{\beta_h}. \tag{10}$$

This tells us that the ratio of the private net benefits between fuels must equal the ratio of their relative emissions rates, and this is equivalent to the ratio of the taxes for each fuel that the producer internalizes. Equation (10) is useful because it identifies a necessary and sufficient condition for cost effective emissions reductions, which is of course also necessary for overall efficiency.

Let us now define a performance standard as an upper limit σ on the producer's average emissions per unit of electricity generation:

$$\frac{\beta_l q_l + \beta_h q_h}{q_l + q_h} \leq \sigma \tag{11}$$

Assuming the standard is binding and feasible means that the equation will hold with equality and that $\beta_l < \sigma < \beta_h$. Substituting (11) into the firms profit maximization problem, and solving for the first-order conditions, we find the following necessary condition for the solution:

$$\frac{p - c_l'(q_l)}{p - c_h'(q_h)} = \frac{\beta_l - \sigma}{\beta_h - \sigma}. \tag{12}$$

The right-hand side represents the ratio of the policy induced costs the firm faces between fuels. Because $\beta_l - \sigma < 0$ and $\beta_h - \sigma > 0$, the standard effectively subsidizes q_l while taxing q_h. Intuitively, there is an incentive to use more of the low emissions fuel because it relaxes the performance constraint.

The key insight comes from a comparison between equations (10) and (12). With the setup here, and assuming the standard causes a reduction in emissions, it can never be cost effective (or efficient). Expression (10) shows how this requires taxing both fuels, whereas (12) shows how the performance standard taxes one and subsidizes the other. The result is an increase in q_l and a decrease in q_h. What is more, it is possible for emissions to increase with the performance standard relative to no policy at all. Intuition for this counterproductive result can be seen right from the standard itself, as one way to comply is to increase output, which can increase emissions even if the average emissions rate declines.

Holland et al. (2009) generalize the basic framework in many ways. They account for price endogeneity, different ways of defining the performance standard to accommodate a range of potential settings, and trading of credits among regulated entities that reduces compliance costs. It is worth noting, however, that unlike a cap-and-trade program the number of credits is not fixed with a performance based standard. While the simple setup described here produces the stark result that performance based standards are less efficient than an emissions tax, others have identified particular circumstances where this need not be the case, and performance standards can be efficient or preferable to taxes in a second-best setting. These results depend on existence of a zero emissions option, perfectly inelastic demand, and whether or not there is leakage or market power (Holland 2009; Holland et al. 2009; Holland 2012; Fell et al. 2017).

9.2 Electricity sector emission rates

China commenced operation of an emissions trading program in 2021 with coverage of the electric power sector. The program is a performance based standard with tradable credits, and it is the largest emissions trading program in the world, covering an estimated 9.3 percent of global emissions (World Bank 2024a). Long and Goulder (2023) provide a detailed description of the particular features of China's program, including the preceding pilot programs that began in 2013. An important feature of the program is the use of different benchmark emissions rates for different types of electricity generators. While intended to address distributional concerns at the regional level, the different benchmark standards further limit the program's potential cost effectiveness. Studies have found that employing a single benchmark would reduce compliance costs significantly, and the compliance costs of the emissions trading system itself far exceed what they could have been with an emissions equivalent cap-and-trade program (Goulder et al. 2022; Goulder et al. 2023).

Although never implemented in the United States, the Obama administration's Clean Power Plan was intended as a performance based policy to reduce CO_2 emissions in the U.S. electricity sector. An interesting feature of the policy design is that states were afforded the flexibility to choose between the performance based approach, which many believed was anchored in the statutory basis of the Clean Air

Act, or an emissions equivalent cap-and-trade program. While both approaches sought to promote the efficiency gains of emissions trading, they were designed subject to different legal constraints, whereby the cap-and-trade approach would be more cost effective, but states needed to opt in (U.S. EPA 2015). The most recent iteration of U.S. federal regulations to reduce CO_2 emissions from the use of fossil fuels in the electricity sector adopts neither approach and reverts back to a command-and-control type of direct regulation on the emission rates of particular electricity generating units (U.S. EPA 2024).

