Reprint 2017-23

Carbon Pricing under Political Constraints: Insights for Accelerating Clean Energy Transitions

V.J. Karplus and J. Jenkins

Reprinted with permission from *The Political Economy of Clean Energy Transitions* (Chapter 3), UNU-WIDER/Oxford University Press, Helsinki, Finland.

© 2017 the authors

The **MIT Joint Program on the Science and Policy of Global Change** combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Joint Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Joint Program brings together an interdisciplinary group from two established MIT research centers: the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the program's work lies MIT's Integrated Global System Model. Through this integrated model, the program seeks to discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

—Ronald G. Prinn and John M. Reilly,
Joint Program Co-Directors

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 F (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu

3

Carbon Pricing under Political Constraints

Insights for Accelerating Clean Energy Transitions

Jesse D. Jenkins and Valerie J. Karplus

3.1 INTRODUCTION

For decades, the economically efficient prescription for the severe consequences of global climate change has been clear: establish a price on emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) that internalizes the far-reaching external costs of climate change in market transactions (e.g., Nordhaus 1992; Stavins 1997; Stern 2007). In sharp contrast to this prescription, a diverse patchwork of climate policy measures has proliferated, and where CO_2 pricing policies do exist, the prices established typically fall far short of the levels necessary to fully internalize the estimated marginal social cost of climate damages.

The failure of governments to establish a pricing (or equivalent market-based) approach to climate change mitigation—or to adequately price carbon when they succeed in doing so—can be largely attributed to a variety of persistent political economy challenges. In particular, climate change mitigation is a global collective action challenge (Olson 1984), demanding coordination among many disparate stakeholders (e.g., nations, emitting industries, individual consumers). Meanwhile, the benefits of climate mitigation are uncertain, unevenly distributed, and accrue primarily to future generations (IPCC 2014), while the costs of climate mitigation are born immediately, with acute distributional impacts for particular constituencies (Burtraw et al. 2002; Bovenberg, Goulder, and Gurney 2005; Rausch and Karplus 2014). Climate mitigation thus has all the hallmarks of an intergenerational principal agent problem (Eisenhardt 1989), with private costs of mitigation out of proportion to the private benefits for many actors. Furthermore, climate policy must be established through political processes, which invoke classic challenges in public choice (Arrow 1970; Black 1987; Buchanan and Tullock 1999; Downs 1957) and are vulnerable to capture by vested interests (Stigler 1971). Voters frequently express limited tolerance for measures that have salient impacts on their private welfare (such as tax or energy price increases) (Kotchen, Boyle, and Leiserowitz 2013; Johnson and Nemet 2010). Industrial sectors with high concentrations of assets that would lose considerable value under carbon pricing policies (e.g., fossil energy extraction, fossil electricity production, fuel refining, concrete production, and energy-intensive manufacturing) have also mounted vociferous and often effective opposition to climate policies. As a result of these public choice dynamics, policy-makers tend to support policies that minimize salient impacts on businesses and households, minimize burdens on strategically important sectors, and/or redistribute rents in a manner that secures a politically-durable coalition. In practice, policy-makers have thus preferred command-and-control regulations that are narrowly targeted (and thus allow for regulatory capture while reducing scope for opposition) and subsidies (which allow for transfers of rents while spreading policy costs broadly and indirectly across the tax base), rather than uniformly pricing CO_2 (Gawel, Strunz, and Lehmann 2014; Karplus 2011).

These persistent political economy constraints motivate a search for climate policies that are politically feasible, environmentally effective, and economically efficient (Jenkins 2014). As in many other domains of economic regulation, second best (Lipsey and Lancaster 1956) climate policy mechanisms abound. By paying close attention to the distributional impacts of different climate policy instruments and their interaction with potentially binding political constraints, economists, political scientists, and policy-makers can help design climate policy responses that are both palatable enough to be implemented today and economically superior to politically feasible alternatives.

In light of these challenges, this chapter aims to develop general insights about the design of climate policy in the face of binding political constraints. We employ a stylized partial-equilibrium model of the energy sector to explore the welfare implications of combining a CO_2 price with the strategic application of revenues to compensate for and/or relieve several potential political constraints on carbon pricing policies. Specifically, we implement constraints of varying severity on: 1) the maximum feasible CO_2 price itself; 2) the maximum tolerable increase in final energy prices; 3) a maximum tolerable decline in energy consumer surplus; and 4) a maximum decline in fossil energy producer surplus. Under each political constraint, we identify the CO_2 price, subsidy for clean energy production, and lump-sum transfers to energy consumers or fossil energy producers that maximizes total welfare.

This chapter begins by contrasting the range of carbon pricing policies implemented across the world with estimates of the full social cost of carbon (Section 3.2). We then introduce our model formulation and stylized representations of four political constraints that could explain the relatively low carbon prices that have been achieved to date in real world policy-making contexts (Section 3.3). We then present numerical results demonstrating that improvements in total welfare and carbon abatement can be achieved by the strategic application of carbon pricing revenues under each of the four political constraints considered (Section 3.4). Finally, we discuss the implications of these findings for climate policy and ongoing research (Section 3.5).

3.2 CARBON PRICING IN THEORY AND PRACTICE

Economists generally conceptualize climate change as a conventional environmental externality caused by emissions of GHGs, which are globally-acting stock pollutants. As such, the traditional economic prescription involves establishing a Pigouvian fee (Pigou 1932) on GHG emissions that corrects for the unpriced externality, either via an emissions tax (Metcalf and Weisbach 2009) or a market-based emissions cap and permit trading mechanism (Coase 1960; Stavins 2008). While there are conceptual and practical differences between CO_2 taxes and emissions trading programmes (Aldy et al. 2010; Weitzman 1974), here we will refer to both instruments collectively as 'carbon pricing policies'. If these instruments successfully establish a carbon price that internalizes the full climate-change-related external damages associated with emissions of CO_2 and other GHGs, the private costs of GHG emitting activities will reflect their marginal social costs, theoretically restoring a level of emissions that is Pareto optimal.

Marginal damage estimates for climate change are expressed in terms of the social cost of CO_2 emissions, or the 'social cost of carbon' (SCC). There is great uncertainty surrounding the true estimate of the SCC, both because damages from climate change under a given level of warming are uncertain and because calculating such figures involves normative judgements such as the appropriate inter-generational discount rate. As shown in Figure 3.1, a review of the literature (Tol 2011) suggests a price on the order of \$75 per tonne CO_2 (tCO_2) in constant 2015 US dollars is necessary in order to internalize the full SCC. The US Environmental Protection Agency also estimates the SCC under different discount rates, which federal agencies apply to estimate the climate benefits of regulations. Average estimates assuming a 3 per cent discount rate increase over the period 2015–50 from \$41 to \$80 per tCO_2 (EPA 2015).

