Regulating Polluting Monopolies from an Equity-Efficiency Perspective

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Abstract

Motivated by environmental justice concerns, we study the regulation of polluting monopolies from an equity-efficiency perspective. People vary by their level of consumption, emissions exposure, share of monopoly profit, and welfare weight. We characterize sufficient statistics equations for the optimal price and pollution tax, and show that their deviation from efficiency results can be attributed to two forces: the incidence of environmental harm and the distributional impact of a price or tax change. Applying our model to the residential electricity market, we find that the dominant equity consideration is the distributional incidence of producer and consumer surplus associated with a price change, resulting in an optimal price as much as 12.7% *below* the efficient one.

*Advised by Professor Jesse Shapiro.

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1 Introduction

Central to addressing climate change is the problem of equity: equity between people and planet, current and future generations, and across socioeconomic groups. The former two have been the focus of modern environmental economics. Nordhaus' seminal work on carbon taxation enables us to estimate societal values for the welfare of future generations and loss of biodiversity and natural landscapes ([19], [20]). However, the last inequality, among groups of people, has had comparatively little economic study. Today, many of the most pollution-intensive sites are in some of the nation's most vulnerable communities. "Cancer Alley" Louisiana is home to a quarter of US petrochemical plants and contains two cities—New Orleans and Baton Rouge—with poverty rates twice the national average [12].[1] There is growing knowledge that environmental harm is not distributionally neutral (see eg, [24], [13]).[2] Moreover, as we transition our economy from fossil fuels to cleaner and, in the near-term, more expensive energy forms, many have voiced a potential affordability concern whereby low-income people may not be able to purchase energy to meet their needs. Therefore, the task of environmental economics is both one of efficiency, reducing harm to the economy and natural environment, and equity, limiting the spatial and socioeconomic inequalities that such markets give rise to.

The tension between the regressive nature of many environmental markets and

[1] According to the US Census Bureau, the poverty rate is 11.5% nationally, 24% in Baton Rouge, and 22.9% in New Orleans.

[2] This is expressed nicely by environmental lawyer Richard Lazarus, who reflects, "[I]f left to the normal workings of political, economic, and social forces... environmental laws could make society as a whole [lot] better off but still harm racial minorities and the poor."[18]

inequities in externality exposure lies at the heart of many environmental policy questions and is particularly important in the case of polluting monopolies. On the one hand, pollution may disproportionately impact vulnerable groups. In the United States racial minorities are disproportionately exposed to PM2.5 pollution and are more likely to live near toxic Superfund sites than their white counterparts ([13], [16]). To prevent more damage accruing to vulnerable groups, accounting for the distributional impacts of externalities would raise the optimal market price. On the other hand, many worry that charging higher prices will harm low-income consumers. In the United States, people often discuss an energy burden, the fact that poorer people spend more of their income on electricity, gas, and oil [4]. Similarly, efforts to set a national gas tax in France were opposed by low and middle-income individuals who viewed the tax as unfair and regressive since many rural workers commuted long distances to city work [6]. Concerns about protecting low-income consumers would induce a lower price. Some of the most central environmental markets—from residential electricity to waste to commercial aviation—are natural monopolies and oligopolies due to high entry costs. These distributional considerations are magnified under imperfect competition since exercising market power often raises price (thus decreasing pollution) but by a means even more regressive than taxation in a competitive market. Thus, for all environmental markets (and polluting monopolies especially), distributional considerations regarding pollution exposure and impacts on low-income consumers are potentially at odds with one another. In the case of the French gas tax, a policymaker might ask: Is a gas tax truly regressive, and if so, how would this change the optimal tax? In the case of US energy sales, a policymaker may ask: How can we balance the need to protect vulnerable communities and avoid undue household financial stress? These questions do not lend themselves to clear answers without formal theoretical and empirical work.

For governments facing the question of how to regulate polluting monopolies the challenges are two-fold: (1) we do not know ex-ante how taking distributional considerations into account would impact the optimal level of market activity relative to an analysis without distributional concerns, and (2) it is not clear how to computationally evaluate such forces. On this first issue, environmental markets often disproportionately impact vulnerable people, raising the optimal price and tax. We call this the *externality burden*. Conversely, higher taxes and prices harm consumers. Thus, if vulnerable people make up a large share of the consumer base, this lowers the optimal price and tax. We call this the *consumer burden*. However, to understand which effect—the externality or consumer burden—dominates, we require a tractable way to reason about their relative magnitudes. On the second issue, specifying welfare weights means making assumptions about society's willingness to redistribute across people, an almost impossible task. Yet, without a way to determine these values, an equity-efficiency model, although perhaps ethically and economically interesting, is neither actionable nor useful.

We present theoretical and computationally-tractable formulas for the optimal price and tax in polluting monopolies and use surplus-maximizing values, those that maximize market surplus less externalities, as a benchmark. We show formally that in markets where the consumer burden (externality burden) dominates, there is a bias towards a lower (higher) price and tax relative to the surplus-maximizing ones.

We seek a representation that is amenable to measurement in the real-world. To this end, we ground our model and results in a probabilistic representation which yields formulas in terms of elasticities, and means of the market shares and welfare weights. When marginal welfare weights and market shares are independent (or uncorrelated), the welfare-maximizing and surplus-maximizing price and tax coincide. Applying our model to the residential electricity market, we show that there is evidence of a large *consumer burden* and minimal evidence of an *externality burden*, implying that electricity prices should be *lower* than surplus-maximizing ones. We interpret this as a signal to policy makers who should be careful to raise prices too much without adequate ex-post distributional measures.

In our model, a single profit-maximizing firm produces a good associated with an environmental externality, assumed to be a function of the quantity sold. The government's problem is to maximize social welfare, which is a function of the market price and tax, and is assumed to have perfect information. The regulator has the choice to set either a price control (price floor or ceiling) or a pollution tax. People get some share of monopoly profits, which are taxed as income, are exposed to different shares of the externality, and consume according to their individual maximization problem. Utilities are quasi-linear and separable in consumption of the relevant good, a numeraire good, and externality exposure. In both price control and taxation settings, the monopolist's incentive compatibility constraints must be met so that the desired outcome and their profit-maximizing choice of price and quantity coincide.

To solve for the optimal policies, we borrow the tools from income taxation: The government maximizes a social welfare function that depends on a policy choice, and local optimum values are characterized by the first-order condition ([10], [23]). In particular, we closely follow the set-up of a linear income tax [22]. Welfare weights are composed of an idiosyncratic scalars (Pareto weights), and an increasing transformation of total utilities. Taking the derivative with respect to the choice variable (price or tax), we obtain local optimum expressions that relate to the expectation of marginal welfare weights and market shares. The welfare-maximizing price is equal the sum of three terms: social marginal cost, the externality burden, and the consumer burden. The relative size of the second and third terms determine whether the consumer burden or externality burden dominates. Likewise, the optimal pollution tax is the sum of terms relating to the welfare-weighted externality, correction for market power, and the tax change burden. Similar to the consumer burden, the tax change burden corresponds to the transfer of revenue from government to producer.

We test the empirical implications of our price control results for the residential electricity market using inverse optimum welfare weights. Inverse optimum weights reflect the implicit distributional values of society inferred from the income tax schedule, and have been calculated empirically [10]. To guide our interpretation, we define marginal welfare cost, the welfare cost of a marginal purchase, as an equity-efficiency analog to marginal social cost. In the case of residential electricity, we find that the consumer burden is the dominant distributional concern, resulting in a marginal welfare cost that is 17% below marginal social cost at current price levels. To give intuition for this result, it implies an optimal price as much as 12.7% lower than the surplus-maximizing one.

1.1 Literature Review

Our work is at the intersection of market regulation, environmental policy, and public finance. To our knowledge, this is the first paper to address all three areas from a theoretical perspective that incorporates the incidence of producer surplus and environmental harm. We will discuss how our work relates to the three relevant bodies of literature: market power and externalities, equity-efficiency and environmental policy, and public finance.

Market power and externalities. Our work adds a distributional lens to literature at the intersection of market power and negative externalities. The argument that monopoly power is second best in external diseconomies can be traced to Buchanan's 1969 paper where he observes that under monopolistic competition, an externality tax can bring the market equilibrium *farther* from the socially optimal equilibrium, leading to a less efficient outcome [5]. More recently, Borenstein and Bushnell documented how US residential electricity prices often exceeded social marginal cost in the mid-2010s, arguing that mark-ups from transmission and reselling could counterbalance the lack of an emissions tax [3]. Implicitly or explicitly, this line of literature has focused on the notion of ex-post distribution, where the most equitable and efficient outcome coincide. Monopolists could pay the government a flat rate for the right to produce, which the government could split among the consumers and the injured parties. Another alternative would be that if the monopolists are especially wealthy and the injured parties relatively poor, a similar outcome could be achieved through income tax redistribution. What makes this approach insufficient is that lump-sum redistribution is rarely employed, making it an unrealistic assumption, and that, despite best efforts to optimize the tax schedule, inequalities still exist and, as we show, are influenced by these markets. To our knowledge, our paper is the first to theoretically address equity concerns in this area.

Equity-efficiency and environmental policy. Our paper extends the use of welfare weights in environmental cost-benefit analysis to market contexts. In 1997, Fankauser explained the theoretical grounds for accounting for the distributional incidence of climate damages, especially when using metrics of willingness-to-pay or willingness-to-accept [8]. Since higher income people have more money to spend, they will generally report preferences with a larger magnitude and have lower marginal utilities. As a way to remedy this distortion, the authors use welfare weights derived from a social welfare and utility function and find that it significantly increases the scale of global damage estimates reported by the IPCC. Another later work applies welfare-weights to cost-benefit analysis, analyzing international policies regarding water quality improvements [21]. Both papers, while instrumental in balancing the welfare considerations in international policy, do not address distributional considerations for a specific environmental markets. Nor do they offer clear empirical guidance, testing a suite of potential welfare-weights. In addition to bringing a welfare perspective to environmental markets, the value-add of our model is that it is easily amendable to real-world measurement.

Public finance and welfare weights. Our work complements existing literature in public economics by offering a more general interpretation of welfare weights for application in a market setting. A paper by Hendren shows that using relative welfare weights implied by the US income tax system could serve as an efficiency benchmark [10]. A budget-neutral intervention is defined to be inverse-optimum efficient if the welfare-weighted expectation (or covariance) of willingness-to-pay is positive. A positive covariance implies that it would cost money to implement the same distribution of costs and benefits through a change in the tax schedule, and therefore can be seen as a stricter version of the Kaldor-Hicks criterion. This test relies on the assumption that willingness-to-pay is determined by income level. A more relaxed interpretation is that if inverse optimum weights approximate distributional preferences, we can use the same expectation test to see whether an intervention improves total welfare, regardless of the heterogeneity among people. Applying this lens to environmental markets, we are able to capture the incidence of market profits and externalities in contrast to any existing consumption taxation work we are aware of. While some papers have addressed how to jointly optimize income and externality taxation ([14], [7], [17]) none that we are aware of capture differences in emissions exposure, and only one accounts for differences in consumption preferences from a theoretical perspective ([7]).

The remainder of this paper is structured as follows: Section 2 discusses the conceptual framework for our equity-efficiency model. Section 3 presents an intuitive example that captures in a simple setting the primary equity-efficiency details. Section 4 describes our general results and formal proofs. Section 5 details the residential electricity application. Section 6 concludes.

2 Conceptual Framework

2.1 Individual Utility

Individuals $i \in \mathcal{I}$ have additive utility $u^i(c, x; p, \tau)$ where c is consumption of a numeraire good, and x is the relevant pollution-intensive good sold at price p given tax τ. Specific to the polluting monopoly, people differ by the share of externality exposure they face, denoted by $e(i)$, the share of monopoly profits they receive, $s(i)$, and—when there is a pollution tax—the share of revenue they get, $\lambda(i)$. This results in total pre-tax income $z = y + s(i) \cdot \pi(p)$ for $\pi(p)$ the monopolist profits discussed in the following section. The maximization problem of individual i is given by

$$\begin{aligned} \max_{c,x} \quad & u^i(c, x; p, \tau) = c + v_i(x) - e(i)E(q) \\ \text{s.t.} \quad & c = (z - T(z)) - x \cdot p + \tau\lambda(i)E(q) \end{aligned}$$

with $e(i)E(q)$ the externality exposure, $T(z)$ the total tax on those at income z, and $\lambda(i)\tau E(q)$, the pollution tax revenue for person i.

While labor supply impacts a person's utility level, we assume additional market profits and externalities are independent of one's labor supply choice, and thus is not central to our model. For a natural monopoly, this reflects the fact that, after fixed investments are made, the incremental costs and labor for a change in output is relatively minimal.

Furthermore, as additional market profits and externalities have an average impact of order $\mathcal{O}(\frac{1}{N})$ for N the population size, we can approximate the first-order condition as

$$(v_i'(x) - e(i)E'(q)) - (p + s(i)\pi'(p)p'(q)) \approx v_i'(x) - p.$$

Let $x_i(p)$ be an individual's optimized consumption choice satisfying the approximated equation. We assume that $x_i(.) \in C^1$ with $x_i'(p) < 0$.

2.2 Monopolist's Problem

Market demand is represented by the Lebesgue integral $q(p) = \int_I x_i(p)d(mi)$. Monopolist profit is given by

$$\pi(p) = p \cdot q(p) - C(q) - \tau E(q),$$

where emissions and costs are increasing and convex. Since it is the sum of C^1 functions, $q(p) \in C^1$ with $q'(p) < 0$. We assume consumption costs do not enter into the producer's problem. This is equivalent to saying that those with price-setting power do not consume the good (an implicit assumption of most models). Further, we define $p_M^* = \text{argmax}_p \pi(p)$ to be the monopolist's optimal price.

Price Control. When the regulator sets a price ceiling (floor), the monopolist has the ability to charge a lower (higher) price, turn away consumers, or exit the market altogether, receiving zero profits. This induces a set of feasible prices $\mathcal{P}$. When there is a price ceiling at $\bar{p}$, $\mathcal{P} = [0, \bar{p}]$. When there is a price floor at $\underline{p}$, $\mathcal{P} = [\underline{p}, \infty)$. Given this set, the monopolist solves

$$\max\{0, \max_{p \in \mathcal{P}, q \leq q(p)} p \cdot q - C(q)\}.$$

Pollution Tax. Under a pollution tax on emissions $E(q)$, the monopolist sets price $p(\tau)$ to maximize profits given the consumer demand curve $q(p)$. From the monopolist's first order condition we have

$$\pi'(p) = p \cdot q'(p) + q(p) - C'(q)q'(p) - q(p) - \tau E'(q)q'(p) = 0$$

so that the optimal price $p^*(\tau)$ satisfies:

$$p^*(\tau) = \tau E'(q) + C'(q) - \frac{q(p)}{q'(p)}.$$

In both settings we assume a unique solution to the monopolist's problem exists. A leading example would be the case of constant elasticity of consumption ϵ_q^p and $C''(q) > -\tau E''(q)$. The second condition automatically holds for $\tau > 0$ and ensures the convexity of marginal cost. The local optimal price is $p^*(\tau) = \frac{\epsilon_q^p}{1+\epsilon_q^p}(C'(q) + \tau E'(q))$. The right-hand side is increasing in p by the convexity of marginal cost, and thus the local optimum is the unique interior optimum.

2.3 Government's Problem

The government's objective is to maximize collective welfare across all individuals. To formalize this, we adopt a social welfare function based on those for optimal income taxation.

Definition 1. Let $\omega(i) \geq 0$ be Pareto weights with an increasing transformation of utilities $G(.) \in C^1$. The *social welfare function* SWF is defined as:

$$SWF = \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p, \tau)) d(mi).$$

The regulatory tools impact utility through their impact on emissions, the level of profit and taxation, and consumer surplus. Importantly, a planner has already optimized the income tax schedule, given their political constraints, and does not have access to lump-sum redistribution.

Optimal Price Control. The optimal price is the value p^*_W that solves

$$\max_{p \in \mathbb{R}^+} \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p, \tau = 0)) d(mi)$$

The corresponding optimal equilibrium $(p^*_W, q(p^*_W))$ is implementable under a price ceiling $\bar{p} = p^*_W$ or floor $\underline{p} = p^*_W$ if one of the monopolist's incentive-compatibility conditions are met. This means that for $\mathcal{P} \in \{[0, p^*_W], [p^*_W, \infty)\}$,

$$\pi(p^*_W) \geq \max\{0, \max_{p \leq \mathcal{P}, q \leq q(p)} p \cdot q - C(q)\}.$$

Optimal Pollution Tax. The optimal pollution tax is the value τ^* that solves

$$\max_{\tau \in \mathbb{R}} \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p(\tau), \tau)) d(mi)$$

so that the monopolist profit maximizes given the tax level.

2.4 Expectation Perspective

Let $\mathcal{I}$, the space of people, have total mass $m(\mathcal{I}) = N$ for m the Lebesgue measure. The core insight of this paper is that, instead of parameterizing groups of people by preferences or characteristics (income, location), we can allow for full heterogeneity, seeking to maximize the population's welfare-weighted expected utility:

$$\frac{SWF}{N} = \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p)) \frac{d(mi)}{N} = \mathbb{E}[G(u^i(c, \ell, x; p))]$$

for probability measure $P = \frac{m(A)}{N}$ for $A \subseteq \mathcal{I}$. Since we do not assume a map between individual characteristics and market shares, a probabilistic perspective is far more general and one that, as we show later, links explicitly to a sufficient-statistics implementation.

Market Shares. As described above, people vary in their relative level of consumption, emissions exposure, profit, and pollution tax revenue. Define an individual's consumption $\tilde{x}_i(p)$ and profit share $\tilde{s}(i)$ as:

$$\tilde{x}_i(p) = \frac{x_i(p)}{q(p)} \text{ , and } \tilde{s}(i) = [1 - T'(z(i))] \cdot s(i) + \frac{1}{N}.$$

For $\tilde{s}(i)$ we separate the net of tax income loss from taxation and gain from redistribution. Recall that $\lambda(i)$ is the share of tax revenue received, and $e(i)$ the share of emissions faced by person i. We can view $(\tilde{x}, \tilde{s}, e, \lambda)$ as maps from $\mathcal{I} \to [0,1]$. They take people i in the people space $\mathcal{I}$ and output shares $(\tilde{x}(i), \tilde{s}(i), e(i), \lambda(i))$ that impact their utility. By construction, each has expectation $\frac{1}{N}$ since they sum to 1.

Welfare Weights. Let $g(i) = \frac{\omega(i)G'(u^i)u_c^i}{\int_{\mathcal{I}} \omega(i)G'(u^i)u_c^i d(mi)}$ be a person's marginal welfare weight. Welfare weights g are likewise imagined as maps that take people i in the people space $\mathcal{I}$ and output the societal value given to a marginal change in consumption for that person. Since weights are relative, $\mathbb{E}[g] = 1$.

Figure 1 displays this set-up, where the market shares and welfare weights are seen as random variables mapping from the People Space to the real line.

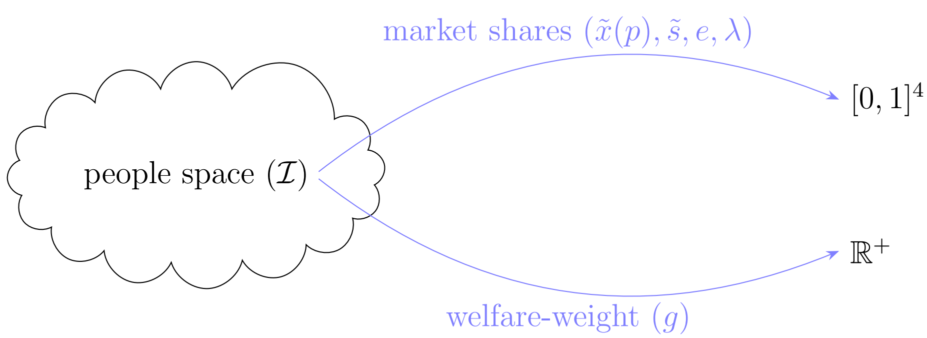

Figure 1: *Individual Characteristics as Random Variables.* Displayed is the core probabilistic representation. The planner maximizes the expected welfare induced by the market over a People Space (our sample space). This is done by finding how market shares co-vary with marginal welfare weights, which are viewed as random variables with a fixed expectation.

3 Intuitive Example

In this section, we use a simple example to explain the equity-efficiency trade-offs that are present in polluting monopolies. Imagine that there are three towns, A, B, C, of size 1 containing identical people. Town B runs a monopoly for a good sold to town A. Town C faces the pollution caused by the market. This general set-up is depicted in Figure 3.

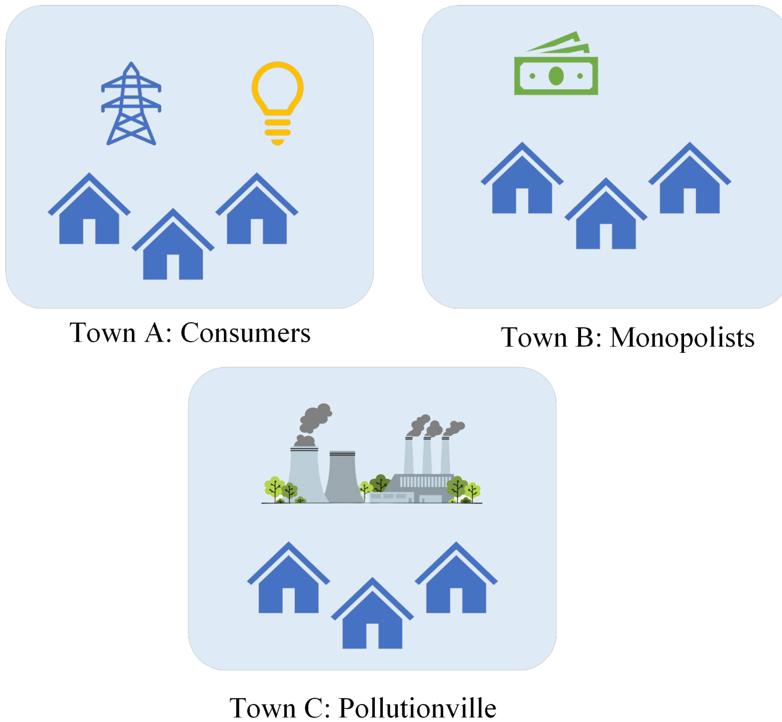

Figure 2: *Diagram of Towns A, B, C.* This figure represents a theoretical example of when consumer surplus, producer surplus, and externality exposure is not distributed equally. All consumer surplus goes to Town A, all producer surplus to Town B, and all pollution to Town C.

When the market operates at price and quantity (p, q), Town B receives $\pi(p)$ in profits, Town A gets utility $v(q)$ from consumption and Town C faces $E(q)$ in externalities. Assume individuals have earnings (y_A, y_B, y_C) and, if a pollution tax τ on emissions is implemented, receive shares $\lambda_A, \lambda_B, \lambda_C$ of the revenue. Utilities are given by

$$u_i = \begin{cases} v(q) + (y_A - p \cdot x) + \lambda_A \tau E(q) & i \in A \\ y_B + \pi(p) + \lambda_B \tau E(q) & i \in B \\ y_C - E(q) + \lambda_C \tau E(q) & i \in C \end{cases} \cdot$$

Let g_A, g_B, g_C be the marginal welfare weights for people in each place. Thus, the government's objective is to maximize

$$SWF = g_A u_A + g_B u_B + g_C u_C.$$

Optimal Price. In the price control setting, the regulator is able to set a price floor or ceiling. As we show in Lemma 7, any price that exceeds the competitive price and corresponding to positive profits can be implemented when $\pi(.)$ is concave. Thus we will solve for the price that maximizes the SWF, which we denote as p^*_W.

At a local optimum, we require

$$\frac{dSWF}{dp} = \frac{d}{dp}(g_A u_A + g_B u_B + g_C u_C) = 0.$$

By the envelope theorem, the impact on the consumers in Town A is the additional cost, $\frac{d}{dp} u_A = -q(p)$. The impact for the monopolists in Town B is the change in profit, $\frac{d}{dp} u_B = \pi'(p) = q(p) + p \cdot q'(p) - C'(q)q'(p)$. Lastly, the benefit to Town C is the reduction in emissions, $\frac{d}{dp} u_C = E'(q)q'(p)$. The first order condition becomes

$$g_A(-q(p)) + g_B(q(p) + p \cdot q'(p) - C'(q)q'(p)) + g_C(E'(q)q'(p)) = 0.$$

Rearranging, we get that the welfare-weighted producer benefit and welfare-weighted externality and consumer costs are equated.

$$g_B(q(p) + p \cdot q'(p) - C'(q)q'(p)) = g_A \cdot q(p) + g_C E'(q)q'(p).$$

Lastly, we can rearrange to get the expression for the associated price p_W^*,

$$p_W^* = \frac{1}{q'(p)g_B}\big(g_A q(p) + g_C E'(q)q'(p) - g_B q(p) + g_B C'(q)q'(p)\big).$$

Define $\epsilon_p^{q,semi} = \frac{q'(p)}{q(p)} < 0$ as the semi-elasticity of demand with respect to price. Substituting this gives the local optimum criteria for p_W^*:

$$p_W^* = \underbrace{C'(q) + E'(q)}_{\text{marginal social cost}} + \underbrace{\frac{g_C - g_B}{g_B} E'(q)}_{\text{externality burden}} + \underbrace{\frac{g_A - g_B}{g_B} \frac{1}{\epsilon_p^{q,semi}}}_{\text{consumer burden}}.$$

This expression reflects setting a price such that the cost to consumers (p_W^*) is equal to what we call the *marginal welfare cost* (MWC) of the purchase. The marginal welfare cost represents the social welfare cost of a marginal purchase. To interpret this, first imagine the market has no externalities and the welfare weights $g_B = g_A = g_C$ are equated. Let $q_W^* = q(p_W^*)$. In this case, $p_W^* = C'(q_W^*)$, the familiar competitive equilibrium result. If q generates an externality then we have $p_W^* = C'(q_W^*) + E'(q_W^*)$, which can be seen as setting price equal to marginal social cost (MSC).

If we allow the welfare weights of towns A, B, C to be different such that $g_B \neq g_C$, then the weight on this externality $E'(q)$ is increasing in the redistribution concerns for those who face the market's emissions. This is intuitive in the sense that the poorer or more vulnerable the community that is harmed, the greater the worry is generally on exposing them to pollution, reflected in a marginal welfare cost that exceeds the marginal social cost.

If the welfare weights of the consumers (g_A) and producers (g_B) are not equal, an additional term that captures the burden of the price change matters. This term describes the surplus moving from producer to consumer: The utility loss for a marginal price change to consumers and direct revenue gain to producers are both q. The larger the proportional demand response to the price change as captured by $|\epsilon_p^{q,semi}|$, the greater the ability of Town A to derive utility elsewhere. This leads to lesser significance of the consumer burden term. Further, the sign and magnitude of the term is governed by the percent difference between g_A and g_B. The higher the distributional weight for Town A relative to Town B, the lower marginal welfare cost is for any price value.

To illustrate the relative policy choices based on each of the welfare weights, we graph the market for different values of (g_A, g_B, g_C). What differentiates this graph from a traditional one is that instead of setting price equal to marginal social cost, we set it to a welfare-weighted cost, MWC, as shown in Equation 3. We will present below two examples where the monopolist's equilibrium and surplus-maximizing equilibrium coincide, but distributional considerations lead the social planner to implement a price control above or below the monopolist's equilibrium.

Environmental Health. First, consider the case when the welfare weights on those facing pollution are high ($g_C > 1$ and $g_A = g_B < 1$). This setting reflects many the fact that many industrial plants release localized air pollutants or toxic chemicals that enter nearby waterways. Since pollution-intensive plants sorting in the places with the least regulatory and political opposition, the spatial equilibrium is that they are disproportionately place in poor and minority neighborhoods. In our model, this implies that the marginal welfare cost is *above* the marginal social cost ($MWC > MSC$). As displayed in Figure 3, the regulator sets a price floor at $\underline{p}$ *above* the Monopolist's optimal price, limiting total sales and thus the pollution in Town C.

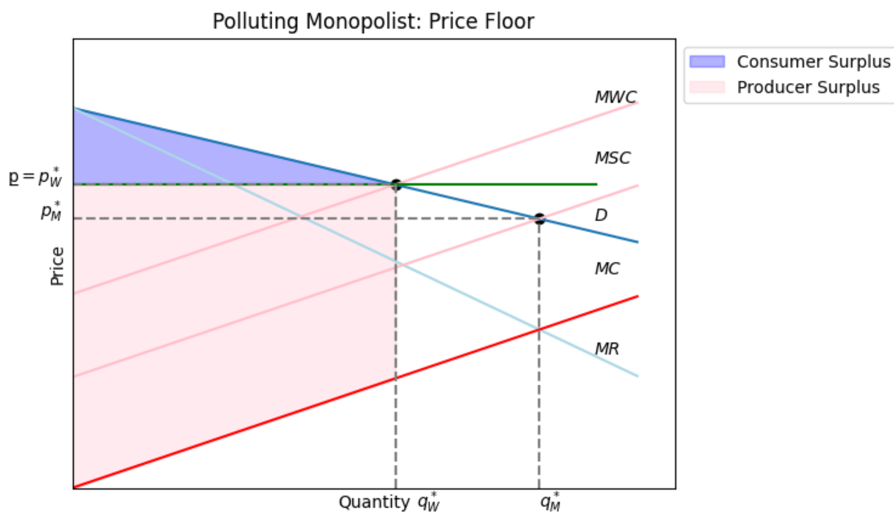

Figure 3: *Externality Burden and Price Floor:* $g_C > 1$. Displayed is an example where the monopolists and surplus-maximizing equilibrium coincide. However, since Town C (the market victims) are especially vulnerable, marginal welfare cost is above marginal social cost. To induce the welfare-maximizing outcome, the planner implements a price floor.

Energy Burden. Second, imagine that the differential between producer and consumer welfare weights is especially high. In practice, a differential is present in household consumption of electricity, natural gas and oil. Since lower-income people spend more of their income on energy costs, many are reticent to raise costs from an equity perspective. In our model, marginal welfare cost is therefore *below* marginal social cost ($MWC < MSC$). Hence the regulator sets a price ceiling at $\bar{p}$ *below* the Monopolist's optimal price, increasing the amount of market surplus given to the consumers (Town B). This setting is displayed in Figure 4.

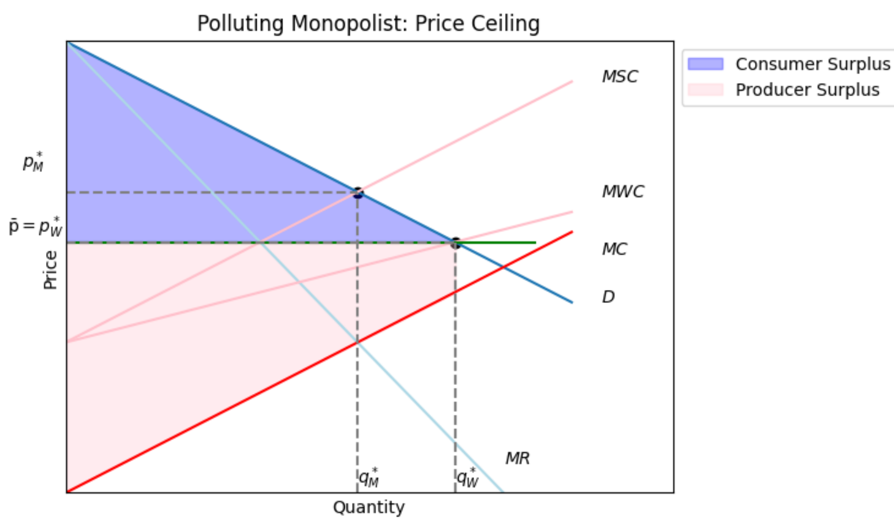

Figure 4: *Consumer Burden & Price Ceiling:* $g_A > g_B$. Here the monopolist's and surplus-maximizing equilibrium coincide. Yet, since the consumers (Town A) are more vulnerable than the producers (Town B), the marginal welfare cost of the price is lower than marginal social cost, accounting for the loss in consumer surplus from a higher price. To induce the welfare-maximizing outcome, the planner implements a price ceiling.

More deeply, these general results also tell us something surprising: including equity considerations cannot even tell us the sign of how the optimal price compares to the monopolist's equilibrium. As we show later, while these effects are often non-trivial, there is not a one-size-fits-all approach.

Optimal Tax. The second question for the regulator is how to set the tax that maximizes social welfare. At a local optimum, we require,

$$\frac{dSWF}{d\tau} = \frac{d}{d\tau}\left(g_A u_A + g_B u_B + g_C u_C\right) = 0.$$

This evaluates to

$$-g_A q(p) p'(\tau) + g_B \frac{d}{d\tau}\pi^\tau(p) - g_C E'(q) q'(p) p'(\tau) + \lambda(E(q) + \tau E'(q) q'(p) p'(\tau)$$

From the envelope theorem we have $\frac{\partial \pi^\tau}{\partial \tau} = -E(q)$ and $p'(\tau) = E'(q)$. Define $\epsilon_\tau^{E,semi} = \frac{dE/d\tau}{E(q)}$ to be the semi-elasticity of emissions with respect to the tax rate. Then the local optimum condition for τ^* is charactized by the equation:

$$\tau^* = \underbrace{\frac{g_C}{\lambda}}_{\text{externality correction}} + \underbrace{\frac{g_A}{\lambda}\frac{1}{E'(q)}\frac{1}{\epsilon_p^{q,semi}}}_{\text{market power correction}} + \underbrace{\frac{g_B - \lambda}{\lambda}\frac{1}{\epsilon_\tau^{E,semi}}}_{\text{tax burden correction}}.$$

Just as before, we can separate τ^* into the sum of three components. First, the social emissions cost term. If welfare weights are equated, this is 1, corresponding to the surplus loss of an additional emissions unit. The larger the distributive preference for those harmed (Town C), the larger the emissions correction term. Second, the market power correction term is negative to counteract the fact that the monopolist's charge a higher price (setting their price to be when marginal revenue and marginal cost are equal). Similar to the consumer burden term for the optimal price, the more inelastic demand is, and the larger the distributive weight for consumers, the greater the magnitude of this term. Lastly, the tax burden term accounts for how, as the tax rises, surplus is transferred from the producers to the government at a rate corresponding to the semi-elasticity of emissions with respect to the pollution tax. This term is positive when the welfare-weighted benefit of government revenue exceeds the welfare-weighted benefit of higher monopoly profits ($\lambda > g_B$) and grows in importance the less market emissions respond to taxation.

As before, we set the monopolist's equilibrium and surplus-maximizing equilibrium to coincide and show graphically the pollution tax setting with linear emissions, cost, and demand curves.

Environmental Health. Recall that in this setting, Town C is a marginalized community ($g_C > g_A = g_B = \lambda$). Reflecting this, the social emissions cost term is larger than the market power correction term, and MWC lies above MSC. Seeking to reduce output, the planner implements a tax so that the profit is maximized (MR and MC^{tax} are equated) precisely at the welfare-maximizing price and quantity induced by τ^*.

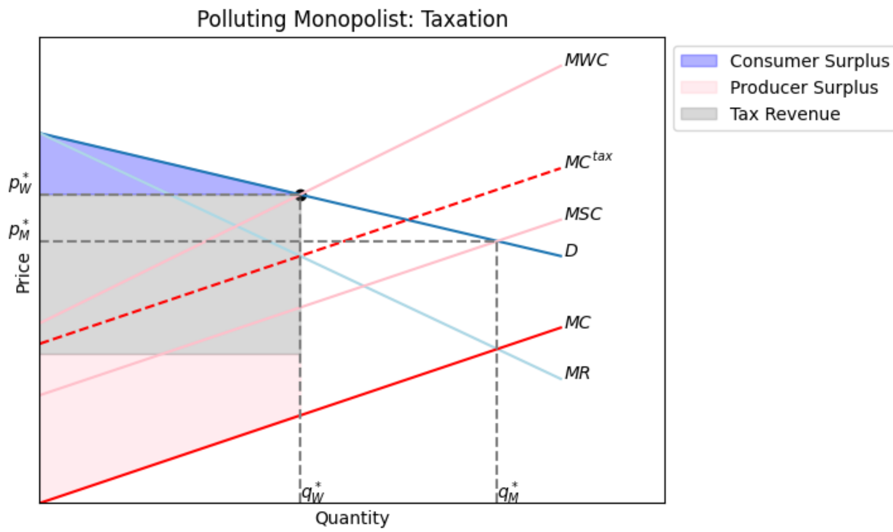

Figure 5: *Emissions Tax:* $g_C > \lambda$. While the surplus-maximizing result is the monopolist's equilibrium, as there is significant welfare cost to pollution in Town C the welfare cost of marginal emissions is higher. This grows the value of the marginal welfare cost, and therefore results in a tax.

Energy Burden. In this setting, there is a higher welfare-weight place on consumers relative to producers and government spending. In our model, this corresponds to $g_A > \lambda = g_B = g_C$. As such, the market power correction term dominates that of the social emissions cost and MWC lies below the MSC. The planner thus implements a *subsidy* ($\tau < 0$) so that the profit is maximized (MR and MC^{tax} are equated) when $MWC = D$.

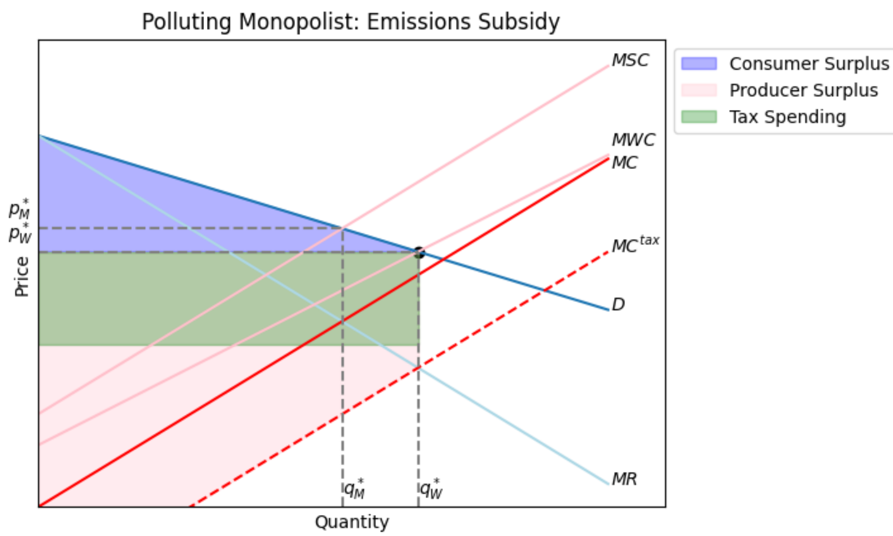

Figure 6: *Emissions Subsidy:* $g_A > \lambda$. In this case, there is a higher marginal welfare cost associated with a rise in price due to the distributional weight of the consumers, thus resulting in a subsidy.

To understand how these effects operate and how to empirically estimate which scenario (subsidy, tax) a market is in motivates a more rigorous perspective detailed in the following section.

4 General Results

In this section, we discuss the optimal price control and pollution tax for our conceptual setting.

4.1 Optimal Price

The government's problem is to pick a price level p to maximize the SWF following Equation 2.3, equivalent to maximizing expected welfare-weighted utility when $\tau = 0$. To start, we ask what point along the demand curve $(p, q(p))$ results in the highest social welfare.

Theorem 2. *For market shares $(g, \tilde{x}, \tilde{s}, e)$, the welfare maximizing price p_W^* and quantity $q_W^* = q(p_W^*)$ satisfy the formula:*

$$p_W^* = \underbrace{C'(q_W^*) + E'(q_W^*)}_{marginal\ social\ cost} + \underbrace{\frac{\mathbb{E}[g \cdot e] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} E'(q_W^*)}_{externality\ burden} + \underbrace{\frac{\mathbb{E}[g \cdot \tilde{x}(p_W^*)] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} \frac{1}{\epsilon_q^{p,semi}}}_{consumer\ burden}.$$

Proof. At a local optimum, the change in the SWF with respect to price is zero.

$$\frac{d}{dp} \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p)) d(mi) = \int_{\mathcal{I}} \omega(i) \frac{d}{dp} G(u^i(c, \ell, x; p)) d(mi)$$

Evaluating the inner portion $\frac{d}{dp} G(u^i(c, \ell, x; p))$:

$$\begin{aligned}
\frac{d}{dp} G(u^i(c, \ell, x; p)) &= G'(u^i) \frac{d}{dp}(u^i(c, \ell, x; p)) && (1)\\
&= G'(u^i) \left(\frac{dc}{dp} u_c^i + \frac{dx}{dp} u_x^i - \frac{dE(q)}{dp} e(i) \right) && (2)\\
&= G'(u^i) \left((s(i)(1 - \tau^y) + \frac{1}{N} \tau) \pi'(p) - x_i(p) - E'(q) q'(p) e(i) \right) && (3)\\
&= G'(u^i) \left(\tilde{s}(i) \pi'(p) - x_i(p) - E'(q) q'(p) e(i) \right) && (4)
\end{aligned}$$

(1) follows from the chain rule, (2) taking a total derivative, (3) from evaluating and using the envelope theorem to get that any change in $x_i(p)$ does not impact utility, and (4) from letting $\tilde{s}(i) = (s(i)(1-\tau^y) + \frac{1}{N}\tau^y)$ be the net-of-tax share of monopolist profit. Since $u_c^i = 1$, we can note that $\frac{\omega(i)G'(u^i)}{\int_{\mathcal{I}} \omega(i)G'(u^i)d(mi)} = g(i)$, the marginal welfare weight. Plugging this value into the derivative above,

$$\frac{d}{dp}SWF = \int_I g(i)\left(\tilde{s}(i)\pi'(p) - x_i(p) - E'(q)q'(p)e(i)\right)d(mi).$$

Define $P = \frac{m(A)}{N}$ as a measure on $\mathcal{I}$. Thus maximizing SWF is equivalent to maximizing the integral of this probability measure

$$\int_{\mathcal{I}} G(u^i(c,\ell,x;p))dP(i) = \mathbb{E}[G(u^i(c,\ell,x;p))]$$

Let $\tilde{x}_i(p) = \frac{x_i(p)}{q(p)}$ be the total share of demand individual i represents at price p and further divide by $\int_{\mathcal{I}} \omega(i)G'(u^i)d(mi)$ to get:

$$\mathbb{E}[g \cdot (\tilde{s} \cdot \pi'(p) - q(p)\tilde{x}_i(p) - E'(q)q'(p)e] = 0.$$

Substituting in the derivative of the supplier's profit function and rearranging:

$$\begin{aligned}
\mathbb{E}[g \cdot \tilde{s}](q(p) + pq'(p) - C'(q)q'(p)) &= \mathbb{E}[g \cdot \tilde{x}(p)]q(p) + \mathbb{E}[g \cdot e]E'(q)q'(p) \\
p = C'(q) + E'(q) + \frac{\mathbb{E}[g \cdot e] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]}E'(q) &+ \frac{\mathbb{E}[g \cdot \tilde{x}(p)] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]}\frac{q(p)}{q'(p)}
\end{aligned}$$

Noting that $\frac{q(p)}{q'(p)} = \frac{1}{\epsilon_q^{p,semi}}$ returns the characterizing equation. $\square$

Definition 3. We say that the monopoly is a *private market in expectation* if the aggregate profit shares at income level y are proportional net of tax income earned by individuals at income level y. Formally:

$$\mathbb{E}[s|y] = \frac{y}{N \cdot \mathbb{E}[y]} \text{ , and } \mathbb{E}[\tilde{s}|y] = \frac{(1 - T(y)}{N \cdot \mathbb{E}[y(1 - T(y))]}.$$

The *private market in expectation* assumption is most tractable way we have off making this value empirical. That said, this assumption may not always be reasonable. For instance, a well-run state monopoly may have profits uniformly distributed through government expenditure corresponding to $\tilde{s}(i) \approx \frac{1}{N}$.

To understand how to frame and work with this formula we offer a few remarks and simplifying assumptions.

Remark 4. When the market is private in expectation (Defn 3), a helpful heuristic for judging the importance of the *consumer burden* is: How does one's share of income spent on consumption vary by income-level? If this share is constant, then the term vanishes. If decreasing, this implies a *consumer burden*, lowering the optimal price. If increasing, this implies a higher optimal price.

This remark also reveals something interesting. If we assume people consume all of their income, on average their consumption would be proportional to their income. Therefore, while some markets exhibit a consumer burden (poor people spending proportionately more than wealthier people), the opposite will be true in other markets (poor people spending proportionately less than wealthier people). An example of a market where wealthier people spend more of their income could be commercial aviation.

Definition 5. We say that demand is *uniformly isoelastic* if $q(p) = \alpha p^{\epsilon_q^p}$ and $x_i(p) = \tilde{x}_i q(p) = \tilde{x}_i \alpha p^{\epsilon_q^p}$ for some $\alpha > 0$.

Under an assumption of *uniformly isoelastic* demand, we do not need to worry about changes in the share of consumption across people and consumption elasticity in response to price changes. Our last result is more generally a reminder that we cannot always be sure that the price formula corresponds to the optimal market price if there are multiple critical points or an exterior solution. Most relevant to for polluting monopolies, if the fixed costs and environmental harm from a market is too high, it is not optimal for the market to not operate.

Corollary 6. *Assume demand is uniformly isoelastic and that $g(i) = \omega(i)$.*[3] *The above characterization in Equation 2 represents a unique global optimum if the following hold:*

1. *SWF is concave with respect to p, equivalent to*

$$|q'(p)| < \frac{\mathbb{E}[g \cdot e](E'(q)q''(p) + (q'(p)^2 E''(q)) - \mathbb{E}[g \cdot \tilde{s}]\pi''(p)}{\mathbb{E}[g \cdot \tilde{x}]}$$

for all $p \in \mathbb{R}^+$.

[3] This means that $G(u)$ is the identity function and removes the dependency of welfare weights on the market price. Alternatively, one could likely make an assumption that marginal in the weighted means are lesser in magnitude compared than the changes in pollution, and consumer and producer surplus.

2. *Social welfare at the optimum is greater than without the market:*

$$\int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p_W^*, \tau = 0)) d(mi) > \int_{\mathcal{I}} \omega(i) G(u^i(c, \ell, x; p = \infty, \tau = 0)) d(mi).$$

Proof. Since a strictly concave function has a unique maximizer, we want to show that condition (1) is equivalent to global concavity. Recall that the first derivative is exactly when the welfare-weighted sum of the producer, consumer and externality costs and benefits are equated:

$$\frac{dSWP}{dp} = \underbrace{\mathbb{E}[g \cdot \tilde{s}]\pi'(p)}_{\text{producer impact}} - \underbrace{\mathbb{E}[g \cdot \tilde{x}]q(p)}_{\text{consumer impact}} - \underbrace{\mathbb{E}[g \cdot e]E'(q)q'(p)}_{\text{externality impact}}$$

Taking a further derivative gives a sense of how these impacts vary with the price level.

$$\frac{d^2SWP}{dp^2} = \underbrace{\mathbb{E}[g \cdot \tilde{s}]\pi''(p)}_{\text{producer impact change}} - \underbrace{\mathbb{E}[g \cdot \tilde{x}]q'(p)}_{\text{consumer impact change}} - \underbrace{\mathbb{E}[g \cdot e](E'(q)q''(p) + (q'(p))^2 E''(q))}_{\text{externality impact change}}$$

Note that $\pi''(.) < 0$ by assumption, and $E'(q)q''(p) + (q'(p))^2 E''(q)) > 0$ for $q''(p) < 0$ (although this may not be true). Thus $\frac{d^2SWP}{dp^2}$ is negative if the impact of the change in consumer surplus value of a higher price $\mathbb{E}[g \cdot \tilde{x}]q'(p)$ is dominated the decreases in producer surplus change and externality benefit change. Since $q'(p) < 0$ this is equivalent to:

$$|q'(p)| < \frac{\mathbb{E}[g \cdot e](E'(q)q''(p) + (q'(p)^2 E''(q)) - \mathbb{E}[g \cdot \tilde{s}]\pi''(p)}{\mathbb{E}[g \cdot \tilde{x}]}$$

The second condition corresponds to the possibility that an exterior solution (no market) is preferred. Since when $p = \infty$ there will be no consumption (people do not have infinite income), we notate the absence of a market as such. In general, this depends on the start-up emissions and costs $C(0) + E(0)$. If these costs are large enough, no amount of market activity will be able to recoup the initial welfare loss. □

4.1.1 Price Controls

A natural question is to ask when, under perfect information, such an equilibrium is implementable with a price ceiling or floor by the social planner. When $\pi''(.)$ is concave, a price floor above the monopolist's optimal price would be binding, as any higher price would result in strictly lower profits. Likewise, a price ceiling below the monopolist's optimal price would be binding, since a lower price would result in strictly lower profits. Further, the monopolist would not sell less than $q(p)$ if $C'(q) < p$, which, by the convexity of C, corresponds to the price exceeding the competitive equilibrium. Lastly, the monopolist will not exit the market if they can still make a profit. This insight is formalized in Lemma 7.

Lemma 7. *Assume $\pi''(.) < 0$. The first best equilibrium (p_W^*, q_W^*) is implementable under a binding price floor or ceiling for $\pi(p_W^*) > 0$ and $p_W^* > p_C$ for p_C the competitive price.*

Proof. There are two cases: $p_W^* > p_M^*$, or $p_W^* \in (p_C, p_M^*]$. For all $p > p_C$, $p - C'(q) > 0$ when $q < q(p)$. Thus, if the monopolist produces, they will always produce $q(p)$ as $p_W^* > p_C$. Hence it suffices to check that no alternative $(p, q(p))$ pair is preferred. If

$p^*_W > p^*_M$ since $\pi''(p) < 0$ and $\pi'(p^*_M) = 0$ by the monopolist's first order condition we have that for any $p > p^*_W$,

$$\pi(p) - \pi(p^*_W) = \int_{p^*_W}^{p} \pi'(p')dp' < \int_{p^*_W}^{p} \pi'(p^*_M)dp' = 0.$$

Thus for $\pi(p^*_W) > 0$, $\pi(p^*_W) \geq \max\{0, \max_{p \leq p^*_W, q \leq q(p)} p \cdot q - C(q)\}$ and a price ceiling is binding. Identically for $p^*_W \in (p_C, p^*_M]$, for any $p < p^*_W$,

$$\pi(p) - \pi(p^*_W) = -\int_{p}^{p^*_W} \pi'(p')dp' < -\int_{p^*_W}^{p} \pi'(p^*_M)dp' = 0.$$

$\pi(p^*_W) \geq \max\{0, \max_{p \geq p^*_W, q \leq q(p)} p \cdot q - C(q)\}$. The price floor is binding. □

4.2 Optimal Pollution Tax

The government's problem is to set a pollution tax τ on emissions to maximize social welfare following Equation 2.3. Recall that the externality $E(q)$ is normalized so that one unit corresponds to a dollar of unweighted surplus and we assume that the monopolist is profit-maximizing given the tax rate.

Theorem 8. *The welfare maximizing tax τ^*, price $p(\tau^*) = p^*_\tau$ and quantity $q^*_\tau = q(p^*_\tau)$ satisfy the formulas:*

$$\tau^* = \underbrace{\frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]}}_{\textit{externality correction}} + \underbrace{\frac{\mathbb{E}[g \cdot \tilde{x}(p^*_\tau)]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{E'(q^*_\tau)\epsilon_q^{p,semi}}}_{\textit{market power correction}} + \underbrace{\frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{\epsilon_E^{\tau,semi}}}_{\textit{tax burden correction}}$$

$$p_\tau^* = \underbrace{C'(q) + E'(q_\tau^*)}_{\textit{marginal social cost}} + \underbrace{\frac{\mathbb{E}[g \cdot e] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} E'(q_\tau^*)}_{\textit{externality burden}}$$

$$+ \underbrace{\frac{\mathbb{E}[g \cdot \tilde{x}(p_\tau^*)] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{\epsilon_q^{p,semi}}}_{\textit{consumer burden}} + \underbrace{\frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{E'(q_\tau^*)}{\epsilon_E^{\tau,semi}}}_{\textit{tax burden}}$$

The proof, identical in style to that of the optimal price, is deferred to Appendix 7.1.

Remark 9. Assuming that government revenue is distributed uniformly ($\lambda(i) = \frac{1}{N}, \forall i$). A useful heuristic to think about the consumer burden is: How does one's consumption of the good vary by income level? If consumption is higher for high-income people (as we would usually expect), this term is positive. *The surprising result is that consumer or energy burdens are less of a distributional concern when their is a pollution tax setting the market level, and actually probably works to raise prices.*

This remark also displays an interesting connection between the optimal market price under a price control and pollution tax setting: As the benchmark for marginal welfare cost is government spending instead of producer profits, the relative importance (and even sign!) of distributional terms are altered. In the following Corollary we formalize this adding a third benchmark, the surplus-maximizing price and quantity $p^*, q^* = q(p^*)$ for which $p^* = C'(q^*) + E'(q^*)$.

Corollary 10. *If the first-order conditions correspond to unique global optimum,* *the following represent sufficient equivalence conditions for* (p^*, p^*_W, p^*_τ)*. When* $g \perp\!\!\!\perp (\tilde{x}, \tilde{s}, e)$, $p^* = p^*_W$*. When* $\mathrm{Cov}(g, \tilde{s}) = \mathrm{Cov}(g, \lambda)$, $p^*_W = p^*_\tau$*, and when* $g \perp\!\!\!\perp (\tilde{x}, \tilde{s}, e, \lambda)$, $p^* = p^*_\tau$.

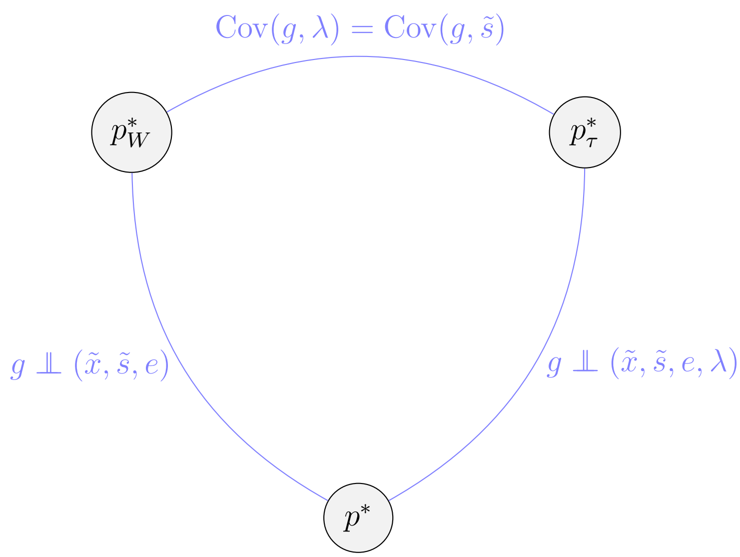

Figure 7: *Graphical Relationship Among Prices.* This figure shows how a probabilistic representation of people links to a sufficient-statistics understanding of how welfare-maximizing prices relate. The surplus-maximizing price is the welfare-maximizing price when welfare weights are uncorrelated (more strongly, independent) from all of the market shares. The optimal price under a pollution tax and price control will be equated only when the covariance between welfare weights and producer profit shares and tax revenues shares are the same.

Proof. Recall that the following hold for each of the prices from Theorems 2 and 8:

$$p_W^* = C'(q_W^*) + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \tilde{s}]} E'(q_W^*) + \frac{\mathbb{E}[g \cdot \tilde{x}] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} \frac{1}{\epsilon_q^{p,semi}}$$

$$p_\tau^* = C'(q_\tau^*) + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]} E'(q_\tau^*) + \frac{\mathbb{E}[g \cdot \tilde{x}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{\epsilon_q^{p,semi}} + \frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{E'(q_\tau^*)}{\epsilon_E^{\tau,semi}}$$

$$p^* = C'(q^*) + E'(q^*)$$

If $g \perp\!\!\!\perp (\tilde{x}, \tilde{s}, e)$, then $\mathbb{E}[g \cdot \tilde{x}] = \mathbb{E}[g \cdot \tilde{s}] = \mathbb{E}[g \cdot e] = \frac{1}{N}$. Thus:

$$p_W^*|_{g \perp\!\!\!\perp (\tilde{x}, \tilde{s}, e)} = C'(q_W^*) + E'(q_W^*) = p^*.$$

If we further assume $g \perp\!\!\!\perp \lambda$, then $\mathbb{E}[g \cdot \lambda] = \frac{1}{N}$ as well. Therefore:

$$p_\tau^*|_{g \perp\!\!\!\perp (\tilde{x}, \tilde{s}, e, \lambda)} = C'(q_\tau^*) + E'(q_\tau^*) = p^*$$

Lastly, $\mathrm{Cov}(g, \tilde{s}) = \mathrm{Cov}(g, \lambda)$ means that $\mathbb{E}[g \cdot \lambda] = \mathbb{E}[g \cdot \tilde{s}]$. Therefore:

$$\begin{aligned} p_W^*|_{\mathbb{E}[g \cdot \lambda] = \mathbb{E}[g \cdot \tilde{s}]} &= C'(q_W^*) + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]} E'(q_W^*) + \frac{\mathbb{E}[g \cdot \tilde{x}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{\epsilon_q^{p,semi}} \\ &= p_\tau^*|_{\mathbb{E}[g \cdot \lambda] = \mathbb{E}[g \cdot \tilde{s}]}. \end{aligned}$$

$\square$

A small note here is that it is possible to be uncorrelated but dependant. For instance, $Z \in \mathcal{N}(0,1)$ and Z^2. However, as these counterexamples are unlikely to arise in real-life, we use independence since it carries a more intuitive significance.

Remark 11. Because surplus maximizing and welfare maximizing prices are equivalent when welfare weights and market shares are uncorrelated (have zero covariance), a test of whether an equity-efficiency analysis is useful is to calculate (or make an educated guess) about their correlation. If one finds that welfare weights and market shares are uncorrelated, then equity-efficiency analysis is probably not needed. Conversely, if one finds that at least one of the market shares are highly correlated with distributional concerns, equity-efficiency analysis is important.

Lastly, similar to Corollary 6, our next result is reminder that the local optimum value may not be unique or represent a global optimum. Again, the most relevant thing to consider is that if the fixed cost and environmental damages are too large, no production could be optimal.

Corollary 12. *Assume demand is uniformly-isoelastic and $g(i) = \omega(i)$. Then the solution τ^* to Equation 8 is the unique global optimum if*

1. *SWF is strictly concave with respect to τ, equivalent to:*

$$\frac{d^2E}{d\tau^2} > -\frac{\frac{dE}{d\tau}\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right)}{(\tau\lambda + g_C)}$$

   for all $\tau \in \mathbb{R}$.

2. *Social welfare at the optimum is greater than without the market:*

$$\int_{\mathcal{I}} \omega(i)G(u^i(c,\ell,x;p^*_\tau,\tau^*))d(mi) > \int_{\mathcal{I}} \omega(i)G(u^i(c,\ell,x;p(\tau),\tau=\infty))d(mi)$$

Proof in Appendix 7.1.

4.3 Comparative Statics

This section asks the question: How does the optimal pollution tax and market price vary based on marginal changes in the *distribution* of market shares? To make this amenable to a comparative statics approach, we assume $G(u^i) = u^i$ so that $g(i) = \omega(i)$ and hence one's welfare weights do not depend on the price or tax. Let $X = (\vec{g}, \vec{\tilde{x}}, \vec{\tilde{s}}, \vec{e}, \lambda) \in \mathbb{R}^{5N}$ be the vector of all market shares and welfare weights where individuals are ordered $1 \leq i \leq N$. For instance, $\vec{g} = (g(1), g(2), \dots, g(N))$. Because of the independence of price, tax and welfare weights, the only relevant incidence parameters are $\mathbb{E}[g \cdot z]$ for $z \in \{\tilde{x}, \tilde{s}, e, \lambda\}$. Thus p_W^* and τ^* are composite functions that take X to the welfare means, and the welfare means to an optimal value expressed by $p_W^*(\{\mathbb{E}[g \cdot z](X)\}_{z\in\{\tilde{x},\tilde{s},e\}}, \tau^*(\{\mathbb{E}[g \cdot z](X)\}_{z\in\{\tilde{x},\tilde{s},e,\lambda\}})$. This allows us to take a *path derivative* to evaluate the change in p_W^*, τ^* induced by a change in the distribution of a given market share. To do this, we first define what a feasible change in a market share is.

Definition 13. We say that a unit vector $V \in \mathbb{R}^{5N}$ specifies a feasible change in market share $z \in \{\tilde{x}, \tilde{s}, e, \lambda\}$ if:

- v_i corresponding to another marker share $z' \neq z$ is zero.
- market shares still sum to 1: $\sum_{i\in\mathcal{I}} v_i = 0$
- all market shares are still non-negative for a small change: there exists an $\epsilon > 0$ such that $\epsilon v_i + z(i) \geq 0$ for all i

where $v(i) = v_i$ is the corresponding change in market share z for individual i.

An example of this for prices could look like $(\vec{0}, \vec{0}, \frac{s}{\|s\|}, \vec{0}, \vec{0})$ where $\vec{0} \in \mathbb{R}^N$ is a vector of only zeros, and $s \in \mathbb{R}^N$ is an alternating vector of $-\frac{1}{2N}$ and $\frac{1}{2N}$. Therefore, this perturbation alternately increases and decreases a person profit share. Given the *feasible change in market share* definition and our assumption on G, we can finally compute the relevant comparative statics.

Corollary 14. *Assume that demand is uniformly isoelastic,* $\frac{\mathbb{E}[g\cdot\tilde{x}]-\mathbb{E}[g\cdot\tilde{s}]}{\mathbb{E}[g\cdot\tilde{s}]} > -|\epsilon_p^q|$*, and* $g(i) = \omega(i)$*. Let* V *be a feasible change in market share* $z \in \{\tilde{x}, \tilde{s}, e\}$*. Then the directional derivative of* p_W^* *with respect* V *is given by:*

$$\partial_V p_W^*(\{\mathbb{E}[g\cdot z]\}_{z\in\{\tilde{x},\tilde{s},e\}}(X)) = \frac{\partial p_W^*}{\partial \mathbb{E}[g\cdot z]}\mathbb{E}[g\cdot v]$$

where $\frac{\partial p_W^*}{\partial \mathbb{E}[g,\tilde{x}]} < 0$*,* $\frac{\partial p_W^*}{\partial \mathbb{E}[g,e]} > 0$*, and* $\frac{\partial p_W^*}{\partial \mathbb{E}[g,\tilde{s}]} > 0 \iff p_M^* > p_W^*$.

Proof in Appendix 7.1. To see how the change in the distribution of market shares impacts the price, all we need to know is how the market share incidence impacts the optimal price, and the incidence of the change in the relevant market share. As suggested by the optimal price formula in Theorem 2, the price is *decreasing* as consumer shares shift to more vulnerable groups, *increasing* as pollution harms more vulnerable communities, and moves towards the profit-maximizing value as the lower income people gain a higher stake in monopolist profits.

Likewise, we can define comparative statics for τ^*.

Corollary 15. *Assume the demand is uniformly isoelastic,* $g(i) = \omega(i)$*,* ϵ_E^τ *is constant and* $|\epsilon_E^\tau| \geq \frac{\mathbb{E}[g\cdot\lambda]-\mathbb{E}[g\cdot\tilde{s}]}{\mathbb{E}[g\cdot\lambda]}$*. Let* V *be a feasible change in market share* $z \in \{\tilde{x}, \tilde{s}, e, \lambda\}$

(Defn 13). Then the directional derivative of τ^* with respect V is given by:

$$\partial_V \tau^*(\{\mathbb{E}[g \cdot z]\}_{z \in \{\tilde{x}, \tilde{s}, e, \lambda\}}(X)) = \frac{\partial \tau^*}{\partial \mathbb{E}[g \cdot z]} \mathbb{E}[g \cdot v]$$

where $\frac{\partial \tau^*}{\partial \mathbb{E}[g, \tilde{x}]} < 0$, $\frac{\partial \tau^*}{\partial \mathbb{E}[g \cdot e]} > 0$, $\frac{\partial \tau^*}{\partial \mathbb{E}[g \cdot \tilde{s}]} > 0$, *and*

$$\left(\frac{\partial \tau^*}{\partial \mathbb{E}[g \cdot \lambda]} > 0 \right) \iff \left(\mathbb{E}[g \cdot e] - \mathbb{E}[g \cdot \tilde{x}] \frac{1}{E'(q)} \frac{p}{|\epsilon_q^p|} - \mathbb{E}[g \cdot \tilde{s}] \frac{\tau}{|\epsilon_E^\tau|} \right) < 0.$$

Proof in Appendix 7.1. Reflecting Theorem 8, and comparative statics for the price, the tax is decreasing (increasing) as consumer (pollution exposure) shares shift to more vulnerable groups. However, since a lower tax is always better for producers, τ^* is strictly decreasing as disadvantaged people earn higher shares of monopoly profits. The result for a change in the distribution of tax revenue is more complex, but essentially captures the trade-off between protecting those exposed to pollution with the harm to producers and consumers from a higher tax rate.

5 Residential Electricity Application

The purpose of this section is to show how the equity-efficiency framework developed in our paper works in practice and show that it is in fact very easy to implement! Electric utilities are one of the canonical examples of natural monopolies and are responsible for an enormous amount of pollution. In 2020, electricity generating units led to about 480 billion dollars of damage from emissions.[4] The residential market

[4]This value can be from summing each pollutant provided by the NEI Inventory and multiplying it by the social cost of the pollutant, which we detail below.

is especially relevant since it is one of the central places where people are concerned about an energy burden (higher prices harming low-income consumers).

Using the estimates from [3] on marginal cost, market price, and marginal externalities, we test the relative importance of the consumer burden and externality burden, and upper-bound the relationship between the surplus-maximizing and welfare-maximizing residential electricity price. Along the way we ask: How large is the energy burden, and are middle-income communities disproportionately harmed by pollution from the power sector?

5.1 Consumer Burden

We use the Residential Energy Consumption Survey (RECS) for 2020 which provides data on electricity consumption for US households. The relevant variables are total dollars spent on electricity, annual gross household income, and the sample weight (the estimated number of households the respondent represents).[5] We use the sample weights and electricity expenditure to calculate the average dollars spent on electricity consumption for each income group (excluding those with $< 5k$). As a preliminary plot, we plot bounds on the share of income spent by income group, confirming a steep decreasing trend consistent with the literature on the energy burden.[6]

[5] These values correspond to DOLLAREL, MONEYPY, and NWEIGHT, respectively.

[6] The error bars are the values generated for the upper and lower bounds on group income (ie $5k, 7.5k, etc.$). By construction, the average share spent lies within these mechanical bounds. For the highest income group, the upper bound corresponds to the 99% income percentile.

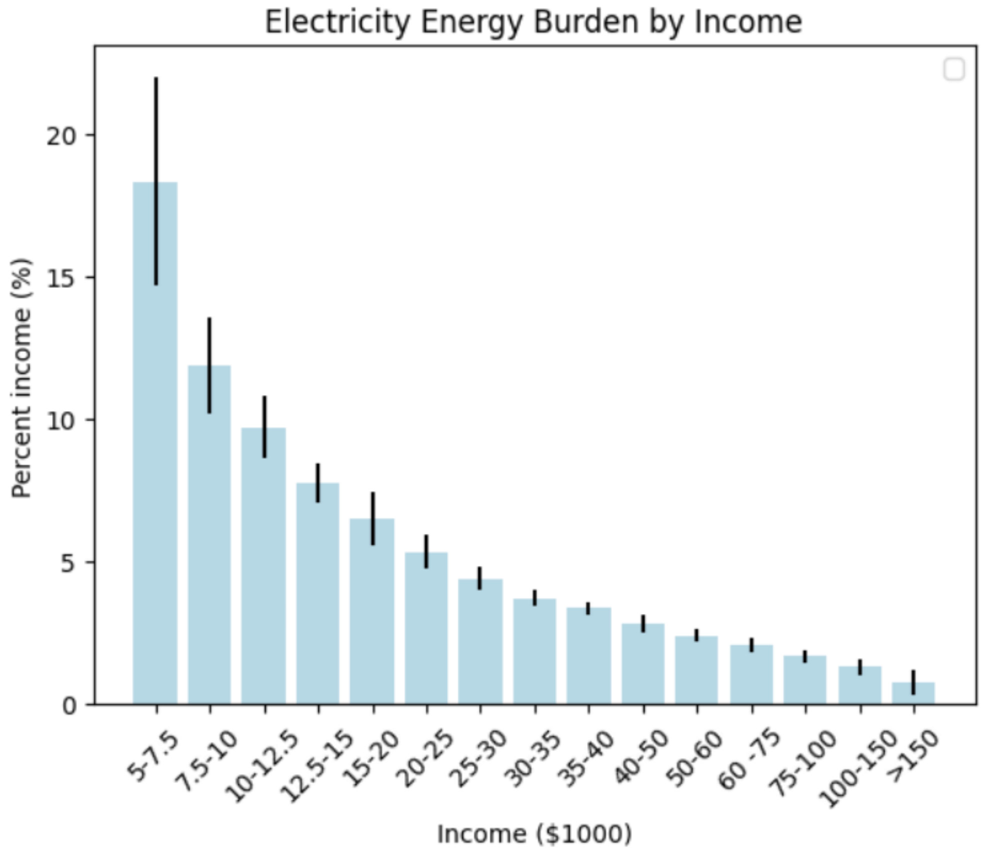

Figure 8: *Electricity Market Consumer Burden.* This figure shows that the share of one's income spent on electricity consumption decreases with total income. When the monopoly is private (as is generally true for residential electricity), this indicates strong evidence of a consumer burden, decreasing the optimal market price.

To calculate the consumer burden term, $\frac{\mathbb{E}[g \cdot x] - \mathbb{E}[g \cdot s]}{\mathbb{E}[g \cdot s]} \frac{1}{\epsilon_q^{p,semi}}$ we use inverse optimum weights to get welfare weights as a function of (household) income percentile [10]. We estimate consumption and profit-share values based on household income percentile with one representative household at every percentile. Representative households have percentile-based welfare weight and energy consumption expenditure estimated for its respective RECS income bracket. To get the consumption share $\tilde{x}_i(p)$, we divide the household's estimated expenditure by total estimated expenditure for all 100 households. Secondly, to calculate $\tilde{s}(i)$, we use the heuristic that, in expectation, one's profits from a firm are proportional to their income (Defn 3) supported by the fact that most US electricity utilities are investor-owned [11].[7] As such, $\tilde{s}(i)$ is the share of total income generated by household i. Lastly, to calculate $\frac{1}{\epsilon_q^{p,semi}}$ we observe that this is $\frac{1}{p}\frac{1}{\epsilon_q^p}$ where ϵ_q^p is -0.39, corresponding to a medium-long-run estimate in the literature [15].[8] Therefore:

$$\begin{aligned}\frac{\mathbb{E}[g\cdot x]-\mathbb{E}[g\cdot s]}{\mathbb{E}[g\cdot s]}\frac{1}{\epsilon_q^{p,semi}} &= p\cdot\left[\frac{\mathbb{E}[g\cdot x]-\mathbb{E}[g\cdot s]}{\mathbb{E}[g\cdot s]}\frac{1}{\epsilon_q^p}\right]\\ &\approx p\cdot\frac{0.986-0.881}{0.881}\frac{1}{-0.39}=-0.246\times p\end{aligned}$$

In Table 2 we show each of those components. This analysis suggests that the consumer burden has a magnitude equal to 24.6% of current price levels. To illustrate the meaning of this, note that (absent an externality burden) for the price to be welfare maximizing, it would have to be equal to only 80% of marginal social cost.[9]

[7]Without access to net-of-tax household incomes, our weights reflect $s(i)$ instead of $\tilde{s}(i)$. While this is limiting, it is also true that many of these companies are traded in the stock market. As capital wealth is distributed more unequally than labor income and top earners have large amounts of capital income, these influences may partially offset one another.

[8]There is heterogeneity in the literature as to what this value is precisely. The estimate we use is above the higher value for elasticity and thus should be interpreted as, if anything, understanding this effect.

[9]Rearranging we have $p+0.246p=MSC$ and thus $MSC=0.80p$.

5.2 Externality Burden

Recall that this term is given by $\frac{\mathbb{E}[g \cdot e]-\mathbb{E}[g \cdot s]}{\mathbb{E}[g \cdot s]}E'(q)$. As $\mathbb{E}[g \cdot s]$ is found in the previous section and $E'(q)$ is estimated in [3], the purpose of this portion is to find the $\mathbb{E}[g \cdot e]$. Emissions come from one of two classes: Criteria Air Pollutants (CAPs) and Greenhouse Gases (GHGs). We assume that the harms from greenhouse gas emissions (stock pollutants) are uniformly distributed as their damage operates on a global scale. Criteria air pollutants give rise to harmful health impacts and operate on local scales, requiring different estimates. The first part is to find the share of total damage accounted for by CAPs. The second part is to calculate its respective incidence.

5.2.1 Share of Local Air Pollution Harm

We use EPA's National Emissions Inventory Data for 2020, filtered to include only Electricity Generation via Combustion facilities [1]. This data contains the county of the facilities and their annual emissions of a set of air pollutants: criteria air pollutants, hazardous air pollutants, and greenhouse gases. We account for those air pollutants for which EPA has released data on their environmental harm. The pollutants, their category, social cost, and total social cost are presented in Table 1. Social cost estimates for greenhouse gases are from EPA's 2023 Report on the Social Cost of Greenhouse Gases [27]. Social cost estimates for criteria air pollutants are from EPA's Sector-based estimates [26]. We use Electricity Generating Units estimates when available and those for Refineries when not. Values are converted from 2016 to 2022 dollars using the CPI Inflation Calculator value of 20%. Put together, we find that 40% of total emissions damage is due to local air pollution from CAPs and the remaining 60% to GHGs.

5.2.2 Local Air Pollution Incidence

Estimate 1. Local Emissions. For our primary estimate, we adopt the heuristic that total county exposure is the social cost of county emissions multiplied by the county population. To calculate the local exposure, we use the NEI data and group pollutants by county, multiplying by the social cost of the pollutant. The local exposure of people in a county is assumed to be proportional to the social cost of local emissions normalized by the sum of population times the social cost. As we no longer have individual-level data, we estimate county welfare weights $g(i)$ by the median household incomes and then normalize across all counties so that the population-weighted welfare weights sum to 1. Data for these values is taken from the US Census for 2021.

Estimate 2. Local Particulate Matter Concentrations. An alternative rule of thumb is that emissions exposure is proportional to air quality measures. A reason why this might be slightly more accurate is that emissions travel because of the wind. For instance, a county with a pollution-intensive plant on a downwind side of the border would, in the limit, have no local exposure from that plant. To test how this hypothesis fares, we use EPA data on $PM2.5$ exposure and assume that other CAPs follow a similar distribution. Our data is taken from the Air Quality Statistics Report for 2022 [25]. One caveat is that it may be the case that there are simply fewer monitors in more vulnerable communities that would pick up the emissions data, as is something that regulators plan to address in recent regulatory changes.[10]

Estimate 3. Differential Susceptibility. The last explanation for differences in externality cost by income is, conditional on exposure, those with lower income may be more likely to develop health complications (what we call *susceptibility*). Some reasons for this would be different levels of pre-existing conditions that put an individual at greater risk from air pollution impacts, unequal access to healthcare, or jobs outdoors. As noted by [2], the evidence for this is best termed "suggestive." Nevertheless since this could be an important channel, we repeat the analysis assuming the only channel is through *susceptibility* and adopt a benchmark presented by [9] where e is proportional to the estimated increase in morbidity from $PM10$ exposure.

5.2.3 Externality Mark-Ups

The first observation is that local emissions and particulate matter concentrations are essentially uncorrelated with the median county income (and thus welfare weights). We show this graphically in Figure 9. The somewhat surprising corollary is that any externality burden is not due to disproportionate harm. While examples of disproportionate harm do exist, this force is not the dominant one at a national level.

[10] See EPA's Final Rule to Strengthen the National Air Quality Health Standard for Particulate Matter.

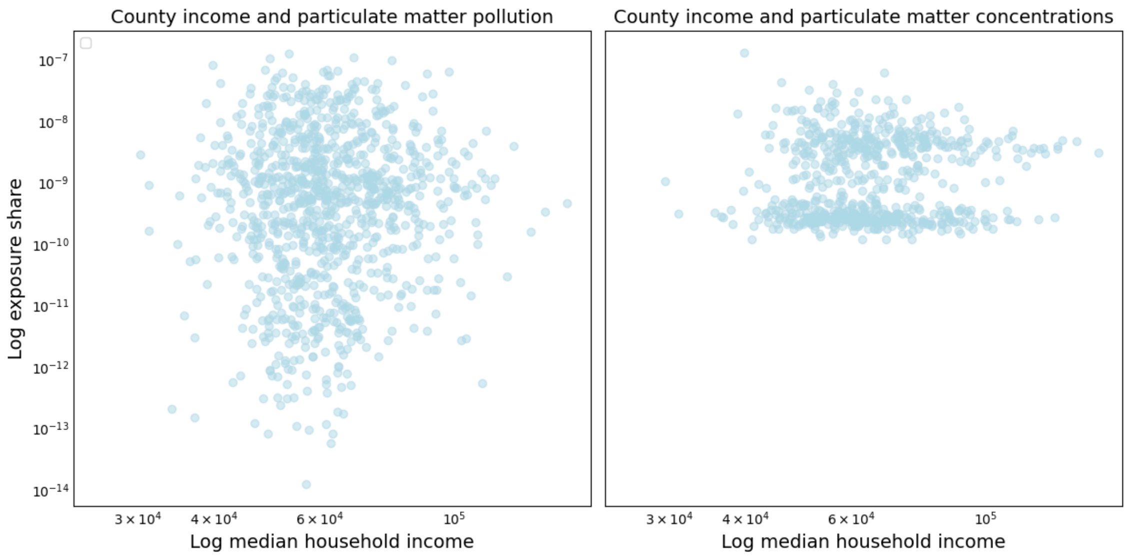

Figure 9: *Externality Burden.* The figure shows no clear relationship between median county income and externality exposure from the electricity market. The left side shows emissions weighted by their social cost. The right side shows PM2.5 measurements in counties. This is evidence that any externality burden is not due to an aggregate trend of disproportionate harm.

However, recall that the percent increase above marginal emissions cost is given by $\frac{\mathbb{E}[g \cdot e]-\mathbb{E}[g \cdot s]}{\mathbb{E}[g \cdot s]}$. Although $g \perp\!\!\!\perp e$ (roughly speaking), g *is* correlated with s. The average welfare weight of the monopolist is below that of the general population ($\mathbb{E}[g \cdot s] = 0.88$). Thus, there still exists a modest mark-up: $\frac{\mathbb{E}[g \cdot e]-\mathbb{E}[g \cdot s]}{\mathbb{E}[g \cdot s]} = 0.14$ for estimates 1 and 2 corresponding to local pollution shares. These results are relatively robust across all three approaches; even the differential susceptibility estimate, dependent on welfare weights by construction, results in only an 18% mark-up. See Table 3 for details.

To conceptualize the magnitude of this finding, note that current price levels would represent an equilibrium only if the price is 8.8% above marginal social cost.[11] Recall that this is far less than our comparable result for the consumer burden, which implies that the price was 20% *below* marginal social cost. The next section compares these two effects.

5.3 Results

We are interested in the relative relationship between marginal social cost and marginal welfare cost. We use the calculations above for incidence coefficients and the values for mean price, marginal cost, and marginal social cost found in [3]. Specifically, we estimate the formula presented in the optimal price result (Theorem 2) that describes the marginal welfare cost of electricity as the sum of marginal cost, the consumer burden term, and the externality burden term.

$$\begin{aligned} MWC - MSC &= \underbrace{\frac{\mathbb{E}[g \cdot e] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} E'(q)}_{\text{externality burden}} + \underbrace{\frac{\mathbb{E}[g \cdot \tilde{x}(p)] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} \frac{1}{\epsilon_q^{p,semi}}}_{\text{consumer burden}} \\ &\approx \underbrace{0.136 \times 6.21}_{\text{externality burden}} - \underbrace{0.246 \times 11.49}_{\text{consumer burden}} \\ &< 0 \end{aligned}$$

The second approximate equivalence follows from plugging in our estimated mean values. We see here that the consumer burden is the dominant force relative to

[11] To arrive at this: $p = 0.14 \times E'(q) + MSC$. Using $C'(q) = 3.72$ and $E'(q) = 6.72$ from [3] Table 5, results in $\frac{0.14 \times E'(q)}{MSC} = 0.88$.

the externality burden since its magnitude is over twice as large and that the two effects work in opposite directions. The net result is that at present levels, the mean marginal welfare cost is *below* the mean marginal social cost by almost \$2 or 17% of current prices.

To understand the significance of this result, we approximate the percent difference between the surplus and welfare maximizing prices for demand that is uniformly isoelastic (Defn 5), leveraging earlier calculations:

$$\begin{aligned}
\frac{p_W^* - p^*}{p^*} &= 1 - \frac{C'(q_W^*) + 1.14 \cdot E'(q_W^*)}{C'(q^*) + E'(q^*)} \frac{1}{1.246} \\
&\leq \frac{C'(q^*) + 1.14 \cdot E'(q^*)}{C'(q^*) + E'(q^*)} \frac{1}{1.246} - 1 \\
&\approx \frac{1.088}{1.246} - 1 = -0.127
\end{aligned}$$

The second step comes from lower-bounding the marginal cost by and marginal emissions cost for q_W^* by the levels at $q^* < q_W^*$. The third step comes from assuming that the relative values of $C'(q^*), E'(q^*)$ are matched by the means measured in [3]. Evaluating (the final step) implies that *the welfare-maximizing price (p_W^*) could be as much as* 12.7% *below the surplus-maximizing one.*[12]

A deeper look reveals insights into the sources of these effects. The consumer burden exists because while rich people tend to consume more electricity than poorer

[12] A natural next question is what this implies relative to current prices. Following MSC in [3], we would get that MWC is well below current prices. However, the opposite is likely to be true. The authors use \$50 for the SCC, while most recent estimates use \$190. We computed aggregated totals for the total damage caused by each of the pollutants and found such a substitution in the SCC to half the emissions damage. Using the rule of thumb that marginal and average emissions have the same concentration would imply that the MWC, even with the consumer burden, lies well above the current average price.

people, they do so less than the change in their incomes. Because most US electricity utilities are private, the average welfare weight of those consuming electricity is less than those profiting from it. Meanwhile, the externality burden exists not because of disproportionate harm but simply because market profits are regressive in nature. To understand how robust this characterization is, note that the break-even point (when both consumer and externality welfare effects are equal) would be when the social marginal cost is 181% of current prices. Since there is no clear aggregate incidence trend, this is invariant from the composition of pollution (local or global).

Our results indicate that the equity effects in this market are dominated by the consumer burden, thus presenting an argument for lower prices relative to the surplus-maximizing ones. The consumer burden force is likely to be increasingly dominant as we transition from emissions-intensive generators to renewable sources. It is also strong empirical evidence of the importance of energy burden considerations in policy discussions regarding a just transition from fossil fuels.

6 Discussion

We develop a computationally tractable framework to account for equity considerations when setting a price control or pollution tax for polluting monopolies. Using a probabilistic representation of people who have different stakes in consumption, producer profit, and externality exposure (market shares), we present sufficient statistics formulas for the optimal price and pollution tax that nest efficiency results as the case when welfare weights and market shares are independent. We empirically test the welfare impacts in the residential electricity market and find significant evidence of a *consumer burden* and minimal evidence of an *externality burden*.

We hope that reasoning about environmental markets and policies through an equity-efficiency lens will be increasingly common and that our notion of a People Space could be a useful framework for doing so. That said, a few aspects of our approach limit its generalizability and robustness.

First, we hope to better understand suitable welfare weights for distributional analysis in environmental settings. Inverse optimum weights are a practical revealed preference approach and better than the unweighted alternative. However, in environmental settings, society likely has preferences for distribution beyond income — from historical emissions exposure to race as reflected in Biden's Justice40 Initiative. Understanding and empirically implementing these preferences — whether through survey methods or another form of revealed preference — is therefore critical in fitting the welfare analysis with societal values.

Second, our assumption of the distributional neutrality of harm from greenhouse gas emissions, while a helpful starting heuristic, is important to relax. Only a subset of individuals are at risk from forest fires, earthquakes, and sea level change. Even conditional on risk, for some a natural disaster may mean the loss of a beach home, while for others it could mean a loss of ancestral homelands and way of life. Moreover, when broadening our People Space to a global one, we may require changing the normalization on g as US citizens are likely less vulnerable than the average global citizen.

Lastly, on a technical note, we do not account for labor supply effects and a dual optimization between taxation and market pricing, as is necessary for fully rigorous welfare analysis. The profit of a firm may impact one's choice to be employed. Change in employment status would have a direct effect on an individual's share of profit (ie $s(i)$ becomes $s_i(p)$) as well as an indirect effect on their utility through a change in labor supply. Relating this to optimal taxation is likely to require assumptions on who leaves at different profit levels and the magnitude of people's labor dis-utility.

Beyond polluting monopolies, defining environmental welfare weights based on societal preferences and accounting for the global incidence of damage (our first two limitations) have important implications for how governments design fair and efficient environmental policies as they seek to put the notion of environmental justice into practice. We hope our formal framework will amplify and advance these conversations by enabling policymakers to concretely evaluate equity-efficiency trade-offs using empirical data.

7 Appendix

7.1 Proofs

Proof. **Proof of Corollary 14**.

Note that from our equation in Theorem 2, since $G'(u^i) = 1$, $g(i) = \omega(i)$ and doesn't depend on one's market share or the markets price and quantity, we can write $p^*_W(X) = p^*_W(\{\mathbb{E}[g \cdot z](X)\}_{z \in \{\tilde{x}, \tilde{s}, e\}})$. Further z does not impact the welfare-weighted expectations for the remaining market shares $\mathbb{E}[g \cdot z']$. Hence the only effect of market share re-distribution on p^*_W is through a change in $\mathbb{E}[g \cdot z]$, ie

$$\partial_V p^*_W = \frac{\partial p^*_W}{\partial \mathbb{E}[g \cdot z]} \partial_V \mathbb{E}[g \cdot z]$$

To calculate the second term, $\partial_V \mathbb{E}[g \cdot z] = \lim_{h \to 0} \frac{\mathbb{E}[g \cdot (z+hv)] - \mathbb{E}[g \cdot z]}{h} = \mathbb{E}[g \cdot v]$. The rest of this proof concerns the calculation of the first term for different market shares.

Note that the equilibrium results in a zero of the C^1 function:

$$f(q) = p(q) \left(1 + \frac{\mathbb{E}[g \cdot \tilde{x}] - \mathbb{E}[g \cdot \tilde{s}]}{\mathbb{E}[g \cdot \tilde{s}]} \frac{1}{|\epsilon^q_p|}\right) - \left[C'(q) + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \tilde{x}]} E'(q)\right].$$

To simplify notation, let $\mathbb{E}[g \cdot \tilde{x}] = g_A$, $\mathbb{E}[g \cdot \tilde{s}] = g_B$, and $\mathbb{E}[g \cdot e] = g_C$. To solve for the derivatives $\frac{\partial p^*_W}{\partial z}$ for $z \in \{g_A, g_B, g_C\}$ we will use the implicit function theorem. This theorem tells us that if (1) $f'(q) \neq 0$ and (2) $\frac{\partial f}{\partial z}, f'(q)$ are continuous, then for $z \in \{g_A, g_B, g_C\}$:

$$\frac{\partial p^*_W}{\partial z} = \frac{1}{-f'(q^*_W)} \cdot \frac{\partial f(q^*_W)}{\partial z}.$$

First we will compute $f'(q)$,

$$f'(q) = p'(q)\left(1 + \frac{g_A - g_B}{g_B}\frac{1}{|\epsilon_p^q|}\right) - C''(q) - \frac{g_C}{g_B}E''(q) < 0$$

The inequality follows from the convexity of C, E with respect to q and that $p'(q) = \frac{1}{q'(p)} < 0$. Each component is continuous by assumption. Thus, $f'(q)$ is negative and continuous.

Taking the derivative with respect each of the parameters to get $\frac{\partial f}{\partial z}$ we have:

$$\begin{aligned}
\frac{\partial f(q)}{\partial g_A} &= \frac{p}{|\epsilon_q^p|} > 0 \\
\frac{\partial f(q)}{\partial g_B} &= -p\frac{g_A}{g_B^2|\epsilon_p^q|} + \frac{g_C}{g_B^2}E'(q) \\
\frac{\partial f(q)}{\partial g_C} &= \frac{1}{g_B}E'(q) < 0
\end{aligned}$$

These are also continuous since the welfare weights are positive. Therefore:

$$\begin{aligned}
\frac{\partial p_W^*}{\partial g_A} &= \frac{p}{|\epsilon_q^p|} \cdot p'(q_W^*) < 0 \\
\frac{\partial p_W^*}{\partial g_B} &= \left(-p\frac{g_A}{g_B^2|\epsilon_p^q|} + \frac{g_C}{g_B^2}E'(q)\right) \cdot p'(q_W^*) \\
\frac{\partial p_W^*}{\partial g_C} &= \frac{1}{g_B}E'(q) \cdot p'(q_W^*) > 0.
\end{aligned}$$

Where $\frac{\partial p_W^*}{\partial g_B}$ is positive when $\left(\mathbb{E}[g \cdot e]E'(q) > \mathbb{E}[g \cdot \tilde{x}]\frac{1}{|\epsilon_p^{q,semi}|}\right)$. Note that a monopolist's optimal price is

$$p_M^* = C'(q) - \frac{1}{\epsilon_q^{p,semi}}$$

Therefore,

$$\begin{aligned}
\frac{\partial p^*}{\partial g_B} > 0 &\iff \left(g_C E'(q^*) > g_B \frac{1}{|\epsilon_p^{q,semi}|} \right) \\
&\iff C'(q) + \frac{g_C}{g_B} E'(q) - \frac{g_A - g_B}{g_B} \frac{1}{\epsilon_p^{q,semi}} > C'(q) + \frac{1}{\epsilon_p^{q,semi}} \\
&\iff C'(q) + \frac{g_C}{g_B} E'(q) > C'(q) - \frac{1}{\epsilon_p^{q,semi}} \\
&\iff p_W^* > p_M^*.
\end{aligned}$$

□

Proof. **Proof of Theorem 8.** At a local optimum, the change in the SWF with respect to the tax is zero.

$$\frac{d}{d\tau} SWF = \int_{\mathcal{I}} \omega(i) \frac{d}{d\tau} G(u^i(c, \ell, x; p)) d(mi)$$

Evaluating the inner portion

$$\frac{d}{d\tau} G(u^i(c, \ell, x; p, \tau)) = G'(u^i) \left(\frac{dc}{d\tau} u_c^i + \frac{dx}{d\tau} u_x^i - \frac{dE(q)}{d\tau} e(i) \right)$$

Note that

$$\frac{dc}{d\tau} u_c^i + \frac{dx}{d\tau} u_x^i = (\tilde{s}(i) \frac{d\pi}{d\tau} - xp'(\tau) + \lambda(i)[E(q) - \frac{dE(q)}{d\tau}]) + (u_x^i - p) x_i'(p)$$

By the envelope theorem, $(u_x^i - p) x_i'(p) = 0$. Also by the envelope theorem, $\frac{d\pi}{d\tau} =$

$-E(q)$. Substituting these values in

$$\frac{d}{d\tau}SWF = \int_{\mathcal{I}} G'(u^i)\omega(i)\left[-\tilde{s}(i)E(q) - xp'(\tau) + \lambda(i)[E(q) - \frac{dE(q)}{d\tau}] - \frac{dE(q)}{d\tau}e(i)\right]d(mi)$$

Letting $g(i) = \frac{\omega(i)G'(u^i)}{\int_{\mathcal{I}}\omega(i)G'(u^i)d(mi)}$, dividing by $\int_{\mathcal{I}}\omega(i)G'(u^i)d(mi)$, and integrating with respect to the probability measure P:

$$\int_{\mathcal{I}} g(i)\left[-\tilde{s}(i)E(q) - xp'(\tau) + \lambda(i)[E(q) - \frac{dE(q)}{d\tau}] - \frac{dE(q)}{d\tau}e(i)\right]P(di) \tag{5}$$

$$= \mathbb{E}\left[g \cdot \left(-\tilde{s}E(q) - x(p)p'(\tau) + \lambda(E(q) + \tau\frac{dE}{d\tau}) - \frac{dE(q)}{d\tau}e\right)\right] = 0 \tag{6}$$

Further letting $\tilde{x}(p) = x(p)/q(p)$:

$$\mathbb{E}[g \cdot \tilde{s}]E(q) + \mathbb{E}[g \cdot \tilde{x}(p)]q(p)p'(\tau) + \mathbb{E}[g \cdot \lambda](E(q) + \tau\frac{dE}{d\tau}) + \mathbb{E}[g \cdot e]\frac{dE}{d\tau} = 0$$

We can rearrange to get an expression for τ at a local optimum:

$$\tau = -\frac{1}{\frac{dE}{d\tau}\mathbb{E}[g \cdot \lambda]}\Bigg(\mathbb{E}[g \cdot \tilde{s}]E(q) + \mathbb{E}[g \cdot \tilde{x}(p)]q(p)p'(\tau) \tag{7}$$

$$+ \mathbb{E}[g \cdot \lambda]E(q) + \mathbb{E}[g \cdot e]\frac{dE}{d\tau}\Bigg) \tag{8}$$

$$= \frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]}\frac{E(q)}{\frac{dE}{d\tau}} + \frac{\mathbb{E}[g \cdot \tilde{x}(p)]}{\mathbb{E}[g \cdot \lambda]}\frac{q(p)p'(\tau)}{E'(q)q'(p)p'(\tau)} + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]} \tag{9}$$

$$= \frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]}\frac{1}{\epsilon_E^{\tau,semi}} + \frac{\mathbb{E}[g \cdot \tilde{x}(p)]}{\mathbb{E}[g \cdot \lambda]}\frac{1}{E'(q)\epsilon_q^{p,semi}} + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]} \tag{10}$$

Let τ^* be the value satisfying the equation above. The last piece is to substitute in to solve for the $p_\tau^* = p(\tau^*)$. By the monopolist's problem we have that

$$p(\tau^*) = \tau^* E'(q) + C'(q) - \frac{q(p)}{q'(p)}.$$

Substituting in the value for τ^*:

$$p_\tau^* = C'(q) + \frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot \lambda]} E'(q) + \frac{\mathbb{E}[g \cdot \tilde{x}(p)] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{1}{\epsilon_q^{p,semi}} + \frac{\mathbb{E}[g \cdot \tilde{s}] - \mathbb{E}[g \cdot \lambda]}{\mathbb{E}[g \cdot \lambda]} \frac{E'(q)}{\epsilon_E^{\tau,semi}}.$$

□

Proof. **Proof of Corollary 15.** As for p_W^*, since the distribution of market shares and welfare weights are only equity parameters in Theorem 2, $\tau^*(\{\mathbb{E}[g \cdot k](X)\}_{k \in \{\tilde{x},\tilde{s},\tilde{s},\lambda\}})$. Hence the only effect of market share re-distribution on p_W^* is through a change in $\mathbb{E}[g \cdot z]$, ie

$$\partial_V \tau^* = \frac{\partial \tau^*}{\partial z} \partial_V \mathbb{E}[g \cdot z]$$

where $\partial_V \mathbb{E}[g \cdot z] = \mathbb{E}[g \cdot v]$.

To simplify notation, let $g_A = \mathbb{E}[g \cdot \tilde{x}]$, $g_B = \mathbb{E}[g \cdot \tilde{s}]$, $g_C = \mathbb{E}[g \cdot e]$ and $\lambda = \mathbb{E}[g \cdot \lambda]$. Note that the equilibrium results in a zero of the C^1 function:

$$f(q) = \tau(q) \left(1 - \frac{\lambda - g_B}{\lambda} \frac{1}{|\epsilon_E^\tau|} \right) - \frac{1}{\lambda} \left[g_C + \frac{g_A}{\epsilon_p^q} \frac{p}{E'(q)} \right]$$

To solve for the derivatives $\frac{\partial \tau^*}{\partial z}$ for $z \in \{g_A, g_B, g_C\}$ we will use the implicit function theorem. This theorem tells us that if (1) $f'(q) \neq 0$ and (2) $\frac{\partial f}{\partial z}, f'(q)$ are continuous, then for $z \in \{g_A, g_B, g_C\}$:

$$\frac{\partial \tau^*}{\partial z} = \frac{1}{-f'(q_\tau^*)} \cdot \frac{\partial f(q_\tau^*)}{\partial z}.$$

First, we will show that $\frac{\partial q_\tau^*}{\partial z}$ is negative and continuous. To start, observe that $\tau'(q) = \frac{1}{q'(p(\tau))p'(\tau)} < 0$. Intuitively this makes sense: In order to induce a higher quantity, requiring a lower price, the tax rate must be lower. Since $q'(.), p'(.)$ are continuous and non-zero, so is $\tau'(q)$. Evaluating the full derivative:

$$\begin{aligned} f'(q) &= \tau'(q)\left(1 - \frac{\lambda - g_B}{\lambda}\frac{1}{|\epsilon_E^\tau|}\right) + \frac{g_A}{\lambda|\epsilon_p^q|}\frac{d}{dq}\left(\frac{p}{E'(q)}\right) \\ &= \tau'(q)\left(1 - \frac{\lambda - g_B}{\lambda}\frac{1}{|\epsilon_E^\tau|}\right) + \frac{g_A}{\lambda|\epsilon_p^q|}\left(\frac{E'(q)p'(q) - E''(q)p}{(E'(q))^2}\right) \end{aligned}$$

First, $\left(1 - \frac{\lambda - g_B}{\lambda}\frac{1}{|\epsilon_E^\tau|}\right) > 0$ since we assume that $|\epsilon_E^\tau| > \frac{\lambda - g_B}{\lambda}$. Therefore the first term is negative. The second term is also negative since $p'(q) = \frac{1}{q'(p)} < 0$. Thus $f'(q) < 0$ globally. Furthermore, it is continuous since each of the component functions are continuous and non-zero.

Taking the derivative with respect each of the parameters to get $\frac{\partial f}{\partial z}$ we have:

$$\begin{aligned} \frac{\partial f(q)}{\partial g_A} &= \frac{1}{\lambda}\frac{p}{|\epsilon_q^p|E'(q)} > 0 \\ \frac{\partial f(q)}{\partial g_B} &= \frac{\tau}{\lambda|\epsilon_\tau^E|} > 0 \\ \frac{\partial f(q)}{\partial g_C} &= -\frac{1}{\lambda} < 0 \\ \frac{\partial f(q)}{\partial \lambda} &= \frac{1}{\lambda^2}\left(g_C - g_A\frac{1}{E'(q)}\frac{p}{|\epsilon_q^p|} - g_B\frac{\tau}{|\epsilon_E^\tau|}\right) \end{aligned}$$

Lastly, to compute the sign of $\frac{\partial \tau^*}{\partial z}$ note that $\frac{\partial \tau^*}{\partial z} = \tau'(q^*_\tau)\frac{\partial q^*_\tau}{\partial z}$. Therefore:

$$\frac{\partial \tau^*}{\partial g_A} = \frac{1}{\lambda}\frac{p}{|\epsilon_q^p| E'(q)} \cdot \tau'(q^*_\tau) < 0$$
$$\frac{\partial \tau^*}{\partial g_B} = \frac{\tau}{\lambda|\epsilon_\tau^E|} \cdot \tau'(q^*_\tau) < 0$$
$$\frac{\partial \tau^*}{\partial g_B} = -\frac{1}{\lambda} \cdot \tau'(q^*_\tau) > 0$$
$$\frac{\partial \tau^*}{\partial \lambda} = \frac{1}{\lambda^2}\left(g_C - g_A \frac{1}{E'(q)}\frac{p}{|\epsilon_q^p|} - g_B \frac{\tau}{|\epsilon_E^\tau|}\right) \cdot \tau'(q^*_\tau)$$

Note that $\frac{\partial f(q)}{\partial \lambda} > 0$ when

$$\left(g_C - g_A \frac{1}{E'(q)}\frac{p}{|\epsilon_q^p|} - g_B \frac{\tau}{|\epsilon_E^\tau|}\right) > 0.$$

Rearranging 8, we see that the optimal tax rate τ^* satisfies an equivalence between the marginal benefit of tax dollars for the government and the marginal benefit of taxation for the market.

$$\underbrace{\lambda\tau(1 - \frac{1}{|\epsilon_E^\tau|})}_{\text{tax revenue value}} = \underbrace{\left(g_C - g_A \frac{1}{E'(q)}\frac{p}{|\epsilon_q^p|} - g_B \frac{\tau}{|\epsilon_E^\tau|}\right)}_{\text{market welfare value}}$$

$$\tau = \frac{1}{\lambda}\frac{\left(g_C - g_A \frac{1}{E'(q)}\frac{p}{|\epsilon_q^p|} - g_B \frac{\tau}{|\epsilon_E^\tau|}\right)}{(1 - \frac{1}{|\epsilon_E^\tau|})}$$

□

Proof. **Proof of Corollary 12.**

First we'd like to see what global concavity holds. Recall that the first derivative of social welfare with respect to the τ is:

$$\frac{dSWF}{d\tau} = -\left(\mathbb{E}[g \cdot \tilde{s}]E(q) + \mathbb{E}[g \cdot \tilde{x}]q'(p)E'(q) + \mathbb{E}[g \cdot \lambda]\left(E(q) + \tau\frac{dE}{d\tau}\right) + \mathbb{E}[g \cdot e]\frac{dE}{d\tau}\right)$$

Let $g_A = \mathbb{E}[g \cdot \tilde{x}]$, $g_B = \mathbb{E}[g \cdot \tilde{s}]$, $g_C = \mathbb{E}[g \cdot e]$, and $\lambda = \mathbb{E}[g \cdot \lambda]$ Taking a further derivative:

$$\begin{aligned}
-\frac{d^2SWF}{d\tau^2} &= g_B\frac{dE}{d\tau} + g_A\frac{d}{d\tau}(\frac{dE}{d\tau}/E'(q)) + \lambda(2 \cdot \frac{dE}{d\tau} + \tau\frac{d^2E}{d\tau^2}) + g_C\frac{d^2E}{d\tau^2} \\
&= g_B\frac{dE}{d\tau} + g_A(\frac{d^2E}{d\tau^2}\frac{1}{E'(q)} - (\frac{dE}{d\tau})^2\frac{E''(q)}{(E'(q))^3}) + \lambda(2 \cdot \frac{dE}{d\tau} + \tau\frac{d^2E}{d\tau^2}) + g_C\frac{d^2E}{d\tau^2} \\
&= \frac{dE}{d\tau}\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right) + \frac{d^2E}{d\tau^2}(\tau\lambda + g_C)
\end{aligned}$$

Note that $\frac{dE}{d\tau} = (E'(q))^2q'(p) < 0$. Thus $\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right) > 0$. Therefore, in order for $\frac{d^2SWF}{d\tau^2} < 0$ we require:

$$\begin{aligned}
&\frac{dE}{d\tau}\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right) + \frac{d^2E}{d\tau^2}(\tau\lambda + g_C) > 0 \\
&\frac{d^2E}{d\tau^2}(\tau\lambda + g_C) > -\frac{dE}{d\tau}\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right) \\
&\frac{d^2E}{d\tau^2} > -\frac{\frac{dE}{d\tau}\left(g_B - g_A\frac{dE}{d\tau}\frac{E''(q)}{(E'(q))^3} + 2\lambda\right)}{(\tau\lambda + g_C)}
\end{aligned}$$

This tells us that the second order reduction on emissions and government revenue reception dominates the effect that the direct effect of a higher tax rate corresponds to lower surplus.

The second condition tells us that the welfare from the optimal level of market activity is greater than than without a market. Since there will be no production when the tax rate is infinite, this is represented by the state $(\tau = \infty, p(\infty))$. $\square$

7.2 Additional Tables and Figures

Table 1: Pollutant Emissions and Social Costs

Pollutant	**Pollutant Type**	**Emissions (Tons)**	**Social Cost (2022 $)**
Carbon Dioxide	GHG	1,615,760,598	190
Sulfur Dioxide	CAP	841,961	87,600
Nitrogen Oxides	CAP	812,086	140,880
Methane	GHG	130,688	1,600
PM2.5 Primary	CAP	90,761	164,400
VOCs	CAP	25,944	134,640
Ammonia	CAP	21,0645	13,800
Nitrous Oxide	GHG	16,626	54,000

Table 2: *Consumer burden estimation.*

Incidence term	Numerical value
$\mathbb{E}[g \cdot s]$	0.881
$\mathbb{E}[g \cdot \tilde{x}(p)]$	0.986
ϵ_p^q	-0.39
consumer burden	$-0.246 \times p$

Table 3: *Externality Burden Statistics.*

Pollution type	Local emissions	Air quality	Susceptibility
Local pollution ($\frac{\mathbb{E}[g \cdot e^{local}]}{\mathbb{E}[e]\mathbb{E}[g]}$)	1.00	0.99	1.05
Pollution average ($\frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[e]\mathbb{E}[g]}$)	1.00	1.00	1.02
Externality burden coefficient ($\frac{\mathbb{E}[g \cdot e]}{\mathbb{E}[g \cdot s]} - 1$)	0.14	0.14	0.18

References

[1] *2020 NEI Data Retrieval Tool.* URL: https://awsedap.epa.gov/public/single/?appid=20230c40-026d-494e-903f-3f112761a208&sheet=5d3fdda7-14bc-4284-a9bb-cfd856b9348d&opt=ctxmenu,currsel (visited on 03/19/2024).

[2] Michelle L. Bell, Antonella Zanobetti, and Francesca Dominici. "Evidence on Vulnerability and Susceptibility to Health Risks Associated With Short-Term Exposure to Particulate Matter: A Systematic Review and Meta-Analysis". In: *American Journal of Epidemiology* 178.6 (Sept. 15, 2013), pp. 865–876. ISSN: 0002-9262. DOI: 10.1093/aje/kwt090. URL: https://doi.org/10.1093/aje/kwt090 (visited on 03/19/2024).

[3] Severin Borenstein and James B. Bushnell. "Do Two Electricity Pricing Wrongs Make a Right? Cost Recovery, Externalities, and Efficiency". In: *American Economic Journal: Economic Policy* 14.4 (Nov. 2022), pp. 80–110. ISSN: 1945-7731. DOI: 10.1257/pol.20190758. URL: https://www.aeaweb.org/articles?id=10.1257/pol.20190758 (visited on 11/12/2023).

[4] Marilyn A. Brown et al. "High energy burden and low-income energy affordability: conclusions from a literature review". In: *Progress in Energy* 2.4 (Oct. 2020). Publisher: IOP Publishing, p. 042003. ISSN: 2516-1083. DOI: 10.1088/2516-1083/abb954. URL: https://dx.doi.org/10.1088/2516-1083/abb954 (visited on 03/28/2024).

[5] James M. Buchanan. “External Diseconomies, Corrective Taxes, and Market Structure”. In: *The American Economic Review* 59.1 (1969). Publisher: American Economic Association, pp. 174–177. ISSN: 0002-8282. URL: https://www.jstor.org/stable/1811104 (visited on 11/12/2023).

[6] Jake Cigainero. “Who Are France’s Yellow Vest Protesters, And What Do They Want?” In: *NPR* (Dec. 3, 2018). URL: https://www.npr.org/2018/12/03/672862353/who-are-frances-yellow-vest-protesters-and-what-do-they-want (visited on 03/28/2024).

[7] Helmuth Cremer and Firouz Gahvari. “Second-best taxation of emissions and polluting goods”. In: *Journal of Public Economics* 80.2 (May 1, 2001), pp. 169–197. ISSN: 0047-2727. DOI: 10.1016/S0047-2727(00)00086-4. URL: https://www.sciencedirect.com/science/article/pii/S0047272700000864 (visited on 02/04/2024).

[8] Samuel Fankhauser, Richard S.J. Tol, and DAVID W. Pearce. “The Aggregation of Climate Change Damages: a Welfare Theoretic Approach”. In: *Environmental and Resource Economics* 10.3 (Oct. 1, 1997), pp. 249–266. ISSN: 1573-1502. DOI: 10.1023/A:1026420425961. URL: https://doi.org/10.1023/A:1026420425961 (visited on 03/27/2024).

[9] Francesco Forastiere et al. “Socioeconomic status, particulate air pollution, and daily mortality: differential exposure or differential susceptibility”. In: *American Journal of Industrial Medicine* 50.3 (Mar. 2007), pp. 208–216. ISSN: 0271-3586. DOI: 10.1002/ajim.20368.

[10] Nathaniel Hendren. "Measuring economic efficiency using inverse-optimum weights". In: *Journal of Public Economics* 187 (July 1, 2020), p. 104198. ISSN: 0047-2727. DOI: 10.1016/j.jpubeco.2020.104198. URL: https://www.sciencedirect.com/science/article/pii/S0047272720300621 (visited on 11/29/2023).

[11] *Investor-owned utilities served 72% of U.S. electricity customers in 2017 - U.S. Energy Information Administration (EIA)*. URL: https://www.eia.gov/todayinenergy/detail.php?id=40913 (visited on 03/19/2024).

[12] Wesley James, Chunrong Jia, and Satish Kedia. "Uneven Magnitude of Disparities in Cancer Risks from Air Toxics". In: *International Journal of Environmental Research and Public Health* 9.12 (Dec. 2012), pp. 4365–4385. ISSN: 1661-7827. DOI: 10.3390/ijerph9124365. URL: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3546767/ (visited on 03/19/2024).

[13] Abdulrahman Jbaily et al. "Air pollution exposure disparities across US population and income groups". In: *Nature* 601.7892 (Jan. 2022). Publisher: Nature Publishing Group, pp. 228–233. ISSN: 1476-4687. DOI: 10.1038/s41586-021-04190-y. URL: https://www.nature.com/articles/s41586-021-04190-y (visited on 03/19/2024).

[14] By Louis Kaplow. "OPTIMAL CONTROL OF EXTERNALITIES IN THE PRESENCE OF INCOME TAXATION*". In: *International Economic Review* 53.2 (May 1, 2012). Publisher: John Wiley & Sons, Ltd, pp. 487–509. ISSN: 1468-2354. DOI: 10.1111/j.1468-2354.2012.00689.x. URL: https://onlinelibrary.wiley.com/doi/10.1111/j.1468-2354.2012.00689.x (visited on 03/30/2024).

[15] Ryan Kellogg and Mar Reguant. "Energy and Environmental Markets, Industrial Organization, and Regulation". In: NBER Working Paper Series (Sept. 2021). DOI: 10.3386/w29235. URL: https://www.nber.org/papers/w29235 (visited on 08/26/2023).

[16] David E. Kramar et al. "A Spatially Informed Analysis of Environmental Justice: Analyzing the Effects of Gerrymandering and the Proximity of Minority Populations to U.S. Superfund Sites". In: *Environmental Justice* 11.1 (Feb. 2018). Publisher: Mary Ann Liebert, Inc., publishers, pp. 29–39. ISSN: 1939-4071. DOI: 10.1089/env.2017.0031. URL: https://www.liebertpub.com/doi/abs/10.1089/env.2017.0031 (visited on 03/30/2024).

[17] A. Lans Bovenberg and Lawrence H. Goulder. "Environmental Taxation and Regulation*". In: *Handbook of Public Economics*. Ed. by Alan J. Auerbach and Martin Feldstein. Vol. 3. Elsevier, Jan. 1, 2002, pp. 1471–1545. DOI: 10.1016/S1573-4420(02)80027-1. URL: https://www.sciencedirect.com/science/article/pii/S1573442002800271 (visited on 03/30/2024).

[18] Richard J. Lazarus. *The making of environmental law*. Second edition. HOLLIS number: 99156636064603941. Chicago ; London: The University of Chicago Press, 2023. ISBN: 978-0-226-82153-5.

[19] William D. Nordhaus. "Optimal Greenhouse-Gas Reductions and Tax Policy in the "DICE" Model". In: *The American Economic Review* 83.2 (1993). Publisher: American Economic Association, pp. 313–317. ISSN: 0002-8282. URL: https://www.jstor.org/stable/2117683 (visited on 03/15/2024).

[20] William D. Nordhaus and Edward Kokkelenberg C., eds. *Nature's Numbers: Expanding the National Economic Accounts to Include the Environment*. Washington, D.C.: National Academies Press, June 28, 1999. ISBN: 978-0-309-07151-2. DOI: `10.17226/6374`. URL: `http://www.nap.edu/catalog/6374` (visited on 03/25/2024).

[21] Väinö Nurmi and Heini Ahtiainen. "Distributional Weights in Environmental Valuation and Cost-benefit Analysis: Theory and Practice". In: *Ecological Economics* 150 (Aug. 1, 2018), pp. 217–228. ISSN: 0921-8009. DOI: `10.1016/j.ecolecon.2018.04.021`. URL: `https://www.sciencedirect.com/science/article/pii/S0921800917318074` (visited on 03/27/2024).

[22] Thomas Piketty and Emmanuel Saez. *Optimal Labor Income Taxation*. Nov. 2012. DOI: `10.3386/w18521`. URL: `https://www.nber.org/papers/w18521` (visited on 03/28/2024).

[23] Emmanuel Saez and Stefanie Stantcheva. "Generalized Social Marginal Welfare Weights for Optimal Tax Theory". In: *American Economic Review* 106.1 (Jan. 2016), pp. 24–45. ISSN: 0002-8282. DOI: `10.1257/aer.20141362`. URL: `https://www.aeaweb.org/articles?id=10.1257/aer.20141362` (visited on 11/15/2023).

[24] P. Grace Tee Lewis et al. "Characterizing vulnerabilities to climate change across the United States". In: *Environment International* 172 (Feb. 1, 2023), p. 107772. ISSN: 0160-4120. DOI: `10.1016/j.envint.2023.107772`. URL: `https://www.sciencedirect.com/science/article/pii/S0160412023000454` (visited on 12/10/2023).

[25] OAR US EPA. *Air Quality - Cities and Counties*. May 4, 2016. URL: https://www.epa.gov/air-trends/air-quality-cities-and-counties (visited on 03/19/2024).

[26] OAR US EPA. *Sector-based PM2.5 Benefit Per Ton Estimates*. Oct. 21, 2014. URL: https://www.epa.gov/benmap/sector-based-pm25-benefit-ton-estimates (visited on 03/19/2024).

[27] OP US EPA. *EPA's "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances"*. Archive Location: United States. Sept. 22, 2022. URL: https://www.epa.gov/environmental-economics/scghg (visited on 03/19/2024).