9.3 Renewable portfolio standards

Renewable portfolio standards (RPS) seek to increase the generation of electricity from renewable sources of energy in order to reduce emissions. In general, a RPS requires that suppliers of electricity meet a minimum share of electricity generation (i.e., a rate based requirement) from approved renewable sources by a specified date. Another feature of many RPS programs is the establishment of trading systems based on renewable energy credits (RECs). Electricity suppliers that use more renewable sources of generation than the RPS requires can earn RECs that can be sold to others that fall short of the RPS requirement. There is wide variability in the particular design features of RPS programs, and many countries have implemented a RPS in various ways, including the United Kingdom, China, Mexico, Australia, and the majority of states in the United States. Deschenes et al. (2023) and Feldman and Levinson (2023) review the literature that seeks to estimate a causal effect of U.S. state RPS programs on various outcomes and provide estimates of their own. The results are generally mixed across studies, but most find state RPS programs have reduced GHG emissions, increased wind generation, and increased electricity prices. In another study, Greenstone and Nath (2024) estimate the cost of CO_2 emissions reductions across U.S. RPS programs as ranging between \$80 and \$210 per ton.

9.4 Low carbon fuel standards

Low carbon fuel standards (LCFS) seek to reduce the average carbon intensity of transportation fuels. A LCFS sets an industry-wide intensity target, and producers or importers of carbon intensive fuels can meet the target through two potential mechanisms. The first is to blend into their supply lower carbon intensity fuels (e.g., biofuels), and the second is to purchase credits from fuel suppliers with lower carbon intensities that fall under the target. The LCFS credits are then traded through a market mechanism that creates incentives to meet the overall, industry-wide intensity target at least cost. In the United States, California's LCFS has been in place since 2007, while Oregon and Washington have more recently followed. Several other states also have pending or recently failed LCFS policies. Other countries and regions with an LCFS are the United Kingdom, the European Union, and British Columbia, Canada. Yeh et al. (2014) provide a detailed overview and evaluation of California's LCFS, its interaction with other policies, and comparisons to other programs. Holland et al. (2009) simulate the effects of a national LCFS in the United States to explore the effects on emissions, efficiency, and cost effectiveness of different program designs.

While the United States does not have a federal LCFS that targets emissions intensity, there is a federal Renewable Fuel Standard (RFS) that was first enacted in 2005 and requires a blending of biofuels into the vehicle fuel supply, with a system of tradable compliance permits referred to as Renewable (fuel) Identification Numbers (RINs). The RFS is effectively a tax on petroleum fuels and a subsidy on biofuels that is revenue neutral. Much of the research focused on the RFS has nevertheless focused on the unintended environmental consequences that occur through shifts in agricultural production (Lark et al. 2022) and on the pass-through of RIN prices to fuel markets (Knittel et al. 2017).

9.5 Vehicle fuel economy standards

Vehicle fuel economy standards are another area were performance based standards have been applied. Two economic rationales motivate these policies: reducing fuel consumption, and therefore emissions, and correcting the behavioral market failure whereby consumers misperceive the benefits of improved energy efficiency (Anderson et al. 2011). Since 1975, the United States has had a Corporate Average Fuel Economy (CAFE) standard, and the particulars of the program have changed over time. The basic contours of the program in place now include an average fuel economy standard that manufactures must meet for a specific category of vehicle, and the creation of tradable credits when a manufacturer exceeds the standard. Other countries have fuel economy standards with a similar structure, including China, Canada, India, Mexico, and the Eurpean Union (Cazzola et al. 2023). There is a large literature with research that evaluates various aspects of CAFE standards. Interest focuses on the benefits and costs that include how the standards affect vehicle prices, sales, composition, attributes, miles traveled, externalities, distributional effects, and implications on the used car fleet, along with comparisons to other policy instruments (Austin and Dinan 2005; Klier and Linn 2012; Jacobsen 2013; Bento et al. 2020).

