Providing Innovation Incentives for the Ecological Transition

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March 2023

Abstract

The transition to a greener economy requires substantial innovation effort, often by firms operating in imperfectly competitive industries. This paper therefore analyzes environmental innovations, product innovations and process innovations in a differentiated oligopoly with a green and a brown firm. It asks how prices, outputs, profits and emissions depend on these different types of innovations, and what the implications for innovation incentives are. The analysis informs the discussion on whether and how policy should intervene to provide incentives for green innovation.

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JEL Codes: Q55, L13
Keywords: Innovation, Environmental Policy, Imperfect Competition

1 Introduction

Successfully confronting ecological challenges such as climate change will require major innovations. Theory suggests that market-based policy instruments such as emissions taxes and tradeable permits can help to provide incentives for such innovations.[1] There is some evidence supporting this view.[2] However, it is well understood that standard price instruments may not suffice to create optimal innovation incentives. Because of the public goods character of innovations, it is generally not possible to provide adequate innovation incentives by relying *exclusively* on emissions taxes.[3] Moreover, policies aimed at inducing technological change are wide-spread. Despite the well-known advantages of broader approaches that apply equally to emissions from different sectors, such policies often explicitly target the development of specific products (*green goods)* that are considered as less polluting than the dominant alternatives (*brown goods*).

The automobile industry is a clear case in point. With the transportation sector corresponding to around a quarter of the global CO2 emissions, tremendous efforts have been made to replace traditional vehicles with internal combustion engines (ICEVs) by electric vehicles (EVs). Automobile producers have recently spent £341 billion within five years on R&D related to electric vehicles.[4] Though it is hard to disentangle to which extent such investments are a direct response to policy changes, it seems plausible that policy has fostered these developments. Many instruments have been used: targeted R&D subsidies, direct payments for consumers who are willing to adopt electric vehicles and complementary investments that increase the value of EVs to consumers (e.g. improvements of the charging infrastructure). This paper studies the ecological and economic effects of such policies as well as those of alternatives such as emissions taxes. The central question is: How suitable are different instruments for inducing innovations that foster the transition from brown to green goods in markets with imperfect competition?

Importantly, firms can carry out different types of R&D which are not mutually exclusive. They can engage in process innovations that cut the costs of producing green goods. Moreover, they can invest in the product quality of green goods, making them more valuable for consumers.[5] Finally, they can improve the environmental aspects of the products, the green ones as well as the brown ones. I will ask how different policies will affect each type of investment, market outcomes and, most importantly, emissions levels.

To analyze these issues, I use a model that shares some features with examples like the automobile industry, but does not claim to fit any particular case perfectly. I introduce

[1]Early theoretical contributions include Downing and White (1986), Malueg (1989), Milliman and Prince (1989), Biglaiser and Horowitz (1994), Parry (1995); they were developed further by Kennedy and Laplante (1999) and Requate and Unold (2003)

[2]Studies like Newell, Jaffe, and Stavins (2010), Hassler, Krusell, and Olovsson (2021), Acemoglu, Aghion, Bursztyn, and Hemous (2012), Noailly and Smeets (2015) Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016) find price effects of innovation, thus providing indirect evidence that market-based instruments could affect innovation (via their effect on prices. Johnstone, Hascic, and Popp (2008), Rogge, Schneider, and Hoffmann (2011) and Calel and Dechezleprêtre (2016) deal with the innovation effects of specific policies. Extensive surveys are Popp (2010), Popp (2019) and Popp, Pless, Haščič, Johnstone et al. (2020).

[3]See, for instance, Carraro and Siniscaico (1994), Carraro and Soubeyran (1996), Katsoulacos and Xepapadeas (1996), Acemoglu et al. (2012), Aghion et al. (2016).

[4]https://www.bdo.co.uk/en-gb/news/2021/top-20-global-carmakers-spend-another-71-7bn-on-r-and-d-as-electric-vehicle-rollout-gathers-pace

[5]For instance, automobile producers can invest into increasing the range of EVs.

a general two-stage duopoly.[6] In the first stage, the firms simultaneously choose their R&D investments. In the second stage, they set prices. The products are differentiated in two dimensions that affect consumer demand. First, the pure consumption value of the product captures all standard features of product quality (comfort, design, complementary infrastructure, etc.) that a self-interested consumer values. Second, the environmental value of the product is inversely related to how polluting it is (e.g. average CO2-emissions per kilometer). At least some consumers value good environmental properties of a product. By definition, the emissions of the green product are lower than those of the brown product. For definiteness, it is useful to think of the brown good as strictly superior in the "pure consumption" dimension (though *Tesla* drivers may find this assumption hard to swallow).[7] Though all consumers value both dimensions, they differ in the extent to which they are willing to pay for improvements in consumption quality and environmental properties, respectively. In this set-up, I decompose the main research questions as follows:

1. How do the environmental effects of innovations depend on the type of the innovation (process, product or environmental innovation) and the identity of the innovator (brown or green firm)? Through which channels do these effects arise?

2. What determines firms' incentives to carry out process innovations, product innovations and environmental innovations, respectively?

3. How should policy instruments be chosen to induce desirable R&D investments? Is it necessary to provide direct support or does it suffice to apply standard market instruments such as emissions taxes or tradeable permits? Which instruments induce "green" investments without compromising too much on other goals?

Environmental Effects: The first set of questions concerns the comparative statics of the second-stage game. Innovations affect the price equilibrium and thereby the firms' outputs. As the specific emissions of their products differ, such a reallocation of output will influence total emissions. On top of this, some innovations may directly affect pollution. Under some (arguably mild) assumptions, several clear results emerge. First, quite generally, *process innovations* of green firms reduce both prices, but more so for the innovator itself than for the brown firm. As a result of the price changes, output is relocated from the brown to the green firm. Unless the output of the green firm increases by a much larger amount than the output of the brown firm decreases, total emissions decline. Second, as a *product innovation* of the green firm attracts more consumers, it typically increases its market share unless the firm prefers to raise its price substantially, so as to exploit the greater willingness-to-pay of the consumers. Again, as a result of such a market share reallocation, overall emissions decline. Third, similar market share reallocations tend to reduce total emissions after an *environmental innovation of the green firm*. Compared to pure product innovations, this tendency is strengthened by the direct beneficial effect that environmental innovations lower the emission intensity of the green firm. Finally, *environmental innovations of the brown firm* are a double-edged sword: The

[6]The paper thus belongs to the literature on environmental policy with imperfect competition that developed in response to the early papers of Buchanan and Stubblebine (1962) and Buchanan (1969). Examples include Barnett (1980) for monopoly, Katsoulacos and Xepapadeas (1995) for Cournot oligopoly and Lange and Requate (1999) for differentiated price competition. Requate (2006) surveys the literature.

[7]The case of a green product that is superior to the brown product will be dealt with in future versions of this paper.

lower emission intensity after the environmental innovation may well be outweighed by the adverse affects of output reallocation towards the brown firm.

Determinants of Innovation Incentives: Concerning innovation incentives, first note that an innovation that would marginally improve a firm's weak dimension (a product innovation of the green firm or an environmental innovation of the brown firm) would reduce product differentiation and thereby lower equilbrium prices, possibly reducing the firms' profits.[8] Next, I therefore focus on the case that innovation incentives are positive and ask what determines their size. Very generally, if a firm becomes stronger in any dimension, this increases its incentives to invest in any dimension. By contrast, if the competitor becomes stronger in any dimension, a firm's innovation incentives decline. Accordingly, the green firm has strong incentives to engage in process and environmental innovations when (i) its environmental advantage is large, (ii) its quality disadvantage is small and (iii) it has relatively low costs. The incentives for product innovations of the green firm are also positively affected by improvements in its relative position, but they remain negative as long as the green firm lags behind the brown firm in this dimension. Intuitively, own investments increase equilibrium outputs and margins, whereas competitor investments decrease them. But obviously having a higher output is more valuable when margins are high and vice versa. As a result, own investments in any dimension are more valuable if a firm is good in any dimension and if the competitor is bad in any dimension.

Policy Analysis: Firms' pricing decisions give rise to three types of externalities. A price increase of a firm (a) is beneficial for the competitor and (b) bad for consumers. Given imperfect competition, it is reasonable to assume that the latter effect dominates the former. If the green firm increases prices, this typically (c) is also bad for the environment as it shifts outputs to the brown firm. All told, without policy interventions prices of the green firm are therefore to high from a welfare perspective.[9] Turning to investment decisions, they can have direct externalities (that do not reflect price changes) and indirect, price-induced externalities. If second-period prices have been taken care of by adequate instruments, only the direct effects matter. Then there is no reason to provide policy support for process innovations, as they do not *directly* affect the competitor, consumers and the environment. However, there is a reason to support environmental innovations: They directly reduce environmental damages, a beneficial effect that the investing firms do not take into account. Further reasons for supporting investments can come from taking price effects into account. Assume, as argued above, that equilibrium prices are biased in that they are too high for the green firm and that there are no policy instruments available that would cure the problem directly. Then subsidizing this firm's process innovations might be called for, as it lowers the prices of green firms more strongly than the prices of brown firms.

Further results are motivated by the question which policy instruments are particularly good to induce innovation. Meaningful results require comparing parameter constellations for which the equilibrium level of total emissions is the same in the absence of any investments. Maximizing the green firm's investment incentives among all such parameter constellations requires that they are particularly favorable for the green firm (high cost ad-

[8]The underlying logic resembles the literature on vertical differentiation, e.g. Shaked and Sutton (1982).

[9]For the brown firm, the case is less clear: While lower prices would be desirable to reduce the deadweight loss from imperfect competition, the resulting output reallocation would typically also lead to higher emissions.

vantage, high environmental advantage and relatively low product quality disadvantage). Thus for instance, everything else fixed, one can achieve the same level of aggregate emission reductions by policies that differ in how much they reduce the specific emissions of the brown firm and the green firm, respectively. In view of the investment effects, it is best to focus on reducing the emissions of the green firm. On a related note, policies that reduce the consumption quality advantage of brown firms (such as adoption subsidies for the green firm), will not only have the direct effect of reducing emissions by increasing the market share of the green firm, they will also increase this firm's innovation incentives, thus reinforcing the positive environmental effects of the policy.

This paper contributes to a large theoretical literature on innovation in polluting industries.[10] This literature focuses on innovations that reduce abatement costs, with a strong emphasis on ranking policy instruments according to their effects on innovation incentives. Among the three types of innovation considered in this paper, the "environmental innovations" that reduce specific emissions are closest to those treated in the literature.[11] There are very few examples of papers that analyze the environmental effects of process innovations that merely reduce production costs. Most importantly, I am not aware of any papers analyzing how (non-environmental) product innovations affect emissions under imperfect competition.

Another important aspect of this paper is its focus on the consumer side. First, though emissions can be interpreted as coming from production, they can also be regarded as by-products of consumption. Second, more importantly, the model allows for the possibility that consumers value products with good environmental properties, with heterogeneity in the extent to which this is the case. This appears adequate to capture salient aspects of, say, the transition from ICEVs to EVs where arguably, environmental concerns may motivate the purchasing decisions at least for some consumers. Several authors have analyzed environmental policy when some consumers have pro-environmental preferences, but these papers usually do not deal with innovation[12] Exceptions are Sengupta (2012) and Langinier and Chaudhuri (2020) who consider environmental innovations (reductions in specific emissions) in a setting with environmentally conscious consumers. Importantly however, the paper considers a monopoly rather than an oligopolistic setting.

Moreover, this paper emphasizes how different types of innovation affect market outcomes (prices, outputs and profits) under imperfect competition. This is useful to understand their effects on emissions, and it helps to understand how the competitive environment, given by the relative costs of the brown and green firm as well as the demand structure, shapes innovation incentives.

Our paper shares some properties with the existing literature. For instance, several authors have pointed out that price instruments do not guarantee first-best optimal investments. For instance, Katsoulacos and Xepapadeas (2006), Phaneuf and Requate (2016, ch. 11.2) argue that sufficiently high knowledge spillovers may lead to insufficient investment even in the presence of an emissions tax and that R&D subsidies may be necessary to rectify the problem. The analysis of this paper shows that, even in the absence of spillovers,

[10]See footnotes 1 and 2.