While a variety of jurisdictions have implemented some form of carbon pricing instrument, real-world examples of CO_2 prices that fall squarely within the central range of SCC estimates are few and far between (Figure 3.1). Sweden (\$130 per tCO_2), Switzerland (\$62), Finland (\$47–62, depending on the fuel), and Norway (\$53) are all at the very high end of the spectrum. Each of these nations is relatively wealthy and has abundant supplies of low-carbon

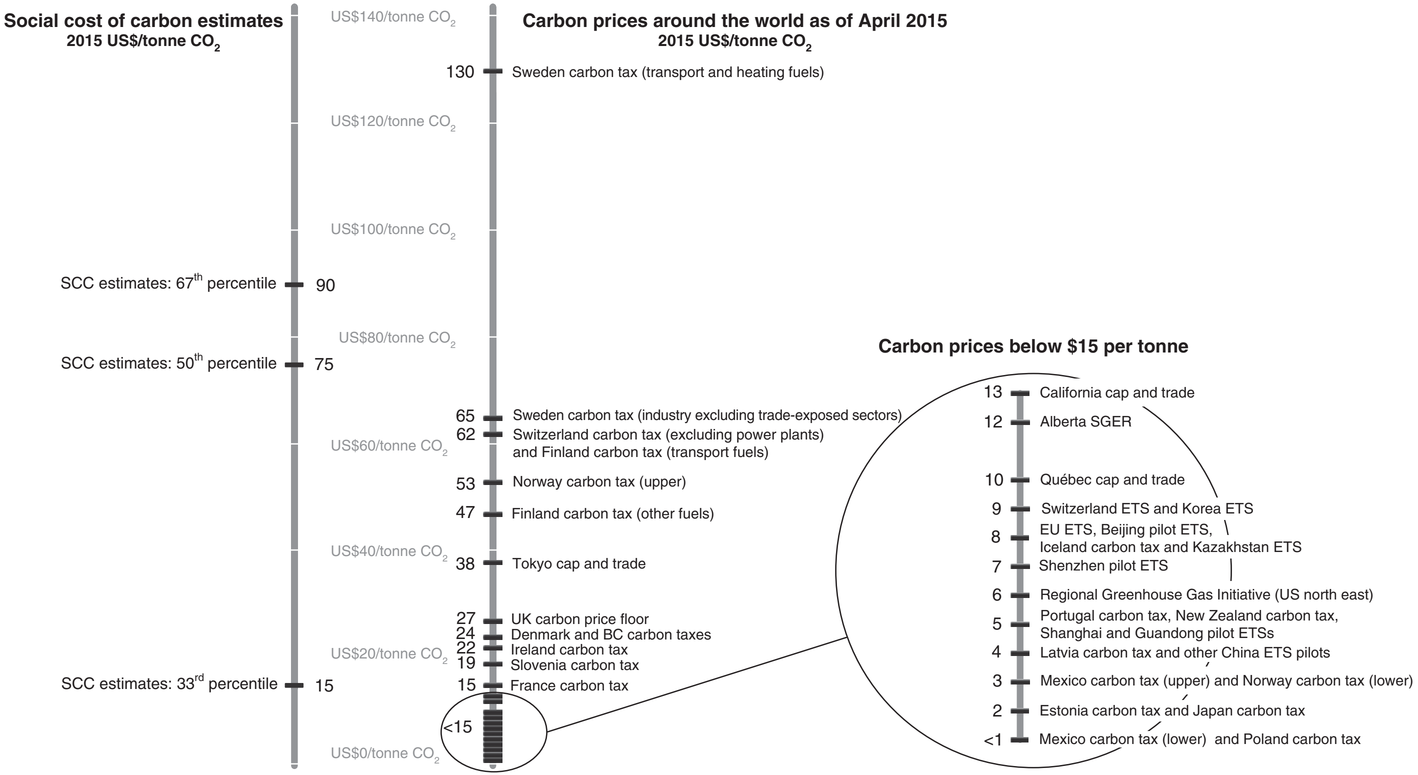

Figure 3.1. CO_2 prices in markets around the world, compared to the social cost of carbon.

Note: Values adjusted to 2015 US dollars; by authors using the US Bureau of Labor Statistics inflation index.

Sources: Authors' illustration. Social cost of carbon estimates from Tol (2011); CO_2 prices from Kossoy et al. (2015).

electricity. Yet even these nations frequently adjust carbon pricing policies in light of political constraints. Sweden, for example, appears to have the highest carbon price in the world. Yet the carbon tax was implemented as part of a series of reforms in 1991 that simultaneously reduced existing energy taxes by 50 per cent. The total effect was to lower overall tax rates on fossil energy consumption (Johansson 2000). Furthermore, Sweden exempts trade-exposed, energy-intensive industries such as pulp-and-paper and mining from the carbon tax entirely, while other industrial emitters pay only half the tax rate. Power plants and district heating are also exempt from the tax and instead fall under the European Union's Emissions Trading System (EU-ETS), which imposes a price of just \$8 per tCO_2 (World Bank 2014). Switzerland similarly allows industrial emitters to opt out of the carbon tax if they participate in the country's own ETS, in which CO_2 permits trade for just \$9 per tonne. Meanwhile, most countries and regions that have implemented CO_2 prices to date have established prices below \$15 per tonne (Kossoy et al. 2015), including the most significant carbon pricing policies established by the world's largest emitters: the EU-ETS, China's ETS pilots, Japan's carbon tax, and two regional programmes in the United States, the US north east's Regional Greenhouse Gas Initiative and California's cap-and-trade programme.

A central premise of this chapter is that political economy constraints explain why the majority of carbon pricing policies around the world today fall well below the central range of estimates of the full social cost of carbon. Any effort to transform the energy system will create economic and political winners and losers, and introducing a CO_2 price is no exception. Climate policy design and instrument choice must therefore contend not only with efficiency concerns, but also with distributional impacts and the resulting implications for political feasibility and durability. Attention to how clever policy design can manage the distributional impacts and costs associated with a clean energy transition while maximizing the efficiency of policy measures is an important (and elusive) challenge.

3.3 MODEL AND SCENARIO IMPLEMENTATION

In this section, we present a stylized model of the energy sector to simulate CO_2 pricing and policy strategies under political economy constraints. The model is based on a single aggregate energy demand function and two energy supply sub-sectors: a CO_2-emitting fossil energy sector and a zero-emissions clean energy sector (e.g., renewable and nuclear energy). For analytical tractability, we assume constant linear slopes for both supply and demand curves.

We further assume the two energy supply sub-sectors are perfectly competitive and are perfect substitutes.

We parameterize the model to roughly approximate the current US energy sector, with 100 Quadrillion British thermal units (Quads) of energy supplied, 80 per cent of which is initially supplied by the fossil energy sub-sector and 20 per cent by the clean energy sub-sector. The initial energy price is \$10 billion per Quad (or \$10 per million British thermal units), yielding an aggregate annual energy expenditure of \$1 trillion. The fossil energy sector emits 5,276 million metric tonnes of CO_2, equivalent to 2013 US energy-related emissions (EIA 2014).

Policy decisions include the level of CO_2 price established, a subsidy per unit of energy supplied by the clean energy sub-sector, and lump-sum transfers to fossil energy producers or energy consumers to compensate for the private welfare impacts of policy decisions. The model is solved to maximize aggregate social welfare over a single time period and is subject to market clearing constraints and one of four stylized representations of commonly-encountered political economy constraints: a direct constraint on the CO_2 price; a constraint on the increase in final energy prices; a constraint on the decrease in net energy consumer surplus; or a constraint on the decrease in net fossil producer surplus. The remainder of this section describes the mathematical formulation of the core model (Section 3.3.1) and the political constraint scenarios explored (Section 3.3.2).

3.3.1 Model Formulation

Energy demand and consumer surplus—The aggregation of household, commercial, and industrial demand for energy is represented as a single aggregate inverse demand function representing the marginal benefit of consumption:

$$MB(q) = d^{-1}(p) = \alpha_d + \beta_d q, \tag{1}$$

where $q = q_f + q_c$ or the sum of both fossil (q_f) and clean (q_c) energy consumed and p is the market clearing price of energy. The marginal benefit of consumption is declining in the quantity consumed ($\beta_d < 0$) and β_d is parameterized based on a plausible initial point estimate of the elasticity of demand. The intercept, α_d, is then set to yield 100 Quads of total consumption in the no-policy case at an initial price of \$10 billion per Quad.