9.6 Feebates

A pricing instrument can also be used to implement a performance based standard. A "feebate" is a combination fee (or tax) on units of output that do not meet a performance standard and a rebate (or subsidy) on those that do. For example, Gillingham (2013) shows an equivalence between CAFE standards and an appropriately calibrated feebate that penalizes and rewards low- and high-fuel economy vehicles, respectively. Underlying this result is a mechanism similar to the price and quantity equivalence we encountered earlier between an emissions tax and a cap-and-trade program when there is no uncertainty. Indeed, accounting for uncertainty, Wang et al. (2022) show that a modified Weitzman (1974) rule can be used to compare feebates and tradable performance standards, with applications to China's emissions trading system and California's LCFS.

10 Policy interactions

We have thus far considered climate policy options one at a time and in isolation, ignoring the possibility for overlapping instruments, objectives, or both. Much of the academic literature and policy implementation in the real world proceeds with the same simplifying assumption. But there are a growing number of instances where climate policies overlap, and understanding how they interact is increasingly important as the number of policies continues to grow. At the same time, many policies seek to accomplish more than one objective, including the reduction of GHG emissions and the promotion of equity and environmental justice. This section provides a discussion of overlapping policies, general equilibrium approaches, and recent policy shifts that encourage greater consideration of distributional and equity effects.

10.1 Overlapping policies

There are many examples of overlapping climate policies. At the most general level, policies that seek to price fossil fuels to internalize externalities are often layered over an entrenched set of preexisting fossil fuel subsidies that push prices in the opposite direction. In the electricity sector, there are policies that subsidize renewable sources of generation, while others mandate their use, price emissions intensive alternatives, or both. With transportation fuels, we have biofuel subsidies concurrent with mandates for their use in low carbon fuel standards. A final example is that we subsidize low emissions vehicles, including electric vehicles (EVs), at the some time there are CAFE standards and targets that mandate future EV sales.

When it comes to overlapping climate policies, issues and opportunities arise across subnational, national, and international levels (Goulder and Stavins 2011; Shobe and Burtraw 2012; Metcalf and Weisbach 2012). The mix of different instruments is sometimes referred to as a "belts and suspenders" approach (Levinson 2012), and a key question is whether, and the degree to which, policies can be mutually reinforcing or in conflict. Policies can be reinforcing when there is more than one market failure or when the administrative costs differ across instruments. Conflicts might arise when, for example, a cap-and-trade program is layered on top of an existing standard. In these cases, an important condition is whether the permit price is greater than or less than the marginal cost of complying with the standard. If the permit price is lower, the standard is binding and cost effectiveness of the cap-and-trade program will be limited. Levinson (2012) suggests even this simple comparison might sound a note of caution for cap-and-trade programs, as permit prices are often lower than predicted. Empirical studies of overlapping policies have, for example, examined how complementary policies affect emissions permit prices (Borenstein et al. 2019), how the presence of both fuel economy and emissions standards can distort credit trading markets (Leard and McConnell 2017), and how renewable energy subsides can increase co-pollutants in a cap-and-trade program (Novan 2017).

Constructing a general framework that accounts for overlapping policies is difficult in part because the underlying rationales are often complex, involving a mix of political economy. Perino et al. (2023) nevertheless make progress on a framework to evaluate the emissions consequences of policies that overlap an existing carbon pricing system. Their framework, which includes empirical illustrations, considers how different policy features create deviations from two extreme cases where an overlapping policy will have no effect. The first is "internal carbon leakage," where a product-market shift causes an offsetting decrease and increase in demand for tradable emissions permits. The second is the "waterbed effect" in the carbon market, where a system-wide decrease in demand for permits only lowers the permit price with no change in emissions because the total allocation is fixed. An immediate result, for example, is that the waterbed effect no longer holds with a carbon tax instead of a cap-and-trade program.

