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An Oligopoly Model to Analyze the Market and Social Welfare for Green Manufacturing Industry

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Keywords

game theory, oligopoly model, market competition, tax and subsidy, social welfare, sustainable manufacturing

Disciplines

Industrial Engineering | Systems Engineering

Comments

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quantitatively showing the effectiveness of tax and subsidy policies in promoting green products.

Keywords: Game Theory, Oligopoly Model, Market Competition, Tax and Subsidy, Social Welfare, Sustainable Manufacturing

1 Introduction

In light of increasing public concerns about the environment and sustainable economic development, an increasing number of products have found their environmentally preferable alternatives. Green products or environmentally preferable products are defined as "products or services that have a lesser or reduced effect on human health and the environment when compared with competing products or services that serve the same purpose."(Executive Order 13101, 1998). Examples of green products include compact fluorescent lamps (CFLs), which use 75% less energy than incandescent bulbs (Energy Star, 2008), organic foods, which are grown and processed without antibiotics, pesticides, or synthetic fertilizers (Environmental Protection Agency, 2008), hybrid gas electric vehicles such as the Toyota Prius, which achieves a fuel economy of 48 city-mpg and 45 highway-mpg, and uses significantly less fuel than the comparable conventional vehicles (Toyota, 2008), and green hotels, which have reduced usage of water, energy, and materials (Sharkey, 2008). Being environmentally preferable does not necessarily imply public acceptance or a significant market share for environmentally friendly products. In competing with ordinary (non-green) products, some green products perform well while others have not achieved their expected level of success (Stoneman et al., 1995; Wong et al., 1996).

Literature Review: There have been several studies on the competition between ordinary and green products. Chen (2001) considers the case of a monopoly producer who designs and produces ordinary and green products. The author concludes that de-

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signing separately for two segments of consumers may result in the same environmental impacts. Conrad (2005) uses a duopoly model to study the non-cooperative competition between two firms that determine the environmental attributes of their products, and then engage in a price competition. The paper suggests that there exist multiple Nash equilibria with varying levels of social welfare, and that properly imposed taxes and subsidies could lead to socially efficient equilibria. Here Nash equilibrium refers to a stable state of a non-cooperative game in which no player can benefit from unilaterally deviating from. Mahenc (2007) finds that when consumers lack full information about the environmental quality of products, green products tend to be over-priced to send a signal of being clean. Corbett and Muthulingam (2007) use probability models to study the motivation of 442 LEED (Leadership in Energy and Environmental Design) certified buildings. They find that a combination of signaling and pursuit of intrinsic benefits can explain the observed adoption pattern.

Competitiveness of Green Products: Most green materials, equipment, and production processes cost significantly higher than ordinary ones, which usually leads to a heavy green price premium. Although encouraging consumer preference for green products have been reported in many surveys (Cramer, 1991; Jones, 2007), few consumers are willing to compromise performance, quality, or price in their purchasing behavior in exchange of 'greenness' (Athavaley, 2007; Nyborg et al., 2006). Second, although consumer awareness of green products has been increasing, a large number is still unfamiliar with green products or their economic and environmental benefits (Sandahl et al., 2006). For example, the Energy Star program was created in 1992, but it was reported that in 2004 only 56% of the American public could recognize the Energy Star label (Energy Star, 2008). Third, some green products fail to perform as well as promised and disappoint green consumers. This can be partially attributed to false or misleading green marketing claims that have impaired the reputation of green products as a whole. Consequently, this has raised consumers' concerns about whether the green price premium they pay is really worthwhile (Dickler, 2008; Mendleson and Polonsky, 1995). In addition, the link between green purchasing decisions and measures

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of environmental consciousness is studied by Schlegelmilch et al. (1996), who suggest that while consumers' environmental concerns would positively affect market shares of green products, “extreme care must be taken to ensure that claims about products’ green credentials are based on solid foundations to prevent the inevitable consumer backlash.” The issue of green credentials is also addressed by Glaser (1999) in the context of green power markets. Morthorst (2000) proposes a green electricity certificate market in Denmark to secure the development of renewable energy technologies.

Objective of This Study: In the paper, We propose an oligopoly model to study the competition between green and ordinary products. The objective of this study is two-fold: to provide guidelines for green producers to understand the underlying factors that determine the competitiveness of green products in the market, and to analyze and compare the effectiveness of tax and subsidy policies in promoting green products. In the model, two types of firms: ordinary production and green production are assumed to compete against each other in a Cournot fashion to maximize their own profits. Here Cournot competition refers to the economic model in which companies compete on the amount of output they produce, which they decide on independently of each other and at the same time.

The remaining sections are organized as follows: Section 2 sets up a benchmark scenario in which only ordinary products exist in the market. The game theory model that studies the competition between green and ordinary products is introduced in Section 3, where the three market indices are also defined. Analysis of the model is detailed in Sections 4. Section 5 applies the models to two empirical examples and compares the equilibrium results with their real market performances. The effectiveness of Pigouvian tax and subsidy policies is studied in Section 6. The paper concludes with summaries and discussions in Section 7.

2 Model for Typical Ordinary Product Market

We start with a case in which green product penetration has not yet started, and only ordinary products are available in the market. Results from this model will be used as benchmark to compare with those from the after-penetration analysis.

The demand function for ordinary products is assumed to be $Q^O = \frac{1}{b}(a - p^O)$, where Q^O and p^O denote supply quantity and price of the ordinary product, respectively, and a and b are constants. The inverse demand function is $p^O = a - bQ^O$.

We assume that the price of a product consists of two components: the upfront price, ρ^O, received by the producing firms, and the consumption cost, λ^O, paid to a third-party, i.e., $p^O = \rho^O + \lambda^O$. Since the consumption cost may be incurred over the product's lifetime, λ^O denotes the present value of the consumption cost. Both economic consumption cost and environmental externalities could be incorporated into λ^O. Consider the Toyota Corolla, an internal combustion engine vehicle, as an example. The upfront price, ρ^O, of a 2008 Corolla is \$17,570, the manufacturer's suggested retail price (MSRP) (Toyota, 2008). If it consumes \$125 worth of gasoline each month for ten years, then the present value gasoline consumption cost is $\sum_{m=1}^{120} 125\alpha^{m-1} = \$8,758$ for $\alpha = 0.99$. Based on the data from Lave and Maclean (2002), the emission cost is calculated to be \$886. Therefore, the consumption cost is $\lambda^O = \$8,758 + \$886 = \$9,644$, and the total price of a Corolla is $p^O = \rho^O + \lambda^O = \$26,328$. It is our assumption that consumers take both the upfront price and the consumption cost into consideration in their purchasing behavior.

There are n firms that produce homogeneous ordinary products and compete in a Cournot fashion, which means that each firm i simultaneously and independently determines its quantity supply q_i^O to maximize its own profit. Let c^O be the unit production cost, then the profit of firm i is given by $\pi_i^O(q_i^O) = (\rho^O - c^O)q_i^O$.

We define social welfare as consumer willingness to pay minus total cost (including consumption and production costs):

$$\Psi := \int_0^{Q^O} (a - bq)dq - \lambda^O Q^O - c^O Q^O = (a - \lambda^O - c^O)Q^O - \frac{b}{2}(Q^O)^2.$$

This definition is equivalent to the summation of consumers' surplus and producers' surplus:

$$\int_0^{Q^O}(a-bq)dq - p^OQ^O + (p^OQ^O - c^OQ^O) = \int_0^{Q^O}(a-bq)dq - \lambda^OQ^O - c^OQ^O = \Psi.$$

Since λ^O includes both economic and environmental consumption costs, the cost of environmental externalities is reflected in the above defined social welfare function.

Proposition 1. *Under Nash equilibrium of this model, the following system output can be derived:*

- *quantity supply of firm i is* $(q_i^O)^* = \frac{a-\lambda^O-c^O}{b(n+1)}, \forall i = 1, ..., n,$
- *total price is* $(p^O)^* = \frac{a+n(\lambda^O+c^O)}{n+1}$, *and*
- *social welfare is* $\Psi^* = \frac{n(n+2)(a+\lambda^O-c^O)^2}{2b(n+1)^2}$.

The above results can be derived by setting $\frac{\partial \pi_i^O}{\partial q_i^O} = 0$.

3 Competition Model for Market with both Ordinary and Green Products

Here we study the market competition after the penetration of green products. Variables defined in Section 2 with the superscript "O" replaced by "G" are the corresponding notations for green products. Section 3.1 describes the demand functions of the two products, Section 3.2 defines three market indices. Settings of the market model with both ordinary and green products are given in Section 3.3.

3.1 Demand Functions

After the penetration of green products, the demand functions of the two products are

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assumed to take the following form:

$$\begin{pmatrix} Q^O \\ Q^G \end{pmatrix} = \frac{a}{b(1-\theta^O\theta^G)} \begin{pmatrix} 1-\theta^G \\ 1-\theta^O \end{pmatrix} - \frac{1}{b(1-\theta^O\theta^G)} \begin{pmatrix} 1 & -\theta^G \\ -\theta^O & 1 \end{pmatrix} \begin{pmatrix} p^O \\ p^G \end{pmatrix}, \qquad (1)$$

whose inverse demand functions are

$$\begin{pmatrix} p^O \\ p^G \end{pmatrix} = \begin{pmatrix} a \\ a \end{pmatrix} - b \begin{pmatrix} 1 & \theta^G \\ \theta^O & 1 \end{pmatrix} \begin{pmatrix} Q^O \\ Q^G \end{pmatrix}. \qquad (2)$$

Here $\theta^O, \theta^G \in (0, 1)$ are substitutability parameters. Unlike Singh and Vives (1984) who assume that substitutability parameters take the same value in both directions, we allow the values of θ^O and θ^G to be different. If $\theta^O \to 1$ ($\theta^G \to 1$), it means that an ordinary (a green) product is almost a complete substitute to a green (an ordinary) product. A negative value could imply complementarity of two products, whereas $\theta^O \to 0$ ($\theta^G \to 0$) indicates that an ordinary (a green) product is neither substitutive nor complementary to a green (an ordinary) product. Since we are considering two versions (ordinary and green) of the same product, the values of θ^O and θ^G are assumed to lie between 0 and 1. To interpret θ^O and θ^G mathematically, we observe that

$$\frac{\partial Q^O(p^O, p^G)}{\partial p^O} : \frac{\partial Q^O(p^O, p^G)}{\partial p^G} = -1 : \theta^G, \qquad (3)$$

$$\frac{\partial Q^G(p^O, p^G)}{\partial p^G} : \frac{\partial Q^G(p^O, p^G)}{\partial p^O} = -1 : \theta^O, \text{ and} \qquad (4)$$

$$Q^O(p^O, p^G = p^O) : Q^G(p^O, p^G = p^O) = (1 - \theta^G) : (1 - \theta^O). \qquad (5)$$

Equation (3) means that the impact of p^G on Q^O is a fraction, θ^G, of that of p^O on Q^O. In other words, if a higher price of ordinary products, $p^O + \Delta p$, reduces the sales of ordinary products by ΔQ^O, then a lower price of green products, $p^G - \Delta p$, reduces the sales of ordinary products by $\theta^G \Delta Q^O$. Equation (4) is symmetric to Equation (3). These two equations indicate that the more substitutive one product is to the other, the more impact its price has on the sales of the other. Equation (5) shows that when green and ordinary products are priced the same, their demand ratio is determined by θ^O and θ^G. Therefore, the ratio $(1 - \theta^G) : (1 - \theta^O)$ measures relative attractiveness of ordinary and green products' design, functionality, and other non-economic attributes.

3.2 Market Indices

We use the following three indices to measure the performance of green products in the market.

Market share of green products

The market share of green products is defined in terms of units of products sold:

$$\beta^G := \frac{Q_G}{Q^G + Q^O}.$$

Green price premium

From the inverse demand functions (2), the price of green products can be written as $p^G = p^O + \Delta p$, where

$$\Delta p := b(1-\theta^O)Q^O - b(1-\theta^G)Q^G$$

is the total green price premium. Intuitively, a higher total green price premium will cause more demand of ordinary products ($\frac{\partial Q^O}{\partial \Delta p} > 0$) and less demand of green ones ($\frac{\partial Q^G}{\partial \Delta p} < 0$). The upfront green price premium is given by

$$\Delta \rho := \rho^G - \rho^O = b(1-\theta^O)Q^O - b(1-\theta^G)Q^G - \lambda^G + \lambda^O.$$

Social welfare

To define social welfare for a product with two differentiated versions, we construct two non-decreasing functions $f_G(t)$ and $f_O(t)$ such that they are continuously differentiable in $(0, 1)$ and that $f_G(0) = 0, f_G(1) = Q^G$ and $f_O(0) = 0, f_O(1) = Q^O$. Functions $f_G(t)$ and $f_O(t)$ represent the process of price discrimination, where the supply quantities of green and ordinary products are gradually increased in such a way that consumer willingness to pay is maximally exploited.

The consumer willingness to pay can be calculated as:

$$
\begin{aligned}
Y &= \int_0^1 \{a - b[f_O(t) + \theta^G f_G(t)]\} df_O(t) + \int_0^1 \{a - b[f_G(t) + \theta^O f_O(t)]\} df_G(t) \\
&= a(Q^O + Q^G) - \frac{b}{2}[(Q^O)^2 + (Q^G)^2] - b\theta^G \int_0^1 f_G(t) df_O(t) - b\theta^O \int_0^1 f_O(t) df_G(t) \\
&= a(Q^O + Q^G) - \frac{b}{2}[(Q^O)^2 + (Q^G)^2] - b\theta^G Q^O Q^G + b(\theta^G - \theta^O) \int_0^1 f_O(t) df_G(t).
\end{aligned}
$$

By the definition of $f_O(t)$, we have

$$
\int_0^1 f_O(t) df_G(t) \geq \int_0^1 0 df_G(t) = 0, \text{ and}
$$

$$
\int_0^1 f_O(t) df_G(t) \leq \int_0^1 Q^O df_G(t) = Q^O Q^G.
$$

Since the functions $f_O(t)$ and $f_G(t)$ are selected to maximize Y, it becomes

$$
Y = a(Q^O + Q^G) - \frac{b}{2}[(Q^O)^2 + (Q^G)^2] - b \min\{\theta^G, \theta^O\} Q^O Q^G.
$$

Subtracting total cost from Y, we get the social welfare function:

$$
\Psi := (a - \lambda^O - c^O)Q^O + (a - \lambda^G - c^G)Q^G - \frac{b}{2}[(Q^O)^2 + (Q^G)^2] - b \min\{\theta^G, \theta^O\} Q^O Q^G. \tag{6}
$$

We assume $a - \lambda^O - c^O > 0$ and $a - \lambda^G - c^G > 0$ so that a positive social welfare is achievable.

3.3 Model Settings for Market with both Ordinary and Green Products

In the market competition model with both ordinary and green products: assume there are n ordinary firms, which specialize in producing ordinary (green) products; there are m green firms, which specialize in producing green products and no firms produce both (realistically if there are firms producing both types of products, the products are typically produced in separate departments and are also competing in the market). Firms compete in a Cournot fashion, and each firm competes against all other firms both within and outside its own group.

Denote q_i^O as the supply quantity of an ordinary firm i and q_j^G as the supply quantity of a green firm j. The total supply quantities of ordinary and green products are given by $Q^O = \sum_{i=1}^{n} q_i^O$ and $Q^G = \sum_{j=1}^{m} q_j^G$, respectively. Unit production cost of an ordinary product is c^O and the unit production cost of a green product is c^G.

4 Analysis of the Model

4.1 Nash Equilibrium

Given total supply quantities from the other ordinary firms $Q_{-i}^O = \sum_{k=1}^{n} q_k^O - q_i^O$ and from green firms Q^G, the profit of an ordinary firm i is

$$\begin{aligned} & \pi_i^O(q_i^O; Q_{-i}^O, Q^G) \\ = \; & (\rho^O - c^O)q_i^O \\ = \; & (p^O - \lambda^O - c^O)q_i^O \\ = \; & [a - b(q_i^O + Q_{-i}^O + \theta^G Q^G) - \lambda^O - c^O]q_i^O \\ = \; & -b(q_i^O)^2 + [a - \lambda^O - c^O - b(Q_{-i}^O + \theta^G Q^G)]q_i^O, \end{aligned} \tag{7}$$

and its best response is

$$q_i^O(Q_{-i}^O, Q^G) = \frac{a - \lambda^O - c^O - b(Q_{-i}^O + \theta^G Q^G)}{2b}. \tag{8}$$

Similarly the best response of a green firm j is

$$q^G \quad G \quad O \qquad a - \lambda^G - c^G - b(Q^G \quad + \theta^O Q^O)$$

$$_j\,(Q_{-j}, Q\quad) = \frac{\quad -j}{2b}. \tag{9}$$

Proposition 2. *Under Nash equilibrium of the market competition model with both* *green and ordinary products, the supply quantities of individual firms are*

$$(q_i^O)^* = \frac{(m+1)(a-\lambda^O - c^O) - m\theta^G(a-\lambda^G - c^G)}{b[(m+1)(n+1) - mn\theta^O\theta^G]}, \ \forall i = 1, \ldots, n, \tag{10}$$

$$(q_j^G)^* = \frac{(n+1)(a-\lambda^G - c^G) - n\theta^O(a-\lambda^O - c^O)}{b[(m+1)(n+1) - mn\theta^O\theta^G]}, \ \forall j = 1, \ldots, m, \tag{11}$$

and their profits are

$$\pi_i^O = b(q_i^O)^2 \tag{12}$$

$$\pi_j^G = b(q_j^G)^2. \tag{13}$$

Equations (10) and (11) can be derived by first taking summation of (8) and (9) over i and j, respectively,

$$Q_i^O = \frac{n(a-\lambda^O - c^O) - b[(n-1)Q_i^O + \theta^G mQ^G]}{2b} \tag{14}$$

$$Q_i^G = \frac{m(a-\lambda^G - c^G) - b[(m-1)Q_i^G + \theta^O nQ^O]}{2b} \tag{15}$$

and then substituting (14) and (15) for Q_i^O and Q_i^G in (8) and (9). Equations (12) and (13) can be derived by substituting (10) and (11) for q_i^O and q_i^G in (7).

4.2 Long-Term Equilibrium

We assume that the ordinary segment of the market has reached maturity in that the number of ordinary firms, n, is fixed, but there could be green firms entering or exiting the market with no barrier.

Define $\eta := \frac{\pi^G}{\pi^O}$ as the relative profitability of a green and an ordinary firm. If $\eta > 1$, then a green firm is more profitable than an ordinary one, and more green firms will be attracted to enter the market; if $\eta < 1$, then some green firms are expected to exit. Assuming that relative profitability is the only incentive for entry and exit, we

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say that the market has reached long-term equilibrium when $\eta = 1$. Under long-term Nash equilibrium, $\pi^G = \pi^O$ and thus $q_i^O = q_j^G$.

Proposition 3. *Supply quantities under long-term equilibrium of the market competition model with both green and ordinary products are*

$$q_i^O = q_j^G = \frac{(a-\lambda^O-c^O)-\theta^G(a-\lambda^G-c^G)}{b[n(1-\theta^O\theta^G)+1-\theta^G]}, \forall i = 1, \ldots, n, \forall j = 1, \ldots, m,$$

and the number of green firms is

$$m = \frac{(n+1)(a-\lambda^G-c^G)-(n\theta^O+1)(a-\lambda^O-c^O)}{(a-\lambda^O-c^O)-\theta^G(a-\lambda^G-c^G)}.$$

The following proposition derives the market indices under long-term equilibrium.

Proposition 4. *Under long-term equilibrium of the market competition model with both green and ordinary products:*

1. *market share of green products is*

$$\beta^G = \frac{(n+1)(a-\lambda^G-c^G)-(n\theta^O+1)(a-\lambda^O-c^O)}{(n-n\theta^O-1)(a-\lambda^O-c^O)+(n-n\theta^G+1)(a-\lambda^G-c^G)},$$

2. *total and upfront green price premiums are*

$$\Delta p = c^G+\lambda^G-c^O-\lambda^O \text{ and } \Delta\rho = c^G-c^O,$$

   and

3. *social welfare is*

$$
\begin{aligned}
\Psi \quad = \quad & \frac{(a-\lambda^O-c^O)-\theta^G(a-\lambda^G-c^G)}{b[n(1-\theta^O\theta^G)+1-\theta^G]}(a-c^O-\lambda^O)n \\
& + \frac{(n+1)(a-\lambda^G-c^G)-(n\theta^O+1)(a-\lambda^O-c^O)}{b[n(1-\theta^O\theta^G)+1-\theta^G]}(a-c^G-\lambda^G) \\
& - \frac{n^2[(a-\lambda^O-c^O)-\theta^G(a-\lambda^G-c^G)]^2}{2b[n(1-\theta^O\theta^G)+1-\theta^G]^2} \\
& - \frac{[(n+1)(a-\lambda^G-c^G)-(n\theta^O+1)(a-\lambda^O-c^O)]^2}{2b[n(1-\theta^O\theta^G)+1-\theta^G]^2} \\
& + \frac{n\min\{\theta^O,\theta^G\}(n\theta^O+1)(a-\lambda^O-c^O)^2}{b[n(1-\theta^O\theta^G)+1-\theta^G]^2} \\
& + \frac{n\min\{\theta^O,\theta^G\}\theta^G(n+1)(a-\lambda^G-c^G)^2}{b[n(1-\theta^O\theta^G)+1-\theta^G]^2} \\
& - \frac{n\min\{\theta^O,\theta^G\}[(n+1)+\theta^G(n\theta^O+1)](a-\lambda^O-c^O)(a-\lambda^G-c^G)}{b[n(1-\theta^O\theta^G)+1-\theta^G]^2}.
\end{aligned}
$$

From the long-term equilibrium results in Proposition 4, we derive managerial insights regarding the competition between ordinary and green products.

Corollary 1. *In order for green products to survive in long-term equilibrium ($\beta^G > 0$), the following condition needs to be met:*

$$
\frac{a-\lambda^G-c^G}{a-\lambda^O-c^O} > \frac{n\theta^O+1}{n+1}.
$$

Corollary 1 is derived by setting the green product market share $\beta^G > 0$. Corollary 1 points out that, unless green technology is sufficiently advanced to make c^G and λ^G small enough, and green design is sufficiently distinct from ordinary products to make θ^O small enough, green products will eventually be eliminated from the market. The pure electric vehicle Insight may be such an example, in which case technology improvement was not able to bring prices low enough to attract demand and high enough to generate a profit, and thus, Honda had to discontinue its production (Lave and Maclean, 2001).

Corollary 2. *In order for green products not to completely eliminate ordinary products from the market in long-term equilibrium ($\beta^G < 1$), the following condition needs to be* *met:*

$$\frac{a-\lambda^G-c^G}{a-\lambda^O-c^O} < \frac{1}{\theta^G}.$$

The remainder of the Model I analysis is based on the following blanket assumption:

$$\frac{n\theta^O+1}{n+1} < \frac{a-\lambda^G-c^G}{a-\lambda^O-c^O} < \frac{1}{\theta^G}. \qquad (16)$$

From Corollaries 1 and 2, this assumption ensures the existence of both ordinary and green firms in the market under long-term equilibrium.

Corollary 3. *When all other conditions are equal, it is easier for green firms to survive as the number of ordinary firms, n, increases.*

This is because the minimal condition for green firms to survive becomes weaker as n increases:

$$\frac{\partial}{\partial n}\frac{n\theta^O+1}{n+1} = -\frac{1-\theta^O}{(n+1)^2} < 0.$$

As a special case, if the ordinary product market has reached perfect competition with infinitely many producers, then it will be the easiest for green firms to survive the market competition, and by Proposition 3 the green product market will also reach perfect competition eventually with infinitely many producers.

Proposition 5. *Under long-term equilibrium of the model with only ordinary products, the difference in upfront prices equals the difference in production costs:* $\rho^G-\rho^O = c^G-c^O$.

Proposition 5 reveals that no matter how much savings green products have over ordinary ones in consumption cost, under long-term equilibrium, the upfront green price premium will only represent the difference in production costs.

Proposition 6. *Compared to the Nash equilibrium of the model with only ordinary* *products, long-term equilibrium of the market model with both ordinary and green products has a lower price of ordinary products and a higher social welfare.*

Proposition 6 shows that one of the contributions of the penetration of green products is that, as long as they can survive in the long term, they will make the market more competitive and force ordinary firms to reduce their prices, which will also increase social welfare.

4.3 Comparative Statics

We study the sensitivity of long-term equilibrium to changes by deriving comparative statics of the market indices with respect to the parameters θ^O, θ^G, c^O, c^G, λ^G, and n.

Proposition 7. *Under long-term equilibrium of the market model with both ordinary and green products, the following comparative statics can be derived:*

$\frac{\partial(index)}{\partial(parameter)}$	θ^O	θ^G	c^O	c^G	λ^G	n
market share of green products β_l^G	$-$	$+$	$+$	$-$	$-$	
total green price premium Δp_l	0	0	-1	1	1	0
upfront green price premium $\Delta \rho_l$	0	0	-1	1	0	0
social welfare Ψ_l	$-$	$+/-$	$+/-$	$-$	$-$	$+$

$\propto [(\lambda^G + c^G) - (\lambda^O + c^O)]$

The following observations and insights can be drawn from Proposition 7:

1. $\frac{\partial \beta^G}{\partial \theta^O} < 0$, $\frac{\partial \beta^G}{\partial \theta^G} > 0$: In order to increase the market share, green products should be designed such that θ^G is large and θ^O is small, which means that, by Equation (5), they should be preferred over ordinary products when economic considerations are removed.
2. $\frac{\partial \beta^G}{\partial c^O} > 0$: Increasing production cost of ordinary products (by imposing taxes, e.g.) will increase the market share of green products.
3. $\frac{\partial \beta^G}{\partial c^G} = \frac{\partial \beta^G}{\partial \lambda^G} < 0$: Reducing production and/or consumption costs of green products (through technology improvement) will increase their market share.

4 $\frac{\partial m^G}{\partial \beta} \propto (\lambda^G + c^G) - (\lambda^O + c^O)$: If green products are less cost efficient ($\lambda^G + c^G > \lambda^O + c^O$), then reducing the number of ordinary firms will only decrease the market share of green products.

5. $\frac{\partial \Delta p}{\partial c^O} = \frac{\partial \Delta \rho}{\partial c^O} = -1$: Every dollar of tax on ordinary products will be entirely passed on to reduce the green price premium Δp and $\Delta \rho$.

6. $\frac{\partial \Delta p}{\partial c^G} = \frac{\partial \Delta \rho}{\partial c^G} = 1$: Symmetric to the above point, every extra dollar of savings in production cost, Δc^G, will be entirely passed on to reduce the total green price premiums Δp and $\Delta \rho$. If we look at the effects on prices of green and ordinary products separately:

$$\frac{\partial p^G}{\partial c^G} = \frac{\partial \rho^G}{\partial c^G} = \frac{n(1-\theta^O\theta^G)+1}{n(1-\theta^O\theta^G)+1-\theta^G} > 1, \text{ and}$$

$$\frac{\partial p^O}{\partial c^G} = \frac{\partial \rho^O}{\partial c^G} = \frac{\theta^G}{n(1-\theta^O\theta^G)+1-\theta^G} > 0.$$

The effect on p^G and ρ^G is more than the change in c^G itself, but p^O and ρ^O are also positively affected, which makes the changes in price premiums, Δp and $\Delta \rho$, equal to the change in production cost, Δc^G.

7. $\frac{\partial \Delta p}{\partial \lambda^G} = 1$, $\frac{\partial \Delta \rho_1}{\partial \lambda^G} = 0$: An extra dollar of savings in consumption cost will only be passed on to reduce the total green price premium, but not upfront price premium. The effects on prices of green and ordinary products are, respectively,

$$\frac{\partial p^G}{\partial \lambda^G} = \frac{n(1-\theta^O\theta^G)+1}{n(1-\theta^O\theta^G)+1-\theta^G} > 1,$$

$$\frac{\partial p^O}{\partial \lambda^G} = \frac{\theta^G}{n(1-\theta^O\theta^G)+1-\theta^G} > 0, \text{ and}$$

$$\frac{\partial \rho^G}{\partial \lambda^G} = \frac{\partial \rho^O}{\partial \lambda^G} = \frac{\theta^G}{n(1-\theta^O\theta^G)+1-\theta^G}.$$

8. $\frac{\partial \Psi^G}{\partial \theta^O} < 0$: The level of social welfare increases as ordinary products become less substitutive to green ones. Qualitatively speaking, this is because the definition of social welfare in (6) favors more distinct products. In an extreme case when θ^O '''' 0, green products are completely non-substituted by ordinary ones, thus their penetration will create an entirely new segment of green consumers, significantly contributing to social welfare. On the other extreme when θ^O '''' 1, green products

have no features to distinguish themselves from ordinary ones in terms of design or functionality, then they cannot attract new consumers except converting some existing ones from ordinary to green, thus social welfare before and after green product penetration will be almost the same. One example of the latter case is green power (Wiser et al., 1999; Wiser and Pickle, 1998). Some consumers may switch from ordinary power suppliers to green suppliers, but will not consume more electricity just because it is generated from renewable resources.

9. $\frac{\partial \Psi^G}{\partial \theta^G} < 0$ or > 0: Symmetric conclusion cannot be made for θ^G. This is because the number of ordinary firms, n, is assumed to be fixed, but that of green firms is not. An increased θ^G could improve green products' competitiveness, attract more green firms into the market, and have a positive effect on social welfare. This positive effect may or may not offset the negative effect of making the two products more similar to each other.

10. $\frac{\partial \Psi^G}{\partial c^O} > 0$ or < 0: Increasing c^O could make green firms relatively more competitive, attract their entries, and have a positive effect on social welfare, which may or may not offset the negative effect of decreasing ordinary firms' cost efficiency.

11. $\frac{\partial \Psi^G}{\partial c^G} = \frac{\partial \Psi^G}{\partial \lambda^G} < 0$: Increasing green products' production and consumption costs will decrease social welfare.

12. $\frac{\partial \Psi^G}{\partial n} > 0$: By Corollary 3, increasing the number of ordinary firms makes it easier for green products to survive, thus increases social welfare. Dean and Brown (1995) have a similar discussion on how pollution regulations may deter new (ordinary) firms' entry and suggest that such regulations "may have the socially undesirable consequence of decreasing competition."

5 Numerical Examples

A firm's decision to initiate green production is influenced mainly by regulations and consumer preference (Wong et al., 1996). The disappointing low market share of some earlier green products, however, has forced firms to reconsider their green marketing strategies (Peattie, 2001). Several studies have focused on consumer profile and its implication on advertising strategies (Roberts, 1996; Rowlands et al., 2003; Stevels et al., 2001).

In this section, two empirical examples are presented to demonstrate the Oligopoly model and derive managerial insight for the market competition and government policy impacts.

- **Corolla vs. Prius**

  In this example, we use the internal combustion engine vehicle Toyota Corolla 2008 as an ordinary product, and the similar sized hybrid gas electric vehicle Toyota Prius 2008 as a green product. Since the vehicle production costs are proprietary, we make the following assumptions. The production cost for Corolla is assumed to be 85% of its MSRP, $17,570 (Toyota, 2008); thus $c^O = \$14,935$. Prius was said to cost far more to make than its sticker price (Jones, 2003; Lave and Maclean, 2002). Taking into account rapid technology improvement in the last few years, we assume that its production cost is the same as its MSRP, $21,760; thus $c^G = \$21,760$ (Toyota, 2008).

  Total consumption costs consist of gasoline costs and emission costs. Gasoline costs are calculated based on a gas price of $3/gallon, combined fuel economy of 30 mpg for Corolla, 46 mpg for Prius, and a ten-year 150,000-mile lifetime. The monthly gasoline cost for Corolla is $125; from the calculation in Section 2, the total discounted gasoline cost is $8,758. The total discounted gasoline cost for Prius is $8,758×(30/46)=$5,712. Based on the data from Lave and Maclean (2002), the emission costs of Corolla and Prius are calculated to be $886 and $440, respectively. Therefore, $\lambda^O = \$9,644$, $\lambda^G = \$6,152$.

  A survey could be used to empirically determine the values of θ^O and θ^G based on the interpretations of Equations (3)-(5). For the purpose of numerical illustration, we subjectively assign that $\theta^O = 0.95$ and $\theta^G = 0.98$. According to Equation (5), this translates to an assumed preference ratio of 2:5 for Corolla and Prius under the condition that they are indifferent in terms of upfront price and consumption cost. Prius is assigned a higher substitutability due to the fact that it has been rated the top car in owner satisfaction as reported by the Consumer Reports Car Owner Satisfaction Survey in 2204-2008 (Consumers Reports, 2008). The value of θ^G is not set equal to 1.0 because concerns have been raised that hybrid gas electric vehicles like Prius may be too quiet, imposing a potential threat to pedestrian safety (Chang, 2008).

Although the sales of Prius have been continuously and strongly increasing since its entry into the U.S. market in 1999, Prius's fuel savings and lower emissions could not justify its higher upfront price ($\lambda^G + c^G > \lambda^O + c^O$). This example could represent some green products that are not (yet) necessarily superior to their ordinary counterparts economically, but are more attractive in non-economic perspectives. Organic foods and renewable electricity may be also such examples.

- **Incandescent lamp vs. CFL**

In this example, we use the incandescent lamp as an ordinary product and the CFL as a green product. Sandahl et al. (2006) report lessons learned from many years of efforts to increase market acceptance of CFLs, which had only about 2% of the national market in 2006 in terms of unit sales. In their report, technical complexity, market availability, and the attitudes of consumers, manufacturers, and retailers are identified as some of the barriers to larger acceptance.

The production costs of an incandescent lamp and a CFL are assumed to be c^O =\$0.35 and c^G =\$2.1, respectively. Energy costs are used as the consumption costs, which are obtained from the Savings Calculator on the Energy Star (2008). For an incandescent lamp, λ^O = \$77, and for a CFL, λ^O = \$15. Since complaints and concerns still exist on CFLs' performance (Sandahl et al., 2006) such as shape, dimming compatibility, light quality, and mercury usage, the substitutability parameters are subjectively set to be θ^O = 0.99, and θ^G = 0.91, translating to an assumed preference ratio of 9:1 for incandescent lamps and CFLs when economic factors are not considered.

This example could represent some green products that have significant long-term economic and environmental benefits but have other undesirable features. Reusable shopping bags may be such an example.

For both examples, we assume that $n = 40, a = 10(c^O + \lambda^O), b = 0.0001a$. The data for the two examples are summarized in Table 1. Using these data, we calculate long-term equilibrium of the market competition model with both green and ordinary products. The equilibrium results are summarized in Table 2. It should be noted in Table 2 that the green price premium Δp for the incandescent lamp vs. CFL example is negative. This is due to significant long-term economic and environmental benefits of the CFL. The result illustrates that if the full economic and environmental benefits are fully recognized by the consumers, the total cost over the life cycle of a CFL is $60.25 less than that of an incandescent lamp. Since the two examples of products are studied on different lifetime horizons, their social welfare values should not be compared to each other.

Table 1: Summary of Data for Numerical Examples

Ordinary vs. Green product	λ^O	λ^G	c^O	c^G	ϑ^O	ϑ^G
Corolla vs. Prius	$9,644	$6,152	$14,935	$21,760	0.95	0.98
Incandescent lamp vs. CFL	$77	$15	$0.35	$2.1	0.99	0.91

Table 2: Results of Numerical Examples

Market competition Long-term equilibrium	Market share of green products β	Green price premium $\Delta p/\Delta \rho$	Social welfare Ψ
Corolla vs. Prius	49.85%	$3,333/$6,826	$1.01B
Incandescent lamp vs. CFL	89.78%	–$60.25/$1.75	$3.70M

Total sales of Corolla and Prius in 2007 were 371,390 and 181,221, respectively (Toyota/Lexus/Scion Pressroom, 2008), which yields a market share of 33% for Prius, compared to the 50% estimate from the models. The Energy Star web site reports that

Energy Star CFL sales accounted for approximately 20% of the light bulb market in the United States in 2007, which is far less than the 90% estimate from the models. We give the following explanations for the differences: (1) market shares for both Prius and CFL have been continuously increasing in the past few years. There is still space for the products to further develop and for the market to approach equilibrium. This is especially true with the production cost reduction. (2) Some consumers may be unaware of or have doubts about green products' benefits, which could shrink their market share potentials. (3) Some real market characteristics may require much more sophisticated models to capture. (4) Assumptions have been made on certain data that are not publicly available, which may also introduce errors to the modeling results.

6 Pigouvian Tax and Subsidy

Since green producers are internalizing some of the negative externalities during the production process, it is appropriate for the government to subsidize such environmentally responsible effort and offset part of the extra cost. The government not only has huge purchasing power (Environmentally Preferable Purchasing, 2008) but also can exercise regulatory leverage to foster green product development. The Energy Policy Act (2005), for example, has been providing tax credits for consumers who purchase fuel efficient cars (Solheim, 2007).Taxes may also be imposed on ordinary production as a penalty for the negative externalities.

Much research has focused on the effectiveness of regulatory policies such as imposing emission taxes on ordinary products and giving subsidies to green products to encourage environmentally responsible production. Bansal and Gangopadhyay (2003) compare the uniform ad-valorem tax policy with a variant policy that levies taxes or offers subsidies based on a firm's environmental quality level. Their results show that "while a uniform subsidy policy improves average environmental quality, a uniform tax policy worsens it. Further, while a discriminatory subsidy policy reduces total pollution and enhances aggregate welfare, a discriminatory tax policy may increase total pollution and may reduce aggregate welfare." More recently, Bansal (2008) finds that tax (subsidy) is more effective when the damage parameter is low (high). Pigouvian tax is shown by Mahenc (2007) to fail to improve social welfare in a market with asymmetric information about the greenness of products. Eichner and Pethig (2000) use a mathematical model to compare five different tax policies in reducing environmental externalities. Turner et al. (1998) survey green taxes in the late 1990s in the context of waste management policies and emerging policy instruments. While green taxation could improve environmental quality if appropriately designed and implemented, they find that it could also cause undesirable consequences due to multiple and possibly conflicting policies introduced during the political process. The attractiveness of three options of green taxes to the public was recently surveyed (Athavaley, 2007). Results show that majority of people support the federal mandate policy that stipulates exactly how firms should reduce emissions. The other less attractive options are "a government-imposed tax on greenhouse-gas emissions, and a cap-and-trade scheme where the government requires emissions cuts and issues firms permits allowing them to emit a certain quantity of greenhouse gases."

We consider the Pigouvian tax $\Delta c^O > 0$ (subsidy $\Delta c^G > 0$) applied to ordinary (green) products, which increases (reduces) the unit production cost to $c^O + \Delta c^O$ (to $c^G - \Delta c^G$). The effects of taxation policies on the market indices under the oligopoly model are analyzed in Sections 6.1. Based on the theoretical and numerical results, recommendations of taxation policies and managerial insights are summarized in Section 6.2.

6.1 Impacts of Taxation Policies to the Market Competition

Effects on market share of green products

Relating to the results from Section 4.3, we obtain

$$\frac{\frac{\partial \beta^G}{\partial c^G}}{\frac{\partial \beta^G}{\partial c^O}} = -\frac{a - \lambda^O - c^O}{a - \lambda^G - c^G},$$

which means that imposing tax and subsidy have different effects on market share of green products. If green products are less cost efficient ($\lambda^G + c^G > \lambda^O + c^O$), then giving one dollar of subsidy increases the market share of green products more than imposing one dollar of tax does.

Effects on green price premium

From the observation points 9 and 10 in Section 4.3, one dollar of tax on ordinary products (or subsidy on green products) will reduce the green price premium, Δp or $\Delta \rho$, by exactly one dollar.

Effects on social welfare

Under taxation policies, social welfare should also include any government revenue through collecting taxes and paying subsidies:

$$\begin{aligned} \Psi \;=\; & (a - c^O - \lambda^O)Q^O + (a - c^G - \lambda^G)Q^G - \frac{b}{2}[(Q^O)^2 + (Q^G)^2] \\ & -b \min\{\theta^G, \theta^O\} Q^O Q^G + \Delta c^O Q^O - \Delta c^G Q^G. \end{aligned} \quad (17)$$

The effects of tax and subsidy on social welfare are presented using the two numerical examples.

For the Corolla vs. Prius example, the zero-tax-and-zero-subsidy policy is found to be optimal in terms of social welfare maximization.

For the Incandescent lamp vs. CFL example, the effects of different tax and subsidy policies are shown in Figures 1, in which optimal tax-subsidy combinations lie on the line segment $\Delta c^G + 0.98\Delta c^O = \$3.7; \Delta c^G, \Delta c^O \geq 0$. We also consider the case in which θ^G increased from 0.91 to 0.915, representing an improved preference ratio from 9:1 to 8.5:1. Under such scenario, the optimal tax-subsidy policy combinations become milder: $\Delta c^G + 0.98\Delta c^O = \$1.9; \Delta c^G, \Delta c^O \geq 0$, which is illustrated with Figures 2.

The differences between the analysis results of both products relate to the production costs and market profiles. The analysis framework presented in this paper illustrates the flexibility of applications in a variety of products.

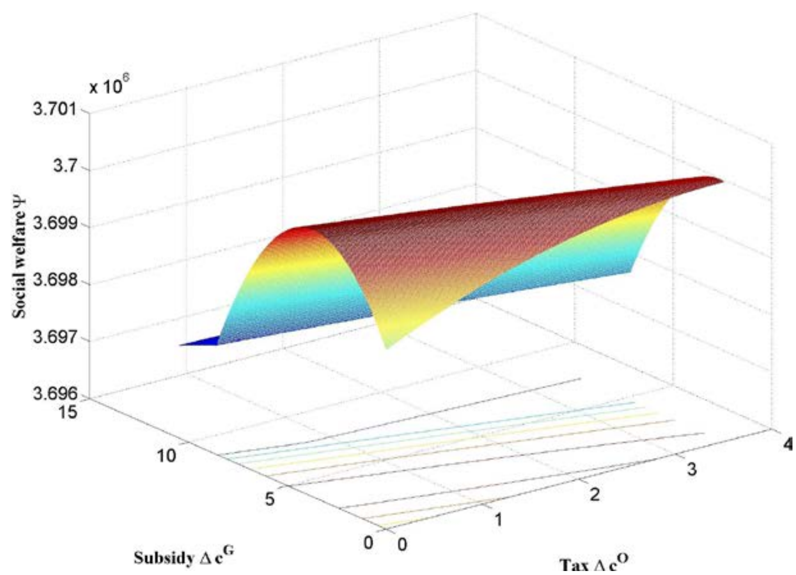

Figure 1: Social Welfare Maximizing Taxation Policies for the Incandescent Lamp vs. CFL Example with $\vartheta^G = 0.91$: $\Delta c^G + 0.98\Delta c^O = \$3.7; \Delta c^G, \Delta c^O \geq 0$.

6.2 Recommended Taxation Policies

Based on the discussions in Sections 6.1, we summarize in Table 3 our recommended taxation policies for improving the market indices of the two examples.

To increase the market share of green products, a dollar of subsidy is more effective than a dollar of tax for those green products that are less cost efficient ($\lambda^G + c^G >$

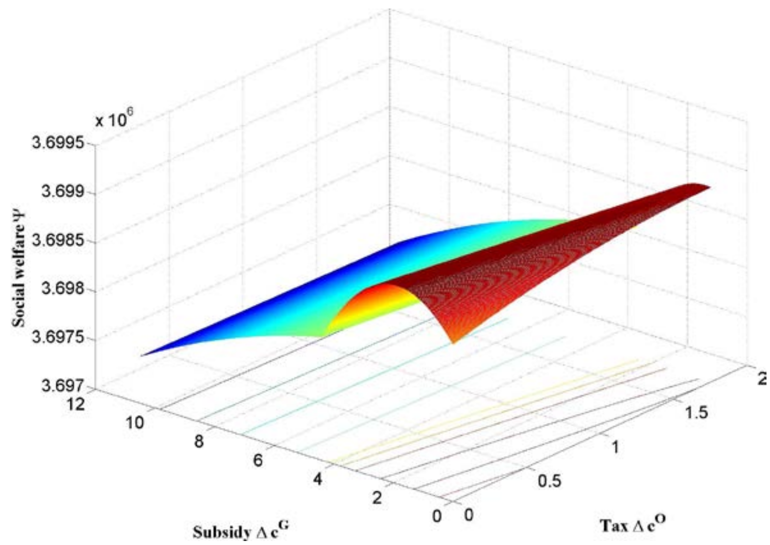

Figure 2: Social welfare maximizing taxation policies for the Incandescent lamp vs. CFL example with $\vartheta^G = 0.915$: $\Delta c^G + 0.98\Delta c^O = \$1.9; \Delta c^G, \Delta c^O \geq 0$.

Table 3: Recommended Taxation Policies for Numerical Examples

	Market share of green products β	Green price premium $\Delta p/\Delta\rho$	Social welfare Ψ
Prius	subsidy	either	neither
CFL	tax	either	combination

$\lambda^O + c^O$) such as Prius. For CFL and other more cost efficient green products, tax is recommended over subsidy. To reduce the green price premium, both tax and subsidy are equally effective: one dollar of tax or subsidy will reduce green premium by exactly one dollar. This result holds true for all green products regardless of their costs or design characteristics.

From the perspective of maximizing social welfare, the zero-tax-and-zero-subsidy policy is recommended for Prius, whereas a range of heavy tax and subsidy policies are found to be optimal for CFL: $\Delta c^G + 0.98\Delta c^O = \$3.7$, which would tax ordinary products and/or subsidize green products for more than their production costs. While we realize these policies are impractical, they demonstrate a point that it is in the society's best interest to promote the highly cost efficient CFLs (with comparable quality), especially when public preference is relatively low compared to incandescent lamps ($\theta^G < \theta^O$).

Besides tax and subsidy, there are other regulations that could be used to promote green products. The Energy Independence and Security Act (2007), for example, sets efficiency standards for electric lights that will see the incandescent lamps phased out of the US market beginning in 2012. As another example, on June 1, 2008, China banned manufacturing, selling, or using ultra-thin plastic bags as a means to call for a return of cloth bags and to cut “white pollution” (Bodeen, 2008).

7 Conclusions

An oligopoly model is proposed in this paper to study the competition in the market with both green and ordinary products. We derive insights for green producers to increase competitiveness of their products and for decision makers to use taxation policies as leverage to promote green products. The modeling framework is comprehensive enough to capture some of the key characteristics of the market and tractable enough to provide managerial insights. We explicitly model how consumers base their purchasing decisions on not only price premium of green products but also the savings in consumption cost. The savings include both economic savings (of reduced energy cost by using Energy Star appliances, for example) and environmental savings (of reduced emissions by driving hybrid gas electric vehicles). Just as firms did not start to produce green products to protect the environment but to explore a new market and increase their profit (Smith et al., 1996), most consumers are willing to pay a green price premium only if their purchase is rewarded with extra benefits. Advances in technology and manufacturing processes have enabled many green products such as CFLs to justify their price premium by significant savings.

The oligopoly model is an extension of the monopoly or duopoly settings in most literature in this area (Bansal and Gangopadhyay, 2003; Bansal, 2008; Chen, 2001; Conrad, 2005; Mahenc, 2007). As such, they allow us to examine the interactions among two groups of producers with possible entries and exits. Minimal conditions are derived for green products to survive market competition. Compared to their ordinary counterparts, most green products are superior in one dimension but weaker in another, at least in the introductory phase. The survival conditions could help producers to determine whether a green product is ready to enter the market and survive the competition. Cost efficiency and innovative design are identified as key elements to survival.

Three market indices are defined to measure the market performance of green products: market share of green products, green price premium, and social welfare. The first two indices are easier to measure, and are generally good indicators of green products' performance: a larger market share and a lower green premium imply a greater consumer acceptance. The third index embraces a societal perspective and takes into account consumers' and producers' surpluses as well as government revenue. The social welfare index provides a legitimate objective function for taxation policy makers to maximize.

Two empirical examples: Corolla vs. Prius and Incandescent lamp vs. CFL. are presented to illustrate the approach. Market share results from both models are more optimistic than real market statistics. We identify pre-equilibrium market dynamics, consumer bias towards green products, and modeling limitations as the main reasons for such differences. We analyze the effectiveness of tax and subsidy policies that can be applied to influence the performance of green products, and recommend product specific policies for improving different market indices.

We conclude the paper by pointing out several future research directions. First, we assume linear demand functions in this paper. More sophisticated demand functions can be incorporated to study more complicated consumer behaviors. Second, this paper focuses on taxation policy from the government. It would be interesting to analyze market response to non-taxation environmental regulations and policies, such as cap-and-trade. Third, as the green technologies evolve, companies will create various level of greenness for products. It will create not two but many versions of products with a (may be) continuous spectrum of greenness. It would be of interest to study how the market responds in this process.

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