Consumer surplus is then expressed as the cumulative benefit of consumption less expenditures on energy and net of the welfare value of any lump-sum transfers (r_d):

$$CS(q, r_d) = \int_0^q MB(q)dq - pq + \varphi_d r_d = \alpha_d q + \frac{1}{2}\beta_d q^2 - pq + \varphi_d r_d. \tag{2}$$

The parameter φ_d captures the 'efficiency' at which sums are transferred to consumers. If this value is set to 1.0, each unit of revenues transferred to consumers translates directly to one unit of increase in consumer surplus. Alternatively, if $\varphi_d < 1.0$, consumers do not value transfers equivalently to the benefits of consumption, requiring greater lump-sum transfers to offset initial private surplus losses. This parameter can therefore be used to capture loss aversion (Kahneman and Tversky 1984) on the part of consumers.

Fossil energy supply and fossil producer surplus—Fossil energy supplies are represented via a linear marginal cost curve with final cost sensitive to the imposition of a CO_2 price (τ):

$$MC_f(q_f, \tau) = \alpha_f + \tau\rho_f + \beta_f q_f, \tag{3}$$

where ρ_f is the CO_2 emissions rate of fossil energy supply. Marginal costs are increasing with the quantity produced ($\beta_f > 0$) and, as with consumer demand, β_f is parameterized based on an initial point estimate of the elasticity of supply. α_f is then set to yield 80 Quads of total fossil energy production in the no-policy case at an initial price of $10 billion per Quad.

Fossil producer surplus is expressed as the sum of revenues less cumulative production costs and tax payments and net of any lump-sum transfers (r_f):

$$\begin{aligned} PS_f(q_f, \tau, r_f) &= pq_f - \int_0^{q_f} MC(q_f, \tau)dq_f + \varphi_f r_f \\ &= pq_f - \alpha_f q_f - \frac{1}{2}\beta_f q_f^2 - \tau\rho_f q_f + \varphi_f r_f. \end{aligned} \tag{4}$$

As with lump-sum transfers to consumers, φ_f represents the 'efficiency' at which lump-sum transfers to producers offset producer surplus losses due to climate policy decisions.

Clean energy supply and clean producer surplus—Clean energy supply is likewise represented as a linear marginal cost curve with final costs adjusted by a per-unit production subsidy (σ) applied to all clean energy production:

$$MC_f(q_f, \sigma) = \alpha_c - \sigma + \beta_c q_c. \tag{5}$$

Marginal costs are increasing with the quantity produced ($\beta_c > 0$), and β_c is again parameterized based on an initial elasticity of supply with α_c then set to yield 20 Quads of total clean energy production in the no-policy case at an initial price of $10 billion per Quad.

Clean energy producer surplus is the sum of revenues and subsidy payments less cumulative production costs:

$$PS_c(q_c, \sigma) = pq_c - \int_0^{q_c} MC(q_c, \sigma)dq_c = pq_c - \alpha_c q_c - \frac{1}{2}\beta_c q_c^2 + \sigma q_c. \tag{6}$$

Note that this formulation applies subsidies to both inframarginal and marginal clean energy production. A more targeted policy measure could reduce the required revenues by applying to marginal production only, reducing the required revenues (and the total transfer to clean energy producers).

Aggregate supply function—The aggregate supply curve corresponding to the marginal cost of supplying an additional unit of energy is the horizontal sum of fossil and clean energy marginal cost functions:

$$MC_t(q,\tau,\sigma) = \left(\frac{\alpha_c - \sigma}{\beta_c} + \frac{\alpha_f + \tau\rho_f}{\beta_f}\right)\left(\frac{\beta_f\beta_c}{\beta_f + \beta_c}\right) + \left(\frac{\beta_f\beta_c}{\beta_f + \beta_c}\right)q. \tag{7}$$

Government revenues and climate damages—Net government revenues produced by the CO_2 tax after transfers to consumers and fossil producers or used to fund clean energy subsidies contribute to overall welfare as follows:

$$R(r_f, r_d, \sigma, \tau) = \varphi_g(\tau\rho_f q_f - \sigma q_c - r_f - r_d). \tag{8}$$

In this case, $\varphi_g > 1.0$ indicates that government revenues offset other distortionary taxes elsewhere and therefore deliver a 'double dividend' (Goulder 1998), increasing their net impact on social welfare. Alternatively, if net revenues are assumed to be utilized inefficiently, this value can be set such that $\varphi_g < 1.0$.

Climate-related damages associated with CO_2 emissions are a simple function of the quantity of fossil energy supplied:

$$E(q_f) = \eta\rho_f q_f, \tag{9}$$

where η is the full social cost of carbon.

Objective function and constraints—The objective function (10) maximizes total social welfare given as the sum of consumer and producer surplus and the welfare value of government revenues less climate-related damages from CO_2 emissions. The model is subject to equilibrium market clearing constraints (11–12).

$$\begin{aligned} Max\,W(\cdot) = {} & \mathrm{CS}(q, r_d) + PS_f(q_f, \tau, r_f) + PS_c(q_c, \sigma) \\ & + R(r_f, r_d, \sigma, \tau) - E(q_f) \end{aligned} \tag{10}$$

$$s.t. p = MB(q) = MC_t(q) = MC_f(q_f, t) = MC_c(q_c, s) \tag{11}$$

$$q = q_f + q_c. \tag{12}$$

3.3.2 Political Economy Constraint Scenarios and Analytical Solutions

Direct CO_2 price constraint—The first political economy constraint considered is a direct constraint on the level of the CO_2 price of the form:

$$\tau \leq \bar{\tau}, \tag{13}$$

where $\bar{\tau}$ is the maximum politically feasible carbon price level and where $\bar{\tau}<\eta$ (the full SCC).

In this case, social welfare (10) is maximized when the CO_2 price approaches the SCC as closely as possible (i.e., $\tau^* = \bar{\tau}$). However, due to the political economy constraint, the carbon price remains below the full SCC (i.e., $\tau^*<\eta$). Therefore, un-internalized climate-related damages remain, which can be reduced further by using revenues to subsidize clean energy adoption and reduce fossil energy consumption. However, the imposition of a subsidy creates several distortions in the market, including a distortion in total consumption, a distortion in fossil energy production, and a distortion in clean energy production. The optimal clean energy subsidy under this constraint is thus the value that equalizes the marginal increase in deadweight loss due to distortions introduced by the subsidy and the marginal decrease in unpriced external damage from CO_2 emissions due to the reduction in fossil fuel consumption driven by the subsidy. See Jenkins and Karplus (2016) for a full derivation of the optimal subsidy level and analysis of comparative statics for this case.

Energy price constraint—The second political economy constraint we consider is a constraint on the change in the equilibrium energy price after policy decisions. This constraint takes the form:

$$p(\tau, \sigma) \leq p^0(1 + \overline{\Delta p}), \tag{14}$$

where $p(\tau, \sigma)$ is the equilibrium energy price as a function of the CO_2 price and clean energy subsidy policy decisions, p^0 is the equilibrium energy price absent policy intervention (i.e., $p(\tau = 0, \sigma = 0)$), and $\overline{\Delta p}$ is the maximum per cent change in energy price permitted by political economy considerations.

Under such a constraint, a CO_2 pricing instrument alone would be suboptimal. The CO_2 price would be allowed to rise only until it exhausts the political tolerance for energy price increases, internalizing a limited portion of the climate-related externality. In this case, however, welfare could be further improved by combining the carbon price with a clean energy subsidy, which by reducing final energy prices *ceteris paribus*, allows for a larger CO_2 price to be established than would otherwise be possible. At the same time, as in the direct CO_2 price constraint case, the subsidy itself leads to substitution of clean energy for fossil energy, further reducing deadweight loss associated with any remaining unpriced climate externality. The welfare-maximizing CO_2 price and clean energy subsidy level under this constraint is thus the combination that internalizes a greater share of the climate externality and induces further reductions in unpriced damages while balancing these benefits against deadweight loss due to market distortions induced by the clean energy subsidy. Again, see Jenkins and Karplus (2016) for a full derivation of the optimal subsidy level and analysis of comparative statics for this case.