[11]A few authors also model technological improvements as reductions in specific emissions; see, e.g., Benchekroun and Chaudhuri (2014), Benchekroun and Chaudhuri (2015), Katsoulacos and Xepapadeas (1996); Phaneuf and Requate (2016, ch. 11.4), Langinier and Chaudhuri (2020)

[12]See, for instance, Arora and Gangopadhyay (1995), Cremer and Thisse (1999), Moraga-Gonzalez and Padron-Fumero (2002), Bansal and Gangopadhyay (2003), Lombardini-Riipinen (2005), Bansal (2008)

providing adequate innovation incentives is a complex problem once one takes into account the multi-dimensionality of the problem and asymmetries between firms.

Finally, the paper owes a lot to the well-established IO literature on innovation. In line with the results of this paper, authors like Bagwell and Staiger (1994) and Leahy and Neary (1997) have argued that, absent spillovers, process innovations of different firms tend to be strategic substitutes. As in the current paper, different types of investment of one firm are complements in Athey and Schmutzler (1995).[13] Moreover, the intuition for the argument that firms may not want to invest in its weak dimension to avoid intense competition goes back to Shaked and Sutton (1982). However, none of these contributions deals with effects on pollution or with environmental policy instruments.

Section 2 introduces the general model and a simple example. In Section 3, I analyze the second (pricing) stage for the general model. In Section 4, I turn to the investment stage. Section 5 sharpens the result sharpens the results in the context of a stylized example. Section 6 concludes.

2 The Setting

Section 2.1 introduces a model which has enough structure to generate meaningful results, but still is general enough to fit many conceivable market environments. Section 2.2 illustrates the general ideas with a particularly tractable special case.

2.1 The General Model

2.1.1 Overview

I consider a two-stage duopoly with firms $i \in \{B, G\}$ where B produces a "brown" product and G produces a "green" product. The green firm has lower specific emissions (emissions per unit output) than the brown firm at the outset of the game.

In stage $t = 1$, both firms can invest in three types of innovations. *Process innovations* lower their production costs. *Product innovations* make their product more attractive without improving its environmental properties. *Environmental innovations* lower the specific emissions attributable to the production and/or consumption of the good.

The investment activities of the firms in these three dimensions determine their relative positions at the beginning of stage $t = 2$, in which they are involved in static differentiated price competition. The firms' demand functions have the standard properties that (for fixed prices) they are positively affected by their own product innovations and negatively affected by their competitor's product innovations. A less common assumption is that an environmental innovation of a firm has a positive effect on its own demand and a negative effect on the competitor's demand. There are three reasons why this might be the case. First, consumers could intrinsically value products with good environmental properties, for instance for altruistic reasons. Second, low emissions could have co-benefits for consumers.[14] Finally, the demand effect of environmental innovations could reflect environmental policy. For instance, consumers may have to pay taxes that depend on the

[13]Related to all these papers, Schmutzler (2013) provides a detailed discussion of complementarities between demand-enhancing and output enhancing measures in the context of increasing competition.

[14]For instance, a green product might be more healthy, or it might save energy costs.

environmental properties of a good, so that, other things equal, improvements in a firm's environmental quality would tend to increase own demand by lowering the tax burden.[15]

At the beginning of each stage of the game, the firms are characterized by state vectors $\mathbf{Y}_i^t := (q_i^t, r_i^t, s_i^t)$. s_i^t is a strictly decreasing function of firm i's marginal costs, which are constant at c_i^t; for definiteness, let $s_i^t = -c_i^t$.[16] q_i^t stands for product quality, reflecting the value of the consumption experience. r_i^t summarizes the environmental quality of the product. Denote the quality subvector $\Theta_i^t := (q_i^t, r_i^t)$, with the generic notation $\theta_i^t \in \{q_i^t, r_i^t\}$ for its components. When referring to an arbitrary component of the state vector $\mathbf{Y}_i^t$, I use the generic notation $\phi_i^t \in \{q_i^t, r_i^t, s_i^t\}$ or simply ϕ^t if the identity of the firm does not matter. Each component of the state vector potentially reflects exogeneous asymmetries and, for $t = 2$, first-stage investments. Further, let $\mathbf{Y}^t = (\mathbf{Y}_B^t, \mathbf{Y}_G^t)$. When there is no danger of confusion, time indices will be dropped.

In the following, I first detail the assumptions for the second, product market competition stage. Thereafter, I deal with the first stage, the investment stage.

2.1.2 Stage 2: Product Market Competition

In stage 2, firms $i \in \{B, G\}$ simultaneously set prices p_i for their respective products. The main properties of the demand functions are reflected in the following assumption.

Assumption 1: (i) *For $i \in \{B, G\}$ and $j \neq i$,*[17] *the demand function is of the form $x^i(p_i, p_j; \Theta_i, \Theta_j)$. In regions where both equilibrium prices and outputs are positive, x^i is decreasing in p_i, increasing in p_j; increasing in Θ_i, decreasing in Θ_j, and continuously differentiable (at least $\mathcal{C}^1$) in all arguments.*
(ii) *For $i = 1, 2$, x^i is such that the profit function*

$$\pi^i(p_i, p_j; \mathbf{Y}_i, \mathbf{Y}_j) = (p_i - c_i)\, x^i(p_i, p_j; \Theta_i, \Theta_j)$$

is twice continuously differentiable and concave in own prices and satisfies strategic complementarities ($\pi_{ij}^i > 0$); moreover $|\pi_{ii}^i| > \pi_{ij}^i$.

All properties hold in standard differentiated duopoly models and in the example in Section 2.2.[18] Further note that the condition that $|\pi_{ii}^i| > \pi_{ij}^i$ implies the standard dominant diagonal condition $\Delta = \pi_{12}^1\pi_{21}^2 - \pi_{12}^1\pi_{21}^2 > 0$.[19]

A firm that produces output x_i generates emissions e_i; this may include emissions in production and consumption. I refer to $\eta_i := e_i/x_i$ as firm i's *specific emissions*. The underlying assumption is that there is an inverse relation between these specific emissions η_i and the environmental quality r_i of a firm. Total emissions are

$$E = E(x_B, x_G; \eta_B, \eta_G) = \eta_B x_B + \eta_G x_G. \tag{1}$$

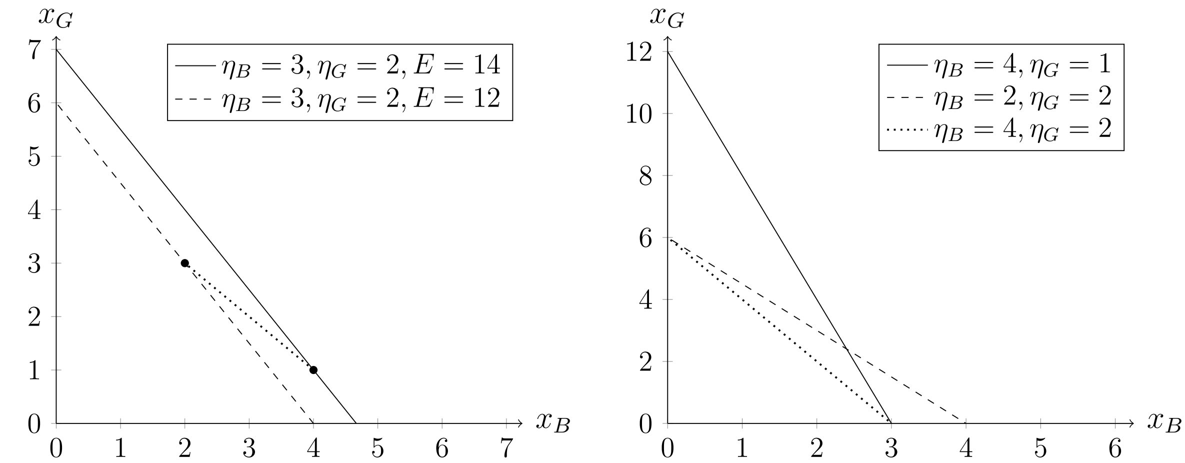
[15] Emission-dependent automobile taxes would be a case in point.

[16] As with demand, the marginal costs could depend on environmental policy. For instance, a linear emissions tax t can be interpreted as an increase in marginal cost.

[17] In the remainder of the paper, I will refer to a generic firm as $i \in \{B, G\}$ and to its competitor as j without further ado.

[18] I use the short-cut notation $\pi_{ii}^i \equiv \frac{\partial^2 \pi^i}{\partial p_j \partial p_l}$, $\pi_{ij}^i \equiv \frac{\partial^2 \pi^i}{\partial p_j \partial p_l}$, etc. for the second derivatives of the profit functions π^i with respect to prices. It is straightforward to translate the statements in Assumption 1(ii) into statements on demand functions. For instance, $\pi_{ij}^i > 0$ obviously corresponds to $\frac{\partial x^i}{\partial p_j} + (p_i - c_i)\frac{\partial^2 x^i}{\partial p_i \partial p_j} > 0$.

[19] In a symmetric setting $|\pi_{ii}^i| > \pi_{ij}^i$ also is implied by dominant diagonals. In the asymmetric setting of this paper, this is not generally the case.



(a) The effects of reallocating output from the brown firm to the green firm

(b) The effects of lowering specific emissions

Figure 1: (a) The figure depicts iso-emission lines for $E = 14$ and $E = 12$ for fixed specific emissions. The arrow captures the emission-reducing effect of shifting two units of output from firm B to firm G. (b) The figure depicts iso-emission lines for $E = 12$ for different specific emissions.

As will be formulated more precisely in Assumption 2 below, a brown firm has higher specific emissions than its green counterpart throughout the game, so that

$$\eta_B > \eta_G.$$

Figure 1 depicts iso-emissions lines in quantity-space. The left part shows how, for given specific emissions, a shift in output from B to G reduces total emissions. The right part shows how reductions in specific emissions for either firm move the iso-emissions curves outwards, meaning that the given aggregate emission level becomes feasible at higher output levels.

2.1.3 Stage 1: Investment Competition

In stage 1, each firm can engage in *product innovations*, which increase q_i, *environmental innovations* which increase r_i (reduce η_i) and *process innovations* which increase s_i (reduce c_i). Recall that, at the beginning of stage 1, firm i has a vector $\mathbf{Y}_i^1 = (q_i^1, r_i^1, s_i^1)$ of initial states. Firm i can increase $\phi_i \in \{q_i, r_i, s_i\}$ by y_i^ϕ by investing $K_i^\phi \left(y_i^\phi\right)$. Thus, with $\mathbf{y}_i = (y_i^q, y_i^r, y_i^s)$, the state vector after the investment stage is $\mathbf{Y}_i^2 = \mathbf{Y}_i^1 + \mathbf{y}_i$. The following assumptions are useful for the existence of a subgame-perfect equilibrium.

Assumption 2: (i) *The choices of y_i^{ϕ} are limited to compact intervals of the form $\left[0, y_{i\phi}^{\max}\right]$ where $y_{i\phi}^{\max}$ may vary across firms $i \in \{B, G\}$ and types of innovation $\phi \in \{q, r, s\}$. Moreover, $q_G^1 + y_{Gq}^{\max} < q_B^1$* and *$r_B^1 + y_{Bq}^{\max} < r_G^1$.*
(ii) *The functions K_i^ϕ are increasing and sufficiently convex;* $(K_i^\phi)'(0) = 0$.

Assumption 2(i) clarifies the above requirement that $\eta_B > \eta_G$: This not only holds at the beginning of the game; in addition, even when the brown firm invests as much as possible, it cannot leapfrog a competitor who does not invest in that dimension. Similarly, the green firm cannot leapfrog the brown firm in the product quality dimension.

Under Assumptions 1 and 2, firm i's objective function is

$$\Pi^i(p_i, p_j; \mathbf{y}_i, \mathbf{y}_j) := \pi^i(p_i, p_j; \mathbf{Y}_i^1 + \mathbf{y}_i, \mathbf{Y}_j^1 + \mathbf{y}_j) - K_i(\mathbf{y}_i), \tag{2}$$

where $K_i(\mathbf{y}_i) := \sum_{\phi_i \in \{q_i, r_i, s_i\}} K_i^{\phi}(y_{i\phi})$.

2.2 A Discrete Choice Example

To illustrate the setting, a simple discrete choice model with the property that total demand is fixed is helpful. The model delivers straightforward closed-form solutions. I first provide the set-up without much ado; then I briefly discuss its restrictive nature.

2.2.1 Assumptions

There is a continuum of heterogeneous consumers who decide which of the two products to buy. For now, I will abstract from the possibility of choosing an outside option.[20] For each good, consumption quality and environmental quality are parameterized by $q_i \in \mathbb{R}$ and $r_i \in \mathbb{R}$, respectively, where

$$\begin{aligned}(q_G, r_G) &= (l, H) \\ (q_B, r_B) &= (h, L),\end{aligned}$$

with $H > L$ and $h > l$. H and L should be thought of as inversely related to specific emissions η_G and η_B, respectively.

Consumers differ in the relative willingness-to-pay (WTP) for each component. They are distributed according to F on the interval $[0, 1]$. For consumer $k \in [0, 1]$, the WTP for product i is given by

$$U_{ki} = v + kr_i + (1 - k)\, q_i \text{ for some } v > 0.$$

Thus $v + q_i$ can be interpreted as the willingness-to-pay of a consumer who only cares about the environmental value for the good of the respective firm; $v + r_i$ is the willingness-to-pay of a consumer who only cares about the pure consumption value. Therefore all consumers agree that both consumption quality and environmental quality are (at least weakly) desirable, but to different degrees. The following notation is useful:

$$\begin{aligned}\Delta_E &\equiv H - L \\ \Delta_Q &\equiv h - l \\ \Delta_c &\equiv c_G - c_B \\ \Delta_p &\equiv p_G - p_B\end{aligned}$$

The signs of these terms are chosen so that Δ_E and Δ_Q are always positive, whereas Δ_c and Δ_p can have both signs.

Absent an outside option, a consumer k buys the green product if and only if

$$kH + (1 - k)\, l - p_G \geq kL + (1 - k)\, h - p_B.$$

[20]As usual, such a market coverage assumption can be justified by assuming that the willingness to pay is high enough.

Straightforward rearrangements show that this is equivalent with $k \geq \frac{\Delta_Q+\Delta_p}{\Delta_E+\Delta_Q}$, so that the demand functions can be rewritten as

$$x^B(p_B, p_G) = F\left(\frac{\Delta_Q + \Delta_p}{\Delta_E + \Delta_Q}\right)$$
$$x^G(p_G, p_B) = 1 - F\left(\frac{\Delta_Q + \Delta_p}{\Delta_E + \Delta_Q}\right)$$

To make further progress, I will now consider the special case of a uniform type distribution F.[21] Demand functions then become linear in prices:

$$x^B(p_B, p_G) = \frac{\Delta_Q + \Delta_p}{\Delta_Q + \Delta_E}$$
$$x^G(p_G, p_B) = \frac{\Delta_E - \Delta_p}{\Delta_Q + \Delta_E}$$

Clearly, $\frac{\partial x^B}{\partial \Delta_Q} > 0$, $\frac{\partial x^B}{\partial \Delta_E} < 0$, $\frac{\partial x^G}{\partial \Delta_Q} < 0$, $\frac{\partial x^G}{\partial \Delta_E} > 0$, in line with Assumption 1(i). Profits are

$$\pi^B(p_B, p_G) = (p_B - c_B)\frac{\Delta_Q + \Delta_p}{\Delta_Q + \Delta_E}; \quad (3)$$
$$\pi^G(p_G, p_B) = (p_G - c_G)\frac{\Delta_E - \Delta_p}{\Delta_Q + \Delta_E}. \quad (4)$$

Thus, the concavity, strategic complementarity and dominant diagonal requirements of Assumption 1(ii) also hold. Finally, it is now straightforward to formulate exogenous restrictions on parameters guaranteeing that no consumer prefers an outside option of value 0 to her net utility corresponding to the equilibrium, thus justifying the assumption that the market is covered in equilibrium.

2.2.2 Discussion

The analysis has shown that the example is consistent with Assumption 1, except that I have not yet shown that a unique equilibrium (with positive prices) exists, which will be done in Proposition 3 below. The example has the advantage that it is simple to calculate the second-stage equilibrium in closed form. However, it has some very special properties. First, every consumer buys exactly one unit of one good in equilibrium. Second, more problematically, the taste distribution is symmetric and uniform. This is obviously an extreme simplification, implying that, on average, consumers care as much about environmental quality as about product quality.[22] Third, and related to the previous points, for the state variables captured in Θ only the differences between the two firms matter for demand, not the absolute variables. Before focusing too much on this special model, I therefore provide some comparative statics and welfare results for the general model.

[21] This is obviously an extreme simplifications; see the discussion in Section 2.2.2.

[22] For instance, an alternative assumption would be that there is an atom at $k = 0$, so that some fraction of the consumers does not value environmental quality at all.

3 General Analysis: Price Competition

This section contains the results that hold at the general level, focusing first on the price stage. Section 3.1 deals with equilibrium existence and uniqueness and with comparative statics results. Section 3.2 addresses comparative statics, showing how second-stage outcomes depend on first-stage investments. Finally, Section 3.3 discusses optimal second-stage allocations.

3.1 Existence and Uniqueness

The conditions under which a unique equilibrium exists are as follows:

Lemma 1. *For every state vector* $\mathbf{Y}$*, a unique Nash equilibrium* $(p_B^*(\mathbf{Y}), p_G^*(\mathbf{Y}))$ *of the pricing subgame exists.*

As the game is supermodular, the existence result directly follows from Theorem 5 in Milgrom and Roberts (1990). Uniqueness follows from standard arguments, building from $|\pi_{ii}^i| > \pi_{ij}^i$ (Assumption 1(ii)). For some purposes, it is convenient to require in addition:

Assumption 3: *The prices* $(p_i^*(\mathbf{Y}))$ *are differentiable functions of the state vector* $\mathbf{Y}$.

The corresponding margins, quantities, emissions and profits of firm i can be written as functions of the state vector as well:[23]

$$\begin{aligned} m_i^*(\mathbf{Y}) &= p_i^*(\mathbf{Y}) - c_i(\mathbf{Y}), \\ x_i^*(\mathbf{Y}) &= x^i(p_B^*(\mathbf{Y}), p_G^*(\mathbf{Y})), \\ e_i^*(\mathbf{Y}) &= \eta_i(\mathbf{Y}) x_i^*(\mathbf{Y}), \\ \pi_i^*(\mathbf{Y}) &= (p_i^*(\mathbf{Y}) - c_i(\mathbf{Y}))\, x_i^*(\mathbf{Y}). \end{aligned}$$

3.2 Innovation Effects

I now ask how the outcome of the pricing game depends on ceteris paribus changes in the vector $\mathbf{Y}^2$ of state variables (costs and qualities) that are exogenous *at this stage*. This obviously includes changes that are brought about by investments in stage 1. I will therefore frame the results as innovation effects.[24] The main goal is to understand the effects of innovation on total emissions. An important channel by which innovations affect emissions is market share: Cost reductions and quality improvements should make the product of the innovator relatively more attractive. The following terminology takes this into account:

Definition 1. *An innovation is* ***regular*** *if it increases the innovator's equilibrium output and reduces the competitor's output. It is* ***strictly regular*** *if the former effect is at least as large as the latter, so that the overall output does not fall. A strictly regular innovation is* ***purely business-stealing*** *if it leaves total equilibrium output unaffected.*

I now consider the effects of different types of innovation, asking in particular when they will be regular and how they affect emissions.

[23] In the following, the dependence of c_i on $\mathbf{Y}$ arises because c_i is a decreasing function of the component s_i of the state vector; similarly η_i is decreasing in r_i.

[24] Though the results are also helpful to understand policy changes or changes in technology or demand that are entirely exogenous to the two-stage game, this requires additional care, as such changes will typically affect the investment vector, making the analysis more complex.

3.2.1 Process Innovations

I first treat the effects of unilateral cost reductions. A plausible conjecture is that the innovator reduces its price, with the competitor following suit, reducing the price by a smaller amount. As a result, one should expect the innovator's output to increase and the competitor's to decrease. This should lead to higher total emissions if the innovator is the brown firm and to lower emissions if it is the green firm. It turns out that this line of thought can be supported, but additional assumptions are required.

Lemma 2. *Suppose the costs of firm i fall marginally. Then:*
(i) Both prices fall.
(ii) Suppose that $\frac{\partial x^i}{\partial p_j} \leq \left|\frac{\partial x^i}{\partial p_i}\right|$ holds in an open neighborhood of the equilibrium. (a) Then the effect on firm i's own output is positive. (b) The effect on the output of firm $j \neq i$ is negative if the innovation is purely business-stealing and, more generally, if and only if

$$\frac{\partial p_i^*/\partial c_i}{\partial p_i^*/\partial c_j} > \frac{|\partial x^j/\partial p_j|}{\partial x^j/\partial p_i}. \tag{5}$$

(iii) The profits of firm $j \neq i$ fall. The profits of firm i increase if and only if

$$x^i\left(p_i^*, x_j^*\right) > (p_i - c_i)\frac{\partial x^i}{\partial p_j}\frac{\partial p_j^*}{ds_i}. \tag{6}$$

Intuitively, (i) the reaction curve of the directly affected firm shifts inwards; inducing it to set lower prices. By strategic complements, the competitor reacts with lower prices as well. (ii) clarifies the conditions under which a process innovation is regular. The result relies on the simple observation that, for an arbitrary parameter ϕ, the total effect of a marginal increase is

$$\frac{dx_i^*}{d\phi} = \frac{\partial x_i^*}{d\phi} + \frac{\partial x_i^*}{\partial p_i}\frac{\partial p_i^*}{\partial \phi} + \frac{\partial x_i^*}{\partial p_j}\frac{\partial p_j^*}{\partial \phi} \text{ for } i = 1, 2; j \neq i. \tag{7}$$

Thus, a general parameter change potentially affects output directly or via the effects on both equilibrium prices. (ii)(a) states that for a process innovation ($\phi = s_i$) the direct positive effect and the indirect effect of higher competitor prices dominate the adverse effect of higher own prices. Condition (5) guarantees that the output reduction of an innovating firm's competitor following the innovator's price reduction dominates the output increase from the competitor's price reduction.[25]

To understand (iii), note more generally that the total marginal profit effect of changing any parameter ϕ of the pricing game is given by

$$\frac{d\pi_i^*}{d\phi} = \frac{\partial \pi_i^*}{d\phi} + \frac{\partial \pi_i^*}{\partial p_j}\frac{\partial p_j^*}{\partial \phi} \text{ for } i = 1, 2; j \neq i. \tag{8}$$

The first term is the direct effect on profits of the firm under consideration; the second term captures the effect that is mediated by a price change of the competitor.[26] Applying

[25] It states that the sensitivity of p_i with respect to c_i must be high relative to the sensitivity with respect to c_j, whereas competitor j's demand must not be too sensitive to p_j relative to p_i.

[26] Reflecting the logic of the envelope theorem, $\frac{\partial \pi_i^*}{\partial p_i}\frac{\partial p_i^*}{\partial \phi} = 0$ as $\frac{\partial \pi_i^*}{\partial p_i} = 0$. Hence, there is no need to account for effects intermediated by a change in firm i's price.

this to $\phi = s_i$, competitor profits thus unambiguously fall (iii) after a reduction in c_i: In addition to the adverse direct effect of lower demand, firm i's cost reduction translates into a lower price p_i which harms firm j by reducing its output. By contrast, a firm's process innovation has conflicting effects on own profits: the positive effect of making every unit output cheaper, captured in a profit increase of x_i^*, and the negative effect from lower competitor prices. Condition (6) guarantees that the former positive effect dominates the latter negative effect.

Effects on Emissions The effects of process innovations on total emissions are given as

$$\frac{dE^*}{ds_i} = \eta_B \frac{\partial x_B^*}{\partial s_i} + \eta_G \frac{\partial x_G^*}{\partial s_i}.$$

Obviously, these effects are fully driven by output changes. They are most transparent in the regular case.

Proposition 1. *(i) A regular process innovation of the green firm reduces total emissions if and only if*

$$\frac{\left|\frac{\partial x_G^*}{\partial s_G}\right|}{\frac{\partial x_B^*}{\partial s_G}} < \frac{\eta_B}{\eta_G}. \tag{9}$$

Hence, a purely business-stealing innovation of the green firm reduces overall emissions. (ii) A strictly regular process innovation of the brown firm increases overall emissions. Hence, a purely business-stealing innovation of the brown firm increases overall emissions.

Intuitively, (i) a regular process innovation of the green firm increases its own output and reduces the competitor's output. In principle, the former effect could lead to higher total emissions in spite of the shift in market share towards the green firm. However, as $\frac{\eta_B}{\eta_G} > 1$, this is only possible if total output increases by a sufficiently large amount, so that (9) is violated. By contrast (ii), as a result of a *strictly* regular process innovation of a brown firm, the output of firm B increases by a greater amount than the output of firm G falls. Because of the higher specific emissions of the former firm, even a one-to-one reallocation of output would increase total emissions, so they increase *a fortiori* when the output of B increases more than the output of G falls.

3.2.2 Demand-enhancing Innovations

I shall now analyze the effects of demand-enhancing innovations, that is, product innovations and environmental innovations, on the second-period outcome. To the extent possible, these innovations will be treated analogously. Again, a key part of the intuition will be that such innovations shift demand towards the innovator, which will tend to increase total emissions if the innovator is the brown firm and reduce them if it is the green firm. However, the details of the argument differ for product and environmental innovations. Moreover, to establish the main results, it is important to understand how the innovations affect prices. To this extent, the following distinctions are critical.

Definition 2. *(i) An increase of $\theta_i \in \{q_i, r_i\}$* ***increases price sensitivity*** *of demand if $\frac{\partial^2 x^i}{\partial p_i \partial \theta_i} < 0$ for $i = 1, 2$; it* ***reduces price sensitivity*** *of demand if $\frac{\partial^2 x^i}{\partial p_i \partial \theta_i} > 0$ for $i = 1, 2$. (ii) An increase of θ_i is* ***competition-softening (intensifying)*** *if $\pi^i_{i\theta_i} > (<) 0$.*

Intuitively, (i) if an innovation increases (reduces) price sensitivity, demand will react more (less) negatively to a price increase after the innovation. Moreover, the terminology in (ii) reflects the fact that a parameter θ_i shifts a firm's reaction curve outwards (towards higher prices) if $\pi^i_{i\theta_i} := \frac{\partial^2 \pi^i}{\partial p_i \partial \theta_i} > 0$ and inwards (towards lower prices) if $\pi^i_{i\theta_i} < 0$. The distinction between innovations that increase or reduce price sensitivity matters for which of the two latter cases holds. To see this, note that

$$\pi^i_{i\theta_i} = \frac{\partial x^i}{\partial \theta_i} + (p_i - c_i) \frac{\partial^2 x^i}{\partial p_i \partial \theta_i}.$$

As $\frac{\partial x^i}{\partial \theta_i} > 0$ by Assumption 1(i), $\pi^i_{i\theta_i} > 0$ always holds if an innovation reduces price sensitivity. If it increases price sensitivity, $\pi^i_{i\theta_i}$ can be positive or negative.

In the leading example, both possibilities in (i) and (ii) will arise (see Section 5). Intuitively, suppose a firm innovates in its strong dimension (the green firm engages in an environmental innovation; the brown firm engages in a product innovation). Then this will mean that the firms become less similar, so that price changes translate into lower price sensitivity, and innovations will be competition-softening. If instead a firm innovates in its weak dimension, then this makes firms more similar and therefore increases price sensitivity. In the example, this effect will be so strong that such innovations will intensify competition. The following result summarizes the effects of demand-enhancing innovations on prices, outputs and profits, depending on whether they are competition-softening or competition-intensifying.

Lemma 3. *Consider a demand-enhancing innovation of firm i.*
(i) If the innovation softens competition, it increases both prices; if it intensifies competition, it reduces both prices.
(ii) (a) The innovation increases firm i's output if

$$\frac{\partial x^i}{\partial \theta_i} + \frac{\partial x^i}{\partial p_j} \frac{\partial p^*_j}{\partial \theta_i} > -\frac{\partial x^i}{\partial p_i} \frac{\partial p^*_i}{\partial \theta_i}. \tag{10}$$

(b) It reduces competitor j's output if

$$\frac{\partial x^j}{\partial \theta_i} + \frac{\partial x^j}{\partial p_j} \frac{\partial p^*_j}{\partial \theta_i} < -\frac{\partial x^j}{\partial p_i} \frac{\partial p^*_i}{\partial \theta_i}. \tag{11}$$

(iii) (a) If the innovation softens competition, it always increases own profits; if it intensifies competition, it reduces the profits of competitor j.
(b) A competition-intensifying innovation increases firm i's own profits if and only if

$$\left| \frac{\partial p^*_j}{\partial \theta_i} \right| < \frac{\frac{\partial x^i}{d\theta_i}}{\frac{\partial x^i}{\partial p_j}}. \tag{12}$$

(c) It reduces competitor j's profits if and only if

$$\frac{\partial p^*_i}{\partial \theta_i} < \frac{\left| \frac{\partial x^j}{d\theta_i} \right|}{\frac{\partial x^j}{\partial p_i}}. \tag{13}$$

Result (i) uses the standard logic of games with strategic complementarities: Competition-softening (intensifying) innovations shift reaction curves in price space outwards (inwards) and, because prices are strategic complements, these price effects reinforce each other. The results in (ii), which jointly guarantee that the innovation of firm i is regular, result from the interplay of direct demand effects and the indirect effects induced by price changes. The focus will be on the case that product innovations soften competition; the case of competition-intensifying innovations is analogous. The term $\frac{\partial x^i}{\partial p_j}\frac{\partial p_j^*}{\partial \theta_i}$ in (10) captures the output effect of the price increase of firm j following the innovation of firm i that reinforces the positive direct effect $\frac{\partial x^i}{\partial \theta_i}$; whereas firm i's own price effect (as captured by $\frac{\partial x^i}{\partial p_i}\frac{\partial p_i^*}{\partial \theta_i}$) weakens these two positive effects. Condition (10) guarantees that the positive effects dominate.[27]

Trivially, in the extreme case that quality does not affect total output (quality improvements are purely business-stealing), the output effects on the competitor are exactly opposite to those on the investing firm. Hence, the condition for a positive effect on the innovator's output is then identical to the condition for a negative effect on the competitor's. More generally, a negative effect on firm j's output requires that the joint effect of the induced price changes does not dominate the direct negative effect ($\frac{\partial x^j}{\partial \theta_i}$). If innovation softens competiton, then the effect of firm j's own higher equilibrium price, $\frac{\partial x^i}{\partial p_j}\frac{\partial p_j^*}{\partial \theta_i}$, strengthens the negative direct effect, whereas the effect of firm i's higher equilibrium price, $\frac{\partial x_i}{\partial p_i}\frac{\partial p_i^*}{\partial \theta_i}$ weakens the positive direct effect. Condition (11) guarantees that the negative effects dominate.

To understand the profit effects (iii), apply (8) to the case that ϕ corresponds to a demand-enhancing innovation of firm i. The direct demand effect on own profits is positive, whereas the direct effect on competitor j's profits is negative. The positive effects of competition-softening innovations on the competitor price reinforce the direct own effects; for competition-intensifying innovations, the competitor price reduction reduces the adverse direct effect. This lies behind the results in (iii)(a).

The cases in (b) and (c) are more subtle as the direct and price-induced effects are conflicting. For competition-intensifying innovations (b), positive direct effects on own demand are weakened by adverse effects on competitor prices; for competition-softening innovations (c), adverse direct effects on competitor j's demand are weakened by positive effects from the increasing price of firm i. Conditions (12) and (13) make sure that the direct effects dominate the price-induced effects.

In the example of Section 2.2, demand-enhancing investments are always purely business-stealing and hence strictly regular, increasing the innovator's output and decreasing the competitor's by the same amount (see Section 5). Their remaining effects will depend on the type of the innovation (product or environmental) and the identity of the firm (brown or green). Innovations in a firm's strong dimension will reduce price sensitivity and thereby increase equilibrium prices and own profits. In spite of the price increase, they reduce the competitor's profits through the demand effect.

Effects on Emissions The following result summarizes the effects of demand-enhancing innovations on total emissions, distinguishing between product innovations and environmental innovations.

[27] In the example in Section 2.2, the direct effects of a product innovation in the strong dimension will dominate, so that an increase in a firm's own quality increases its output.

Proposition 2. *(i) A purely business-stealing product innovation of firm G reduces total emissions; a purely business-stealing product innovation of firm B increases them. An arbitrary regular product innovation of firm G reduces total emissions if and only if*

$$\frac{\frac{\partial x^G}{\partial q_G}}{\left|\frac{\partial x^B}{\partial q_G}\right|} < \frac{\eta_B}{\eta_G}. \tag{14}$$

A regular product innovation of firm B increases total emissions if and only if

$$\frac{\left|\frac{\partial x^G}{\partial q_B}\right|}{\frac{\partial x^B}{\partial q_B}} < \frac{\eta_B}{\eta_G}. \tag{15}$$

(ii) (a) A purely business-stealing environmental innovation of G reduces total emissions. An arbitrary regular environmental innovation of G reduces total emissions if and only if

$$\eta_G \frac{\partial x^G}{\partial r_G} < \eta_B \left|\frac{\partial x^B}{\partial r_G}\right| + \left|\frac{\partial \eta_G}{\partial r_G}\right| x^G \tag{16}$$

(b) A regular environmental innovation of firm B only reduces total emissions if

$$\left|\frac{\partial \eta_B}{\partial r_B}\right| x^B > \left|\eta_G \frac{\partial x^G}{\partial r_B} + \eta_B \frac{\partial x^B}{\partial r_B}\right| \tag{17}$$

To see (i), note that the effect of a product innovation of firm i is given by

$$\frac{dE^*}{dq_i} = \eta_B \frac{\partial x_B^*}{\partial q_i} + \eta_G \frac{dx_G^*}{dq_i}. \tag{18}$$

The entire emissions effect reflects output changes. If an innovation of firm G is regular, it shifts the output from the more polluting to the less polluting firm. This must reduce total emissions unless the overall output increases. Even then, the overall output increase has to be large compared to the ratio in pollution intensity of the two firms if the increasing emissions of firm G are to outweigh the decreasing emissions of firm B; condition (14) prevents this. The argument for the innovation of the brown firm is essentially the opposite.

Like a product innovation, an environmental innovation (iia) of firm G has output relocation effects, with $\eta_B \frac{\partial x^B}{\partial r_G}$ capturing the reduction in emissions of the brown firm and $\eta_G \frac{\partial x^G}{\partial r_G}$ capturing the increase of the green firm. Following the logic for the product innovation, their sum must be negative for a regular environmental innovation. In contrast with the case of product innovations, there is another emission-reducing effect, $\frac{\partial \eta_G}{\partial r_G} x^G$, which captures the lower specific emissions of G. Condition (16) guarantees that the emission-reducing effects dominate. By contrast, (iib) for a regular environmental innovation of firm B, the effects of its own reduction in specific emissions and the output reallocation go in different directions. Only if the direct effect of lower specific emissions dominates the effect of reshuffling output from the green to the brown firm, will overall emissions decline; see Condition (17).

3.3 Optimal Policy

I now provide some thoughts on the optimal policy in the pricing stage, assuming for now that investment levels and thus the quality and production cost levels are fixed. Using the notation $\mathbf{p} := (p_B, p_G)$, we write $\sigma\left(\mathbf{p}; \mathbf{Y}^1\right)$ stands for consumer surplus. Moreover,

$$\delta\left(\mathbf{p}; \mathbf{Y}^1\right) := D\left(\eta_B\left(\mathbf{Y}^1\right) x^B\left(\mathbf{p}; \mathbf{Y}^1\right) + \eta_G\left(\mathbf{Y}^1\right) x^G\left(\mathbf{p}; \mathbf{Y}^1\right)\right)$$

refers to the damages arising in the allocation corresponding to the price vector $\mathbf{p}$. Thus, second-period welfare is

$$W^2\left(\mathbf{p}; \mathbf{Y}^1\right) = \pi_B\left(\mathbf{p}; \mathbf{Y}^1\right) + \pi_G\left(\mathbf{p}; \mathbf{Y}^1\right) + \sigma\left(\mathbf{p}; \mathbf{Y}^1\right) - \delta\left(\mathbf{p}; \mathbf{Y}^1\right).$$

From Assumption 1(ii), π^i is increasing in p_j and concave and hence single-peaked in p_i. In addition, the analysis will rely on the following assumption:

Assumption 4: (i) *Consumer surplus $\sigma\left(\mathbf{p}; \mathbf{Y}^1\right)$ is decreasing in both prices.*
(ii) *Damages $\delta\left(\mathbf{p}; \mathbf{Y}^1\right)$ are decreasing in p_B, increasing in p_G.*
(iii) *$W^2\left(\mathbf{p}; \mathbf{Y}^1\right)$ is concave in prices.*

(i) and (iii) are standard. As to (ii), by Assumption 1(i), a reduction in the price of firm i increases its own demand x^i and decreases competitor demand x^j. In the special case that total demand is fixed, these effects obviously have the same size, so that (from $\eta_B > \eta_G$), a price reduction of firm B increases total damages and a price reduction of firm G reduces them. When innovations are not purely business-stealing, this need not hold: For instance, while a reduction in p_G reduces the output and thereby the emissions of firm B, it might increase output and emissions of firm G so much that total emissions increase. Generalizing the logic beyond the case of fixed total output, I therefore assume explicitly that the substitution effect between the two firms dominates the total demand effect, as required by (ii).

Given Assumption 4(iii), maximizing total welfare at an interior price vector would require

$$\frac{\partial W^2}{\partial p_i} = \frac{\partial \pi^i}{\partial p_i} + \left(\frac{\partial \pi^j}{\partial p_i} + \frac{\partial \sigma}{\partial p_i} - \frac{\partial \delta}{\partial p_i}\right) = 0 \tag{19}$$

The first term $\frac{\partial \pi^i}{\partial p_i}$ is zero in the second-period equilibrium without policy interference. The terms in bracket capture three different externalities. A price increase of firm i is beneficial for the competitor and bad for consumers. Given imperfect competition, it is reasonable to assume that the latter effect dominates the former, so that $\frac{\partial \pi^j}{\partial p_i} + \frac{\partial \sigma}{\partial p_i} < 0$. As $\frac{\partial \delta}{\partial p_G} > 0$ by Assumption 3, equilibrium prices of firm G are thus unambiguously too high in equilibrium. For Firm B, this is less clear. Following well-known considerations on environmental policy under imperfect competition, there is a tradeoff between correcting the product market distortions and the environmental distortions, which one can optimally resolve with suitable taxes or subsidies.

4 General Analysis: Investment Behavior

I now deal with investment choices. I first provide conditions for the existence of a unique subgame-perfect equilibrium (SPE) and characterize its properties. Thereafter, I discuss optimal policy.

4.1 Equilibrium Existence and Characterizations

In the Appendix, I show that the maintained assumptions guarantee existence.

Lemma 4. *The game has a subgame-perfect equilibrium.*

Next, consider the determinants of investment behavior in the SPE. To this end, decomposing profits as the product of margins and outputs is helpful:

$$pi_i^* (\mathbf{Y}) = m_i^* (\mathbf{Y}) \, x_i^* (\mathbf{Y})$$

Therefore, applying the product rule to the first-order condition directly implies:

Lemma 5. *For $\phi_i \in \{q_i, r_i, s_i\}$, if the equilibrium investment level y_i^ϕ is positive, it is characterized by the requirement that*

$$m_i^* \left(\mathbf{Y}^2\right) \frac{\partial x_i^*}{\partial \phi_i} + x_i^* \left(\mathbf{Y}^2\right) \frac{\partial m_i^*}{\partial \phi_i} = K_\phi' \left(y_i^\phi\right),$$

.

Note that an interior equilibrium need not exist: Intuitively, while $\frac{\partial x_i^*}{\partial \phi_i} > 0$ is one of the regularity requirements; even for regular innovations, it is not clear that $\frac{\partial m_i^*}{\partial \phi_i} > 0$. The latter condition will typically hold for process innovations. By definition, it also holds for demand-enhancing innovations that soften competition, but, as the example will show, not necessarily for those that intensify competition.

From now on, the focus will be on the determinants of innovation incentives when they are positive. At an abstract level, if at every $\mathbf{Y}^2$ the vector with components $m_i^* \left(\mathbf{Y}^2\right)$, $x_i^* \left(\mathbf{Y}^2\right)$, $\frac{\partial x_i^*}{\partial \phi_i} \left(\mathbf{Y}^2\right)$ and $\frac{\partial m_i^*}{\partial \phi_i} \left(\mathbf{Y}^2\right)$ increases weakly as a result of some change in the economic environment or some policy variable, then investment incentives will increase weakly. The limitation of this statement is that most interesting exogeneous changes affect these variables in different ways. An exception would be an increase in market size, for instance by a simple replication of the original market. This would typically leave prices and margins unaffected, but would lead to higher output x_i^* and a greater reaction of the equilibrium quantity to the innovation $\frac{\partial x_i^*}{\partial \phi_i}$, thus increasing investment incentives. Distinguishing more carefully between different types of innovation gives the following result:[28]

Corollary 1. *Suppose an investment level y_i^ϕ is positive in equilibrium.*
(i) For process innovations, the investment levels y_i^s are given by

$$x_i^* \left(\mathbf{Y}^2\right) + m_i^* \left(\mathbf{Y}^2\right) \frac{\partial x^i}{\partial p_j} \frac{\partial p_j^*}{\partial s_i} \left(\mathbf{Y}^2\right) = K_{s_i}' \left(y_i^s\right).$$

(ii) For demand-enhancing innovations, the investment levels y_i^θ are given by

$$m_i^* \left(\mathbf{Y}^2\right) \left(\frac{\partial x_i^*}{\partial \theta_i} \left(\mathbf{Y}^2\right) + \frac{\partial x_i}{\partial p_j} \frac{\partial p_j^*}{\partial \theta_i} \left(\mathbf{Y}^2\right) \right) = K_{\theta_i}' \left(y_i^\theta\right).$$

[28] These results can be obtained in two ways. First, one can use Lemma 5, spell out $\frac{\partial x_i^*}{\partial \phi_i}$ and $\frac{\partial m_i^*}{\partial \phi_i}$ for the respective ϕ_i and then insert the first-order condition for the second period. Alternatively, using the logic of the envelope theorem, one can note that the left-hand sides correspond to $\frac{\partial \pi^i}{\partial \phi_i} + \frac{\partial \pi^i}{\partial p_j} \frac{\partial p_j}{\partial \phi_i}$ in each case.

Lemma 5 and Corollary 1 will be useful to see through which channels environmental policies that do not directly target investments can nonetheless affect them via their influence on the second-period equilibrium. For process innovations, (ceteris paribus) policies that positively affect equilibrium outputs will be conducive to investments (as they increase the value of the direct profit effect of lower costs), whereas policies that increase margins typically dampen the effect because they increase the adverse effect of lower competitor prices. By contrast, for demand enhancing innovations, as long as $\frac{\partial x_i^*(\mathbf{Y})}{\partial \theta_i} + \frac{\partial x_i}{\partial p_j}\frac{\partial p_j^*(\mathbf{Y})}{\partial \theta_i} > 0$, which is necessary for positive investment incentives, high margins foster investment.

4.2 Optimal Policy

Even though the framework abstracts from knowledge spillovers and therefore from a source of positive externalities, the scope for market failure is substantial. Not only does each firm have four action variables (price and three investment levels), in addition, there are intrinsic asymmetries between firms which would necessitate differential treatment. In the following, I outline what types of externalities might arise and how policy could deal with them.

To deal with welfare issues, define

$$\begin{aligned} W^1(\mathbf{p};\mathbf{y}) &= W^2\left(\mathbf{p};\mathbf{Y}^1+\mathbf{y}\right) - K_B(\mathbf{y}_B) - K_G(\mathbf{y}_G). \\ \widehat{W}(\mathbf{y}) &= W^1\left(\mathbf{p}^*\left(\mathbf{Y}^1+\mathbf{y}\right);\mathbf{y}\right) \end{aligned}$$

Contrary to W^2, both expressions include first-period investments as arguments. W^1 treats prices and investments as independent arguments, thus corresponding to the objective of a regulator who chooses R&D investments and prices independently. By contrast, $\widehat{W}(\mathbf{y})$ only contains investments as arguments, assuming that prices are determined by the market.

First, consider maximization of W^1. In addition to $\frac{\partial W^2}{\partial p_i} = 0$ (condition (19)), this would require

$$\frac{\partial \pi^i}{\partial s_i} = K'_{s_i}\left(y_i^s\right) \tag{20}$$

$$\frac{\partial \pi^i}{\partial \theta_i} + \left(\frac{\partial \pi^j}{\partial \theta_i} + \frac{\partial \sigma}{\partial \theta_i} - \frac{\partial \delta}{\partial \theta_i}\right) = K'_{\theta_i}\left(y_i^\theta\right) \tag{21}$$

To interpret these conditions, it is helpful to think of a version of the game where firms simultaneously choose investments and prices. It is simple to see that, in this case, condition (20) would correspond to Nash behavior. Intuitively, process innovations only affect competitors, consumers and emissions via equilibrium prices, not directly. In the simultaneous games, price choices are not influenced by investment choices, so the price-induced externalities disappear as well.

From this perspective, without price effects, the only way to improve welfare by changing investment behavior concerns demand-enhancing innovations. Consider the externality term $\left(\frac{\partial \pi^j}{\partial \theta_i} + \frac{\partial \sigma}{\partial \theta_i} - \frac{\partial \delta}{\partial \theta_i}\right)$ that only consists of direct (non-price-induced) effects. $\frac{\partial \pi^j}{\partial \theta_i}$ is negative, reflecting the competitor's demand reduction; $\frac{\partial \sigma}{\partial \theta_i}$ is positive by Assumption 4. The damage term $-\frac{\partial \delta}{\partial \theta_i}$ exists only for environmental innovations. It is positive, as lower specific emissions lower damages (as long as prices are fixed). To sum up, abstracting from price effects, the only *environmental* reason for supporting environmental innovations would arise from the reduction in damages brought about by lower specific emissions thanks to an environmental innovation.

The scope for interventions becomes larger if the regulator can only set investment levels, whereas prices adjust according to the second-stage Nash equilibrium. A natural reference point is the SPE, which in addition to the second-stage conditions $\frac{\partial \pi^i}{\partial p_i} = 0$ has to satisfy the following investment conditions:

$$\frac{\partial \pi^i}{\partial \phi_i} + \frac{\partial \pi^i}{\partial p_j}\frac{\partial p_j}{\partial \phi_i} = K'_{\phi_i}\left(y_i^{\phi}\right).$$

Compare this with the conditions for the second-best optimum where the regulator chooses the investment vector $\mathbf{y}$ so as to maximize $\widehat{W}(\mathbf{y})$. This leads to optimality conditions

$$\frac{\partial \pi^i}{\partial s_i} + \frac{\partial p_i^*}{\partial s_i}\frac{\partial W^2}{\partial p_i} + \frac{\partial p_j^*}{\partial s_i}\frac{\partial W^2}{\partial p_j} = K'_{s_i}\left(y_i^s\right)$$
$$\frac{\partial \pi^i}{\partial \theta_i} + \frac{\partial \pi^j}{\partial \theta_i} + \frac{\partial \sigma}{\partial \theta_i} - \frac{\partial \delta}{\partial \theta_i} + \frac{\partial p_i^*}{\partial \theta_i}\frac{\partial W^2}{\partial p_i} + \frac{\partial p_j^*}{\partial \theta_i}\frac{\partial W^2}{\partial p_j} = K'_{\theta_i}\left(y_i^{\theta}\right)$$

In addition to the direct externalities, the regulator must also take the price-induced externalities into account. For demand-enhancing innovations, they are summarized in the term[29]

$$\frac{\partial p_i^*}{\partial \theta_i}\left(\frac{\partial \pi^j}{\partial p_i} + \frac{\partial \sigma}{\partial p_i} - \frac{\partial \delta}{\partial p_i}\right) + \frac{\partial p_j^*}{\partial \theta_i}\left(\frac{\partial \sigma}{\partial p_j} - \frac{\partial \delta}{\partial p_j}\right).$$

For instance, if a demand-enhancing innovation is competition-softening, the regulator will have a reason to support (curtail) innovation based on the induced price effects if the respective externality term in brackets is positive (negative).

The policy implications will depend on the type of innovation.

First, consider a process innovation that reduces firm i's cost. These cost reductions have no *direct* effect on competitor profits, consumer surplus or environmental damages – all such effects are price-mediated. Thus, there is no externality-based policy rationale for directly supporting process innovations if policy interventions can correct for second-stage externalities. However, from Lemma 2 process innovations reduce both prices ($\frac{\partial p_i^*}{\partial s_i} < 0$). As $\frac{\partial \pi^j}{\partial p_i} > 0$, they lower the competitor's prices. As $\frac{\partial \sigma}{\partial p_i} < 0$, the price reduction has a positive effect on consumers. Finally, the environmental effect will depend on which firm innovates. Focusing on the green firm, the effect will be positive ($\frac{\partial \delta}{\partial p_i} < 0$) if the beneficial effect that firm G has higher market share than the more polluting firm B dominates over the market expansion effect of firm G – for instance, if the process innovation is purely business-stealing. Thus, one could, in principle, justify supporting process innovations as a means to lower distorted prices of firm G with the aim of reducing environmental damages.

Second, consider a product innovation that improves the consumption features of the green good, without any effect on specific emissions. The direct externalities are the demand stealing effect ($\frac{\partial \pi_B}{\partial q_G} < 0$) on the competitor, the effect on consumer surplus ($\frac{\partial s}{\partial q_G} > 0$) and the environmental effect ($\frac{\partial \delta}{\partial q_G}$). The latter effect works towards lower damagesm as the innovation shifts market shares to the green firm. The price effects typically weaken

[29]The term $\frac{\partial \pi^i}{\partial p_j}\frac{\partial p_j^*}{\partial \theta_i}$ does not occur here, because it is an effect on the innovator's own profit.

the direct effects. As product innovations of the green firm tend to increase demand-sensitivity (see Section 3.2.2), they will reduce prices, which will hurt the competitor, but benefit consumers. The high price will lead to more environmental damages unless the output of firm G falls so much that there is a strong reduction in total output which dominates the adverse output reallocation from the green to the brown firm.

Third, consider environmental innovations. No matter which firm innovates, the direct effects on the competitor's profit will be negative, whereas the direct effect on consumers will be positive. Even the *direct* environmental effect is more subtle: While the reduction in specific emissions is always beneficial, this is not necessarily true for the resulting output changes. If the brown firm innovates, this will tend to increase its market share at the expense of the green firm, which increases damages. By contrast, If the green firm innovates, the resulting reallocation of market share reinforces the positive direct effect of lower specific emissions. However, it is still conceivable that the innovation could increase emissions if the output of the green firm increases sufficiciently. Now suppose that price effects have not been internalized. Recall that environmental innovations of the green firm will soften competition, whereas those of the brown firm will intensify it. In the former case, the effects of higher prices on the competitor and consumers will reduce the direct effects; similarly, they will reduce the environmental effects by reducing demand for the green good. In the latter case, the innovation of the brown firm will reinforce the direct effects.

5 Analysis for the Discrete-Choice Example

This section illustrated the general ideas for the discrete-choice example with uniformly distributed consumers. I will characterize the equilibrium prices, outputs, profits and emissions in terms of exogenous parameters. This is useful to characterize the equilibrium investment incentives, and to sharpen the policy discussion.

5.1 Second-Period Equilibrium

The following simple result characterizes the equilibrium.

Proposition 3. *Suppose that*

$$2\Delta_E + \Delta_Q > \Delta_c > -\left(\Delta_E + 2\Delta_Q\right).$$

Then the example has a unique interior equilibrium

$$p_G^* = \frac{2\left(\Delta_E + c_G\right) + \Delta_Q + c_B}{3}$$
$$p_B^* = \frac{\Delta_E + c_G + 2\left(\Delta_Q + c_B\right)}{3}$$

The condition in Proposition 3 holds if neither firm has a substantial cost advantage over the other one (relative to the two quality differences). Then, in equilibrium at least the consumers with strong environmental preferences will buy from the green firms, whereas the consumers with strong consumption preferences will buy from the brown firm. Equilibrium prices then depend positively on the costs of both firms, but also on the differentiation in each dimension (Δ_E, Δ_Q). Thus, if a firm improves in one of these two dimensions, prices will only increase if this is the dimension where the firm is stronger than the opponent. In this case, the innovation will soften competition further, whereas the opposite is true if a firm improves in the dimension where it is lagging. Reflecting the general analysis, an innovation in a firm's weak dimension increases price sensitivity sufficiently to reduce prices. Proposition 3 immediately implies the following observation on equilibrium outputs and profits.

Corollary 2. *Suppose the conditions of Proposition 3 hold. Then:*
(i) Equilibrium outputs are given as

$$x_B^* = \frac{2\Delta_Q + \Delta_E + \Delta_c}{3\left(\Delta_Q + \Delta_E\right)} \text{ and } x_G^* = \frac{2\Delta_E + \Delta_Q - \Delta_c}{3\left(\Delta_Q + \Delta_E\right)}. \tag{22}$$

(ii) Equilbrium profits are

$$\pi_B^* = \frac{\left(2\Delta_Q + \Delta_E + \Delta_c\right)^2}{9\left(\Delta_Q + \Delta_E\right)} \text{ and } \pi_G^* = \frac{\left(2\Delta_E + \Delta_Q - \Delta_C\right)^2}{9\left(\Delta_Q + \Delta_E\right)}. \tag{23}$$

Contrary to prices, outputs and profits depend exclusively on the differences in qualities and costs: Greater cost differences always shift output to the cheaper firm. Similarly, any increase in the difference in qualities shifts output to the firm that has higher quality in the respective dimension ($\frac{dx_G^*}{d\Delta_E} > 0$, $\frac{dx_G^*}{d\Delta_Q} < 0$, $\frac{dx_B^*}{d\Delta_E} < 0$, $\frac{dx_B^*}{d\Delta_Q} > 0$). Further, if a firm's cost falls, its profit increases, whereas the competitor's fall. By contrast, both firms benefit from an increase in differentiation in either dimension – both profits are increasing in Δ_E as well as Δ_Q. This has an important implication: Only leaders in a particular dimension have incentives to marginally increase their quality in that dimension.[30]

Next consider total emissions $E = \eta_B x_B + \eta_G x_G$. The following result follows immediately from Corollary 2:

Corollary 3. *Suppose the conditions of Proposition 3 hold. Then total emissions are:*

$$E = \frac{\eta_B\left(2\Delta_Q + \Delta_E + \Delta_C\right) + \eta_G\left(2\Delta_E + \Delta_Q - \Delta_C\right)}{3\left(\Delta_Q + \Delta_E\right)}. \tag{24}$$

An increase in the cost differential Δ_c or firm B's consumption quality advantage Δ_Q unambiguously increases aggregate emissions by shifting more output to the polluting firm. An increase in the environmental quality advantage Δ_E of firm G not only shifts output to the less polluting firm; in addition, the latter's specific emissions fall; both effects support lower emissions.[31] By contrast, though a reduction in the specific emissions of firm B has a direct negative effect on specific emissions (which works towards lower aggregate emissions), the resulting increase in B's market share works towards higher aggregate emissions. A more definite result requires tying one's hands about the relation between

[30] To connect these results to the general analysis in Section 3.2.2, note that the example satisfies Assumption 1(i) as well as $\frac{\partial^2 x^B}{\partial\Delta_Q\partial p_B} > 0$, $\frac{\partial^2 x^B}{\partial\Delta_E\partial p_B} > 0$, $\frac{\partial^2 x^G}{\partial\Delta_Q\partial p_B} < 0$ and $\frac{\partial^2 x^G}{\partial\Delta_E\partial p_B} < 0$. Therefore, an increase in Δ_E or Δ_Q reduces the price sensitivity of demand. Moreover, at the equilibrium $\frac{\partial^2 \pi_B}{\partial\Delta_Q\partial p_B} > 0$, $\frac{\partial^2 \pi_B}{\partial\Delta_E\partial p_B} = 0$, $\frac{\partial^2 \pi_G}{\partial\Delta_E\partial p_G} > 0$, $\frac{\partial^2 \pi_G}{\partial\Delta_Q\partial p_G} = 0$. Thus, an innovation is competition-softening if it increases Δ_E or Δ_Q.

[31] The former effect is captured by the derivative of E with respect to Δ_E; the latter effect by the derivative with respect to η_G.

specific emissions and environmental quality as a factor determining willingness-to-pay. In a simplistic specification ($r_i = -\eta_i$), the pollution-reducing effect dominates.

All the above observations are in line with the results of the general model for the applicable case that innovations are purely demand-stealing. They also show the relevance of the distinction between demand-enhancing innovations that increase price sensitivity and those that decrease it.

5.2 Innovation Incentives

As discussed in Section 4, the levels of investment depend on their marginal benefits and marginal costs. For the case at hand, one can easily express the marginal benefits of the different types of investment as functions of parameters (see Appendix 7.4.3); they can be obtained from the respective derivatives of the profit expressions in (23).

In line with the general Lemma 2 (applied to the case of purely business-stealing innovations), a process innovation increases the innovator's profit, so that innovation incentives are positive. The issue is more complex for demand-enhancing innovations: As seen above, only innovations in a firm's strong dimension increase profits. Thus, the green firm only has incentives for environmental innovations and the brown firm only has incentives for product innovations.

Turning to the determinants of the innovation incentives, it is critical to point out that, reflecting the specific assumptions of the example, they all depend exclusively on Δ_Q, Δ_E and Δ_C. Any change of these expressions that improves a firm's position relative to the competitor increases its investment incentives in each of the three dimensions. Focussing on firm G, if its environmental advantage Δ_E is higher, or its consumption disadvantage Δ_Q or the cost differential Δ_C is lower, then its incentive to invest in any of the three dimensions increases. Put differently, one firm's different investments are complementary to each other, whereas the investments of one firm and those of the other are strategic substitutes. Note, however, that the incentives of firm G to invest in q_i will typically remain negative, even if its relative position improves.

5.3 Policy Issues

Based on the results of Sections 5.1 and 5.2, one can sketch some conclusions on the effects of various policy instruments, without going into excessive technical detail. Though most of the discussion applies more generally, for some statements it is necessary to sharpen the condition in Proposition 3 to $|\Delta_C| < \Delta_E$.

5.3.1 Emissions Taxes

Emissions taxes can be considered as reductions in Δ_c: As $\eta_B > \eta_G$, such taxes increase compliance costs more for B than for G. Thus, echoing the discussion in Section 5.1, their second-stage effect is that they reduce overall emissions by moving output from the more polluting to the less polluting firm. The effects on innovation incentives are more subtle. As emission taxes correspond to a reduction of Δ_C, they improve the relative position of firm G in the product market and therefore, as discussed in Section 5.2, they increase its marginal incentives to engage in any type of investment. By reducing Δ_C further, the resulting additional process innovations increase firm G's market share further, thereby contributing to additional emissions reductions. Similar arguments apply to additional environmental innovation. However, it still remains true that firm G has negative incentives to invest in q_G as doing so would intensify competition. By similar arguments, the emissions tax reduces investment incentives of the brown firm, thereby contributing to an increase in Δ_E and reductions in Δ_Q and Δ_C, respectively.

5.3.2 Adoption Subsidies

Consider adoption subsidies, which reduce the purchasing price for consumers of the green product by some fixed amount, thus effectively increasing its attraction without changing its environmental properties. Therefore, their second stage effects correspond to a reduction in the green firm's disadvantage Δ_Q – for sufficiently high output subsidies, Δ_Q could even become negative. Accordingly, keeping the firms' investment levels fixed, subsidies reduce emissions by shifting output towards the green firm. The anticipated reduction in Δ_Q in favor of the green firm (weakly) increases all investment incentives of the green firm and (weakly) decreases those of the brown firm. For process innovations, the joint effect of higher investments is to increase the market share of G, again reinforcing the negative effect on total emissions. Moreover, the green firm will have stronger incentives for environmental innovation (whereas the brown firm will still not want to invest). As a result, the brown firm will have lower incentives to improve product quality. Nonetheless, the green firm will still not want to invest in product quality, unless the subsidies are so high that Δ_Q becomes negative. The joint effect of the increase in Δ_Q on investments is to reduce emissions further, beyond the extent that comes from the immediate response of consumers to the adoption subsidies.

5.3.3 Investment Subsidies

Consider investment subsidies that reduce the marginal cost of investment. Unlike taxes and adoption subsidies, these instruments obviously have no *direct* effects on the product market, they only operate through their effects on the investment decisions. The relation between the different investments is crucial to obtain simple comparative statics results. Recall that all investments of one firm are mutually complementary, whereas the investments of different firms are strategic substitutes. Thus, a reduction in the marginal costs of any single type of investment (weakly) increases a firm's investment in all three dimension, leading to a (weak) reduction in the other firms investments in all three dimensions. Recall that the previous analysis suggests that all types of investments of the green firm tend to lead to lower emissions – thus, fostering an investment in one dimension has the additional effect of fostering investments that reduce emissions further. By contrast, subsidizing environmental investments of the brown firm *may* reduce total emissions, but they are complementary for this firm with process and product innovations that tend to increase total emissions.

5.3.4 Ranking of Instruments

A long-standing debates asks how policy instruments compare with respect to innovation incentives. To make this question meaningful, it is necessary to avoid comparing apples and oranges. This can be achieved by comparing instruments that would induce the same level of emissions in the absence of innovations. Moreover, in light of the above considerations, I take an abstract approach whereby I identify the effects of a policy by identifying how it affects Δ_C, Δ_E and Δ_Q. Thus, for instance, an emissions tax would correspond to a reduction in Δ_C, an adoption subsidy for the green good to a reduction in Δ_Q.

I then compare innovation incentives for parameter constellations for which total emissions (3) are constant. In this fashion, various results can be derived numerically.[32] For instance, keeping consumption qualities (and thus Δ_Q) fixed, constant emissions require that any increase in one of the specific emissions is compensated by a reduction in the other one. Among the different parameter constellations that satisfy this requirement, innovation incentives of the green firm (in all dimensions) are highest when the difference in specific emissions between the brown firm and green firm are highest.

Conversely, keeping environmental properties fixed, reducing the consumption quality differential between the two firms simultaneously reduces aggregate emissions (abstracting from investments) and increases investment incentives.

6 Conclusions

This paper has investigated the incentives for engaging in green innovations. To this end, I analyzed a differentiated duopoly with a brown firm and a green firm. The brown firm produces goods with high production quality, but low environmental quality. Both firms can engage in process innovations, product innovations and environmental innovations. I derived plausible conditions under which innovations of the green firm lower aggregate emissions. For process and product innovations, this essentially results from output relocation towards the green firm. For environmental innovations, the reduction in the green firm's specific emissions reinforces the effect. Environmental innovations of the brown firm only lead to lower aggregate emissions if the beneficial effect from the firm's lower specific emissions dominate adverse effects from its increased market share. Under quite general conditions, process and product innovations of the brown firm increase total emissions.

The results also suggest that firms may have limited incentives to invest in their weak dimensions, as they run the risk of intensifying competition in this way. Further, different types of investments are typically complementary in the sense that a firm that is strong in one dimension benefits more from strengthening the other dimension. With this in mind, instruments for emissions reduction foster the innovation incentives of the green firm in all dimensions if they foster the relative position of the green firm relative to the brown firm.

The analysis also contains some results regarding the rationale for directly supporting innovations. When suitable price policies are available, there is no need for supporting process innovations of green firms; however, this changes when price instruments are not available. By contrast, there is a case for supporting environmental innovations of the green firm even when price instruments are available.

Future versions of this paper will extend the analysis, in particular, the welfare discussion. Most likely, the paper will contain a (discrete choice) model of intermediate generality that replaces the current example by allowing for more general valuation distributions.

[32] Details available on request.

7 Appendix

This appendix contains proofs and calculations required to corroborate the results mentioned in the main text. Section 7.1 gives the details for the general pricing game, including existence and uniqueness of the equilibrium and some auxiliary results. Section 7.2 provides the link between the two stages by proving the claims about the effects of innovations on the first stage. Section 7.3 deals with existence and uniqueness of the SPE in the general game. Finally, Section 7.4 provides the details for the example.

7.1 Pricing Game

7.1.1 Pricing Equilibrium: Proof of Lemma 1

As the game is supermodular, the existence result directly follows from Theorem 5 in Milgrom and Roberts (1990). To see uniqueness, note that total differentiation of π_i^i gives the slope of the reaction curve of firm i as $\frac{dp_i}{dp_j} = \frac{\pi_{ij}^i}{|\pi_{ii}^i|}$. Thus, $|\pi_{ii}^i| > \pi_{ij}^i$ (Assumption 1(ii)) implies that both reaction functions have slope smaller than 1 and can therefore intersect at most once.

7.1.2 Auxilliary Results

Each firm maximizes the function $\pi^i(p_i, p_j; \Theta_i, \Theta_j) = (p_i - c_i)\, x^i(p_i, p_j; \Theta_i, \Theta_j)$. This function depends on parameters $\phi \in \{q_B, r_B, s_B; q_G, r_G, s_G\}$. With slight abuse of notation, the unique product market equilibrium corresponding to ϕ (fixing the remaining components of $\mathbf{Y}$ will be written as $(p_B^*(\phi), p_G^*(\phi))$ and the corresponding quantities and emissions as

$$
\begin{aligned}
x_i^*(\phi) &= x_i^*(p_B^*(\phi), p_B^*(\phi), \\
e_i^*(\phi) &= \eta_i x_i^*(\phi) \\
\pi_i^*(\phi) &= (p_B^*(\phi) - c_i(\phi))\, x^i(p_i, p_j, \phi)
\end{aligned}
$$

Using the short-cut notation $\pi_{jk}^i \equiv \frac{\partial^2 \pi^i}{\partial p_j \partial p_k}$; $\pi_{j\phi}^i \equiv \frac{\partial^2 \pi^i}{\partial p_j \partial \phi}$, the following standard comparative statics result emerges:

Lemma 6. *For* $\Delta = \pi_{BB}^B \pi_{GG}^G - \pi_{BG}^B \pi_{GB}^G (> 0)$, *price effects are:*

$$
\begin{aligned}
\frac{dp_B}{d\phi} &= \frac{\pi_{BG}^B \pi_{G\phi}^G - \pi_{B\phi}^B \pi_{GG}^G}{\Delta} \\
\frac{dp_G}{d\phi} &= \frac{\pi_{GB}^G \pi_{B\phi}^B - \pi_{G\phi}^G \pi_{BB}^B}{\Delta}
\end{aligned}
$$

Proof. Total differentiation of F.O.C. yields

$$
\begin{bmatrix} \pi_{BB}^B & \pi_{BG}^B \\ \pi_{GB}^G & \pi_{GG}^G \end{bmatrix} \begin{bmatrix} dp_B \\ dp_G \end{bmatrix} = - \begin{bmatrix} \pi_{B\phi}^B & d\phi \\ \pi_{G\phi}^G & d\phi \end{bmatrix}
$$

and thus the result. □

Using the fact that, by Assumption 1(i), $\Delta > 0$, $\pi_{BG}^B > 0$, $\pi_{GB}^G > 0$, $\pi_{BB}^B < 0$ and $\pi_{GG}^G < 0$, gives the following useful result:

Corollary 4. *An increase in ϕ weakly increases (decreases) both prices if* $\pi^G_{G\phi} = D^G_\phi + p_G D^G_{G\phi} \geq (\leq) 0$ *and* $\pi^B_{B\phi} = D^B_\phi + p_B D^B_{B\phi} \geq (\leq) 0$.

Intuitively, the conditions of Lemma 6 (and Corollary 4) guarantee that the parameter change shifts both firms' reaction curves outwards (inducing them to set higher prices). Strategic complements guarantee that the resulting incentives to increase prices reinforce each other. Whether the conditions $\pi^i_{i\phi} \geq 0$ hold, depends on the interaction of two effects: On the one hand, the parameter increase shifts demand (D^i_ϕ), on the other hand it affects the slope of the demand function ($D^i_{i\phi}$). A positive effect on the level of demand and a negative effect on the absolute value of its slope ($\left|D^i_{i\phi}\right| = \frac{\partial}{\partial\phi}\left|\frac{\partial D^i}{\partial p_i}\right|$) would work towards a positive value of $\pi^i_{i\phi}$.

7.2 Innovation Effects

7.2.1 Effects of Process Innovations: Proof of Lemma 1

(i) By Assumption 2, $\Pi^i_{ij} \geq 0$. the game satisfies strategic complements. Moreover, $\Pi^i_{is_i} \geq 0$. Thus the game is supermodular, with increasing differences in (p_i, s_i). According to Theorem 5 in Milgrom and Roberts (1990), the result follows.

(ii) The effect of a cost reduction of firm i on its equilibrium output is $\frac{\partial x^*_i}{\partial p_i}\frac{\partial p^*_i}{\partial s_i} + \frac{\partial x^*_i}{\partial p_j}\frac{\partial p^*_j}{\partial s_i}$. For $\phi = s_i$, Lemma 6 implies

$$\frac{\partial p_i}{\partial s_i} = \frac{-\pi^i_{is_i}\pi^j_{jj}}{\triangle} < 0$$

$$\frac{\partial p_j}{\partial s_i} = \frac{\pi^j_{ji}\pi^i_{is_i}}{\triangle} < 0$$

Hence, $\left|\pi^j_{jj}\right| > \pi^j_{ji}$ implies $\left|\frac{\partial p^*_i}{\partial s_i}\right| > \left|\frac{\partial p^*_j}{\partial s_i}\right|$. Thus, the result follows from the assumption that $\frac{\partial x^i}{\partial p_j} \leq \left|\frac{\partial x^i}{\partial p_i}\right|$ holds near the equilibrium.

(iii) follows directly from $\frac{d\pi^*_i}{ds_i} = \frac{\partial\pi^*_i}{\partial s_i} + \frac{\partial x^*_i}{\partial p_j}\frac{\partial p^*_j}{\partial s_i}$ and $\frac{d\pi^{j*}}{ds_i} = \frac{\partial\pi^*_j}{\partial s_i} + \frac{\partial x^*_j}{\partial p_i}\frac{\partial p_i}{\partial s_i}$.

7.2.2 Effects of Demand-Enhancing Innovations: Proof of Lemma 3

(i) For a competition-softening innovation, $\pi^i_{i\theta_i} > 0$. As $\pi^i_{ij} > 0$ by Assumption 2, application of Corollary 4 directly shows that both prices increase. The argument for a competition-intensifying innovation is analogous.
(ii) Both statements are direct implications of (7).
(iii) According to (8), the total profit effect of a change in any parameter ϕ is $\frac{d\pi^*_i}{d\phi} = \frac{\partial\pi^*_i}{\partial\phi} + \frac{\partial\pi^*_i}{\partial p_j}\frac{\partial p^*_j}{\partial\phi}$. For a demand-enhancing innovation of firm i ($\phi = \theta_i$), the direct effect $\frac{\partial\pi^*_i}{\partial\phi}$ is positive. The price-induced effect (the second term on the r.h.s) is positive if the innovation is competition-softening. This gives the first statement in (a). Further, applying (8) to a demand-enhancing innovation of firm i, the direct effect $\frac{\partial\pi^*_j}{\partial\phi}$ on the competitor is negative. The price-induced effect (the second term on the r.h.s) is negative if the innovation is competition-softening. This gives the second statement in (a).