While empirical evaluations of policy in the academic literature often take great care to control the confounding effects other policies, more attention in theoretical work to the cases where overlapping policies might be important is an area of need. Finally, with respect to management of overlapping policies in practice, there is a need for more institutionalization of reporting, especially in the domain of clean energy subsidies, where a complicated patchwork of incentives potentially undermines the effectiveness of clean energy subsidies (Aldy et al. 2022).

10.2 General equilibrium approaches

Climate policies will have broad effects on the economy, if they are big enough to meaningfully reduce GHG emissions. In these cases, partial equilibrium perspectives will be limited in their ability to fully inform policy design and evaluation. Much progress has been made over the last three decades on general equilibrium analysis of environmental policies. An important insight of the literature is recognition of how large scale policies, such as those seeking to address climate change, will interact with pre-existing tax distortions. Questions about the "double dividend hypothesis" have spurred research is this area.

Might there be two distinct benefits (i.e., dividends) of imposing a revenue-raising climate policy, such as a carbon tax or a cap-and-trade system with auctioned permits. That a welfare gain occurs because of the reduction in emissions is clear. More subtle is the potential for a second dividend, whereby tax revenue from the climate policy can be used to reduce other distortionary taxes such as those on labor or capital. The second dividend's possibility captures imagination because, if true, it means that climate policy is beneficial even without concern for the environmental benefits.

The direct mechanisms underlying the two dividends are referred to as the

"Pigouvian welfare" effect and the "revenue recycling" effect. Complicating matters, however, is a third mechanism that might arise because of interactions between a newly imposed climate policy and pre-existing distortionary taxes, referred to as the "tax interaction" effect. Early research cast doubt on the existence of the second dividend, finding that a negative tax interaction effect is likely to outweigh the beneficial revenue recycling effect (Bovenberg and de Mooij 1994; Parry 1995). Subsequent analyses have found grounds for more optimism (Bovenberg and Goulder 1997; Parry and Bento 2000). Bento (2024) provides a recent overview of how different assumptions affect results in the literature and their empirical importance, and Freire-Gonzalez (2018) provides a detailed meta-analysis. Although evidence on the double dividend is mixed, two things are clear: the environmental rational for climate policy is robust, and recognizing that policy formation takes place in a second-best setting can affect instrument choice (Parry et al. 1999; Fullerton and Metcalf 2001; Bovenberg and Goulder 2002).

General equilibrium approaches have also been used recently to examine the distributional effects of climate policy. Goulder et al. (2019) provide an example. They consider how an economy-wide carbon tax in the United States will affect households, accounting for both use-side and source-side effects. Use-side effects arise because changes in prices affect purchasing power, and source-side effects are due to changes in income. Goulder et al. (2019) confirm the results of previous studies showing that use-side effects are regressive, source-side effects are progressive, and the net effect appears to be progressive or at least close to proportional. A further contribution of their analysis is estimation of the efficiency sacrifices necessary to avoid distributional outcomes that adversely affect low income households.

10.3 Distributional effects and equity objectives

Economics has a long tradition of separating efficiency and distributional concerns when is comes to the design and evaluation of policy. But as concerns about equity and distributional impacts continue to grow, economists are being pushed to do more, and appropriately so. The shift in focus is evident in research on climate policy, where an increasing number of papers characterize the distributional consequences of both proposed and actual policies. The Goulder et al. (2019) paper just discussed provides and example of a proposed policy. More generally, studies have considered the distributional consequences of a range of policies, including gasoline taxes, cap-and-trade programs, fuel economy standards, building codes, and renewable energy subsides. Borenstein and Davis (2024) provide a recent example that is typical, although they consider several different policies. They examine the distributional impacts of U.S. tax credits for heat pumps, solar panels, and electric vehicles. The overall finding, consistent with others in the literature, is that tax credits disproportionately benefit higher-income households. The results illustrate how policies that aim to address climate change, and therefore promote efficiency, often have undesirable distributional consequences.

The causality can also run in the other direction, when policies that aim to address distributional concerns have an efficiency cost. Arthur Okun (1975) famously characterizes the general tradeoff with the analogy of a leaky bucket: accomplishing redistribution goals comes with an efficiency loss, with the bucket representing redistribution efforts and having less water (because of the leak) the efficiency cost. Climate policies are nevertheless increasingly designed with equity in mind. In an international context, multilateral climate funds, such those part of the Green Climate Fund and the Global Environmental Facility, establish windows of funding for particular countries or regions rather than allocating funds globally to maximize impact. The Justice40 Initiative in the United States is another example, where 40 percent of the benefits of climate, clean energy, and other public investments are to be directed towards regions specifically designated as disadvantaged. Rudik et al. (2025) provide estimates of the equity-efficiency tradeoff of the Justic40 Initiative on climate related spending of the 2021 U.S. Bipartisan Infrastructure Law.

More research along these lines is surely forthcoming, as equity goals of climate policy are becoming more explicit and major climate regulations establish more of a track record. While these tradeoffs are important to identify and evaluate, questions of interpretation are open to debate. There is an argument for why linking climate and equity objectives makes both harder to accomplish (Levinson and Fullerton 2022), the thrust of which is that regulation should focus on expanding the size of the pie, and redistribution should be left to the tax system. But these arguments assume feasibility of separate policies to accomplish different objectives, and whether this counterfactual is possible is itself likely to be its own source of debate.

Also likely to further scholarly interest in equity and distributional issues are recent revisions to the U.S. official guidance on how to conduct federal benefit-cost analysis (OMB 2023). In particular, the guidance opens the door for federal agencies to use distributional weights for the impacts on different groups based on estimates of diminishing marginal utility of income. While many might find the approach appealing because it up-weights impacts on lower income groups, questions and concerns arise because weighted benefit-cost analysis no longer has the same basis in welfare economics (Adler 2016; Banzhaf 2023). The approach also raises questions that are likely to become more important for climate policy in particular. Distributional weighting is already used in some cases for estimation of the SCC (Anthoff and Emmerling 2019). But will countries choose to apply the same inequality aversion across countries as they do within their own country? We have already discussed in Section 2.3 questions about whether countries will seek to internalize domestic or global climate damages, and equity weighting adds another dimension in need to even further research. Indeed, when discussing distributional weighting, the new guidance focuses on domestic benefits and costs, and there is relatively little mention of international impacts, other than to state that altering the approach "may be appropriate when analyzing regulations with international scope" (OMB 2023, p. 67).

11 Voluntary and information based approaches

Voluntary and information based approaches (VIBAs) to climate policy seek to provide more complete information so that markets can adjust more efficiently and opportunities can emerge for voluntary actions to address climate challenges. This final section includes discussion about information disclosure, voluntary programs, and the ways that VIBAs might serve as complements or substitutes for other climate policies.

11.1 Disclosure strategies

One source of market failure with respect to climate change is incomplete or asymmetric information. Market participants are often unaware, or are unable to observe, how their consumption and production choices affect emissions, or how investments face different policy or climate risks. Markets will not function efficiently with such incomplete information. Individuals who want to reduce their personal carbon footprint may prefer goods and services with lower carbon intensities, but they can only find the low-carbon alternatives if the information is available or at least not too costly to obtain. Moreover, investors believing more stringent climate policies are forthcoming will only know which firms are most exposed if information on emissions is available. Nevertheless, the provision of complete and accurate information is rarely incentive compatible and suffers from further under-provision because it is a public good.

Information disclosure policies seek to solve these market failures through the improved provision of information, which in turn can promote efficiency through various adjustments in product, capital, and labor markets, as well as by spurring the potential for judicial and legislative action. Tietenberg (1998) identifies information disclosure policies as the "third wave" of environmental policy, following the first wave of command-and-control regulations and the second wave of market-based instruments.

Policies that mandate climate related disclosures are beginning to gain traction, requiring that companies report their GHG emissions along with information about climate-related risks. Prominent examples, both scheduled to take effect in 2026, are recent legislation in California applicable to companies doing business in the state, and the U.S. Securities and Exchange Commission's requirements for all publicly traded companies reporting in U.S. markets. These follow the EU's Corporate Sustainability Reporting Directive that commenced in 2024 and has specific requirements related to emissions, risks, and company policies. While it is too early to tell how these disclosure policies will affect markets and emissions, research to answer these questions is sure to be forthcoming. Greenstone et al (2023) provide an early indication of what the reporting might look like based on a third-party data set of global companies. They make comparisons across industries and countries, focusing not only emissions, but also the economic value of damages in accordance with the notion of implicit subsides discussed in Section 4.3.

11.2 Voluntary programs

While the policies just discussed implement mandatory disclosure, there are many voluntary disclosure programs around the world that focus on reporting emissions and climate risk. Examples include the Carbon Disclosure Project (CDP) and the Global Reporting Initiative (GRI). Many of the voluntary programs exist not only to report information, but to signal environmental and climate commitments such that participants gain reputational benefits. For example, the Net-Zero Banking

Alliance is a United Nations convened program of global banks that receive membership through commitments to activities that promote reaching net-zero GHG emissions. Another example is the Climate Neutral Certification that companies can obtain if they comply with the third-party protocol of the Climate Impact Partners, which stipulates specific measures to reduce emissions.

There is an environmental economics literature focused on voluntary programs. In an early theoretical contribution, Segerson and Miceli (1998) consider, for example, how the threat of future regulation can induce participation in a voluntary program, with potentially positive or negative consequences for environmental quality. Voluntary programs can be designed to tap into consumer willingness to pay for impure public goods, which combine a private benefit with provision of an environmental public good (Kotchen 2006). A paper by van 't Veld and Kotchen (2011) shows how club theory can illuminate the understanding of voluntary programs, as membership provides a non-rival and excludable benefit, and the program's sponsor (e.g., government, industry, or a nongovernmental organization) will affect the expected program impacts. A number of studies have sought to evaluate the effectiveness of voluntary programs (Morgenstern and Pizer 2007; Borck and Conglianese 2009), and perhaps unsurprisingly, the results are quite mixed. Only some find significant effects on environmental outcomes, and the results differ by industry and phases of the program. Many studies also face empirical challenges owing to the way that voluntary participation is endogenous to the outcomes of interest, and programs are likely to have spillover effects (Zhou et al. 2020).

11.3 Behavioral approaches

Another form of climate policy is the strategic use of information to nudge behavioral change in ways that tap into social and psychological mechanisms. There is large literature on the topic that employs both observational and experimental methods, with many applications to energy conservation and the adoption of renewable energy technologies. One approach is the use of social comparisons that report information along with a normative signal about what constitutes pro-social behavior. Opower Home Energy Reports are a prominent example, whereby electric utilities notify households of their own electricity consumption in comparison to those of other similar households, indicating that lower consumption (i.e., efficiency) is a pro-social behavior. Allcott (2011) and Allcott and Rogers (2014) find that the Opower messaging decreases electricity consumption, persistency of the notifications matter, and some long-term (although smaller) behavioral adjustments remain even after notifications cease. Others have examined the effect of moral suasion to induce conservation behavior and compared its effects to pricing instruments (Reiss and White 2008; Ito et al. 2018). Peer effects also exert a positive influence on energy and climate related behaviors, with evidence in particular on the adoption of residential solar photovoltaic panels (Gllingham and Bollinger 2012), and information about behavioral motives is being used to develop programs that promote participation in renewable energy programs (Jacobsen et al. 2013; Carattini et al. 2024).

11.4 Complements or substitutes

The appeal of VIBAs from a policy perspective is their potential for relatively low cost and cost-effective interventions. But because of the global public goods nature of the climate change problem, VIBAs are unlikely to be effective substitutes for more direct and centralized forms of climate policy on a large scale. Even the most successful VIBAs still face powerful disincentives for private provision of GHG emission reductions—a global public good. That is, while VIBAs may help mitigate emissions in many settings, the instances in which they themselves will produce economically efficient outcomes in practice are likely to be few and far between.

The ways in which VIBAs can serve as complements or substitutes for other forms of climate policy is an important question. In the United States, for example, fuel economy labels on new vehicle purchases reinforce fuel economy standards, and certified energy efficient appliances through the EnergyStar program also qualify for rebates. In other settings, however, the pursuit of a VIBAs can crowd out policies that might be more effective, as VIBAs are less likely to face political opposition compared to alternative policies that impose new taxes or regulatory standards. Finally, a recent strand of research focuses on how recognizing the presence of voluntary behaviors interacts with centralized policies and can affect instrument choice (Costello and Kotchen 2022; Chan 2024; Kaufmann et al. 2024). This provides another example of the ways in which researchers are increasingly focused on policy interactions as discussed in Section 10.

12 Conclusion

The aim of this paper has been to provide an overview of the standard economics "toolkit" of climate policy instruments. As mentioned at the outset, the focus has been on policies that create incentives for the internalization of at least some portion of the external costs associated with GHG emissions. Important topics that are missing, but will be covered in other chapters, include but are not limited to adaptation, finance, industrial policy, innovation, research and development, and international agreements. While a bit of formal modeling has been inserted at points, the discussion has been primarily narrative and intended to convey basic ideas and on-ramps to the literature where readers can find more advanced and detailed treatments in both theoretical and empirical papers. The preceding discussion has also sought to provide real-world examples of the different policy instruments. Efforts have been made to reference examples from around the world, yet there is an unmistakable bias towards those in the United States, reflecting only the author's greater familiarity.

All of the policy instruments discussed here apply not only to the problem of climate change, but also environmental problems more generally. Hence it is reasonable to ask: what, if anything, is different about the economics of climate policy that is not already covered in the economics of environmental policy? A theme of this paper, which provides and answer by way of emphasis, is that climate change is ultimately a problem of global collective action. This means that when it comes to climate change, regulators do not have authority to set policy that covers the full scope of the problem, which also includes future generations. In this way, climate change is fundamentally different from most other environmental problems. This often means that climate policy is not set with overall efficiency as the objective, and this differs from the typical focus of environmental economics on the design of policy to maximize efficiency. While this feature of climate policy poses significant real-world challenges, it also creates new frontiers for research.

What are the promising directions for future research? While making predictions is a risky business, some of the topics covered here may provide insight in at least a few areas. First, there is a need for more scholarly attention on the question of what should be the objectives of climate policy. Tremendous effort is focused on estimating various aspects of the SCC, but how policymakers should use these estimates in the formation of climate policy is a more nuanced question than scholars often recognized or acknowledge. Moreover, to the extent that target consistent approaches gain traction, there will be an increasing need for estimates of economy-wide marginal abatement costs. Second, we can expect a surge of interest in empirical research that evaluates the cost effectiveness of green subsidy policies given the scale of these programs as part of an emergence of green industrial policy in the United States and other countries. This research is important to provide insight on how to use public resources most effectively. Third, research is needed on how to improve markets for carbon offsets—accounting for measurement, verification and pricing—because these markets, troubled as they may seem, provide opportunities for gains from trade that can significantly reduce the costs of lowering GHG emissions. Finally, an important area of emerging climate policy research focuses on open economies and trade policy. This is fundamentally important because of the way that stabilizing the climate is a global public good and economies are linked through trade. While advances have been made to the understanding of emissions taxes in these settings, which are typically the favored instrument of economists, little attention has been given to the role of subsidies, which are increasingly a favored instrument of policymakers.

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