Consumer surplus constraint—Limits on the decrease in energy consumer surplus due to climate policy form an additional political economy constraint, captured in our model as follows:

$$CS(\tau,\ \sigma,\ r_d) \geq CS^0(1-\overline{\Delta CS}), \tag{15}$$

where $CS(\tau,\ \sigma,\ r_d)$ is final consumer surplus as a function of the carbon price and clean energy subsidy decisions and net of any lump-sum transfers, CS^0 is the consumer surplus absent policy intervention, and $\overline{\Delta CS}$ is the maximum per cent change in producer surplus allowed by political economy considerations.

Assuming efficient transfers, the first-best solution is within reach under a constraint of this form. The welfare-maximizing strategy under this constraint is to establish a CO_2 price equal to the full SCC ($\tau^* = \eta$) while offsetting the impact on consumer surplus via lump-sum transfers (r_c). While a clean energy subsidy can also reduce the final impact on consumer surplus by reducing the final energy price paid by consumers, this strategy is less efficient than a lump-sum transfer, as the subsidy introduces several distortions into the market.

In the case that either $\varphi_c < 1.0$ or $\varphi_g > 1.0$, this strategy incurs additional efficiency losses, which must be balanced against the reduction in climate-related deadweight loss that results from relaxing the indirect constraint on carbon prices. If $\varphi_c < 1.0$, representing loss aversion on the part of energy consumers, the most efficient strategy to mitigate the impact on consumer surplus will include a non-zero clean energy subsidy, as the subsidy also mitigates consumer surplus loss by reducing final energy prices. Indeed, the welfare-maximizing strategy when $\varphi_c < 1.0$ would equalize the marginal deadweight loss associated with distortions due to the clean energy subsidy with the deadweight loss associated with the inefficiency of compensatory transfers to consumers. Cases where $\varphi_c < 1.0$ could therefore also be considered a hybrid of the energy price and consumer surplus constraints.

Fossil producer surplus constraint—The final political economy constraint we consider is a constraint on the decline in fossil energy producer surplus induced by climate policy decisions:

$$PS_f(\tau,\ \sigma,\ r_f) \geq PS_f^0(1-\overline{\varDelta PS_f}), \tag{16}$$

where $PS_f(\tau,\ \sigma,\ r_f)$ is final fossil producer surplus as a function of carbon tax and clean energy subsidy decisions and net of any lump-sum transfers, PS_f^0 is the producer surplus absent policy intervention, and $\overline{\Delta PS_f}$ is the maximum per cent change in producer surplus allowed by political economy considerations.

As with the consumer surplus constraint, assuming transfers are frictionless, the welfare-maximizing strategy is to impose a CO_2 price equal to the full SCC ($\tau^* = \eta$) while compensating fossil energy producers as required to satisfy the political economy constraint via lump-sum transfers (r_f). As a clean energy subsidy would only further reduce fossil producer surplus and introduce market distortions, $\sigma^* = 0$ under this constraint.

Again, if either $\varphi_f < 1.0$ or $\varphi_g > 1.0$, transfers to producers incur additional welfare losses. In this case, the optimal transfer would equalize the marginal reduction in climate-related deadweight loss achieved by offsetting producer surplus impacts and relaxing the indirect constraint on the carbon price on the one hand, and the marginal deadweight loss associated with the inefficiency of compensatory payments and the impact of distortionary taxes elsewhere in the economy on the other.

3.4 RESULTS

In this section, we present results for a numerical simulation using the model presented in Section 3.3. To demonstrate the mechanisms by which strategic allocation of carbon pricing revenues achieves superior performance, we compare two cases for each of the four political constraint scenarios defined in Section 3.3.2. a case in which a CO_2 price is introduced and all revenues collected are retained by the state, and a case in which some portion of the revenues from the CO_2 charge are used to achieve either additional CO_2 reductions by subsidizing clean energy or to offset the burden on producers or consumers through government transfers. Figures 3.2 and 3.3 demonstrate the improvement in total welfare and CO_2 emissions reductions, respectively, under each of the four forms of political economy constraints considered herein.

In all cases, we assume the full SCC is \$75 per tCO_2 (as per the median estimate from Figure 3.1), initial elasticities of demand and supply of -0.8 and 0.8 respectively, and that φ_g, φ_f and φ_c equal 1.0 (i.e., all transfers are frictionless). See Jenkins and Karplus (2016) for analysis of the sensitivity of outcomes to alternative values for the price elasticities of supply and demand.

3.4.1 Direct Constraint on the CO_2 Price

In a world where the politically-feasible CO_2 price remains below the full SCC, using revenues to subsidize clean energy results in additional welfare gain and

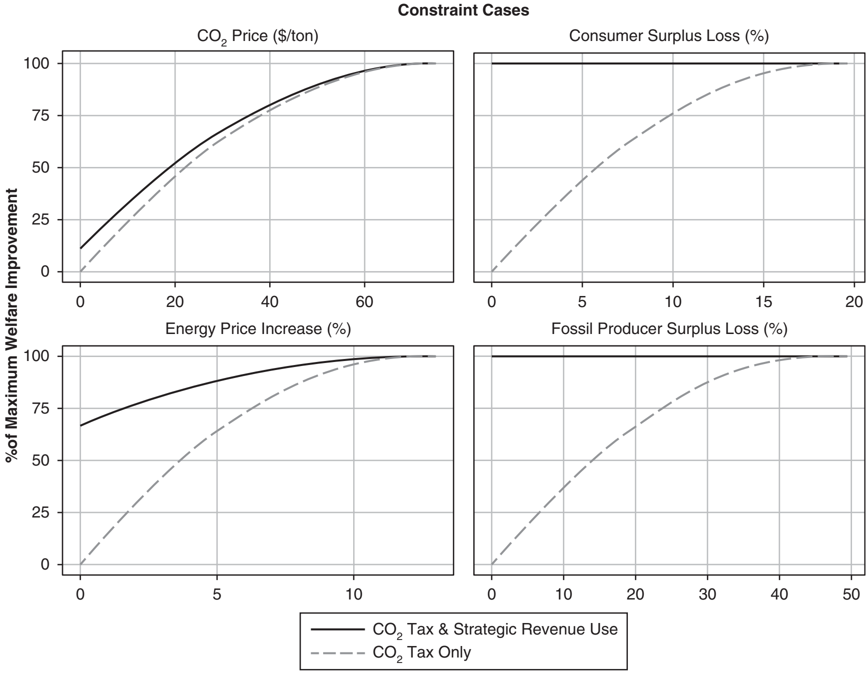

Figure 3.2. Total welfare gain under four political constraint scenarios.
Source: Authors' analysis and illustration.

CO_2 emissions reduction, relative to the constrained no-subsidy case, as shown in Figures 3.2 and 3.3. The largest welfare gains from the subsidy occur when the CO_2 price constraint binds at low levels. In the absence of any carbon price at all, the welfare-maximizing clean energy subsidy achieves 11 per cent of the maximum reduction in CO_2 and improvement in welfare achievable under the first-best carbon pricing level, given these parameters. If the allowable carbon tax is constrained at very low levels, funding the optimal clean energy subsidies may require additional revenues from elsewhere in government budgets, and the policy as a whole will be revenue consuming (see Figure 3.5). When the CO_2 price rises, the welfare and emissions performance improvements from the clean energy subsidy decline. This is because the optimal subsidy level decreases as the damages associated with emissions are steadily internalized by the carbon price. In all cases, a non-zero subsidy improves overall welfare unless the carbon price equals the full SCC. In addition, as revenues from the tax increase, the optimal policy becomes revenue generating (see Figure 3.5).