(b) again follows from (8) with $\phi = \theta_i$, which is positive if and only if $\frac{\frac{\partial \pi_i^*}{d\theta_i}}{\frac{\partial \pi_i^*}{\partial p_j}} > -\frac{dp_j^*}{d\theta_i}$. The statement then follows from $\frac{\frac{\partial \pi_i^*}{d\theta_i}}{\frac{\partial \pi_i^*}{\partial p_j}} = \frac{\frac{\partial x^i}{d\theta_i}}{\frac{\partial x^i}{\partial p_j}}$. (c) is analogous.

7.2.3 Effects of Demand-Enhancing Innovations on Emissions: Proof of Proposition 2

All the claims rely on the fact that total emissions are given as

$$E = \eta_B x_B^* + \eta_G x_G^*.$$

To see (i), note that the effect of a product innovation of firm i is $\eta_B \frac{\partial x^B}{\partial q_G} + \eta_G \frac{\partial x^G}{\partial q_G}$. For a purely business-stealing innovation, $\frac{\partial x^B}{\partial q_G} = -\frac{\partial x^G}{\partial q_G}$. The first result thus follows from $\eta_B > \eta_G$. The second result follows from the requirement that $\eta_B \frac{\partial x^B}{\partial q_G} + \eta_G \frac{\partial x^G}{\partial q_G} > 0$ by rearranging, noting that $\frac{\partial x^B}{\partial q_G} < 0$ and hence $\left| \frac{\partial x^B}{\partial q_G} \right| = -\frac{\partial x^B}{\partial q_G}$ for a regular product innovation.

To see (ii), note that the innovation also affects η_G in this case, so that $E = \eta_B x_B^* (r_G) + \eta_G (r_G) x_G^* (r_G)$ and thus

$$\frac{dE}{dr_G} = \eta_B \frac{\partial x^B}{\partial r_G} + \eta_G \frac{\partial x^G}{\partial r_G} + \frac{\partial \eta}{\partial r_G} x^G.$$

This immediately implies the two claims in (ii) because they guarantee that $\eta_B \frac{\partial x^B}{\partial r_G} + \eta_G \frac{\partial x^G}{\partial r_G} < 0$.

The proof of (b) is analogous.

7.3 Existence and Uniqueness: Proof of Lemma 4

By Lemma 1, the second-stage game has a unique equilibrium $(p_B^* (\mathbf{Y}^1), p_G^* (\mathbf{Y}^1))$ for every first-period play $\mathbf{Y}^1$; the resulting equilibrium payoffs are given by $(\pi_B^* (\mathbf{Y}^1), \pi_G^* (\mathbf{Y}^1))$. Thus, a strategy profile $\left(\widetilde{\mathbf{Y}}_\mathbf{B}^0, \widetilde{\mathbf{Y}}_\mathbf{G}^0, \widetilde{p}_B (\mathbf{Y}^1), \widetilde{p}_G (\mathbf{Y}^1)\right)$ is a subgame-perfect equilibrium if and only if it satisfies $(\widetilde{p}_B (\mathbf{Y}^1), \widetilde{p}_G (\mathbf{Y}^1)) = (p_B^* (\mathbf{Y}^1), p_G^* (\mathbf{Y}^1))$ for every first-period play $\mathbf{Y}^1$ and $\left(\widetilde{\mathbf{Y}}_\mathbf{B}^0, \widetilde{\mathbf{Y}}_\mathbf{G}^0\right)$ is a Nash equilibrium of the static game with payoff functions $\pi_B^* (\mathbf{Y}^1)$ and $\pi_G^* (\mathbf{Y}^1)$. The conditions of Lemma 1 guarantee that the latter game has a Nash equilibrium. Existence of this equilibrium follows from the standard Debreu-Glicksberg-Fan result that, together with compactness and convexity of the strategy set, quasiconcavity and continuity of the objective function guarantee existence.[33] The assumptions on the strategy set directly follow from Assumption 2. Assumption 3 implies that $p_B^* (\mathbf{Y}^1)$ and $p_G^* (\mathbf{Y}^1)$ are continuous. As the demand functions are continuous by Assumption 1(i), the objective function is continuous. Finally, the assumption that the cost function is sufficiently convex guaranteees that the objective function is quasiconcave.

[33] See Theorem 1.2 in Fudenberg and Tirole (1991).

7.4 Details for the Example

This section provides the details for the example of Section 2.2. It deals with the equilibrium characterization, the comparative statics results, and the claims on innovation incentives.

7.4.1 Equilbrium Characterization

To show why Proposition 3 holds, note that the above expressions for profits give the first-order conditions as:

$$c_B + \Delta_Q + p_G - 2p_B = 0$$
$$c_G + \Delta_E + p_B - 2p_G = 0$$

and reaction functions

$$p_B = \frac{c_B + \Delta_Q + p_G}{2}$$
$$p_G = \frac{c_G + \Delta_E + p_B}{2}$$

The candidate equilibrium is

$$p_B = \frac{\Delta_E + c_G + 2\left(\Delta_Q + c_B\right)}{3}$$
$$p_G = \frac{2\left(\Delta_E + c_G\right) + \Delta_Q + c_B}{3}$$

Equilibrium margins are

$$m_B = \frac{\Delta_E + 2\Delta_Q + \Delta_C}{3}$$
$$m_G = \frac{2\Delta_E + \Delta_Q - \Delta_C}{3}$$

Hence,

$$\Delta_p = \frac{\Delta_E - \Delta_Q + \Delta_c}{3}$$

For an interior equilibrium, it is necessary that consumer 0 buys from firm B and consumer 1 buys from G. This requirement is fulfilled if and only if the following conditions both hold:

$$\Delta_Q > -\Delta_p$$
$$\Delta_E > \Delta_p$$

Inserting Δ_p, the parameter restrictions correspond to the conditions in Proposition 3.

7.4.2 Comparative Statics

Using $\Delta_E = H - L$ and $\Delta_Q = h - l$ he second-stage equilibrium can be written as

$$p_B = \frac{H - L + c_G + 2\,(h - l + c_B)}{3}$$
$$p_G = \frac{2\,(H - L + c_G) + h - l + c_B}{3}$$

From this, the effects of parameters on equilibrium prices are

$$\frac{dp_B}{dH} = \frac{dp_B^*}{dc_B} = \frac{1}{3}; \frac{dp_B^*}{dL} = -\frac{1}{3}; \frac{dp_B^*}{dh} = \frac{dp_B^*}{dc_G} = \frac{2}{3}; \frac{dp_B^*}{dl} = \frac{-2}{3}$$
$$\frac{dp_G^*}{dh} = \frac{dp_G^*}{dc_B} = \frac{1}{3}; \frac{dp_G^*}{dl} = -\frac{1}{3}; \frac{dp_G^*}{dH} = \frac{dp_G^*}{dc_G} = \frac{2}{3}.$$

Moreover, the effects of parameters on equilibrium outputs follow as

$$\frac{dx_B^*}{dH} = -\frac{dx_B^*}{dL} = \frac{c_B - c_G - h + l}{3\,(H - L + h - l)^2} < 0$$
$$\frac{dx_B^*}{dh} = -\frac{dx_B^*}{dl} = \frac{1}{3}\frac{H - L + c_B - c_G}{(H - L + h - l)^2} > 0$$
$$\frac{dx_B^*}{dc_G} = -\frac{dx_B^*}{dc_B} = \frac{1}{3\,(H - L + h - l)^2} > 0$$

and

$$\frac{dx_G^*}{dH} = -\frac{dx_G^*}{dL} = -\frac{c_B - c_G - h + l}{3\,(H - L + h - l)^2} > 0$$
$$\frac{dx_G^*}{dh} = -\frac{dx_G^*}{dl} = -\frac{1}{3}\frac{H - L + c_B - c_G}{(H - L + h - l)^2} < 0$$
$$\frac{dx_G^*}{dc_G} = -\frac{dx_G^*}{dc_B} = -\frac{1}{3\,(H - L + h - l)^2} < 0$$

Corollary 3 helps to obtain the effects of parameters on total emissions. Under the conditions of Proposition 3, the right bracket in the numerator of E is positive, so that total emissions are increasing in η_G. The effects of η_G and Δ_C are also obviously positive. Finally, note that

$$\frac{\partial E^*}{\partial \Delta_E} = \frac{(\eta_G - \eta_B)\,(\Delta_C + \Delta_Q)}{3\,(\Delta_Q + \Delta_E)^2}$$
$$\frac{\partial E^*}{\partial \Delta_Q} = \frac{(\Delta_C - \Delta_E)\,(\eta_G - \eta_B)}{3\,(\Delta_Q + \Delta_E)^2}$$

Thus, an increase in $\partial \Delta_E$ reduces overall emissions. An increase in $\partial \Delta_Q$ reduces emissions as long as the cost differential between firms is not too pronounced.

7.4.3 Innovation Incentives

This subsection will show how all investment incentives depend positively on a firm's relative position in each dimension. The focus will be on firm G; the argument for B is similar. In all cases, the statement requires that the relevant second derivatives are positive. This will follow immediately, in some cases by appealing to the conditions under which Proposition 3 holds and to the more restrictive requirement that $|\Delta_C| < \Delta_E$.

First consider cost reduction incentives, which are given as

$$\frac{\partial \pi_G^*}{\partial s_G} = \frac{2\Delta_E + \Delta_Q - \Delta_C}{3\left(\Delta_Q + \Delta_E\right)} > 0$$

The incentives for cost reductions depend on a firm's state variables as follows:

$$\frac{\partial^2 \pi_G^*}{\partial s_G \partial q_G} = \frac{\left(\Delta_E - \Delta_C\right)}{3\left(\Delta_Q + \Delta_E\right)^2} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial s_G \partial r_G} = \frac{\left(\Delta_C + \Delta_Q\right)}{3\left(\Delta_Q + \Delta_E\right)^2} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial s_G^2} = \frac{1}{3\left(\Delta_Q + \Delta_E\right)} > 0$$

Next, consider incentives for an environmental innovation of firm G, given as

$$\frac{\partial \pi_G^*}{\partial r_G} = \frac{1}{3}\left(\Delta_C + 3\Delta_Q + 2\Delta_E\right)\frac{\Delta_Q + 2\Delta_E - \Delta_C}{\left(\Delta_Q + \Delta_E\right)^2} > 0$$

The incentives for environmental innovations depend on a firm's state variables as follows:

$$\frac{\partial^2 \pi_G^*}{\partial r_G^2} = \frac{\left(\Delta_C + \Delta_Q\right)^2}{3\left(\Delta_Q + \Delta_E\right)^3} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial r_G \partial q_G} = \frac{2\left(\Delta_E - \Delta_C\right)\left(\Delta_C + \Delta_Q\right)}{3\left(\Delta_Q + \Delta_E\right)^3} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial r_G \partial s_G} = -\frac{2\left(\Delta_C + \Delta_Q\right)}{3\left(\Delta_Q + \Delta_E\right)^2} > 0$$

Next, consider incentives for a product innovation of firm G, given as

$$\frac{\partial \pi_G^*}{\partial q_G} = \frac{1}{3}\left(\Delta_C + \Delta_Q\right)\frac{2\Delta_E + \Delta_Q - \Delta_C}{\left(\Delta_Q + \Delta_E\right)^2} > 0$$

The incentives for product innovations depend on a firm's state variables as follows:

$$\frac{\partial^2 \pi_G^*}{\partial q_G^2} = \frac{2\left(\Delta_E - \Delta_C\right)^2}{3\left(\Delta_Q + \Delta_E\right)^3} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial r_G \partial q_G} = \frac{2\left(\Delta_E - \Delta_C\right)\left(\Delta_C + \Delta_Q\right)}{3\left(\Delta_Q + E\right)^3} > 0$$

$$\frac{\partial^2 \pi_G^*}{\partial q_G \partial s_G} = \frac{2\left(\Delta_E - \Delta_C\right)}{3\left(\Delta_Q + \Delta_E\right)^2} > 0$$

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