Research Article

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Technology Adoption under Negative External Effects

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Abstract: This paper shows that, in the presence of negative production external effects (e.g., waste, pollution), market-driven technology adoption is socially inefficient. Two distinct market structures are considered within the neoclassical framework: perfect competition and monopoly. In both cases, there is a range of cost structures under which firms prefer the adoption of inferior technologies. A number of policy instruments are considered in terms of their welfare enhancing properties.

Keywords: external effects; technology adoption; planned obsolescence; quotas; Pigouvian taxation

JEL Classification: D62; Q5

1 Introduction

This paper studies technology adoption in the presence of negative external effects under two distinct market structures within the neoclassical framework: perfect competition and monopoly. In the basic setting, two different technologies, A and B, can be used to produce a durable good. The two technologies differ in the amount of pollution/waste generated as a by-product of the underlying manufacturing process, as well as in the durability of their output units. On one hand, technology A is cleaner than technology B, in the sense that it generates less pollution/waste. On the other hand, technology A produces a more durable version of the product at hand

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than technology *B*. These assumptions are natural, since product durability reduces pollution/waste. Accordingly, consumers value *A*-units more than *B*-units for two reasons: first, *A*-units are more durable; second, they pollute less. While consumers take account of the pollution/waste that affects them directly, they neglect its effects on others. This is a standard assumption in economic models with non-depletable external effects.

While technology *A* is superior in terms of its manufacturing process' external effects and the intrinsic "quality" of its output, technology *A* may be more costly than technology *B*. Throughout the analysis, we maintain the assumption that technology *B* is socially inferior, in the sense that the social cost of x *B*-units exceeds that of an "equivalent" quantity of *A*-units, i.e., a quantity of *A*-units that yields the same utility as x.

Under laissez-faire, firms adopt the socially inferior technology for a range of parameter values, regardless of the underlying market structure. This can be viewed as an instance of *planned obsolescence*, understood as "deliberate" production of goods with inferior lifespans.[1]

The market-driven adoption of the socially inferior technology is a direct consequence of the negative external effect. While the social cost of x *B*-units exceeds that of an "equivalent" quantity of *A*-units, in the neoclassical setting, it is the private benefits (resp., costs) of consumption (resp., production) that guide the interaction of "rational" agents in the marketplace; and these private benefits/costs are misaligned with their social counterparts in such a way that the traded quantity of *B*-output ends up being "excessive." On one hand, the consumers' private benefits from the consumption of *B*-output are "too high" because they exclude the negative welfare effects of pollution/waste on other consumers. On the other hand, the firms' private production costs under technology *B* are "too low" in that they omit the negative welfare effects of pollution/waste on the population.

Pollution/waste quotas and Pigouvian taxes are considered as a means to mitigate the deadweight loss from market-driven technology adoption. The policy analysis differs significantly across market structures.

In the textbook analysis of perfectly competitive market economies with external effects, quotas and Pigouvian taxes are equally effective in correcting market failures. By contrast, Pigouvian taxation proves to be a superior policy tool in our perfectly competitive setting. In fact, in the perfectly competitive case, Pigouvian taxes are universally welfare enhancing (i.e., welfare enhancing regardless of the tax rate and for all parameter values). Quotas, by contrast, are suboptimal, in that they do not induce the adoption of the socially efficient technology. Intuitively,

1 Alternative definitions of planned obsolescence are discussed below.

quotas do not alter the firms' marginal cost functions, and so, as long as the quota is not binding, B-units of output are traded, as in the laissez-faire equilibrium. Once the quantity of B-units reaches the quota, the cap on waste/pollution binds, and so no extra good (in the form of A-units or B-units) can be produced. Pigouvian taxes on B-output, by contrast, do increase the firms' marginal cost of B-output, and a large enough tax induces the adoption of technology A.

These results do not carry over to the case of monopoly. Indeed, there exist parameter configurations under which *any* quota (resp., Pigouvian tax) exacerbates the inefficiency of the "unfettered" monopoly allocation. Intuitively, while A-output tends to crowd out B-output when pollution/waste quotas or Pigouvian taxes on B-output are imposed, the quantity of A-output traded by a monopolist need not be large enough to outweigh the welfare loss from reduced consumption of B-output. In fact, a monopolist does not factor in the social gains from replacing B-units by A-units and keeps A-output at a suboptimal level below the efficient quantity of A-output. The resulting A-output shortfall may be large enough to ensure a welfare loss.

An alternative policy, based on a combination of quotas on B-output and subsidies on the consumption of A-output, is introduced as an example of a welfare enhancing market intervention.

The idea that government policy is needed to promote the adoption of cleaner technologies is not new. Acemoglu et al. (2012) and Acemoglu et al. (2016) emphasize the role of carbon taxes and research subsidies in preventing an environmentally disastrous laissez-faire equilibrium. They do so in a framework with a fixed market structure in which the use of carbon in manufacturing constrains the firms' production possibility sets. This negative externality differs from the direct external effect on consumer welfare considered in this paper.

The literature on planned obsolescence goes back to at least Galbraith (1958). While most of the early work on this topic uses durability as a proxy for obsolescence, which is in line with the notion adopted in this paper, it does not rationalize planned obsolescence as a direct consequence of non-depletable negative external effects.

In Rust (1986), the existence of a secondary market for a durable good whose primary market is monopolistic creates an incentive for the monopolist to distort product durability from the socially optimal level in order to restrain competition from the secondary market. Bulow (1986) obtains planned obsolescence (defined as the production of goods with inefficiently short useful lives) as a consequence of the perfection constraint of a dynamically consistent durable goods monopolist/oligopolist. Unlike in our setting, Bulow (1986) obtains an efficient level of durability under perfect competition.

More recent papers on planned obsolescence (see, e.g. Choi 1994; Ellison and Fudenberg 2000; Hahn and Kim 2015; Hendel and Lizzeri 1999; Miao 2010; Waldman 1993) focus not only on product durability but also on a monopolist's incentive to introduce new versions of a product over time. The central theme in this strand of the literature is the monopolist's failure to internalize the effect of newly introduced products on the "value" of units previously sold.

While most of the literature on planned obsolescence focuses on monopolistic markets for durable goods, a few papers have shown that this phenomenon may also arise in perfectly competitive markets as a mechanism to mitigate adverse selection problems in secondary markets (Grout and Park 2005) or to discipline producers whose products do not conform to adequate quality standards (Strausz 2009). Our rationale for planned obsolescence in perfectly competitive markets with negative externalities is complementary to these analyses based on incomplete information about product quality.

2 The Model

Firms can choose between two alternative technologies, A and B, for the production of a good, x. Technology A (resp., B) yields A-units (resp., B-units) of good x. A non-depletable negative external effect—e.g., waste, pollution—is a by-product of the manufacturing process. The external effect is relatively significant under technology B and negligible under technology A.

One possible interpretation is that, to an extent, technology A generates less pollution/waste because each unit of good x has a longer lifespan when manufactured using technology A, thereby generating less waste. In order to accommodate this interpretation, it is assumed that, from the consumers' perspective, α B-units of good x, where $\alpha > 1$, yield the same utility, excluding the external effect on individual welfare, as one A-unit of good x. This equivalence represents the utility gain from good durability, but it does not factor in the negative external effect on welfare.

Consumers have quasilinear preferences over two goods, good x and a numeraire, y. If technology B is adopted (and good x is measured in B-units), consumer i's utility function is given by

$$g_i(x_i) + y_i - e(x), \quad i = 1, \ldots, N,$$

where N is the number of consumers, $x = x_1 + \ldots + x_N$ represents the aggregate quantity of good x, x_i (resp., y_i) denotes agent i's consumed quantity of good x (resp., y), $g_i(x_i)$ satisfies $g_i'(\cdot) > 0$, $g_i''(\cdot) < 0$, and $\lim_{x_i \to 0} g_i'(x_i) = \infty$, and $e(x)$ represents the externality cost at $x = x_1 + \ldots + x_N$, with $e(0) = 0$, $e'(\cdot) > 0$, $e''(\cdot) > 0$, and $\lim_{x \to 0} e'(x) < \infty$.

The term $g_i(x_i)$ represents the "gross" utility derived from the consumption of x_i B-units, excluding i's utility cost from the external effect, $e(x)$, which represents the welfare cost experienced by consumer i as a result of the "pollution/waste" generated by the aggregate amount of B-units consumed, x.

If technology A is adopted and x_i is measured in A-units, consumer i's utility function is given by

$$g_i(\alpha x_i) + y_i. \tag{1}$$

Note that the gross utility of x_i A-units, $g_i(\alpha x_i)$, is the same as the utility of αx_i B-units, which is consistent with the stated equivalence between A-units and B-units of good x.

While the amount of waste/pollution generated by the manufacturing process based on technology A has no welfare consequences (see (1)), we do assume that there is a positive—albeit negligible—amount of waste/pollution associated with each A-unit. This assumption is important for the welfare analysis conducted in Section 5.

We will consider two alternative market structures: perfect competition and monopoly. In each case, the primary focus will be on the firms' technology adoption. Specifically, emphasis will be placed on the general inefficiency of the market-driven technology adoption and its welfare implications.

3 Technology Adoption under Perfect Competition

Both technologies, A and B, exhibit constant marginal costs, $c_A > 0$ and $c_B > 0$, respectively, and no fixed costs. It is assumed that technology A is socially, technically more efficient, in the sense that the social, marginal cost of production is always lower under technology A:

$$\frac{c_A}{\alpha} < c_B + Ne'(x), \quad \text{for all } x.$$

This inequality implies that, starting at any aggregate quantity, x, of B-units, the social, marginal cost of an infinitesimal increase, $\mathrm{d}x$, in the quantity of B-units, $(c_B + Ne'(x))\mathrm{d}x$, exceeds the marginal cost of an equivalent increase in terms of A-units, $\frac{c_A}{\alpha}\mathrm{d}x$.

Under the adoption of technology B, consumer i solves the following problem:

$$\max_{(x_i, y_i)} g_i(x_i) + y_i - e(x)$$

$$\text{s.t. } p_x x_i + y_i = w_i,$$

where $x = x_1 + \ldots + x_N$, p_x denotes the price of good x (the price of the numeraire, y, is normalized to 1), and w_i represents consumer i's endowment.

At an interior solution,

$$g_i'(x_i) - e'(x) = p_x. \tag{2}$$

Under quasilinearity of preferences, the first-order condition (2) is particularly amenable to interpretation. Indeed, the left-hand side of (2) represents consumer i's willingness to pay for an extra (marginal) unit of good x. Because this willingness to pay is independent of good y, (2) can be viewed as consumer i's inverse, individual demand function.

As shown in Figure 1, the (inverse) market demand resulting from the consumers' individual demands (equation (2)) is given by

$$p_x = G(x) - e'(x),$$

where $G(\cdot)$ denotes the horizontal sum of the $g_i'(\cdot)$ maps.

Under the adoption of technology A, consumer i solves

$$\max_{(x_i, y_i)} g_i(\alpha x_i) + y_i$$

$$\text{s.t. } p_x x_i + y_i = w_i.$$

At an interior solution,

$$\alpha g_i'(\alpha x_i) = p_x.$$

The corresponding market (inverse) demand is given by

$$p_x = \overline{G}(x),$$

where $\overline{G}(\cdot)$ denotes the horizontal sum of the maps $x \mapsto \alpha g_i'(\alpha x)$. It is easy to see that $\overline{G}(x) = \alpha G(\alpha x)$ (recall that $G(\cdot)$ denotes the horizontal sum of the $g_i'(\cdot)$ maps).

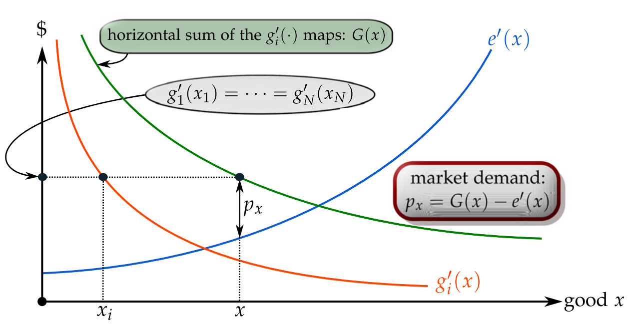

Figure 1: Market demand under technology *B*.

More generally, when the aggregate consumption of A-units and B-units is z_A and z_B, respectively, i's utility from the consumption of a_i A-units and b_i B-units is given by[2]

$$g_i(\alpha a_i + b_i) + y_i - e(z_B).$$

Thus, consumer i's willingness to pay for an extra (marginal) A-unit (resp., α extra (marginal) B-units) is $\alpha g_i'(\alpha a_i + b_i)$ (resp., $\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B)$). Consequently, if A-units and B-units are traded at prices p_A and p_B, respectively, consumer i will replace A-units with B-units (or buy extra B-units, if $a_i = 0$) whenever

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - p_B > \alpha g_i'(\alpha a_i + b_i) - p_A,$$

while consumer i will unload B-units and add A-units whenever

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - p_B < \alpha g_i'(\alpha a_i + b_i) - p_A.$$

The market supply curve is infinitely elastic at the constant marginal cost level.

As is commonly assumed in the neoclassical framework, at a competitive equilibrium with free entry, the market clears and entrants cannot outcompete incumbent firms.

While the condition

$$\frac{c_A}{\alpha} < c_B + Ne'(x), \quad \text{for all } x, \tag{3}$$

implies that technology A is socially, technically more efficient than technology B, if

$$\frac{c_A}{\alpha} > c_B + e'(x), \quad \text{for all } x \text{ such that } G(x) - e'(x) > 0,$$

then *no* competitive firm adopts technology A in equilibrium.

Proposition 1. *While technology A is socially, technically more efficient than technology B, in the sense that the social marginal cost of production is always lower under technology A (see* (3)*), if*

$$\frac{c_A}{\alpha} > c_B + e'(x), \quad \textit{for all } x \textit{ such that } G(x) - e'(x) > 0, \tag{4}$$

then no competitive firm adopts technology A in equilibrium.

2 Note that the sum of a_i A-units and b_i B-units is expressible, in terms of "equivalent" A-units (resp., B-units), as $a_i + \frac{b_i}{\alpha}$ (resp., $\alpha a_i + b_i$). Therefore, consumer i's "gross" utility of a_i A-units and b_i B-units (which excludes the utility cost of the external effect) is equal to the "gross" utility of $a_i + \frac{b_i}{\alpha}$ A-units, $g_i\left(\alpha\left(a_i + \frac{b_i}{\alpha}\right)\right) = g_i(\alpha a_i + b_i)$; this, in turn, is equal to the "gross" utility of $\alpha a_i + b_i$ B-units.

To understand this proposition, suppose first that all active firms adopt technology A. In this case, market clearing implies that

$$\alpha g_i'(\alpha x_i) = p_x = c_A, \quad i = 1, \dots, N.$$

Now consider an entrant adopting technology B for the production of good x and charging a unit price p_B slightly below $c_A - \alpha e'(0)$. The first α B-units generate an external cost for any one consumer equal to $\alpha e'(0)$. Consequently, a consumer i replacing her last A-unit with the first α B-units of good x obtains a net gain of $c_A - \alpha e'(0) - p_B > 0$: on one hand, the consumer's valuation of the last A-unit, $\alpha g_i'(\alpha x_i)$, is equal to its price, c_A, and so there is no net loss from the one-unit decrease in consumption; on the other hand, the first α B-units are valued at $\alpha g_i'(\alpha x_i) - \alpha e'(0) = c_A - \alpha e'(0)$, while the consumer pays only $p_B < c_A - \alpha e'(0)$ for the extra B-units. Overall, the consumer gains from the shift in consumption. And so does the entrant, since the price charged, $p_B \approx c_A - \alpha e'(0)$, exceeds the unit cost under the adoption of technology B, c_B.[3]

Consequently, if all firms adopt technology A, entry is profitable, implying that universal adoption of technology A cannot be sustained in equilibrium.

More generally, it can be shown that technology A is not actively employed in equilibrium. Indeed, suppose that z_A A-units (resp., z_B B-units) are traded. In equilibrium, A-units (resp., B-units) must be sold at price $p_x = c_A$ (resp., $p_x = c_B$), otherwise, firms either make losses or can be undercut and outcompeted by rivals. At these prices, an agent, i, who consumes a_i A-units and b_i B-units obtains a net gain of $\alpha g_i'(\alpha a_i + b_i) - c_A$ (resp., $\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B$) from buying an extra A-unit (resp., α extra B-units) of good x. By (4), we have

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B > \alpha g_i'(\alpha a_i + b_i) - c_A, \tag{5}$$

implying that consumers prefer to buy B-units of good x, and, in fact, they prefer to replace A-units of good x by B-units of good x.[4]

Consequently, the socially, technically efficient technology, A, is not employed in equilibrium. In equilibrium, x_B B-units are traded at price $p_x = c_B$, where x_B satisfies $G(x_B) - e'(x_B) = c_B$. This is, in fact, a competitive equilibrium: for the reasons pointed out in the previous paragraph, there would be no demand for any A-units offered at a price greater than or equal to c_A.

The market-driven adoption of the socially inferior technology is a direct consequence of the negative external effect. While the social cost of x B-units exceeds

3 It is easy to see that, because $c_B > 0$ and (4) holds, we have $c_A > \alpha(c_B + e'(0)) \geq c_B + \alpha e'(0)$.

4 The inequality (5) follows from (4) because $c_A > \alpha(c_B + e'(z_B))$ and $G(z_B) - e'(z_B) > 0$. The last inequality follows from the fact that z_B is market clearing only if $G(z_B) - e'(z_B) = p_x = c_B$.

that of an "equivalent" quantity of A-units, market participants respond to their private benefits/costs, which differ from their social counterparts. Under the conditions of Proposition 1, this discrepancy leads to an excessive traded quantity of B-output. On one hand, the consumers' private benefits from the consumption of B-output are "too high" because they exclude the negative welfare effects of pollution/waste on other consumers. On the other hand, the firms' private production costs under technology B are "too low" in that they omit the negative welfare effects of pollution/waste on the population.

We can evaluate the welfare loss at the unique competitive equilibrium, $(x = x_B, p_x = c_B)$, by comparing it to the case when all firms adopt the superior technology, A.

At the unique competitive equilibrium, $(x = x_B, p_x = c_B)$, the economy's net gain/loss is given by

$$W_B := \sum_{i=1}^{N}\left(\int_0^{x_{iB}} g_i'(x_i)\mathrm{d}x_i\right) - c_B x_B - Ne(x_B) = \int_0^{x_B} G(x)\mathrm{d}x - c_B x_B - Ne(x_B),$$

where x_{iB} denotes the equilibrium quantity consumer by agent i. If each agent i consumes $\frac{x_{iB}}{\alpha}$ A-units instead, the economy's net gain is given by

$$\int_0^{x_B} G(x)\mathrm{d}x - \frac{c_A x_B}{\alpha}.$$

This gain exceeds W_B by virtue of (3). Therefore, the net welfare gain (relative to the unique competitive equilibrium) from an allocation whereby each agent i consumes $\frac{x_{iB}}{\alpha}$ A-units is

$$c_B x_B + Ne(x_B) - \frac{c_A x_B}{\alpha}. \tag{6}$$

Because

$$g_1'(x_{1B}) = \ldots = g_N'(x_{NB}) = c_B + e'(x_B),$$

we have

$$\alpha g_1'\left(\alpha \cdot \frac{x_{1B}}{\alpha}\right) = \ldots = \alpha g_N'\left(\alpha \cdot \frac{x_{NB}}{\alpha}\right) =: m,$$

and so, when each agent i consumes $\frac{x_{iB}}{\alpha}$ A-units, the marginal willingness to pay for A-units, m, is common across agents. If $m \neq c_A$, then further welfare gains can be obtained by moving to an allocation whereby each agent i consumes x_{iA} A-units, where $\alpha g_i'(\alpha x_{iA}) = c_A$. This generates an overall extra welfare gain of

$$\sum_{i=1}^{N}\left(\int_{\frac{x_{iB}}{\alpha}}^{x_{iA}} \alpha g_i'(\alpha x_i)\mathrm{d}x_i\right) - c_A\left(x_A - \frac{x_B}{\alpha}\right) = \int_{\frac{x_B}{\alpha}}^{x_A} \overline{G}(x)\mathrm{d}x - c_A\left(x_A - \frac{x_B}{\alpha}\right), \tag{7}$$

where $x_A := \sum_{i=1}^{N} x_{iA}$, if $x_A > x_B/\alpha$,

$$-\sum_{i=1}^{N}\left(\int_{x_{iA}}^{\frac{x_{iB}}{\alpha}} \alpha g_i'(\alpha x_i)\mathrm{d}x_i\right) + c_A\left(\frac{x_B}{\alpha} - x_A\right) = -\int_{x_A}^{\frac{x_B}{\alpha}} \overline{G}(x)\mathrm{d}x + c_A\left(\frac{x_B}{\alpha} - x_A\right), \tag{8}$$

where $x_A := \sum_{i=1}^{N} x_{iA}$, if $x_A < x_B/\alpha$.

Consequently, the overall deadweight loss at the unique competitive equilibrium is given by the sum of the two expressions (6) and (7) if $x_A > x_B/\alpha$, (6) and (8) if $x_A < x_B/\alpha$.

4 Technology Adoption under Monopoly

Suppose that there is a sole vendor—a monopolist—on the supply side of the market. The cost structure associated with technology A (resp., B) takes the following general form: $F_A + c_A(x)$ (resp., $F_B + c_B(x)$), where F_A (resp., F_B) represents the fixed cost and $c_A(\cdot)$ (resp., $c_B(\cdot)$) denotes the variable cost function.

We make the following assumptions:

- Producing $\frac{z_B}{\alpha}$ A-units is more cost effective than producing z_B B-units:

  $$F_A + c_A(z_B/\alpha) < F_B + c_B(z_B) + Ne(z_B); \tag{9}$$

  here, z_B denotes a profit maximizing B-quantity when technology A is not employed, i.e., a solution to

  $$\max_{x_B \geq 0} (G(x_B) - e'(x_B))x_B - F_B - c_B(x_B).$$

- Suppose that the monopolist produces and sells $x_A > 0$ A-units and $x_B > 0$ B-units of output. Then, the production plan (x_A, x_B) can be improved upon, from a welfare perspective, by replacing the B-output x_B by an equivalent quantity of A-output, x_B/α, i.e., producing $x_A + \frac{x_B}{\alpha}$ A-units is more cost effective:

  $$F_A + c_A\left(x_A + \frac{x_B}{\alpha}\right) < F_B + c_B(x_B) + Ne(x_B) + F_A + c_A(x_A).^5 \tag{10}$$

5 Because a production plan that employs both technologies will be adopted by the monopolist only if it maximizes the monopolist's overall profit, it suffices to assume that condition (10) holds only for profit-maximizing pairs (x_A, x_B).

Thus, it is socially, technically inefficient for the monopolist to employ technology B to produce some of its output.

While the monopolistic market structure contrasts sharply with that of perfect competition considered in Section 3, it also leads to the adoption of the inferior technology if the following condition is satisfied:

$$F_A + c_A(z_A) > F_B + c_B(\alpha z_A) + e'(\alpha z_A)\alpha z_A,$$

where z_A represents any profit maximizing output level under the adoption of technology A, i.e., a solution to

$$\max_{x\geq 0} \overline{G}(x)x - F_A - c_A(x). \tag{11}$$

When technology A is not employed, the monopolist's profit maximizing problem is given by

$$\max_{x_B\geq 0} (G(x_B) - e'(x_B))x_B - F_B - c_B(x_B). \tag{12}$$

Proposition 2. *Suppose that there is a solution to* (12) *that yields positive profits. If*

$$F_A + c_A(z_A) > F_B + c_B(\alpha z_A) + e'(\alpha z_A)\alpha z_A \tag{13}$$

for any solution z_A to (11)*, then the monopolist adopts the inferior technology B to produce at least some of its output.*

In Section 5.2, we illustrate, by means of an example, that condition (13) is compatible with conditions (9) and (10). In fact, the example exhibits a range of parameter values for which all three conditions are satisfied.

To understand Proposition 2, note first that, if there is a solution to (11) that yields non-positive profits, the monopolist will adopt technology B to produce at least some of its output, since, by assumption, there is a solution to (12) that yields positive profits.

If, on the other hand, there is a solution to (11) that yields positive profits, any solution to (11) must be interior, and so the unit price charged by the monopolist at an A-quantity z_A is

$$p_A := \overline{G}(z_A) = \alpha g_i'(\alpha z_{iA}), \quad \text{for all } i,$$

where z_{iA} represents the quantity of z_A consumed by agent i. Alternatively, the monopolist can produce and sell αz_A B-units at unit price $p_B := \frac{p_A}{\alpha} - e'(\alpha z_A)$: at this price, consumer i demands αz_{iA} B-units, since $g_i'(\alpha z_{iA}) - e'(\alpha z_A) = p_B$, and the aggregate demand for B-units is αz_A.

We claim that the monopolist's profit from selling αz_A B-units at price p_B exceeds that from selling z_A A-units at price p_A. Indeed, by (13), it follows that monopoly profits are higher when αz_A B-units are sold at price p_B:

$$\left(\frac{p_A}{\alpha} - e'(\alpha z_A)\right)\alpha z_A - F_B - c_B(\alpha z_A) > p_A z_A - F_A - c_A(z_A).$$

Therefore, the monopolist adopts the inferior technology B to produce at least some of its output.

The intuition for Proposition 2 should by now be familiar: private benefits/costs from the consumption and production of good x disregard the negative welfare effects of pollution/waste on the economy as a whole, and are therefore misaligned with their social counterparts. Under the conditions of Proposition 2, the quantity of B-output produced ends up being too high.

Note that Proposition 2 remains silent on the monopolist's specific profit-maximizing production plan. In general, a production plan can be represented by a pair (x_A, x_B), where x_A (resp., x_B) denotes the quantity of A-output (B-output) produced. Under linear prices, and in the absence of price discrimination, a production plan must be priced in such a way that it precludes "personal arbitrage," i.e., the possibility that a consumer to whom one type of product is directed may have a preference, at the going prices, for the other product type.

Suppose that x_A A-units (resp., x_B B-units) are traded at price p_A (resp., p_B). At these prices, an agent, i, who consumes a_i A-units and b_i B-units obtains a net gain of $\alpha g_i'(\alpha a_i + b_i) - p_A$ (resp., $\alpha g_i'(\alpha a_i + b_i) - \alpha e'(x_B) - \alpha p_B$) from buying an extra A-unit (resp., α extra B-units) of good x. If

$$\alpha g_i'(\alpha a_i + b_i) - p_A > \alpha g_i'(\alpha a_i + b_i) - \alpha e'(x_B) - \alpha p_B,$$

i.e., if $p_A < \alpha e'(x_B) + \alpha p_B$, then i wishes to reduce her consumption of B-units. Similarly, if $p_A > \alpha e'(x_B) + \alpha p_B$, then i wishes to reduce her consumption of A-units. Consequently, if both x_A and x_B are positive, the market clears under the following conditions: (i) $p_A = \alpha e'(x_B) + \alpha p_B$; (ii) $p_A = \overline{G}(x_A + \frac{x_B}{\alpha}) = \alpha G(\alpha x_A + x_B)$; and (iii) $p_B = G(\alpha x_A + x_B) - e'(x_B)$. Condition (i) precludes consumer arbitrage, while conditions (ii) and (iii) ensure that prices reflect the consumers' marginal utilities at the traded quantities.[6]

Thus, a production plan maximizes the overall profit if it solves

6 Condition (i) is implied by conditions (ii) and (iii).

$$\max_{(x_A,x_B)\geq 0} (G(\alpha x_A + x_B) - e'(x_B))x_B - \mathbb{1}_{x_B}(F_B + c_B(x_B)) + \alpha G(\alpha x_A + x_B)x_A$$
$$- \mathbb{1}_{x_A}(F_A + c_A(x_A)),$$

where

$$\mathbb{1}_x := \begin{cases} 1 & \text{if } x > 0, \\ 0 & \text{if } x = 0. \end{cases}$$

We know that, under the hypothesis of Proposition 2 (and in the absence of price discrimination), a production plan (x_A, x_B) is profit maximizing only if $x_B > 0$.

The deadweight loss resulting from the adoption of the "wrong" technology can be measured as the overall welfare gain that would obtain if the quantity x_B were replaced by an equivalent output level in terms of A-units, $\frac{x_B}{\alpha}$. Both quantities yield the same gross utility surplus, and so the welfare gain is given by the difference in the associated social costs:

$$F_B + c_B(x_B) + Ne(x_B) + \mathbb{1}_{x_A}(F_A + c_A(x_A)) - \left[F_A + c_A\left(x_A + \frac{x_B}{\alpha}\right)\right]. \tag{14}$$

This difference is positive by (9) and (10).

The overall deadweight loss at a given monopoly allocation (x_A, x_B) is compounded by the shortfall (or excess) in equivalent A-output, relative to the efficient quantity of A-output, x_A^*, which satisfies $\overline{G}(x_A^*) = c_A'(x_A^*)$; it can be calculated as the sum of the following two quantities: (i) the welfare gain from replacing the quantity of B-output x_B by an equivalent quantity of A-output, $\frac{x_B}{\alpha}$, a gain expressed in (14); and (ii) the welfare gain from adjusting the quantity of A-output, $x_A + \frac{x_B}{\alpha}$, to the efficient A-level, x_A^*.

5 Policy Analysis

A number of policies are considered as a means to diminish the inefficiencies from the market-driven technology adoption. In the perfectly competitive case, we look at the welfare effects of pollution/waste quotas and Pigouvian taxes. In the textbook analysis of market economies with external effects, these two policy instruments are equally effective in correcting market failures. By contrast, Pigouvian taxation proves to be a superior policy tool in our context.

Under a monopolistic market structure, neither quotas nor Pigouvian taxes are generally welfare enhancing. In fact, there are parameter configurations for which *any* quota (resp., Pigouvian tax) leads to welfare losses. While sufficiently large quotas/taxes tend to increase (resp., decrease) the traded quantity of A-output (resp., B-output), the welfare gains from the additional A-units need not be large enough, under a monopolistic market structure, to outweigh the welfare losses from reduced trade in B-output. Consequently, alternative policies are needed to expand the production of A-units beyond the monopoly output. As an example of such policy, we consider consumer subsidization of A-units, and show that certain combinations of quotas and consumer subsidies are welfare enhancing, relative to the unfettered market equilibrium.

5.1 Perfect Competition

Throughout this subsection, we maintain the assumptions from the analysis in Section 3: condition (3) (which states that technology A is socially, technically more efficient than technology B) and condition (4) (which guarantees the universal adoption of technology B in equilibrium).

Recall that, at the unique competitive equilibrium under perfect competition, x_B B-units are traded price $p_x = c_B$, where x_B satisfies

$$G(x_B) - e'(x_B) = c_B.$$

Consider now a mandated quota on the emissions/waste generated as a by-product of the manufacturing process governed by technology B. This mandated quota effectively caps the aggregate quantity of B-units at some output level $\overline{x}_B < x_B$.

Recall that the productive process based on technology A generates a positive amount of waste/pollution, however negligible. This assumption has important implications for the welfare effects of quotas and taxes. In keeping with the assumption that technology A has no associated external effect on consumer welfare, the amount of A-waste can be viewed as negligible.

The effect of the mandated quota depends on its magnitude relative to the level x_A such that $c_A = \overline{G}(x_A)$. To see this, note first that $x_A < \frac{x_B}{\alpha}$. Indeed, if $x_A \geq \frac{x_B}{\alpha}$ were true, then $c_A = \overline{G}(x_A) \leq \overline{G}(\frac{x_B}{\alpha})$ would hold, implying that, if x_B B-units were traded at price $p_x = c_B$, any one consumer would gain $\overline{G}(\frac{x_B}{\alpha}) - c_A \geq 0$ from buying one A-unit, while the consumer's gain from buying an extra α B-units, priced at $p_x = c_B$, would only be $\alpha(G(x_B) - e'(x_B) - c_B) = 0$, contradicting the fact that, under (4), consumers always prefer to buy B-units of good x.

Since $\overline{x}_B < x_B$, either $x_A \leq \frac{\overline{x}_B}{\alpha}$ or $0 \leq \frac{\overline{x}_B}{\alpha} < x_A$. If $x_A \leq \frac{\overline{x}_B}{\alpha}$, $\overline{x}_B$ B-units are traded, in equilibrium, at price $p_x = c_B$. In this case, no consumer benefits from buying A-units at price $p_x = c_A$, and so technology A is not employed. Indeed, if $\overline{x}_B$ B-units are traded, a consumer's willingness to pay for A-units is $\overline{G}(\frac{\overline{x}_B}{\alpha}) \leq \overline{G}(x_A) = c_A$ or lower.

Relative to the unfettered equilibrium, the mandated quota, $\overline{x}_B$, is welfare enhancing. To see this, note first that the quantity of B-units that maximizes the economy's overall (conditional) welfare, i.e., the quantity x_B^* such that

$$G(x_B^*) = c_B + Ne'(x_B^*),$$

is less than αx_A. Indeed, because $c_A = \overline{G}(x_A) = \alpha G(\alpha x_A)$, we have $\frac{c_A}{\alpha} = G(\alpha x_A)$. This, together with (3), yields

$$G(x_B^*) = c_B + Ne'(x_B^*) > \frac{c_A}{\alpha} = G(\alpha x_A),$$

implying that $x_B^* < \alpha x_A$.

Starting at x_B, a marginal reduction in the quantity of B-units is welfare enhancing in that the corresponding reduction in the cost of the external effects outweighs the surplus loss from lower consumption. Indeed, for the first marginal one-unit reduction in agent i's consumption, i's surplus loss is $G(x_B) - e'(x_B) > 0$, which is exactly offset by the cost savings, c_B. But there is also an effect on the other consumers' welfare: each consumer other than i gains $e'(x_B)$, the marginal cost of the external effect. Overall, the welfare gain from a one-unit, marginal reduction in the quantity of B-units is $(N-1)e'(x_B)$. Further output reductions bring about additional welfare gains, as long as the aggregate quantity of B units is greater than x_B^*. Because $x_B^* < \alpha x_A \leq \overline{x}_B$, the mandated quota $\overline{x}_B$ is welfare enhancing, relative to the unfettered equilibrium. In this range, the quota-induced welfare increase is inversely related to the size of the quota.

So far, we have considered a quota $\overline{x}_B < x_B$ such that $x_A \leq \frac{\overline{x}_B}{\alpha}$. It remains to consider the case when $0 \leq \frac{\overline{x}_B}{\alpha} < x_A$. As before, in this case, $\overline{x}_B$ B-units are traded at price c_B in equilibrium, and technology A is not employed. The welfare effect of the quota is, however, ambiguous, unlike in the case when $x_A \leq \frac{\overline{x}_B}{\alpha}$.

The reason for the universal adoption of technology B under a quota $\overline{x}_B$ with $\frac{\overline{x}_B}{\alpha} < x_A$ should by now be familiar: given that the zero-profit condition requires that A-units (resp., B-units) be traded at price c_A (resp., c_B), consumers always prefer B-units over A-units. Once the quantity of B-units reaches the quota, $\overline{x}_B$, the cap on waste/pollution binds, and so no extra good x (in the form of A-units or B-units) can be produced.

Mandated quotas $\overline{x}_B$ with $\overline{x}_B < \alpha x_A$ may or may not be welfare enhancing (relative to the unfettered equilibrium), depending on how close $\overline{x}_B$ is to the quantity of B-units that maximizes the economy's overall (conditional) welfare, x_B^*. If the mandated quota $\overline{x}_B$ is greater than or equal to x_B^*, the policy is welfare enhancing. Otherwise, i.e., if $\overline{x}_B < x_B^*$, the welfare effect is generally ambiguous and depends on the relative weight of the welfare losses from the output reduction beyond x_B^*.

As an alternative policy, consider a Pigouvian tax that levies $\$\tau$ per unit of emissions/waste produced by any firm. For simplicity, suppose that a firm's B-waste is proportional to its output by a factor $\gamma_B > 0$, so that γ_B measures emissions/waste per unit of B-output.[7]

Unlike the quota, the tax bears on the firms' marginal cost function, thereby distorting the firms' incentives to employ the inefficient technology, B. It will be shown that the economy's overall welfare is generally higher under the Pigouvian tax than under the quota.

To begin, we consider the case when $\tau \leq \underline{\tau}$, where $\underline{\tau}$ is defined by

$$\underline{\tau} := \frac{G(\alpha x_A) - e'(\alpha x_A) - c_B}{\gamma_B}. \tag{15}$$

If firms adopt technology B, B-units are priced at the new marginal cost, $c_B + \tau\gamma_B$, and the aggregate quantity traded in the market is $x_B(\tau)$ with

$$G(x_B(\tau)) - e'(x_B(\tau)) = c_B + \gamma_B \tau. \tag{16}$$

Given (15), it is clear that $\tau \leq \underline{\tau}$ implies that $x_B(\tau) \geq \alpha x_A$. Thus, if technology B is universally adopted in equilibrium, the welfare effect of a tax τ with $\tau \leq \underline{\tau}$ is, in terms of the overall welfare generated, identical to that of a quota $\overline{x}_B = x_B(\tau) \in [\alpha x_A, x_B)$. Just as quotas $\overline{x}_B = x_B(\tau) \in [\alpha x_A, x_B)$ are welfare enhancing, so too are Pigouvian taxes $\tau \leq \underline{\tau}$.

To see that technology B is universally adopted in equilibrium under a tax τ with $\tau \leq \underline{\tau}$, note that, for any quantity $x \in [0, x_B(\tau)]$ of B-units, we have

$$\frac{c_A}{\alpha} - c_B - \tau\gamma_B - e'(x) \geq \frac{c_A}{\alpha} - c_B - \tau\gamma_B - e'(x_B(\tau)) = G(\alpha x_A) - G(x_B(\tau)) \geq 0,$$

where the last inequality in the displayed equation follows from the fact that $x_B(\tau) \geq \alpha x_A$ and the last equality in the displayed equation holds because

$$c_A = \overline{G}(x_A) = \alpha G(\alpha x_A) \tag{17}$$

and (16) holds. Consequently,

$$\frac{c_A}{\alpha} > c_B + \tau\gamma_B + e'(x), \quad \text{for all } x \in [0, x_B(\tau)).$$

As in Section 3, this implies that firms do not adopt technology A in equilibrium.

Next, suppose that $\tau > \underline{\tau}$. Let $x_B(\tau)$ be implicitly defined as follows:

$$c_B + \tau\gamma_B + e'(x_B(\tau)) = \frac{c_A}{\alpha}, \tag{18}$$

7 The parameter γ_A measures emissions/waste per unit of A-output. While γ_A is positive, it is taken to be approximately zero, in keeping with the assumption that technology A's pollution/waste is negligible.

if such an $x_B(\tau)$ exists; otherwise, set $x_B(\tau) := 0$. Note that $x_B(\tau) < \alpha x_A$. Indeed, (15) and (17) imply that

$$c_B + \underline{\tau}\,\gamma_B + e'(\alpha x_A) = \frac{c_A}{\alpha}, \tag{19}$$

and so, since $\tau > \underline{\tau}$, it follows that

$$c_B + \tau\gamma_B + e'(\alpha x_A) > \frac{c_A}{\alpha}. \tag{20}$$

Consequently, because $e''(\cdot) > 0$, (18) can only hold if $x_B(\tau) < \alpha x_A$.

We claim that, in equilibrium, $x_B(\tau)$ B-units are traded at price $c_B + \tau\gamma_B$ and $x_A - \frac{x_B(\tau)}{\alpha}$ A-units are traded at price c_A. To see this, suppose that z_A A-units (resp., z_B B-units) are traded. In equilibrium, A-units (resp., B-units) must be sold at price c_A (resp., $c_B + \tau\gamma_B$), otherwise, firms either make losses or can be undercut and outcompeted by rivals. At these prices, an agent, i, who consumes a_i A-units and b_i B-units obtains a net gain of $\alpha g_i'(\alpha a_i + b_i) - c_A$ (resp., $\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B - \alpha\tau\gamma_B$) from buying an extra A-unit (resp., α extra B-units) of good x. By (18) and the condition $e''(\cdot) > 0$, we have

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B - \alpha\tau\gamma_B > \alpha g_i'(\alpha a_i + b_i) - c_A$$

whenever $z_B < x_B(\tau)$, implying that consumers prefer to buy B-units of good x. Consequently, if the aggregate quantity of B-units traded in the market, z_B, is less than $x_B(\tau)$, no A-units are consumed. At $z_B \leq x_B(\tau)$, the consumers' marginal willingness to pay for B-units is $G(z_B) - e'(z_B)$, which exceeds the unit price for B-units, $c_B + \tau\gamma_B$; this is clearly the case if $x_B(\tau) = 0$; if $x_B(\tau) > 0$, then (18) holds, and we have

$$\begin{aligned}
G(z_B) - e'(z_B) &\geq G(x_B(\tau)) - e'(x_B(\tau)) \\
&> G(\alpha x_A) - e'(\alpha x_A) \\
&= \frac{c_A}{\alpha} - e'(\alpha x_A) \\
&= c_B + \tau\gamma_B,
\end{aligned}$$

where the first strict inequality follows from the fact that $x_B(\tau) < \alpha x_A$ and the last equality holds by (18).

If $z_B > x_B(\tau)$ and $x_B(\tau)$ satisfies (18), by (18) and the condition $e''(\cdot) > 0$, we have

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B - \alpha\tau\gamma_B < \alpha g_i'(\alpha a_i + b_i) - c_A,$$

implying that consumers prefer to buy A-units of good x. If $z_B > x_B(\tau)$ and $x_B(\tau)$ does not satisfy (18), then $x_B(\tau) = 0$ and[8]

$$c_B + \tau\gamma_B + e'(x_B(\tau)) > \frac{c_A}{\alpha},$$

and so

$$\alpha g_i'(\alpha a_i + b_i) - \alpha e'(z_B) - \alpha c_B - \alpha\tau\gamma_B < \alpha g_i'(\alpha a_i + b_i) - c_A,$$

again implying that consumers prefer to buy A-units of good x. Therefore, the quantity of B-units traded in equilibrium is precisely $x_B(\tau)$.

If $x_B(\tau)$ B-units and no A-units were traded, the consumers' marginal willingness to pay for A-units would be $\overline{G}(\frac{x_B(\tau)}{\alpha}) > \overline{G}(x_A) = c_A$ (where the inequality follows from the fact that $x_B(\tau) < \alpha x_A$), implying that producing and selling A units would be profitable. When the aggregate quantity of B-units (resp., A-units) is $x_B(\tau)$ (resp., $x_A - \frac{x_B(\tau)}{\alpha}$), the consumers' marginal willingness to pay for A-units, $\overline{G}(x_A)$, is precisely the marginal production cost, c_A.

We conclude that, in equilibrium, $x_B(\tau)$ B-units are traded at price $c_B + \tau\gamma_B$ and $x_A - \frac{x_B(\tau)}{\alpha}$ A-units are traded at price c_A.

Pigouvian taxes $\tau > \underline{\tau}$ are also welfare enhancing, relative to the unfettered equilibrium. Indeed, we know that a tax $\tau = \underline{\tau}$, whose associated equilibrium aggregate output level is αx_A B-units, is welfare improving. Consequently, because a tax $\tau > \underline{\tau}$ reduces the aggregate quantity of B-output traded in the market to $x_B(\tau) < \alpha x_A$ B-units, and since, under τ, this reduction, $\alpha x_A - x_B(\tau)$, is replaced by an equivalent quantity of (externality-free) A-units, $x_A - \frac{x_B(\tau)}{\alpha}$, it follows that Pigouvian taxes $\tau > \underline{\tau}$ are welfare enhancing.

The welfare gains from a Pigouvian tax $\tau > \underline{\tau}$ are directly related to the associated B-output $x_B(\tau)$, i.e., the corresponding aggregate quantity of B-units traded in equilibrium. By (19), as $\tau > \underline{\tau}$ tends to $\underline{\tau}$, $x_B(\tau)$ (defined implicitly by (18)) approaches αx_A. Moreover, there exists $\overline{\tau} > \underline{\tau}$ such that $x_B(\tau) = 0$ for $\tau \geq \overline{\tau}$ and $x_B(\tau) > 0$ for $\tau < \overline{\tau}$.[9] As $\tau \in (\underline{\tau}, \overline{\tau})$ increases to $\overline{\tau}$, $x_B(\tau)$ decreases to 0, and the economy's overall welfare increases. At $\tau \geq \overline{\tau}$, technology A is universally adopted, and the efficient quantity of A-output, x_A, is traded in equilibrium.

8 If $c_B + \tau\gamma_B + e'(x_B(\tau)) < \frac{c_A}{\alpha}$ were true, then, because the map $f\colon [x_B(\tau), \alpha x_A] \to \mathbb{R}$ defined by $f(x) := c_B + \tau\gamma_B + e'(x)$ is continuous and $f(x_B(\tau)) < \frac{c_A}{\alpha} < f(\alpha x_A)$ (recall (20)), there would exist, by the Intermediate Value Theorem, $x^* \in [x_B(\tau), \alpha x_A]$ such that $f(x^*) = c_B + \tau\gamma_B + e'(x^*) = \frac{c_A}{\alpha}$, contradicting the assumption that $x_B(\tau)$ does not satisfy (18).

9 This flows from the following observations. First, recall that the map $\tau \in (\underline{\tau}, \infty) \mapsto x_B(\tau) \in \mathbb{R}_+$ is defined implicitly by (18) whenever an $x_B(\tau)$ satisfying (18) exists, and otherwise $x_B(\tau) = 0$. Second, as $\tau \to \underline{\tau}$, $x_B(\tau) \to \alpha x_A > 0$. Third, there is a unique $\overline{\tau} > \underline{\tau}$ such that $c_B + \overline{\tau}\gamma_B + e'(0) = \frac{c_A}{\alpha}$, implying that $x_B(\overline{\tau}) = 0$. Note that $x_B(\tau) > 0$ for $\underline{\tau} < \tau < \overline{\tau}$ and $x_B(\tau) = 0$ for $\tau \geq \overline{\tau}$.

Thus, unlike quotas, Pigouvian taxes do induce the adoption of the socially efficient technology, A. Any quota $\overline{x}_B$ is dominated, in terms of the overall welfare generated, by any Pigouvian tax $\tau > \underline{\tau}$ such that $x_B(\tau) \leq \overline{x}_B$. Indeed, we know that, if $\overline{x}_B \geq \alpha x_A$, reducing the quantity of B-units to αx_A is welfare enhancing; if, in addition, some of the αx_A B-units are replaced by an equivalent amount of A-units, total welfare is further increased. A Pigouvian tax $\tau > \underline{\tau}$ reduces the quantity of traded output to αx_A, in terms of equivalent B-output, and replaces the last $\alpha x_A - x_B(\tau)$ B-units by an equivalent amount of A-units, $x_A - \frac{x_B(\tau)}{\alpha}$, thereby increasing the economy's overall welfare, relative to a quota $\overline{x}_B \geq \alpha x_A$. The reason why quotas $\overline{x}_B < \alpha x_A$ are dominated by Pigouvian taxes $\tau > \underline{\tau}$ such that $x_B(\tau) \leq \overline{x}_B$ is simple: under the quota, $\overline{x}_B$ B-units are traded in equilibrium, and technology A is not adopted, while any $\tau > \underline{\tau}$ such that $x_B(\tau) \leq \overline{x}_B$ effectively replaces some of the $\overline{x}_B$ B-units (specifically, the last $\overline{x}_B - x_B(\tau)$ B-units) by an equivalent amount of A-units ($\frac{\overline{x}_B}{\alpha} - \frac{x_B(\tau)}{\alpha}$ A-units), and, in addition, generates the production of an additional $x_A - \frac{\overline{x}_B}{\alpha}$ A-units.

These findings are encapsulated in the following proposition.

Proposition 3. *Quotas do not induce the adoption of the socially efficient technology, A, and are welfare enhancing—relative to the unfettered equilibrium—only if they are large enough—namely, if $\overline{x}_B \in [x_B^*, x_B)$ or if $\overline{x}_B < x_B^*$ is close enough to x_B^* to ensure that the welfare loss from the output reduction beyond x_B^* is relatively small. By contrast, a Pigouvian tax τ does induce the adoption of the socially efficient technology, A, if $\tau > \underline{\tau}$, and is always welfare enhancing (even if $\tau \leq \underline{\tau}$), relative to the unfettered equilibrium. Moreover, any quota $\overline{x}_B$ is dominated, in terms of the overall welfare generated, by any Pigouvian tax $\tau > \underline{\tau}$ such that $x_B(\tau) \leq \overline{x}_B$. Finally, technology A is universally adopted under any tax $\tau \geq \overline{\tau}$, and the efficient quantity of A-output, x_A, is traded in equilibrium.*

5.2 Monopoly

Under a monopolistic market structure, quotas and Pigouvian taxes may yield, in some cases, a bigger deadweight loss, relative to the unfettered monopoly allocation. This contrasts with the perfectly competitive case considered in Section 5.1, where Pigouvian taxes were shown to be universally welfare enhancing (i.e., welfare enhancing in all cases, for all parameter values).

In this section, we first point out that there are parameter configurations for which quotas/Pigouvian taxes always lead to welfare losses. We then identify a welfare-enhancing class of alternative policies, based on a combination of quotas and consumer subsidization of A-units.

As in Section 4, the cost structure associated with technology A (resp., B) takes the following general form: $F_A + c_A(x)$ (resp., $F_B + c_B(x)$), where F_A (resp., F_B) represents the fixed cost and $c_A(\cdot)$ (resp., $c_B(\cdot)$) denotes the variable cost function. Furthermore, we maintain, throughout this section, the following assumptions from Section 4: conditions (9) and (10), which ensure that it is socially, technically inefficient for the monopolist to employ technology B; and condition (13), which, by Proposition 2, implies that an "unfettered" monopolist adopts the inferior technology B to produce at least some of its output.

Consider a mandated quota on the emissions/waste generated by technology B, which effectively caps the aggregate quantity of B-units at $\bar{z}_B$. As per the analysis in Section 4, the quota has no effect if it is not binding, i.e., if it does not constrain the monopolist's ability to set its B-output at a profit-maximizing level, i.e., if $\bar{z}_B \geq \hat{x}_B$ for some profit-maximizing production plan $(\hat{x}_A, \hat{x}_B)$ that solves

$$\begin{aligned} \max_{(x_A,x_B)\geq 0} \; & (G(\alpha x_A + x_B) - e'(x_B))x_B - \mathbb{1}_{x_B}(F_B + c_B(x_B)) + \alpha G(\alpha x_A + x_B)x_A \\ & - \mathbb{1}_{x_A}(F_A + c_A(x_A)), \end{aligned} \tag{21}$$

where

$$\mathbb{1}_x := \begin{cases} 1 & \text{if } x > 0, \\ 0 & \text{if } x = 0. \end{cases}$$

When facing a quota $\bar{z}_B$, the monopolist solves the following constrained profit maximization problem:

$$\begin{aligned} \max_{(x_A,x_B)} \; & (G(\alpha x_A + x_B) - e'(x_B))x_B - \mathbb{1}_{x_B}(F_B + c_B(x_B)) + \alpha G(\alpha x_A + x_B)x_A \\ & \quad - \mathbb{1}_{x_A}(F_A + c_A(x_A)) \\ \text{s.t.} \; & \\ & 0 \leq x_A \\ & 0 \leq x_B \leq \bar{z}_B \\ & x_B = \bar{z}_B \Rightarrow x_A = 0 \end{aligned} \tag{22}$$

The last constraint implies that no A-output may be produced whenever the pollution/waste quota is exhausted by the manufacturing process based on technology B.

It can be shown that, under a monopolistic market structure, neither quotas nor Pigouvian taxes are generally welfare enhancing. In fact, there exist parameter configurations for which *any* quota (resp., Pigouvian tax) leads, invariably, to welfare losses. This contrasts with the case of perfect competition, considered in Section 5.1, where it was shown that Pigouvian taxes are universally welfare enhancing. An example illustrating the fact that any quota (resp., Pigouvian tax) may lead to a welfare reduction is furnished in Section 6.

The problem with quotas and Pigouvian taxes under a monopolistic market structure can be intuitively understood as follows. While sufficiently large quotas/taxes tend to promote technology A to the detriment of technology B and result in an increase (resp., decrease) in the traded quantity of A-output (resp., B-output), these policies need not induce a large enough quantity of A-output under a monopolistic market structure. This "scarcity" of A-output is driven entirely by monopoly behavior: first, the monopolist does not factor in the social gains from replacing B-units by A-units; second, the monopolist uses its market power to its advantage, contracting A-output relative to the efficient A-level.

There are, of course, ways to improve upon the "unfettered" monopoly allocation, from a (neoclassical) welfare perspective. After all, we have been assuming, all along, that replacing any quantity of B-units by its equivalent A-output level leads to a welfare improvement. In this regard, any monopoly allocation involving the production of B-units is inefficient, and any regulatory policy promoting technology A, inducing the production of a "sufficiently" large amount of A-output, relative to the unfettered allocation, is welfare improving.

As a means to expand monopoly A-output, one might consider consumer subsidization of A-units. When combined with large enough quotas, certain subsidies are welfare enhancing. To see this, note first that, if $F_B > 0$ (an assumption that we maintain in the remainder of this section), then a sufficiently restrictive quota (i.e., a low enough quota) $\bar{z}_B$ induces specialization in technology A by the monopolist. Indeed, it should be clear that, if $F_B > 0$, and if $\bar{z}_B$ is low enough, any solution (y_A, y_B) to the problem (22) satisfies $y_B = 0$, implying that $y_A = z_A$, where z_A solves

$$\max_{x \geq 0} \overline{G}(x)x - F_A - c_A(x)$$

(recall that $\overline{G}(x) = \alpha G(\alpha x)$). Thus, in the absence of consumer subsidization of A-output, the monopolist produces and sells, under such a restrictive quota, z_A A-units. But we know that z_A may be too low to compensate for the loss of B-output induced by the quota, so that the quota, by itself, need not be welfare enhancing.

A consumer subsidy of $\$s$ per unit of A-ouput produces a vertical shift of the market inverse demand for A-output, $\overline{G}(x)$. Indeed, under the subsidy, consumer i's demand for A-output is determined by a solution to the following problem:

$$\max_{(x_i, y_i)} g_i(\alpha x_i) + y_i$$

$$\text{s.t. } p_x x_i + y_i = w_i + s x_i.$$

At an interior solution,

$$\alpha g_i'(\alpha x_i) + s = p_x.$$

The corresponding market (inverse) demand is given by

$$p_x = \overline{G}(x) + s.$$

Consequently, the monopolist's problem under the adoption of technology A becomes

$$\max_{x_A \geq 0} (\overline{G}(x_A) + s)x_A - F_A - c_A(x_A),$$

and the corresponding first-order condition is

$$\overline{G}'(x_A)x_A + \overline{G}(x_A) + s = c_A'(x_A). \tag{23}$$

The left-hand side of this equation represents the "old" marginal revenue function (in the absence of subsidies), $MR(x_A) = \overline{G}'(x_A)x_A + \overline{G}(x_A)$, plus the subsidy s; it can be viewed as the "new" marginal revenue under the subsidy, an upward shift of the $MR(\cdot)$ curve by s.

There is a subsidy level that induces the efficient quantity of A-output, x_A^*, which satisfies

$$\overline{G}\left(x_A^*\right) = c_A'\left(x_A^*\right).$$

Indeed, setting $s = s^* := -\overline{G}'\left(x_A^*\right)x_A^*$ implies that the first-order condition (23) is satisfied at x_A^*.

A low enough quota on B-output, one that induces specialization in technology A, together with a subsidy $s = s^*$, leads to a welfare gain, relative to the "unfettered" monopoly allocation. This gain can be calculated as follows. Suppose that (y_A, y_B) is the solution to problem (21) chosen by the monopolist in the absence of quotas and subsidies. By Proposition 2, we know that, under (13), $y_B > 0$ holds. Suppose that we replace the quantity y_B of B-output by an equivalent quantity of A-units, y_B/α. This switch to technology A is welfare improving and leads to a welfare gain equal to

$$F_B + c_B(y_B) + Ne(y_B) - (F_A + c_A(y_B/\alpha)) > 0 \qquad \text{if } y_A = 0 \text{ (by (9))}; \tag{24}$$

$$\begin{aligned} &F_B + c_B(y_B) + Ne(y_B) + F_A + c_A(y_A) \\ &\quad - \left(F_A + c_A\left(y_A + \frac{y_B}{\alpha}\right)\right) > 0 \end{aligned} \qquad \text{if } y_A > 0 \text{ (by (10))}. \tag{25}$$

To see this, note that the (net) social gain from replacing the quantity y_B of B-output by an equivalent quantity of A-units is given by the social utility gain minus the cost of the subsidy program to the government plus the social cost savings:

$$\begin{aligned}
&\int_0^{y_B/\alpha} (\overline{G}(x)+s)\mathrm{d}x - \int_0^{y_B} G(x)\mathrm{d}x - (sy_B/\alpha)\\
&\quad + F_B + c_B(y_B) + Ne(y_B) - (F_A + c_A(y_B/\alpha))\\
&= \int_0^{y_B/\alpha} \alpha G(\alpha x)\mathrm{d}x - \int_0^{y_B} G(x)\mathrm{d}x + s\int_0^{y_B/\alpha} \mathrm{d}x - (sy_B/\alpha)\\
&\quad + F_B + c_B(y_B) + Ne(y_B) - (F_A + c_A(y_B/\alpha))\\
&= \int_0^{y_B/\alpha} G(\alpha x)\mathrm{d}(\alpha x) - \int_0^{y_B} G(x)\mathrm{d}x + s\int_0^{y_B/\alpha} \mathrm{d}x - (sy_B/\alpha)\\
&\quad + F_B + c_B(y_B) + Ne(y_B) - (F_A + c_A(y_B/\alpha))\\
&= F_B + c_B(y_B) + Ne(y_B) - (F_A + c_A(y_B/\alpha)) \qquad \text{if } y_A = 0;\\
&\int_{y_A}^{y_A+(y_B/\alpha)} (\overline{G}(x)+s)\mathrm{d}x - \int_{\alpha y_A}^{\alpha y_A+y_B} G(x)\mathrm{d}x - (sy_B/\alpha)\\
&\quad + F_B + c_B(y_B) + Ne(y_B) + F_A + c_A(y_A)\\
&\quad - \left(F_A + c_A\left(y_A + \frac{y_B}{\alpha}\right)\right)\\
&= F_B + c_B(y_B) + Ne(y_B) + F_A + c_A(y_A)\\
&\quad - \left(F_A + c_A\left(y_A + \frac{y_B}{\alpha}\right)\right) \qquad \text{if } y_A > 0.
\end{aligned}$$

Hence the expressions in (24) and (25).

The quota being considered here, acting in combination with the subsidy s^*, results in the aggregate quantity of A-output x_A^*, i.e., the efficient quantity of A-output, which need not coincide with the quantity $y_A + (y_B/\alpha)$ of A-output. The welfare gain calculated above, which results from replacing the quantity y_B of B-output with its equivalent quantity of A-output, y_B/α, would be the actual overall welfare gain from the combined policy if the quantity $y_A + (y_B/\alpha)$ happened to coincide with x_A^*. In the case when $y_A + (y_B/\alpha) \neq x_A^*$, the overall welfare gain from the combined policy would be calculated as the sum of the welfare gain given in (24) and (25) and the welfare gain resulting from adjusting the quantity of A-output from $y_A + (y_B/\alpha)$ to the efficient quantity of A-output, x_A^*. This additional welfare gain can be expressed as follows:

$$\int_{y_A+\frac{y_B}{\alpha}}^{x_A^*} [\overline{G}(x) - c_A'(x)]\mathrm{d}x \quad \text{if } y_A + (y_B/\alpha) < x_A^*, \tag{26}$$

and

$$\int_{x_A^*}^{y_A+\frac{y_B}{\alpha}} [c_A'(x) - \overline{G}(x)]\mathrm{d}x \quad \text{if } y_A + (y_B/\alpha) > x_A^*. \tag{27}$$

Because x_A^* is the efficient quantity of A-output, it follows that the integrals in (26) and (27) are positive. For subsidies $s < s^*$ combined with a sufficiently restrictive quota that induces the monopolist's specialization in technology A, the monopolist's profit maximizing A-output, $\hat{x}_A$, lies between the monopoly quantity of A-output in the absence of subsidies, z_A, and the efficient quantity of A-output, $x_A^* > z_A$. Since, in general, $\hat{x}_A \neq x_A^*$, there is no guarantee that the integrals in (26) and (27) will remain positive once x_A^* is replaced by $\hat{x}_A$. Consequently, subsidies $s < s^*$ need not be welfare improving. In general, s needs to be close enough to s^* to ensure that the integrals in (26) and (27) (with $\hat{x}_A$ replacing x_A^*) are not "too negative," so that any potential losses from adjusting the quantity of A-output from $y_A + (y_B/\alpha)$ to $\hat{x}_A$ do not outweigh the welfare gains from replacing the quantity of B-output y_B by its equivalent quantity of A-output, y_B/α, i.e., the welfare gains from (24) and (25).

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Appendix A

In this section, we illustrate, by means of a simple example, that, for certain configurations of parameter values, quotas imposed on a monopolist may well be welfare reducing.

Suppose that $g_i(x_i) = 2d_i\sqrt{x_i}$, $c_A(x) = ax^2$, $c_B(x) = bx^2$, $e(x) = \theta x^2$, and $F_A = F_B$, where d_i, a, b, and θ are all positive. These functional forms yield

$$G(x) = \frac{d}{\sqrt{x}}$$

and

$$\overline{G}(x) = \alpha G(\alpha x) = \alpha \frac{d}{\sqrt{\alpha x}} = \frac{d\sqrt{\alpha}}{\sqrt{x}},$$

where

$$d := \sqrt{\sum_{i=1}^{N} d_i^2}.$$

The quantity of B-units x_B^* that maximizes the economy's overall (conditional) welfare, i.e., such that

$$G\left(x_B^*\right) = c_B'\left(x_B^*\right) + Ne'\left(x_B^*\right),$$

is given by

$$x_B^* = \left(\frac{d}{2(b+N\theta)}\right)^{2/3}. \tag{28}$$

The monopolist's profit maximizing A-output when technology B is not employed, i.e., the solution z_A to

$$\max_{x_A \geq 0} \overline{G}(x_A)x_A - F_A - c_A(x_A), \tag{29}$$

is given by

$$z_A = \left(\frac{d\sqrt{\alpha}}{4a}\right)^{2/3}. \tag{30}$$

The monopolist's profit maximizing B-output when technology A is not employed, i.e., the solution z_B to

$$\max_{x_B \geq 0} (G(x_B) - e'(x_B))x_B - F_B - c_B(x_B), \tag{31}$$

is given by[10]

$$z_B = \left(\frac{d}{4(b+2\theta)}\right)^{2/3}. \tag{32}$$

Conditions (9), (10), and (13) place the following constraints on the parameters.

– Condition (9) can be expressed as

$$a < \alpha^2(b + N\theta). \tag{33}$$

10 Under the relevant configuration of parameter values, the monopolist's profits at z_B will be positive, which is consistent with the assumption made in Proposition 2. See footnote 12.

– Condition (10) is expressible as

$$\frac{2ax_A}{(x_B/\alpha)} + a < \frac{F_B}{(x_B/\alpha)^2} + \alpha^2(b + N\theta).$$

By (33), this inequality holds if $\frac{2ax_A}{(x_B/\alpha)} < \frac{F_B}{(x_B/\alpha)^2}$, i.e., if

$$2ax_A x_B < \alpha F_B.$$

This inequality does not need to hold for all (x_A, x_B); it suffices to assume that it holds for any solution to the problem (21) (see footnote 5). Because a solution $(\hat{x}_A, \hat{x}_B)$ to (21) satisfies $\hat{x}_A \le z_A$ and $\hat{x}_B \le z_B$, it suffices to assume that

$$2az_A z_B < \alpha F_B. \tag{34}$$

– Condition (13) can be expressed as

$$a > \alpha^2(b + 2\theta).$$

In sum, the following constraints guarantee that conditions (9), (10), and (13) are satisfied:

$$\alpha^2(b + 2\theta) < a < \alpha^2(b + N\theta) \quad \text{and} \quad 2az_A z_B < \alpha F_B. \tag{35}$$

Using (30) and (32), we can rewrite the second equation as follows:

$$a < \left(\frac{2^4 F_B^3}{d^4}\right)\alpha^2 2(b + 2\theta)^2. \tag{36}$$

Next, we wish to choose a parameter configuration that will serve our purposes, i.e., one for which *any* quota yields a welfare loss. This configuration will be chosen in such a way that the conditions in (35)—and hence conditions (9), (10), and (13)—are satisfied. To this end, we seek parameter values for which

$$z_B = \left(\frac{d}{4(b + 2\theta)}\right)^{2/3} \le x_B^* = \left(\frac{d}{2(b + N\theta)}\right)^{2/3}. \tag{37}$$

(see (32) and (28)). Arranging terms yields

$$N \le 4 + \frac{b}{\theta}.$$

Setting

$$N = 4 + \frac{b}{\theta}, \tag{38}$$

and plugging this expression into the first equation in (35) yields

$$\alpha^2(b+2\theta) < a < \alpha^2 2(b+2\theta).$$

Consequently, under (38), (37) holds, and (35) becomes

$$\alpha^2(b+2\theta) < a < \alpha^2 2(b+2\theta) \quad \text{and} \quad 2az_A z_B < \alpha F_B. \tag{39}$$

Next, note that, because the second equation can be written as in (36), if

$$b+2\theta \geq 1 \quad \text{and} \quad 2^4 F_B^3 \geq d^4, \tag{40}$$

then $2az_A z_B < \alpha F_B$ whenever $\alpha^2(b+2\theta) < a < \alpha^2 2(b+2\theta)$.

In sum, given (38) and (40), the following constraints guarantee that conditions (9), (10), and (13) are satisfied:

$$\alpha^2(b+2\theta) < a < \alpha^2 2(b+2\theta). \tag{41}$$

We claim that, for

$$b+2\theta = 1 \quad \text{and} \quad 0.4d^{4/3} \approx \left(\frac{d}{2}\right)^{4/3} < F_B = F_A < \frac{7d^{4/3}}{2^4} \approx 0.44d^{4/3}, \tag{42}$$

and for a large enough within the bounds in (41), i.e., for

$$a \left\{ \begin{matrix} \approx \\ < \end{matrix} \right\} 2\alpha^2, \tag{43}$$

any binding quota $\bar{z}_B$ results in a welfare loss. Note that (42) implies (38) and (40). Indeed, the second equation in (40) is expressible as $F_B \geq (d/2)^{4/3}$, which is implied by the second equation in (42).

To see that, under (42) and (43), any binding quota $\bar{z}_B$ results in a welfare loss, note first that, in the absence of quotas, the monopolist does not employ technology A, i.e., it sets its output at z_B (see (32)). To see this, it suffices to show that the monopolist's profit at z_B exceeds the maximum profit under the adoption of both technologies.[11] The monopolist's profit at z_B is given by

$$\Pi(z_B) = \frac{3d^{4/3}}{2^{8/3}} - F_B \approx 0.47d^{4/3} - F_B > 0, \tag{44}$$

where the inequality follows from (42).[12] The monopolist's maximum profit at a production plan that employs both technologies, i.e., a production plan (x_A, x_B) with

11 By Proposition 2, we know that the monopolist does not shut down technology B.

12 Note that, by (44), the first assumption in the statement of Proposition 2 is satisfied.

$x_A > 0$ and $x_B > 0$, is the monopolist's profit at an interior solution to the problem (21); such a maximizer must satisfy the following first-order conditions:

$$\alpha G'(\alpha x_A + x_B)(\alpha x_A + x_B) + \alpha G(\alpha x_A + x_B) = c'_A(x_A); \tag{45}$$

$$G'(\alpha x_A + x_B)(\alpha x_A + x_B) + G(\alpha x_A + x_B) = e''(x_B)x_B + e'(x_B) + c'_B(x_B). \tag{46}$$

Combining both equations gives

$$c'_A(x_A) = \alpha c'_B(x_B) + \alpha e''(x_B)x_B + \alpha e'(x_B).$$

In our example, this equation becomes

$$x_B = 2\alpha x_A.$$

Combining this equation with either (45) or (46) gives

$$x_A = \frac{d^{2/3}}{2^2 3^{1/3}\alpha} \quad \text{and} \quad x_B = \frac{d^{2/3}}{2 \cdot 3^{1/3}}.$$

The monopolist's combined profit at (x_A, x_B) is given by

$$\Pi(x_A, x_B) = \frac{(3d)^{4/3}}{2^3} - F_A - F_B = \frac{(3d)^{4/3}}{2^3} - 2F_B.$$

Since

$$\frac{(3d)^{4/3}}{2^3} - 2F_B < 0 \Leftrightarrow F_B > \frac{(3d)^{4/3}}{2^4} \approx 0.27d^{4/3},$$

and since the last inequality holds by (42), it follows that $\Pi(x_A, x_B) < 0$. Consequently, $\Pi(z_B) > 0 > \Pi(x_A, x_B)$.

Thus, in the absence quotas, the monopolist does not adopt technology A and sets its B-output at z_B. In this scenario, there are three cases to consider:

- *Case 1.* Under the quota, the monopolist does not employ technology A. This case is easy to handle, since any binding quota decreases the quantity of B-units traded in the market to a level below z_B (the profit maximizing B-output in the absence of quotas); since (37) holds (so that the efficient quantity of B-units, x_B^*, exceeds z_B), the quota pushes market output further away from the efficient B-level, x_B^*; this yields a welfare loss (since there is no A-output to replace the lost B-units).
- *Case 2.* Under the quota, the monopolist switches to technology A. In this case, the monopolist produces and sells z_A (the profit maximizing A-output, see (30)) instead of z_B. This leads to a welfare loss. Indeed, the overall welfare at z_A is given by

$$
\begin{aligned}
W(z_A) &= \int_0^{z_A} \overline{G}(x)\mathrm{d}x - c_A(z_A) - F_A \\
&= 2\mathrm{d}\sqrt{\alpha z_A} - az_A^2 - F_A \\
&\approx \frac{d^{4/3}}{2} - F_A,
\end{aligned}
$$

while the overall welfare at z_B can be expressed as

$$
\begin{aligned}
W(z_B) &= \int_0^{z_B} G(x)\mathrm{d}x - Ne(z_B) - c_B(z_A) - F_B \\
&= 2\mathrm{d}\sqrt{z_B} - (b + N\theta)z_B^2 - F_B \\
&= 2\mathrm{d}\sqrt{z_B} - 2(b + 2\theta)z_B^2 - F_B \\
&\approx \frac{3}{2^{5/3}} d^{4/3} - F_B \\
&\approx 0.94d^{4/3} - F_B;
\end{aligned}
$$

since $F_A = F_B$, it follows that $W(z_B) > W(z_A)$. Intuitively, the profit maximizing quantity of A-units, z_A, is too low relative to the profit maximizing quantity of B-units, expressed in equivalent A-units, z_B/α. We know that replacing z_B B-units by the equivalent quantity of A-units, z_B/α, would lead to a welfare gain. This is, in fact, precisely our assumption from (9). While the quantity z_B/α of A-output need not coincide with the efficient quantity of A-output, x_A^*, which satisfies $\overline{G}\left(x_A^*\right) = c_A'\left(x_A^*\right)$, moving from z_B/α to x_A^* would bring about additional welfare gains. The monopolist, however, produces and sells too little A-output relative to x_A^*. Since, in our example, z_B/α happens to coincide with x_A^*, z_A is too low also in relation to z_B/α.

– *Case 3.* It remains to consider the case when the monopolist adopts both technologies once the quota is implemented. This means that there is a solution (y_A, y_B) to problem (22) such that $y_A > 0$ and $y_B > 0$. But since the feasible region for problem (22) is a subset of that for problem (21), it follows that the monopolist's maximum profit for problem (22) is less than or equal to that for problem (21). Since, in our example, the maximum profit for problem (21) is negative (a fact that was established earlier), we see that the adoption of both technologies under the quota yields negative profits. The monopolist is better off by specializing in technology A, setting its A-output at z_A (see (30)), which yields a profit of

$$\Pi(z_A) = \frac{7d^{4/3}}{16} - F_A \approx 0.44d^{4/3} - F_A > 0,$$

where the inequality follows from (42). Thus, the monopolist never adopts both technologies under the quota.

We have illustrated that, under certain configurations of parameter values, any quota imposed on a monopolist may well be welfare reducing. The same is true about Pigouvian taxes. Indeed, replacing quotas by any Pigouvian tax in the above example leads to a welfare loss.

To see this, consider a Pigouvian tax that levies $\$\tau$ per unit of emissions/waste. As in Section 5.1, suppose that the monopolist's B-waste is proportional to its B-output by a factor $\gamma_B > 0$, so that γ_B measures emissions/waste per unit of B-output. Under the tax, the monopolist solves the following problem:

$$\begin{aligned} \max_{(x_A,x_B)\geq 0} \; & (G(\alpha x_A + x_B) - e'(x_B))x_B - \mathbb{1}_{x_B}(F_B + \tau\gamma_B x_B + c_B(x_B)) \\ & + \alpha G(\alpha x_A + x_B)x_A - \mathbb{1}_{x_A}(F_A + c_A(x_A)), \end{aligned} \tag{47}$$

In our example, an "unfettered" monopolist specializes in B-output, setting its level equal to z_B. Three case are possible under the Pigouvian tax τ:

- *Case 1.* Under the tax, the monopolist does not employ technology A. In this case, there is no material difference between taxes and quotas when it comes to identifying the welfare effects of these policies: just as in the case of a binding quota, a binding tax decreases the quantity of B-units traded in the market to a level below z_B; since (37) holds (so that the efficient quantity of B-units, x_B^*, exceeds z_B), the tax pushes market output further away from the efficient B-level, x_B^*; this yields a welfare loss (since there is no A-output to replace the lost B-units).
- *Case 2.* Under the tax, the monopolist switches to technology A. In this case, the monopolist produces and sells z_A (the profit maximizing A-output, see (30)) instead of z_B, and we already know from the analysis of quotas that, in our example, this switch leads to a welfare loss.
- *Case 3.* Under the tax, the monopolist adopts both technologies. This means that there is a solution (y_A, y_B) to problem (47) such that $y_A > 0$ and $y_B > 0$. But, just as we showed that the maximum profit for problem (21) is negative, it can be shown that the maximum profit for problem (47) is negative. As in the quota case, the monopolist is better off by specializing in technology A, setting

its A-output at z_A (see (30)), which yields a profit of

$$\Pi(z_A) = \frac{7d^{4/3}}{16} - F_A \approx 0.44d^{4/3} - F_A > 0.$$

Thus, in our example, the monopolist never adopts both technologies under the tax, just as it did not adopt both technologies under a quota.

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