The direct constraint on CO_2 prices is in many ways the most challenging constraint to overcome via the strategic use of carbon pricing revenues.

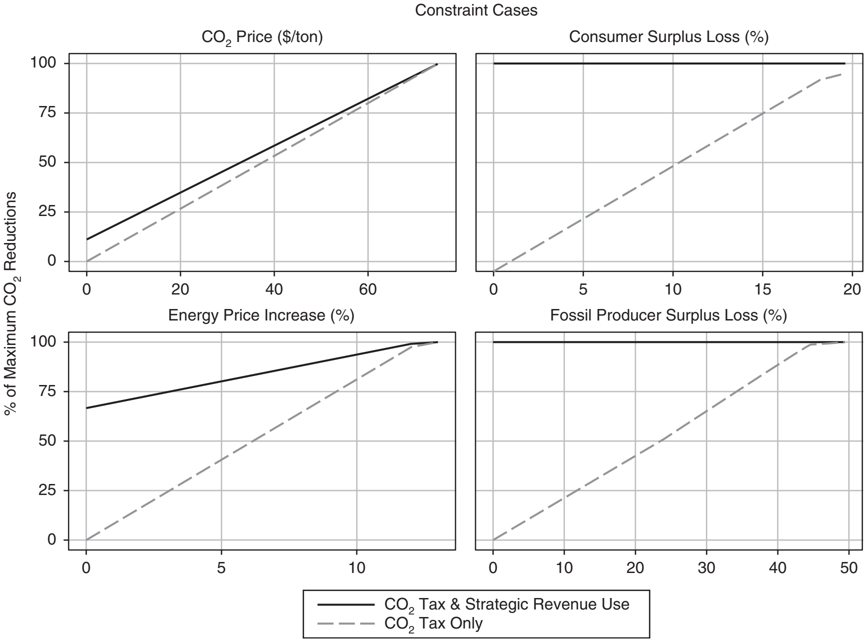

Figure 3.3. Total CO_2 emissions under four political constraint scenarios.

Source: Authors' analysis and illustration.

Subsidizing clean energy in this case does not *relax* the constraint itself, but merely compensates for the low carbon price by delivering additional abatement. However, this abatement comes at the cost of economic distortions introduced by the subsidy, delivering relatively modest improvements in overall welfare. By contrast, under the other constraints, use of revenues not only generates additional abatement but also directly relaxes the constraint itself, allowing for higher carbon prices to be achieved than would otherwise be possible.

3.4.2 Constraint on Final Energy Price Increases

Under a constraint on the allowable energy price increase, employing carbon pricing revenues to subsidize clean energy enables a significantly higher price of CO_2, as demonstrated in Figure 3.4. As clean energy subsidies reduce final energy prices, *ceteris paribus*, deploying revenues to subsidize clean energy alternatives effectively relaxes the constraint on the energy price increase. For example, using clean energy subsidies to offset the rising costs of energy enables a carbon price of $35 per tCO_2 even when only a negligible increase

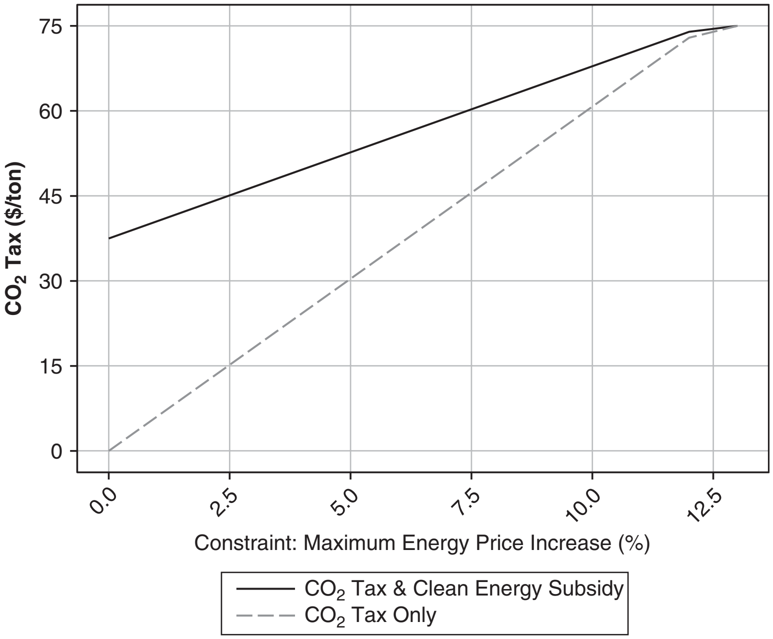

Figure 3.4. CO_2 price achieved under binding constraint on energy price increases, with and without employing revenues to subsidize clean energy.

Source: Authors' analysis and illustration.

in final energy prices is permitted. In addition, as in the carbon price constraint case, the clean energy subsidy drives additional abatement that would not be achieved via the carbon price alone, further improving overall welfare. These benefits again trade off against the deadweight loss due to distortions induced by the clean energy production subsidy.

In combination, the carbon price and clean energy subsidy deliver much greater CO_2 reductions than a carbon price alone, especially when the energy price increase is constrained at low levels (Figure 3.3). Given the parameters assumed here, nearly two-thirds of the optimal reduction in CO_2 emissions can be achieved without increasing final energy prices at all. Employing revenues to fund clean energy subsidies improves the environmental performance of the policy intervention until the full social cost of carbon is internalized. Overall welfare improves similarly when revenues are used to subsidized clean energy production, achieving two-thirds of the optimal welfare gain even when no increase in energy prices is permitted, rising to nearly 90 per cent when a 5 per cent increase in final energy prices is tolerated (Figure 3.2).

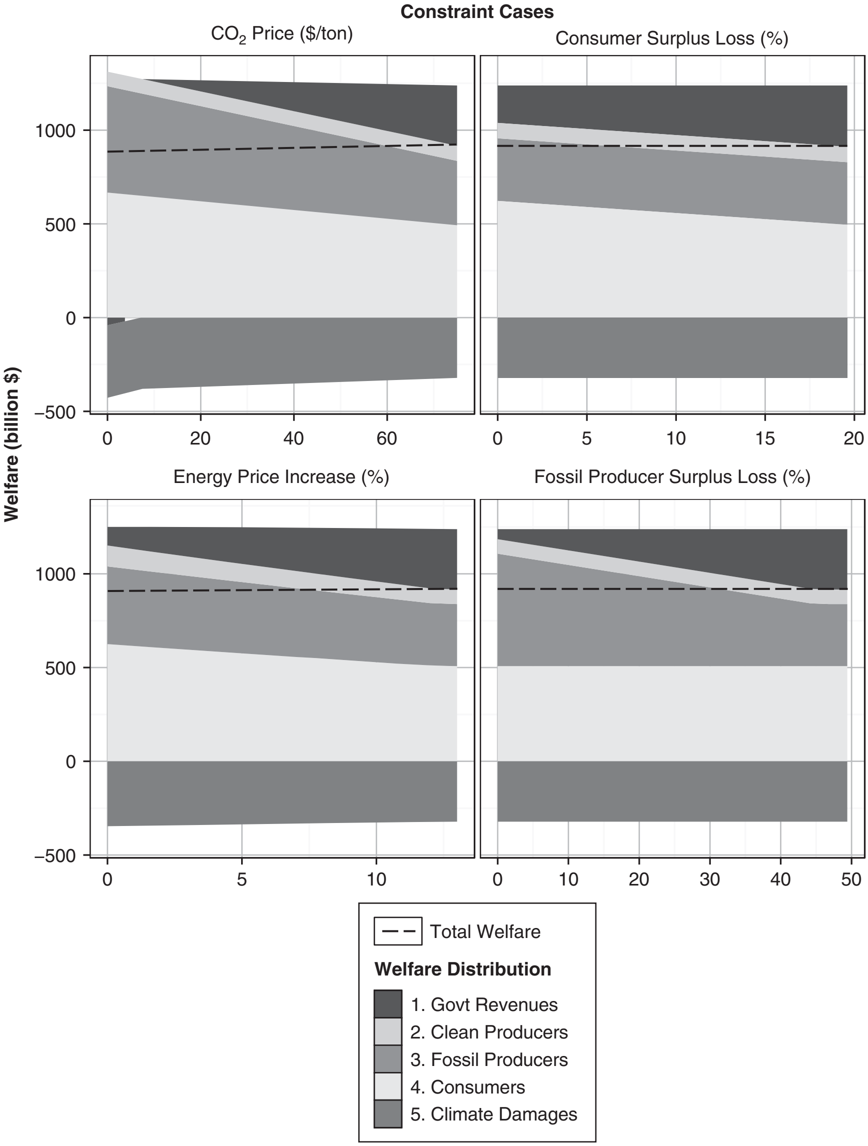

Figure 3.5. Disposition of welfare under four political constraint scenarios.
Source: Authors' analysis and illustration.

3.4.3 Constraints on Net Energy Consumer and Fossil Producer Surplus Loss

Unlike the prior cases, where political constraints continue to result in a second-best CO_2 pricing level, redistributing carbon revenues as lump-sum transfers allows the private surplus losses for energy consumers or fossil producers to be fully offset. As a result, under constraints on consumer or producer surplus loss, the strategic use of revenues makes the optimal carbon price immediately feasible, provided transfers are frictionless and available funds are sufficient. When compensatory transfers are utilized, the CO_2 externality can be fully internalized, maximizing welfare (Figure 3.2) and driving optimal CO_2 emissions levels for all values of the constraint (Figure 3.3). In contrast, if compensatory transfers are not employed, the available CO_2 price rises linearly under this form of constraint as the allowable consumer or producer surplus loss increases, and welfare and emissions outcomes are similarly constrained.

Importantly, this first-best outcome depends on lump-sum transfers being frictionless and consumers and producers exhibiting no loss aversion, two assumptions which in practice may be unrealistic. These results thus raise three important questions: 1) what is the real loss, if any, due to frictions or administrative overhead, which would reduce the efficiency of transfers; 2) what is the opportunity cost of using revenues for transfers rather than to reduce other distortive government taxes; and 3) what is the additional compensation, if any, demanded by loss-averse consumers and producers (i.e., do recipients of transfers demand more than a dollar of compensation to offset each dollar of foregone surplus)? Our framework provides a way to consider transfer inefficiency and loss aversion in calculations of deadweight loss, which will have implications for the optimal CO_2 price, CO_2 emissions abatement, and distribution of welfare impacts. We will leave a full analysis of these implications for future work.

3.4.4 Disposition of Welfare

As Figure 3.5 illustrates, the distribution of welfare under the four political economy constraint cases differs significantly. As one might expect, consumers and fossil producers are best off under the respective cases where political constraints motivate direct transfers to offset any surplus losses they incur due to policy intervention. At the same time, consumers are almost equally well off when revenues are used to subsidize clean energy in the face of a constraint on energy price increases. Here, clean energy subsidies drive incremental substitution of clean for dirty energy and keep final energy prices low, insulating energy consumers from welfare losses. Similarly, as total reductions in fossil energy use are modest under the case where the CO_2 price is directly constrained, fossil producers are nearly as well off in this case as they are under the direct constraint on fossil producer losses. Political constraints on the carbon price or energy price increases may therefore be interpreted as the indirect expression of concern about producer or consumer surplus losses, respectively, particularly in cases where consumers and producers exhibit significant loss aversion and thus view compensatory payments in an inferior light.

Clean energy market share and the growth of clean energy producer surplus is most significant under the energy price constraint (Figure 3.5). If the size and relative economic importance of clean energy production sectors positively affects the political durability of coalitions that support climate mitigation policy and increases tolerance for future increases in carbon prices, combining a carbon price with subsidies for clean energy producers may yield additional dynamic benefits. Similarly, incrementally higher deployment of clean energy in the near term could drive learning-by-doing, economies of scale, or induced research and innovation, decreasing the cost of clean energy supply in the future, although the magnitude of these benefits is uncertain. Over time, the result would be greater mitigation at a given cost, an important dynamic benefit to consider.

3.5 CONCLUSION AND IMPLICATIONS FOR POLICY AND RESEARCH

Global experience to date suggest that the distributional impacts of carbon pricing policies on energy producers and consumers make it difficult to legislate CO_2 price levels needed to fully internalize the climate change externality. This reality points to two important ongoing agendas for research: one aimed at improving on existing estimates of the social cost of carbon and evaluating the impacts of fully internalizing these damages through CO_2 pricing, and another that starts from the presently feasible set of alternatives, taking political constraints as binding in the near term, and evaluates options for improving welfare and expanding this feasible set over time. In the latter case, the goal is to identify policy designs that are not too distant from the efficient frontier and that alter the relative influence of actors in ways that support gradual convergence towards a socially optimal CO_2 price. Although methods for estimating the SCC are still hotly debated, as long as prevailing CO_2 prices remain below the lower end of the SCC range, as they do in many CO_2 pricing systems at present, focusing on political constraints is important to answering the critical question: how do we begin to address climate change-related externalities as efficiently and effectively as possible given today's political realities?

In this analysis, we investigated the impact of four different political economy constraints on carbon pricing, focusing on how the stringency of the constraints affect the welfare gain associated with alternative uses of CO_2

price revenues. We find that in all cases, using revenues to subsidize additional abatement or offset private surplus loss improves total welfare, relative to a constrained case where revenues are simply used for general government purposes. We show that compensating for a direct constraint on the CO_2 price delivers modest gains, because the benefits associated with additional abatement are offset by deadweight loss resulting from over-consumption induced by clean energy subsidies. In this respect, a constraint on the absolute level of the CO_2 price constitutes the most restrictive case. By contrast, greater welfare gains are possible under a constraint on energy price increases, as carbon pricing revenues can be used to subsidize clean energy and keep final energy prices low, allowing a higher carbon price to be achieved than would otherwise be possible. Indeed, when revenues are deployed to subsidize clean energy, a substantial CO_2 price is possible even if no increase in final energy prices is tolerated at all. Finally, using revenues to offset consumer and producer surplus loss supports a return to optimal CO_2 price levels and a first-best solution—with the important caveat that compensatory transfers must be frictionless and consumers and producers do not exhibit loss aversion.

While the analysis presented herein develops intuition about how constraints function individually and in an idealized context, reality is inevitably more complex. An important question for decision-makers and political scientists involves establishing which political economy constraints bind in the jurisdiction in question and through which mechanisms they operate. In practice, multiple political economy constraints may bind at the same time—for example, a high CO_2 price may be unavailable because covered parties are concerned about the resulting energy price increase, or the magnitude of the impact on consumer and producer surplus, or all of these. In the face of multiple political economy constraints, one potential solution would be to dip into government budgets to further subsidize CO_2 abatement or to offset reductions in consumer and producer surplus. However, this option requires careful consideration of the opportunity cost of channelling additional funds to relieve political economy constraints, as potential second-best solutions will compete with each other, and with other possible uses of public funds, for available government revenues. Ultimately, the political feasibility of this path is constrained by public decision-making on appropriate spending priorities, and the nature of the climate change problem is such that near-term public investments with more concrete benefits may be preferred.

Our analysis shows that it is possible to achieve the first-best CO_2 price if revenues can be used to offset consumer and producer surplus losses. In reality, however, none of the transfers discussed here are likely to be frictionless. It is important therefore to also understand the real and perceived value of these transfers to recipients and the general equilibrium implications of changes in government revenues. Transfers to support clean energy subsidies may also have associated frictions, which will magnify the relative inefficiency of the subsidy. On the other hand, more targeted subsidies which only apply to supra-marginal suppliers could reduce the overall revenues required to drive clean energy adoption and associated mitigation, an important consideration in cases where subsidy programmes entail additional efficiency losses (i.e., due to foregone opportunities to reduce other distortionary taxes). The nature and magnitude of these frictions and their efficiency implications will be specific to particular contexts, increasing the importance of understanding and quantifying their impact on interests and incentives.

The main objective of this exercise was to put an analytical framework around the question of how we can get started down a relatively efficient path to a lower carbon world. The answer will be different, depending on the unique political economy of the climate issue across nations and regions. We conclude by briefly illustrating the guidance this framework would offer policy-makers under different prevailing political constraints.

First, in jurisdictions without significant domestic fossil energy production sectors, political constraints are likely to centre on concerns about the impact of climate mitigation policies on household incomes and the economic competitiveness of domestic industries. In such cases, the prevailing constraint is likely to be the unwillingness of energy consumers to bear the burden of higher energy prices and associated surplus loss. Our results suggest that an effective policy strategy in the face of such constraints would be to establish a carbon price while employing revenues to make clean energy cheaper and mitigate the impact on final energy prices (i.e., via subsidies). Any remaining politically-salient losses to energy consumers could be offset with lump-sum transfers as needed (e.g., to trade-exposed industries or low-income households).

Second, in jurisdictions where influential fossil energy producers and industrial energy consumers are aligned in opposition to CO_2 pricing, neutralizing opposition from industrial energy consumers by subsidizing clean energy adoption and keeping energy input prices low could remove a major barrier to CO_2 pricing, while allowing the CO_2 price to rise to a meaningful level. Remaining resistance from the fossil energy industry could then be addressed through transfer payments—either taken from CO_2 price revenues or elsewhere in the government budget. This strategy may be most viable in jurisdictions with strong domestic fossil energy sectors and relatively large energy-intensive industrial sectors, such as steel, aluminum, concrete, or pulp and paper production.

Under either case, if political constraints relax over time, whether as an endogenous outcome of policy or a shift in stakeholder preferences, CO_2 prices could rise towards the full social cost of carbon, achieving further welfare gains. The dynamic impacts of near-term policy decisions on political constraints over time is thus an additional key consideration worthy of future research. For example, encouraging near-term deployment of clean energy to an extent that realizes benefits from scale economies, learning, and a growing clean energy constituency with a strong interest in its own continued survival and growth could have significant impacts on the political durability of climate policy over time.

Clean energy transitions will inevitably create winners and losers. The scenarios and analysis presented herein suggest illustrative paths by which the costs and distributional impacts of a clean energy transition could be smoothed over time, gradually nudging the possible in the direction of the optimal.

REFERENCES

Aldy, J. E., A. J. Krupnick, R. G. Newell, I. W. H. Parry, and W. A. Pizer (2010). 'Designing Climate Mitigation Policy'. *Journal of Economic Literature*, 48(4): 903–34.

Arrow, K. J. (1970). *Social Choice and Individual Values*. Second Edition. New Haven, CT: Yale University Press.

Black, D. (1987). *The Theory of Committees and Elections*. Dordrecht: Springer.

Bovenberg, A. L., L. H. Goulder, and D. J. Gurney (2005). 'Efficiency Costs of Meeting Industry Distributional Constraints under Environmental Permits and Taxes'. *RAND Journal of Economics*, 36(4): 951–71.

Buchanan, J. and G. Tullock (1999). *The Calculus of Consent*. Collected Edition. Indianapolis, IN: Liberty Fund, Inc.

Burtraw, D., K. Palmer, R. Bharvirkar, and A. Paul (2002). 'The Effect on Asset Values of the Allocation of Carbon Dioxide Emission Allowances'. *The Electricity Journal*, 15(5): 51–62.

Coase, R. H. (1960). 'The Problem of Social Cost'. *Journal of Law and Economics*, 3: 1–44.

Downs, A. (1957). *An Economic Theory of Democracy*. First Edition. New York: Harper and Row.

EIA (2014). 'U.S. Energy-Related Carbon Dioxide Emissions, 2013'. US Energy Information Administration.

Eisenhardt, K. M. (1989). 'Agency Theory: An Assessment and Review'. *The Academy of Management Review*, 14(1): 57–74.

EPA (Environmental Protection Agency) (2015). 'Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis'. US Environmental Protection Agency.

Gawel, E., S. Strunz, and P. Lehmann (2014). 'A Public Choice View on the Climate and Energy Policy Mix in the EU—How Do the Emissions Trading Scheme and Support for Renewable Energies Interact?' *Energy Policy*, 64: 175–82.

Goulder, L. H. (1998). 'Environmental Policy Making in a Second-Best Setting'. *Journal of Applied Economics*, 1(2): 279.

IPCC (Intergovernmental Panel on Climate Change) (2014). 'Climate Change 2014: Impacts, Adaptation, and Vulnerability'. IPCC, Geneva.

Jenkins, J. D. (2014). 'Political Economy Constraints on Carbon Pricing Policies: What Are the Implications for Economic Efficiency, Environmental Efficacy, and Climate Policy Design?' *Energy Policy*, 69: 467–77.

Jenkins, J. D. and V. J. Karplus (2016). 'Carbon Pricing under Binding Political Constraints'. UNU-WIDER Working Paper No. 44/2016. Available at: <https://www.wider.unu.edu/publication/carbon-pricing-under-binding-political-constraints> (accessed 12 October 2016).

Johansson, B. (2000). 'Economic Instruments in Practice 1: Carbon Tax in Sweden'. OECD Workshop on Innovation and the Environment, Paris, 19 June.

Johnson, E. and G. F. Nemet (2010). 'Willingness to Pay for Climate Policy: A Review of Estimates'. University of Wisconsin-Madison, La Follette School Working Paper No. 2010-011.

Kahneman, D. and A. Tversky (1984). 'Choices, Values, and Frames'. *American Psychologist*, 39(4): 341–50.

Karplus, V. J. (2011). 'Climate and Energy Policy for U.S. Passenger Vehicles: A Technology-Rich Economic Modeling and Policy Analysis'. PhD Thesis, Massachusetts Institute of Technology.

Kossoy, A., G. Peszko, K. Oppermann, N. Prytz, A. Gilbert, N. Klein, L. Lam, and L. Wong (2015). 'Carbon Pricing Watch 2015'. World Bank Group.

Kotchen, M. J., K. J. Boyle, and A. A. Leiserowitz (2013). 'Willingness-to-Pay and Policy-Instrument Choice for Climate-Change Policy in the United States'. *Energy Policy*, 55: 617–25.

Lipsey, R. G. and K. Lancaster (1956). 'The General Theory of Second Best'. *The Review of Economic Studies*, 24(1): 11–32.

Metcalf, G. E. and D. Weisbach (2009). 'The Design of a Carbon Tax'. *Harvard Environmental Law Review*, 33(2): 499–556.

Nordhaus, W. D. (1992). 'An Optimal Transition Path for Controlling Greenhouse Gases'. *Science (New York, N.Y.)*, 258(5086): 1315–19.

Olson, M. (1984). *The Rise and Decline of Nations: Economic Growth, Stagflation, and Social Rigidities*. New Haven, CT, and London: Yale University Press.

Pigou, A. C. (1932). *The Economics of Welfare*. Fourth Edition. London: Macmillan.

Rausch, S. and V. J. Karplus (2014). 'Markets versus Regulation: The Efficiency and Distributional Impacts of U.S. Climate Policy Proposals'. *The Energy Journal*, 35(1): 199–228.

Stavins, R. N. (1997). 'Policy Instruments for Climate Change: How Can National Governments Address a Global Problem?' *The University of Chicago Legal Forum*, 6: 293–329.

Stavins, R. N. (2008). 'Addressing Climate Change with a Comprehensive US Cap-and-Trade System'. *Oxford Review of Economic Policy*, 24(2): 298–321.

Stern, N. (2007). *The Stern Review on the Economics of Climate Change*. Cambridge: Cambridge University Press.

Stigler, G. J. (1971). 'The Theory of Economic Regulation'. *The Bell Journal of Economics and Management Science*, 2(1): 3–21.

Tol, R. S. (2011). 'The Social Cost of Carbon'. *Annual Review of Resource Economics*, 3(1): 419–43.

Weitzman, M. L. (1974). 'Prices vs. Quantities'. *Review of Economic Studies*, 41(January): 477–91.

World Bank (2014). 'Putting a Price on Carbon with a Tax'. World Bank.

Joint Program Reprint Series - Recent Articles

For limited quantities, Joint Program publications are available free of charge. Contact the Joint Program office to order.
Complete list: http://globalchange.mit.edu/publications

2017-23 Carbon Pricing under Political Constraints: Insights for Accelerating Clean Energy Transitions. Karplus, V.J. and J. Jenkins, Chapter 3 in: *The Political Economy of Clean Energy Transitions*, D. Arent, C. Arent, M. Miller, F. Tarp, O. Zinaman (eds.), UNU-WIDER/Oxford University Press, Helsinki, Finland (2017)

2017-22 "Climate response functions" for the Arctic Ocean: a proposed coordinated modelling experiment. Marshall, J., J. Scott and A. Proshutinsky, *Geoscientific Model Development* 10: 2833–2848 (2017)

2017-21 Aggregation of gridded emulated rainfed crop yield projections at the national or regional level. Blanc, É., *Journal of Global Economic Analysis* 2(2): 112–127 (2017)

2017-20 Historical greenhouse gas concentrations for climate modelling (CMIP6). Meinshausen, M., E. Vogel, A. Nauels, K. Lorbacher, N. Meinshausen, D. Etheridge, P. Fraser, S.A. Montzka, P. Rayner, C. Trudinger, P. Krummel, U. Beyerle, J.G. Cannadell, J.S. Daniel, I. Enting, R.M. Law, S. O'Doherty, R.G. Prinn, S. Reimann, M. Rubino, G.J.M. Velders, M.K. Vollmer, and R. Weiss, *Geoscientific Model Development* 10: 2057–2116 (2017)

2017-19 The Future of Coal in China. Zhang, X., N. Winchester and X. Zhang, *Energy Policy,* 110: 644–652 (2017)

2017-18 Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide. Kearns, J., G. Teletzke, J. Palmer, H. Thomann, H. Kheshgi, H. Chen, S. Paltsev and H. Herzog, *Energy Procedia*, 114: 4697–4709 (2017)

2017-17 An aerosol activation metamodel of v1.2.0 of the pyrcel cloud parcel model: development and offline assessment for use in an aerosol–climate model. Rothenberg, D. and C. Wang, *Geoscientific Model Development,* 10: 1817–1833 (2017)

2017-16 Role of atmospheric oxidation in recent methane growth. Rigby, M., S.A. Montzka, R.G. Prinn, J.W.C. White, D. Young, S. O'Doherty, M. Lunt, A.L. Ganesan, A. Manning, P. Simmonds, P.K. Salameh, C.M. Harth, J. Mühle, R.F. Weiss, P.J. Fraser, L.P. Steele, P.B. Krummel, A. McCulloch and S. Park, *Proceedings of the National Academy of Sciences,* 114(21): 5373–5377 (2017)

2017-15 A revival of Indian summer monsoon rainfall since 2002. Jin, Q. and C. Wang, *Nature Climate Change,* 7: 587–594 (2017)

2017-14 A Review of and Perspectives on Global Change Modeling for Northern Eurasia. Monier, E., D. Kicklighter, A. Sokolov, Q. Zhuang, I. Sokolik, R. Lawford, M. Kappas, S. Paltsev and P. Groisman, *Environmental Research Letters,* 12(8): 083001 (2017)

2017-13 Is Current Irrigation Sustainable in the United States? An Integrated Assessment of Climate Change Impact on Water Resources and Irrigated Crop Yields. Blanc, É., J. Caron, C. Fant and E. Monier, *Earth's Future*, 5(8): 877–892 (2017)

2017-12 Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios. Kim, J.B., E. Monier, B. Sohngen, G.S. Pitts, R. Drapek, J. McFarland, S. Ohrel and J. Cole, *Environmental Research Letters*, 12(4): 045001 (2017)

2017-11 Climate model uncertainty in impact assessments for agriculture: A multi-ensemble case study on maize in sub-Saharan Africa. Dale, A., C. Fant, K. Strzepek, M. Lickley and S. Solomon, *Earth's Future* 5(3): 337–353 (2017)

2017-10 The Calibration and Performance of a Non-homothetic CDE Demand System for CGE Models. Chen, Y.-H.H., *Journal of Global Economic Analysis* 2(1): 166–214 (2017)

2017-9 Impact of Canopy Representations on Regional Modeling of Evapotranspiration using the WRF-ACASA Coupled Model. Xu, L., R.D. Pyles, K.T. Paw U, R.L. Snyder, E. Monier, M. Falk and S.H. Chen, *Agricultural and Forest Meteorology*, 247: 79–92 (2017)

2017-8 The economic viability of Gas-to-Liquids technology and the crude oil-natural gas price relationship. Ramberg, D.J., Y.-H.H. Chen, S. Paltsev and J.E. Parsons, *Energy Economics*, 63: 13–21 (2017)

2017-7 The Impact of Oil Prices on Bioenergy, Emissions and Land Use. Winchester, N. and K. Ledvina, *Energy Economics*, 65(2017): 219–227 (2017)

2017-6 The impact of coordinated policies on air pollution emissions from road transportation in China. Kishimoto, P.N., V.J. Karplus, M. Zhong, E. Saikawa, X. Zhang and X. Zhang, *Transportation Research Part D*, 54(2017): 30–49 (2017)

2017-5 Twenty-First-Century Changes in U.S. Regional Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. Gao, X., C.A. Schlosser, P.A. O'Gorman, E. Monier and D. Entekhabi, *Journal of Climate*, online first, doi: 10.1175/JCLI-D-16-0544.1 (2017)

2017-4 The CO_2 Content of Consumption Across U.S. Regions: A Multi-Regional Input-Output (MRIO) Approach. Caron, J., G.E. Metcalf and J. Reilly, *The Energy Journal*, 38(1): 1–22 (2017)

2017-3 Human Health and Economic Impacts of Ozone Reductions by Income Group. Saari, R.K., T.M. Thompson and N.E. Selin, *Environmental Science & Technology*, 51(4): 1953–1961 (2017)

2017-2 Biomass burning aerosols and the low-visibility events in Southeast Asia. Lee, H.-H., R.Z. Bar-Or and C. Wang, *Atmospheric Chemistry & Physics*, 17, 965–980 (2017)

2017-1 Statistical emulators of maize, rice, soybean and wheat yields from global gridded crop models. Blanc, É., *Agricultural and Forest Meteorology,* 236, 145–161 (2017)

MIT Joint Program on the Science and Policy of Global Change

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge MA 02139-4307 (USA)

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu