

Green Veblen Effect: Sustainability in Pollution Management

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Abstract

We know that green products may initially exhibit a Veblen effect—demand increasing with prices—often followed by a decrease in price. The global understanding of these joint phenomena still needs to be improved, impeding appropriate profit-maximizing policies. Our article fills the gap by tying sustainable dynamic policies to pollution management with green consumers. This article develops an optimal control framework for production and pollution abatement, accounting for both the demand-side, with green consumption, and the supply-side, with polluting production. Results investigate the conditions characterizing the initial green Veblen phenomenon and show how to manage a green Veblen product over time. Our results pave the way to more profitable strategies accounting for sustainability.

Key words: green Veblen effect, sustainability, pollution management, optimal control

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1 Introduction

Brands such as *Patagonia* and *Reformation* owe some of their market success to their reduction of pollution emissions (*The New York Times*, 2019, *Business Insider*, 2020). Furthermore, in a study by Drozdenko et al. (2011), survey respondents were willing to pay 9.5% more for a green music player than a conventional one. Similar is found for *green products*, those that are more environmentally friendly, by Nielsen (Adams, 2014). Thus, successful firms must consider how their environmental impact affects consumers' willingness to pay.

Willingness to pay more for green products may sometimes be surprising, as consumers may increase their purchase frequency (demand) despite an inflated price for the green product. When made available to retail consumers, the *Impossible Burger* was two to four times more expensive than its animal-based (non-green) analogs (Gilbert, 2019). However, at the same time, the *Impossible Burger* was selling out in grocery stores at a rate of more than six times the following highest-selling product (Shoup, 2019). Despite its high price, the increased demand led to shortages of the *Impossible Burger* in early 2019 (MarketLine, 2019). Incredibly, *Beyond Meat*, an *Impossible Burger* competitor, is also seeing increased demand over time, despite an increase in price during the same period (Reinicke, 2019). Specifically, in July 2019, sales increased 208% while the price increased 15.5%; in August 2019, sales increased 147.8% while the price increased 15.9%. We say a product sold to *green consumers*, environmentally conscious consumers, exhibits the *green Veblen effect* if its demand and price evolve in the same direction, as observed by *Beyond Meat* in 2019. We formally define the green Veblen effect in Definition 2.

The classical Law of Demand states that the demand for a product decreases with its price. In contrast, the *Veblen effect*, for which a higher price relates to greater demand (Bagwell and Bernheim, 1996; Wood, 1993), seems to contradict the Law of Demand. *Conspicuous consumption* may explain the Veblen effect: consumers purchase luxury, expensive products to signal their wealth (Bagwell and Bernheim, 1996; Bernheim, 1994; Corneo and Jeanne, 1997). For products sold to green consumers, the *green Veblen effect* is similarly explained by *conspicuous conservation* (Griskevicius et al., 2010; Sexton and Sexton, 2014). Indeed, in their seminal article, Griskevicius et al. (2010) conclude that consumers may purchase greener products to signal their environmental concern, raising their social status. For example, the success of the Toyota Prius is attributed to conspicuous conservation (*The Atlantic*, 2015). However, unlike the Toyota Prius where the use of the product is inherently public, consumers who voluntarily

purchase green electricity to power their homes, or purchase plant-based meat alternatives to eat, need not advertise their purchase. Consumers purchasing energy generated by renewable sources pay more than they would for electricity generated through other sources (MacDonald and Eyre, 2018). Similarly, purchasing plant-based substitutes for meat products, *Beyond Meat* or *Impossible Burger*, is not publicly advertised and is more expensive. Thus, green consumption may not always involve conspicuousness, and the green Veblen effect may come from consumers' care for the environment.

The overarching research question of this paper is *what are the drivers behind the green Veblen effect?* We address the question by considering a firm's joint dynamic production and pollution management decisions. More precisely, this article analyzes the interplay between production quantity, pollution abatement effort (investment in a cleaner – less polluting–production process), stock of pollution (total pollution to date), and price. We investigate the dynamic behavior of a firm with an optimal control model. In the model presented in detail in Section 3, production quantity and abatement effort are the control variables, and stock of pollution is the state variable. Explicitly accounting for abatement effort, fundamentally differentiates this work from nominal Veblen work that is grounded on product scarcity. Our model possesses the following features: 1) The firm decides on the production quantity and the abatement effort; 2) Pollution emissions increase with production quantity and decrease with abatement effort; 3) Green consumers are willing to pay more for a greener product; 4) The firm incurs a tax on its pollution emissions. With the listed conditions, the model links polluting-production and green-consumption. We show that the green Veblen effect may occur even when the Law of Demand is satisfied.

The contributions of this work are the following:

- Show that a product may experience the green Veblen effect, though it is sold to green consumers that obey the Law of Demand. Numerical studies show that the green Veblen effect may appear only at the beginning of the product life cycle. Knowing the green Veblen effect may occur at the start of a product life cycle empowers managers to leverage the impact in their pricing, marketing, and roll-out policies.
- Propose a pricing formula for any products sold to green consumers that may exhibit the green Veblen effect. The pricing formula addresses the managerial puzzle of how much more to charge for a product, having demand increase with price. In line with observations in practice and the Law of Demand, the profit-maximizing price is finite. This result reconciles the Law of Demand opposing

forces and the green Veblen effect.

- Identify why and when the green Veblen effect is observed. Understanding the green Veblen effect is the first step to managing it over time.
- Investigate four popular pricing policies for the linear demand case: Skimming (declining), penetration (increasing), u-inverted, and u. Of the four investigated pricing policies, only two appear: skimming (declining) and u-inverted. In other words, the price may increase or decrease at the beginning of the product life cycle, but it continuously decreases at the end. Knowing what pricing policies lead to the green Veblen effect allows managers to focus on good policies.

The remainder of this paper discusses the related research on pollution, sustainability, and the green Veblen effect in Section 2. The optimal control model, based on continuous time, is formulated with a general (non-linear) demand in Section 3 and analyzed in Section 4. We present the analytic results on the optimal policies and the green Veblen effect in Section 5. We provide numerical experiments in Section 6, emphasizing the different stages of the product life cycle and the green Veblen effect. Section 7 discusses the theoretical and managerial contributions of this research. Section 8 concludes the article.

2 Related Work

We now discuss previous work related to this research, emphasizing applications of dynamic optimization. We identify two related streams of literature. The first stream focuses on sustainability and pollution management. The second stream considers Veblen products. We present these streams, explaining the link with this research. For a better understanding, Table 1 shows selected optimal control models in each literature stream, presented in chronological order. The table summarizes the state dynamics and main contribution of each paper. The table helps to distinguish better the mathematical formulations and the managerial insights from the literature, clarifying this research positioning.

2.1 Sustainability and Pollution Management

The first stream of literature concerns optimal control applications to sustainability and pollution management. Sustainability (or sustainable development) refers to the use of resources to satisfy human needs

Table 1: Selected Optimal Control Models for the Two Related Streams of Literature: 1) Sustainability and Pollution Management; 2) Veblen Products

References	State Dynamics	Main Contributions
Stream 1: Sustainability and Pollution Management		
Li (2013, 2016)	$\frac{dB}{dt} = u - \delta B$	Production and inventory with emissions permits and pollution abatement
De Giovanni (2014)	$\frac{dG}{dt} = \alpha a_M + \beta a_R - l - \delta G$	Manufacturer and retailer investment in green advertising with goodwill
Li and Pan (2014)	$\frac{dS}{dt} = E - u - \delta S$	Impact of production and inventory on pollution abatement
El Ouardighi et al. (2016aa,2018a,b)	$\frac{dS}{dt} = \sum E_i - AbS$	Improvable environmental absorption efficiency through restoration
Martín-Herrán and Rubio (2018b)	$\frac{dS}{dt} = q - Y - \delta S$	Pollution abatement investment under an emissions tax
El Ouardighi et al. (2019)	$\frac{dS}{dt} = \sum \alpha_j D_j - \sum \delta_j u_j$	Pollution abatement for different competition and strategy types
Liu and De Giovanni (2019)	$\frac{dE}{dt} = mU - kD - nE$	Green process innovation and environmental performance in a supply-chain
Arguedas et al. (2020)	$\frac{dS}{dt} = V - \delta S$	Comparison of pollution regulations allowing non-compliance
Dawid et al. (2020)	$\frac{dK}{dt} = U - \delta_K K$	Investment in green energy with goodwill increasing demand
	$\frac{dG}{dt} = f(K)a - \delta_G G$	
Stream 2: Veblen Products		
Kort et al. (2006)	$\frac{dG}{dt} = k(h(q) - G)$	Production policy with brand (goodwill) construction for fashion products, leading to different price regimes with short-term profits and long-term brand dilution
Caulkins et al. (2011)	$\frac{dG}{dt} = \alpha(\beta p - G)$	Pricing policy of a conspicuous product during a recession with frozen capital markets and introducing the role of goodwill
Huschto et al. (2011)	$\frac{dG}{dt} = k(\gamma p(t - \sigma) - G)$ $\frac{dC}{dt} = pD - c + \delta C$	Role of control delay σ in the pricing of conspicuous consumption and role of available cash
Huschto and Sager (2014)	$\frac{dG}{dt} = k(\gamma p - G)$ $\frac{dC}{dt} = pD - c + \delta C$	Impact of a recession in the pricing of conspicuous consumption with uncertainty on the recession strength and role of available cash
Chenavaz and Eynan (2020)	$\frac{dG}{dt} = A(a, G)$	Reconciliation of the Veblen effect with the Law of Demand by distinguishing the partial and total effect of price on demand

Notes. For clarity, the variable notations are unified: A goodwill dynamics, a advertising, Ab absorption efficiency of the environment, B abatement capital, C available cash, D demand, E emissions, G goodwill, I inventory, J stock of clean technology, K green capital stock, l advertising lag, q production, S stock of pollution, U investment (non-abatement), u abatement effort, V environmental performance, Y installed abatement capacity. Also, i and j are country and firm indices; α , β , c , δ , γ , k , m , and n are positive parameters. Eventually, $h(q)$ is an inverse demand function of q . For brevity, only the state equations relating to this research appear.

without deteriorating the natural system (Brundtland et al., 1987; Eghbali et al., 2022; Fan et al., 2019; Li et al., 2019, 2022; Omoloso et al., 2021). Pollution refers to the contamination of the natural environment, causing negative or harmful effects (Adner and Levinthal, 2001; Benchekroun and Long, 2012; Jørgensen et al., 2010; Nkuiya and Costello, 2016). Firms can manage their pollution by engaging in pollution abatement—using technology or other means to reduce pollution emissions. An abatement cost is the cost to reduce a negative environmental externality, such as pollution (Arguedas et al., 2020; Cai et al., 2023; El Ouardighi et al., 2021; Yeung and Petrosyan, 2019). In the remainder of the section, first is discussed work in optimal control regarding the optimization of pollution abatement efforts made by firms. Next is considered sustainability and pollution abatement with competition. Lastly, is discussed pollution abatement in the presence of environmental policies. The end of the section highlights the research gap in the sustainability and pollution management stream that this work addresses.

Closely related to this work, the optimization of pollution abatement efforts made by firms, such as investments in green technology or greener production processes, is well-studied in the literature (Yi et al., 2021). Modeling environmentally conscious consumers and the associated goodwill, Dawid et al. (2020) study investment in green energy and De Giovanni (2014) focuses on green advertising. Similarly, the modeling of environmentally conscious consumers with investment in environmentally-friendly operations is proposed by Saha et al. (2017) for additional investment in preservation technology, by Dai and Zhang (2017) with differentiated prices, and by Zhang et al. (2017) and Liu and De Giovanni (2019) within a supply-chain context. Similar to these works, this article uses an optimal control model in the sustainability context where firms engage in pollution abatement efforts. We also model environmentally conscious consumers: those whose willingness to pay increases as the firm utilizes a greener production process. Unlike these works, this analysis focuses on why and when the optimal decisions (such as abatement, quantity, price, etc.) of the firm give rise to the green Veblen effect, rather than the behavior of the policies alone.

Optimal control applications to sustainability and pollution management with competition are well studied in the literature. Jørgensen et al. (2010) and Benchekroun and Long (2012) review dynamic games of pollution management and cooperative environmental management, respectively. El Ouardighi et al. (2019) investigate how different types of competition and strategy types impact the pollution production of two firms who invest in pollution abatement, and El Ouardighi et al. (2016bb) study how pollution

abatement levels are impacted by double marginalization. Jiao et al. (2021) examine how asymmetric regions abate air pollution. Other applications of differential games to pollution management include Liu et al. (2022); Teng et al. (2022); Wei and Luo (2020); Wei and Wang (2021). Similarly, this article utilizes optimal control to investigate pollution managed by a firm. However, this research does not consider competition.

Polluting production processes and abatement investment with environmental policies is also well studied in the literature. For example, Pan and Li (2015) account for only an emissions tax; Martín-Herrán and Rubio (2018a,b) model an emissions tax and a production subsidy; Arguedas et al. (2020) consider a pollution threshold beyond which a firm pays a fine. Under demand uncertainty, Bigerna et al. (2019) study green technology investments by a firm at various subsidy levels. Regarding pollution abatement under emissions permit policies, Li (2013, 2016) considers dynamic production-inventory policies to manage emission permit banking and pollution abatement efforts. In the same setting, Chang et al. (2018) determine the optimal abatement investment in a transboundary pollution game. Also studying transboundary pollution games, Jiang et al. (2019) investigate how introducing the eco-compensation criterion impacts pollution abatement efforts. De Frutos and Martín-Herrán (2019) and Vardar and Zaccour (2018) add a spatial dimension to a transboundary pollution model, where firms can invest in pollution abatement or adaptation over specific geographical regions. Following the above research, this contribution also considers a firms' abatement investment decisions under an environmental policy, in the considered case specifically, an emissions tax. Unlike the research discussed in this paragraph, this article uses a decision-theoretic model without any transboundary conditions.

Missing from the literature is an investigation of the existence and analysis of the green Veblen effect in the context of pollution abatement. That is, how pollution abatement activities by firms may give rise to the green Veblen effect in the presence of green consumers, the focus of this article. Our research specifically fills this gap by analyzing the conditions under which the green Veblen effect emerges.

2.2 Veblen Products

The third stream of literature concerns the Veblen (1899) effect. Veblen (1899) argues that conspicuous consumption is an honorific expense made to show one's wealth. Consequently, a conspicuous consumer increases their prestige by purchasing luxury, highly conspicuous, products (Kort et al., 2006); conspicuous

customers are willing to pay more for a functionally equivalent, luxury, product (Bagwell and Bernheim, 1996). Scholars identify a Veblen effect if price and demand move in the same direction (Wood, 1993). Similarly, the green Veblen effect is defined as price and demand evolving in the same direction. Such definition seems to contradict the Law of Demand which states that price and demand evolve in opposite directions. For the remainder of this section is first discussed research on conspicuous consumption, on optimal control applied to conspicuity, and conspicuous conservation. The conclusion highlights the differences and similarities between conspicuous conservation this work.

In a seminal article, Leibenstein (1950) accounts for conspicuous consumption in the theory of consumer demand, showing the role of social factors. Signaling models distinguishing exclusivity and conformity are applied to Veblen products. For instance, Bernheim (1994), Bagwell and Bernheim (1996), Corneo and Jeanne (1997), and Hopkins and Kornienko (2004) provide conditions for consumption of conspicuous products to signal wealth, and, in turn, boosting social status. Network effects also allow us to understand Veblen effects. Amaldoss and Jain (2005a), Amaldoss and Jain (2005b), Deb (2009), and Wang et al. (2017) assume consumption externalities, with snobs (leaders) and followers looking for privileged and standard products, respectively. Moldovanu et al. (2007) propose a principal-agent model, where conspicuity is defined relatively instead of absolutely, with the principal designing the organization while the agents care about their relative position in the organization. Aoyagi et al. (2016) examine a duopoly with consumers' preferences influenced by extrinsic valuation of the product. The relationship between advertising and the Veblen effect originates from Pepall and Reiff (2016). In line with this literature, this article analytically models the green Veblen effect. This literature use a static modeling approach, whereas this article uses a dynamic approach, to investigate the role of time. Some literature uses game-theoretic approaches. In contrast, we use a decision-theoretic model.

There is scant literature investigating conspicuous consumption with optimal control. An optimal control model allows for a dynamic investigation. In their founding contribution, Kort et al. (2006) offer a discussion of Veblen products; they assume an inverse demand function with the price linked to the brand image of the firm, in contrast to previous research where price is a firm decision. The management of conspicuous products during an economic recession by appropriate pricing is undertaken by Caulkins et al. (2011), Huschto et al. (2011), and Huschto and Sager (2014). Recently, Chenavaz and Eynan (2020) reconcile the Veblen effect with the Law of Demand, meaning conspicuous consumption does not

drive the Veblen effect. Their research emphasizes the intermediary role of advertising and goodwill and distinguishes between the partial and total effects of price on demand. Following the above research, the green Veblen effect is modeled within an optimal control framework. Further, the previous work investigates the Veblen effect for non-green products, which are mostly luxury products. In contrast, we model all products sold to green consumers that may experience the green Veblen effect.

Several empirical studies have documented conspicuous conservation. Griskevicius et al. (2010) examine the behavior of consumers to go “green to be seen,” showing their acceptance to pay more for greener products in order to signal their green concern. Sexton and Sexton (2014) find a higher willingness to pay for greener products and in the range of \$430-4,200 for the Toyota Prius, calling this form of conspicuous conservation the Prius effect. Conspicuous conservation has been further studied in other contexts by Cervellon (2013) for sustainable luxury and by Lisberg Jensen and Elahi (2017) for green clothing. Building on this empirical literature, the assumption is made that consumers are willing to pay more for a greener product in the analytical model.

In most analytic research mentioned above, the Veblen effect comes from conspicuous consumption. In contrast and building on the empirical research, this article considers a product sold to green consumers. We show that the green Veblen effect may be observed when selling a product to green consumers.

Most previous analytic research assumes the Veblen effect in the first place; extant empirical research show the existence of the green Veblen effect. In contrast, in {this research, the green Veblen effect is explained, as a result from the model. The green Veblen effect is also associated to the introductory/early stage of the product life cycle. In other words, previous research holds the *what* of the green Veblen effect; this research answers the *why* and *when* of the green Veblen effect.

3 Model Formulation

This section develops an optimal control model of a firm that accounts for the pollution it emits in the production process. For simplicity, market clearing prices are assumed, thus all production is sold (i.e., production equals demand). The firm decides on the investment effort in pollution abatement (or abatement effort), $u(t) \geq 0$, and on the production quantity (or demand), $q(t) \geq 0$, over time, t . For tractability, we assume the production of an infinitely divisible product. Both abatement effort and

production quantity (or quantity) decisions affect the stock (level) of pollution, $S(t) \geq 0$. More precisely, current pollution (or rate or flow of pollution), $\frac{dS}{dt}$, may take any real value, decrease with the abatement effort and increase with the quantity. The price paid by consumers decreases with quantity, modelled with an inverse demand function. As with market clearing prices, using an inverse demand function is equivalent to using a demand function. Recall, the consideration of green consumers. More precisely, green consumers are willing to pay more for greener products, that is for products with a less polluting production process. Consequently, the price paid by green consumers is dictated by $P(q(t), S(t)) \geq 0$. Producing more means that the firm sells more, but at a lower price, because 1) more products are on the market and 2) pollution increases. Abatement effort in greener processes translates into a greater fixed cost, but it also increases the selling price. Note that abatement effort and quantity affect future pollution, triggering a dynamic trade-off with each decision of the firm. Indeed, current profit is linked to abatement effort and quantity decisions. Whereas future profit is also tied to the future pollution level, determined by current and future abatement efforts and quantity decisions. Such intertemporal elements lend themselves to dynamic analysis.

The next subsections offer an optimal control framework to investigate the model. Let the length of the product life cycle, T , be fixed and finite, with time t in $[0, T]$ continuous. Table 2 gives the notations used in this section.

3.1 Pollution Dynamics

The dynamics of stock of pollution, $S(t)$, writes for each t in $(0, T)$

$$\frac{dS}{dt}(t) = \alpha q(t) - \beta u(t) - \delta S(t), \quad (1)$$

with the initial stock of pollution $S(0) = S_0$ and the parameters $\alpha, \beta > 0$ and $\delta \geq 0$.

For simplicity, the remainder of the paper omits arguments from the functions whenever there is no confusion, in particular the time argument. Current pollution increases with quantity, q , (Martín-Herrán and Rubio, 2018a,b), and decreases with abatement effort, u (Chang et al., 2018; De Frutos and Martín-Herrán, 2019; Li, 2013, 2016; Li and Pan, 2014, El Ouardighi et al. 2016bb,2019). If $\delta > 0$, then stock of pollution is naturally degraded in the environment. In this case, stock of pollution decreases over time,

Table 2: Main Notations

T	= length of the product life cycle (parameter),
r	= discount rate (parameter),
τ	= tax rate on pollution emissions (parameter),
α	= impact of production quantity on pollution increase (parameter),
β	= impact of abatement effort on pollution decrease (parameter),
δ	= autonomous degradation of pollution (parameter),
$u(t)$	= pollution abatement effort at time t (control variable),
$q(t)$	= product quantity produced at time t (control variable),
$S(t)$	= stock of pollution at time t (state variable),
$\frac{dS}{dt}$	= $\alpha q - \beta u - \delta S$ is the pollution dynamics; referred to as current pollution,
c_0	= base marginal production cost (parameter),
c_1	= pollution sensitivity of marginal production cost (parameter),
$C\left(\frac{dS}{dt}\right)$	= $c_0 - c_1 \frac{dS}{dt}$ = pollution-dependent marginal production cost,
$\lambda(t)$	= current-value of stock of pollution shadow price at time t ,
$P(q, S)$	= inverse demand function,
$\pi(u, q, S)$	= $(P - c_0)q - (\tau - c_1)(\alpha q - \beta u - \delta S) - \frac{1}{2}u^2$ = current profit,
$H(u, q, S, \lambda)$	= $\pi + \lambda \frac{dS}{dt}$ = current-value Hamiltonian.

The time index is dropped where appropriate.

as often assumed (Chang et al., 2018; Li and Pan, 2014; Martín-Herrán and Rubio, 2018a; Nkuiya and Costello, 2016). If $\delta = 0$, as implicitly in El Ouardighi et al. (2016bb,2019), then stock of pollution does not naturally degrade over time and the only way to address stock of pollution is through abatement. In this case, any stock of pollution is cumulative and cannot naturally decrease.¹

3.2 Consumer Behavior and Market Price

This paper models green consumers on a continuum along which consumers have different levels of greenness. As consumers become greener, their willingness to pay for greener products increases (Binder and Blankenberg, 2017; Dawid et al., 2020; Griskevicius et al., 2010; Lisberg Jensen and Elahi, 2017; Sexton and Sexton, 2014; Yao et al., 2022). Similar to Kort et al. (2006) and Chenavaz and Jasimuddin (2017), recall in the model, the price is determined by an inverse demand function. As mentioned above, the price, P , depends on the quantity sold and on the stock of pollution, that is for each $q, S > 0$,

$$P = P(q, S). \tag{2}$$

¹If $\delta < 0$, then the environment is a natural generator of pollution El Ouardighi et al. (2016a,2018a,b), e.g., forest fires and volcanoes. For simplicity of result interpretation, this case is not explicitly considered.

The price decreases (strictly) with the quantity sold, q , following the Law of Demand. As with green consumers, the price decreases (weakly) with stock of pollution, S . That is, consumers may care about current pollution or they may be indifferent. Formally, for each q , $S > 0$,

$$\frac{\partial P}{\partial q} < 0, \quad \frac{\partial P}{\partial S} \leq 0. \quad (3)$$

The inverse demand function, (2), and associated properties, (3), represent a general formulation allowing flexibility in the relationships between price, quantity, and stock of pollution. The green Veblen effect, may seem to contradict the properties in (3). For clarity, the following definitions clarify the two different measures of price impact on quantity.

Definition 1. *The **Law of Demand** is satisfied when the direct effect of price on quantity is negative. Formally, $\frac{\partial q}{\partial P} < 0$.*

Definition 2. *There is a **green Veblen effect** when the total effect of price on quantity is positive. Formally, $\frac{dq}{dP} > 0$.*

Remark 1. *Note that the Law of Demand represents a standard assumption made in (3). In contrast, the green Veblen effect, if it exists, corresponds to a result determined by Proposition 5. Contrary to intuition, there is a priori no contradiction between the Law of Demand and the green Veblen effect. Indeed, they measure different impacts of price on demand.*

The properties of the inverse demand function are not too restrictive. A popular parametric example of equation (2), also satisfying properties (3), is the linear demand function

$$P = m - aq - bS. \quad (4)$$

In equation (4), $m > 0$ is the market price potential and $a > 0$ and $b \geq 0$ are the price sensitivity to quantity and stock of pollution, respectively. A similar linear inverse demand function is used in Kort et al. (2006) in the context of brand image in the fashion industry.

Remark 2. *The demand function assumed in equation (2), with properties (3), and the parametric example in equation (4) satisfy the Law of Demand, according to which price and quantity evolve in opposite*

directions. In particular, price decreases with greater quantity. In other words, it is assumed that the Law of Demand holds.

3.3 Marginal Production Cost

By assumption, a greener production process pleases green consumers, since a greener process pollutes less (Bi et al., 2017; Dawid et al., 2020; Krass et al., 2013; Nouira et al., 2014). Thus, green consumers incentivize firms to invest in greener production processes (Dawid et al., 2020; De Giovanni, 2014; Saha et al., 2017).

The marginal production cost function, $C\left(\frac{dS}{dt}\frac{1}{q}\right) \geq 0$, depends on the current pollution per unit, $\frac{dS}{dt}\frac{1}{q}$. Consequently, $C = C\left(\frac{dS}{dt}\frac{1}{q}\right)$ is the current marginal production cost from producing q units, resulting in $\frac{dS}{dt}$ emissions, at time t . To appeal to green consumers, the firm must invest in pollution abatement, resulting in lower current pollution per unit. In other words, polluting less per unit produced increases the marginal production cost, while polluting more per unit produced decreases the marginal production cost (Krass et al., 2013). Therefore, the marginal production cost decreases with the current pollution per product, that is $C' \leq 0$. A variable marginal production cost assumption is common in the dynamic optimization literature (Ben-Daya et al., 2008; Li et al., 2004; Ou and Feng, 2019).

To simplify the analysis, a linear marginal production cost is defined, satisfying the previous cost function properties:

$$C\left(\frac{dS}{dt}\frac{1}{q}\right) = c_0 - c_1\frac{dS}{dt}\frac{1}{q}, \quad (5)$$

with the base marginal production cost, $c_0 \geq 0$, and the cost savings from current pollution per unit produced, $c_1 \geq 0$. Roughly speaking, c_1 represents the added per unit cost of a less polluting process, that is the marginal cost of a greener process. Parameters c_0 and c_1 are such that $C \geq 0$, that is $\frac{c_0}{c_1} \geq \frac{dS}{dt}\frac{1}{q}$. In the vein of Sana (2010) and Kutzner and Kiesmüller (2013), the model assumes a linear marginal production cost.

The firm pays a tax rate, $\tau \geq 0$, associated to the current pollution (Bencheikroun and Van Long, 1998, 2002; Krass et al., 2013; Martín-Herrán and Rubio, 2018a,b). The assumption

$$\tau \geq c_1, \quad (6)$$

represents a technical condition required for an interior solution. This assumption implies that there is no cost-side incentive for the firm to pollute more, even if the marginal production cost decreases with more emissions. In other words, the tax on current pollution is high enough that it cannot be overcompensated by a lower production cost, if the firm uses a more polluting production process. With greater current pollution, the pollution cost may either increase (case $\tau > c_1$) or remain the same (case $\tau = c_1$, see Remark 3). The net cost (per unit) of current pollution is $\tau - c_1$, satisfying $\tau - c_1 \geq 0$.

3.4 Profit

The current profit function, π in \mathbb{R} , depends on abatement effort, u , quantity, q , stock of pollution, S , that is $\pi = \pi(u, q, S)$. More precisely, the current profit is measured by the markup (price minus marginal production cost) multiplied by the quantity, minus the tax on current pollution and the cost of abatement effort:

$$\pi(u, q, S) = \left[P(q, S) - C \left(\frac{dS}{dt} \right) \right] q - \tau \frac{dS}{dt} - \frac{1}{2} u^2. \quad (7)$$

The cost of pollution abatement effort is a quadratic function, similar to Arora and Ceccagnoli (2006); Atasu and Subramanian (2012). Quadratic cost is also common in the optimal control literature Arguedas et al. (2020); Dai and Zhang (2017); De Giovanni (2014); El Ouardighi et al. (2018a); Jiang et al. (2019); Li (2014); Pan and Li (2015); Peng et al. (2019); Vardar and Zaccour (2018); Zhang et al. (2017). Assuming profit is concave in u and q implies a concave relation between S and u . (See Sethi et al. 2008 for a similar interpretation.)

Substituting the pollution dynamics (1) and the cost function (5), into equation (7) and simplifying results in:

$$\pi(u, q, S) = [P(q, S) - c_0]q - (\tau - c_1)[\alpha q - \beta u - \delta S] - \frac{1}{2} u^2. \quad (8)$$

Eventually, the profit function corresponds to the markup multiplied by the quantity, minus the net cost of pollution multiplied by the current pollution, minus the cost of pollution abatement.

Remark 3. *The profit function, (8), reveals that the tax on current pollution, τ , and the cost of a less polluting process per unit produced, c_1 , exert impacts on profit of same magnitude, but of opposite sign. Indeed, there is $\frac{\partial \pi}{\partial \tau} = -\frac{\partial \pi}{\partial c_1}$, which is equal to the current pollution, $\frac{dS}{dt}$, according to (1).*

3.5 Firm's Dynamic Optimization Problem

The firm maximizes the intertemporal profit over the product life cycle, $[0, T]$, by simultaneously choosing the abatement effort, u , and the quantity, q , over time, t . In the maximization process, the firm accounts for the dynamics of stock of pollution, S . Let the discount rate be $r \geq 0$. The objective function of the firm is written as:

$$\begin{aligned} & \max_{u(\cdot), q(\cdot) \geq 0} \int_0^T e^{-rt} \pi(u(t), q(t), S(t)) dt, \\ & \text{subject to } \frac{dS}{dt}(t) = \alpha q(t) - \beta u(t) - \delta S(t), \text{ for each } t \text{ in } [0, T], \text{ with } S(0) = S_0. \end{aligned} \quad (9)$$

4 Model Analysis

This section analyzes the model, providing the optimality conditions. Let $\lambda(t)$ in \mathbb{R} , be the co-state variable or stock of pollution shadow price dynamics at time t . The Hamiltonian, H , measures the intertemporal profit, adding the current profit, (8), to the future profit $\lambda \frac{dS}{dt}$, with $\frac{dS}{dt}$ given by (1). The Hamiltonian writes² as:

$$H(u, q, S, \lambda) = [P(q, S) - c_0]q + (\lambda + c_1 - \tau)(\alpha q - \beta u - \delta S) - \frac{1}{2}u^2.$$

Assuming their existence, the interest is restricted to inner solutions for the measurable controls: abatement effort, u , and quantity, q . Thus, the profit-maximizing decisions have to satisfy the necessary first- and second-order conditions of the Hamiltonian (10a)-(10e). Also, the maximum principle imposes (10f). for each $u > 0$, $q > 0$, $S > 0$, λ in \mathbb{R} , and t in $(0, T)$, there is:

²Before the simplification and with the explicit account for time, the Hamiltonian reads as $H(u(t), q(t), S(t), \lambda(t)) = [P(q(t), S(t)) - c_0]q(t) + (c_1 - \tau)[\alpha q(t) - \beta u(t) - \delta S(t)] - \frac{1}{2}[u(t)]^2 + \lambda(t)[\alpha q(t) - \beta u(t) - \delta S(t)]$.

$$\frac{\partial H}{\partial u} = 0 \implies u = \beta(\tau - c_1 - \lambda), \quad (10a)$$

$$\frac{\partial H}{\partial q} = 0 \implies P + q \frac{\partial P}{\partial q} - \alpha(\tau - c_1 - \lambda) - c_0 = 0, \quad (10b)$$

$$\frac{\partial^2 H}{\partial u^2} < 0 \implies -1 < 0, \quad (10c)$$

$$\frac{\partial^2 H}{\partial q^2} < 0 \implies -q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q} > 0, \quad (10d)$$

$$\frac{\partial^2 H}{\partial u^2} \frac{\partial^2 H}{\partial q^2} - \left(\frac{\partial^2 H}{\partial u \partial q} \right)^2 > 0 \implies -q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q} > 0, \quad (10e)$$

$$\frac{d\lambda}{dt} = r\lambda - \frac{\partial H}{\partial S} \implies \frac{d\lambda}{dt} = r\lambda - q \frac{\partial P}{\partial S} + \delta(\tau - c_1 - \lambda), \quad (10f)$$

with the transversality condition $\lambda(T) = 0$.

Let $u^*(q)$ denote the optimal abatement effort, for a given quantity, q , which corresponds to (10a). Similarly, let $q^*(u)$ denote the quantity for a given abatement effort, satisfying (10b). The intertemporal profit, H , is maximized with abatement effort and quantity pair such that $(u^*, q^*) = (u^*(q), q^*(u))$. In the remainder of the article, the abatement effort and quantity are said to be *optimal* in the sense of maximizing the intertemporal profit. For ease of exposition, the * superscript notation is often omitted where there is no ambiguity.

5 Analytic Results

This section presents the analytical results. Recall that this article establishes the relationship between change in quantity and change in price, as it is studying the green Veblen effect. The green Veblen effect is derived in Section 5.2. However, the optimal decisions with respect to time is determined first in Section 5.1. The section concludes with an example of the linear demand function in Section 5.3. For completeness, Appendix A derives the value of the shadow price and its sign, along with the abatement effort and price.

5.1 Optimal Policies and Relationships

This section first determines the market clearing price for a general demand function. This result is crucial in establishing the relationship between optimal price and optimal quantity, a relationship needed in defining the green Veblen effect. This section later determines the dynamics for quantity and abatement effort, allowing to identify when the two are complements or substitutes.

Proposition 1. *The optimal abatement effort and price read for each t in $[0, T]$ as:*

$$u(t) = \beta \left[\tau - c_1 - \int_t^T e^{(\delta-r)(x-t)} \left(q(x) \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx \right], \quad (11a)$$

$$P(t) = -\frac{\partial P}{\partial q} q + c_0 + \alpha \left[\tau - c_1 - \int_t^T e^{(\delta-r)(x-t)} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx \right]. \quad (11b)$$

Proof. Substitute λ from Lemma 2 in Lemma 4. □

Proposition 1 provides formulas to compute the optimal values of the control u and of the variable of interest P . Note that the results are not in closed form, as (11a)-(11b) depend on q . Yet, the formulas allow for comparative statics.

Following (11a), the abatement effort, u increases with the impact of the abatement effort, β , the tax rate, τ , and the degradation of pollution, δ , ($\frac{\partial u}{\partial \beta} > 0$, $\frac{\partial u}{\partial \tau} > 0$, and $\frac{\partial u}{\partial \delta} > 0$). Abatement effort is independent of the base unit cost, c_0 , and the impact of quantity on pollution, α , ($\frac{\partial u}{\partial c_0} = 0$ and $\frac{\partial u}{\partial \alpha} = 0$). It decreases with the pollution sensitivity of the cost, c_1 , and the discount factor, r , ($\frac{\partial u}{\partial c_1} < 0$ and $\frac{\partial u}{\partial r} < 0$). Further, if the firm is myopic, $r \rightarrow \infty$, or at the end of the product's life cycle, $t = T$, the abatement effort is still positive with $u = \beta(\tau - c_1)$. Consequently, the firm always invests in pollution abatement, except if $\tau = c_1$, then, the firm is indifferent to additional pollution.

Following (11b), price, P , increases with the impact of quantity on pollution, α , the tax rate, τ , and the degradation of pollution, δ , ($\frac{\partial P}{\partial \alpha} > 0$, $\frac{\partial P}{\partial \tau} > 0$, and $\frac{\partial P}{\partial \delta} > 0$). As expected, it increases with the base unit cost, c_0 , but, curiously, it decreases with the pollution sensitivity of the cost, c_1 , ($\frac{\partial P}{\partial c_0} > 0$ and $\frac{\partial P}{\partial c_1} < 0$). Finally, the price is independent of the impact of the abatement effort, β , and decreases with the discount factor, r , ($\frac{\partial P}{\partial \beta} = 0$ and $\frac{\partial P}{\partial r} < 0$).

The insights of Proposition 1 differ, but remain consistent with extant academic literature (Li, 2013, 2014, 2016). For instance, the study by Aïd and Biagini (2021) revealed that the optimal abatement

effort increases with the tax rate and the marginal pollution damage. This finding aligns with the results presented in (11a), where the abatement effort, u , increases with the tax rate, τ , and the degradation of pollution, δ . Additionally, the survey of Chen et al. (2020) found that product prices increase with the marginal pollution damage. This finding is in line with (11b), where the price, P , increases with pollution degradation, δ .

In a nutshell, Proposition 1 provides useful formulas to compute the optimal abatement effort and price in a dynamic setting, and the results correspond to those in the literature.

We now turn the interest to the optimal relationship between abatement effort and price. Let the price elasticity of demand be $e_P = -\frac{\partial q}{\partial P} \frac{P}{q}$.

Proposition 2. *For the general demand function (2), the optimal price for t in $[0, T]$ is:*

$$P = \frac{e_P}{e_P - 1} \left(c_0 + \frac{\alpha}{\beta} u \right), \quad (12)$$

with u given by Proposition 1.

Proof. Comparing the first-order conditions (10a)-(10b) and eliminating λ yields $P = -\frac{\partial P}{\partial q} q + c_0 + \frac{\alpha}{\beta} u$. Then dividing both sides by P and introducing the elasticity notation yields $1 = \frac{1}{e_P} + \frac{1}{P} (c_0 + \frac{\alpha}{\beta} u)$. Then rearranging provides the result. \square

Proposition 2 generalizes the static pricing rule of Amoroso-Robinson in a dynamic context and the rule of Kalish (1983, equation (3), page 138) in a pollution abatement context. The Amoroso-Robinson static pricing rule is

$$P = \frac{e_P}{e_P - 1} c,$$

where c is the marginal cost. Kalish (1983) extends the Amoroso-Robinson static pricing rule to the dynamic setting to find the optimal price as

$$P = \frac{e_P}{e_P - 1} (c - \lambda).$$

Note that the setting of this article may derive an analog to Kalish (1983) by substituting (24b) into (12) and derive:

$$P = \frac{e_P}{e_P - 1} (c_0 + \alpha[\tau - c_1 - \lambda]). \quad (13)$$

Proposition 2 is a dynamic analog of the classic static pricing rule of the monopolist, with markup over marginal cost tied to demand elasticities, similar to the preceding results. As seen in equation (13), part of the impact of abatement effort on price is static, via the net cost on current pollution, $\tau - c_1$, paid at time t . Another part of the impact is dynamic, via the stock of pollution shadow price, λ , which affects future selling price and net cost, and in turn, future profits.

Proposition 2 presents the optimal relationship among the price, P , and the control variables, u and q . However, it does not reveal the conditions under which the variables change over time. When Proposition 2 holds, then marginal revenues equal marginal costs at each instant of time. To maximize profits, any change in marginal revenue and in marginal cost must compensate each other. The interplay between quantity and pollution abatement effort captured in (12) is not evident in (2). It is thus interesting to examine the relationship among quantity, abatement effort, and stock of pollution. To offer a dynamic analysis on this optimal relationship and gather managerial insights, let us now turn to the time derivative of the first order conditions, (10a)-(10b).

Proposition 3. *The optimal relationship among the dynamics of quantity, abatement effort, and stock of pollution for t in $(0, T)$ reads as*

$$\frac{dq}{dt} \left(\underbrace{-q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q}}_{+} \right) + \frac{du}{dt} \underbrace{\frac{\alpha}{\beta}}_{+} = \frac{dS}{dt} \left(\underbrace{\frac{\partial P}{\partial S}}_{-} + \underbrace{q \frac{\partial^2 P}{\partial q \partial S}}_{\pm} \right). \quad (14)$$

Proof. The time derivative of the inverse demand function is: $\frac{dP}{dt}(q(t), S(t)) = \frac{\partial P}{\partial q} \frac{dq}{dt} + \frac{\partial P}{\partial S} \frac{dS}{dt}$. The rearranged time derivative of (10b) is: $\frac{dq}{dt} \left(-q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q} \right) = \frac{dS}{dt} \left(\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S} \right) + \alpha \frac{d\lambda}{dt}$, noting that $\frac{d}{dt} \left(\frac{\partial P}{\partial q} \right) = \frac{\partial^2 P}{\partial q^2} \frac{dq}{dt} + \frac{\partial^2 P}{\partial q \partial S} \frac{dS}{dt}$. The time derivative of (10a) offers $\frac{d\lambda}{dt} = -\frac{1}{\beta} \frac{du}{dt}$. Substituting $\frac{d\lambda}{dt}$ in the time derivative of (10b) and rearranging completes the proof. \square

Proposition 3 examines the relationship among the dynamics of the controls, q and u , on the left hand-side and that of the state, S , on the right hand-side. On the left hand-side of (14), the second factor of the first term, $-q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q}$, is positive because of the second-order condition (10d) and the second factor of the second term, $\frac{\alpha}{\beta}$, is positive as a ratio of two positive parameters. On the right hand-side, the sign of the second factor, $\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S}$, is unknown and depends on the inverse demand function (2) and the cross derivative assumptions (3). There is no direct role of price in Proposition 3, but an indirect role.

Indeed, the slope of the inverse demand function appears in both sides of (14). The sign of $\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S}$ is an important element determining the relationship between u and q , as both impact the price and stock of pollution (cf. Proposition 5).

We now investigate the dynamics of abatement effort with respect to time.

Proposition 4. *The dynamics of abatement effort read for t in $(0, T)$,*

$$\frac{du}{dt}(t) = \beta \left[\underbrace{q(t) \frac{\partial P}{\partial S}}_{-} \underbrace{-\delta(\tau - c_1)}_{-} + \underbrace{(\delta - r)}_{\pm} \underbrace{\lambda(t)}_{-} \right], \quad (15)$$

with λ from Lemma 2.

Proof. Considering (10a), then it is obvious that $\frac{du}{dt} = -\beta \frac{d\lambda}{dt}$. Substituting $\frac{d\lambda}{dt}$ from (10f) offers the result. \square

There are three terms in the second factor of the right hand side of (15). The first and second terms, $q(t) \frac{\partial P}{\partial S} - \delta(\tau - c_1)$, exert a negative influence over the whole product life cycle. The third term, $(\delta - r)\lambda(t)$, is positive if $r > \delta$ and negative if $r < \delta$, but loses influence over time, vanishing at the end of the product life cycle as $\lambda(t)$ tends to zero as t approaches T . Therefore, u may increase or decrease at the beginning of the product life cycle; it must decrease at the end of the product life cycle. On the one hand, if $r > \delta$ and r is ‘large enough,’ then u is more likely to increase. On the other hand, if $r < \delta$, then u decreases over time. In the case the firm is far-sighted, $r = 0$, then u always decreases over time. However, for a nearly myopic firm, $r \gg 0$, then u first increases and then decreases.

Taken together, Propositions 3 and 4 make a dynamic relationship between several operational variables. Such relationships are classical between marketing-mix levers, such as price, quality, advertising, goodwill, and demand (Chenavaz, 2017; Chenavaz and Eynan, 2020; Chenavaz and Jasimuddin, 2017; Ni and Li, 2019; Vörös, 2019). The distinguishing feature here is that the relationship appears between quantity, abatement effort, and stock of pollution, which are sustainable operations levers. To our knowledge, this feature is absent from previous literature on optimal control applications.

5.2 Green Veblen Effect

Recall the inverse demand function, (2), $P = P(q(t), S(t))$. The time derivative of the inverse demand function, as computed in the proof of Proposition 3, is

$$\frac{dP}{dt} = \frac{\partial P}{\partial q} \frac{dq}{dt} + \frac{\partial P}{\partial S} \frac{dS}{dt}. \quad (16)$$

Lemma 1. *The total effect of quantity on price for each q , $S > 0$ is,*

$$\frac{dP}{dq} = \underbrace{\frac{\partial P}{\partial q}}_{-} + \underbrace{\frac{\partial P}{\partial S}}_{-} \underbrace{\frac{dS}{dq}}_{\pm}. \quad (17)$$

Proof. Assume $\frac{dq}{dt} \neq 0$ and the state S depend on the controls u and q . Recalling the optimality notation, there is $S^* = S^*(u, q)$. Because of an optimal relationship between the controls, there is also $u^* = u^*(q)$. Therefore, $S^* = S^*(u^*(q), q) = S^*(q)$, and S only depends on q . Omit now the optimality notation. Apply the time elimination method of Mulligan and Sala-i Martin (1991) to use $\frac{\frac{dP}{dt}}{\frac{dq}{dt}} = \frac{dP}{dq}$ and $\frac{\frac{dS}{dt}}{\frac{dq}{dt}} = \frac{dS}{dq}$. Substitute the last elements in (16) and rearrange. \square

Lemma 1 clarifies the different elements at play to understand the green Veblen effect. It distinguishes the production effects on price: the total production effect, $\frac{dP}{dq}$, the direct production effect, $\frac{\partial P}{\partial q}$, and the indirect production effect, $\frac{\partial P}{\partial S} \frac{dS}{dq}$. Obviously, the total production effect on price sums the direct and indirect production effects. The indirect production effect represents the multiple of the direct effect of pollution on price, $\frac{\partial P}{\partial S}$, and the total effect of quantity on pollution, $\frac{dS}{dq}$. The indirect production effect on price exists because of the intermediary role of pollution on the production-price relationship. The rationale is that quantity impacts pollution, which in turn, also affects price. Both direct effects $\frac{\partial P}{\partial q}$ and $\frac{\partial P}{\partial S}$ are assumed negative in (3). On the contrary, both total effects $\frac{dP}{dq}$ and $\frac{dS}{dq}$ correspond to results, which may be either positive or negative. Consequently, even if $\frac{\partial P}{\partial q}$ is negative by assumption, $\frac{dP}{dq}$ may be positive or negative, depending on the indirect production effect. We now visualize how the different effects may give rise to the green Veblen effect.

Figure 1 provides intuition of the effects at play for the green Veblen effect. More precisely, Figure 1 depicts the optimal price, P^* , for a given quantity (or demand), q , in Figure 1(a), and the new optimal price, $P_2^{*'}$, after an increase in quantity, q' in Figure 1(b). When quantity increases from q to q' , the direct

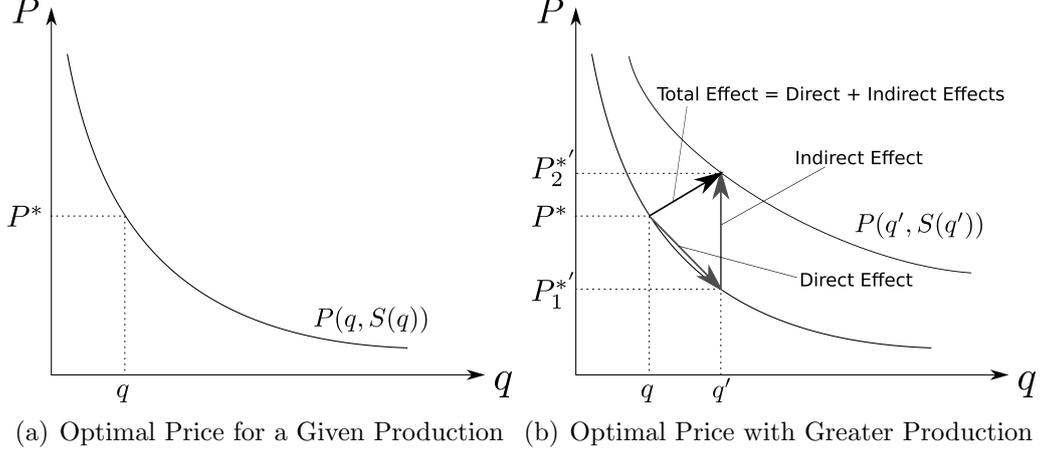


Figure 1: The Case of a Green Veblen Effect

effect lowers the price from P^* to P_1^{*} , along the demand function, $P(q, S(q))$. An indirect effect also exerts influence through the intermediary role of current pollution. The indirect effect may be positive according to Lemma 1, if the *total* effect of quantity on the stock of pollution is negative, that is $\frac{dS}{dq} < 0$. P_2^{*} represents the optimal price, when both the direct and indirect effects are taken into account. If $\frac{dS}{dq} < 0$, then the indirect effect is positive and the inverse demand function shifts up. The positive indirect effect mitigates the lowering of price due to the direct effect ($P_2^{*} > P_1^{*}$). Interestingly, if the indirect production effect is strong enough, it outweighs the direct effect and the optimal price increases, as depicted in Figure 1(b) ($P_2^{*} > P^*$). When the indirect production effect is positive and sufficiently large, and current pollution decreases with quantity, then price increases with demand and the green Veblen effect is observed. From the results, it follows that the shape of the demand function, that is its slope (first-order derivative) and curvature (second-order derivative) affect the existence and magnitude of the green Veblen effect.

In the case of a strong indirect effect, the green Veblen effect is observed. Specifically, it appears that, after higher quantity from q to q' , higher prices emerge—price increases from P^* to P_2^{*} . Importantly, this result is compatible with the Law of Demand, for which quantity increases as price decreases from P^* to P_1^{*} in usual settings, when the indirect effect is not strong. The positive price-production relationship in the green Veblen effect does not arise from conspicuous consumption, as is common the Veblen effect literature. Instead, the green Veblen effect comes from price increasing with quantity, as a result of the firm's quantity and abatement effort policies, linked via price.

Remark 4. *The necessary and sufficient condition for the green Veblen effect to appear is that the total*

effect of quantity on stock of pollution, $\frac{dS}{dq}$, must be negative and “strong enough.” Formally, assuming $\frac{\partial P}{\partial S} \neq 0$, there is for each q , $S > 0$,

$$\frac{dP}{dq} > 0 \iff \frac{dS}{dq} < -\frac{\frac{\partial P}{\partial q}}{\frac{\partial P}{\partial S}} < 0.$$

Recalling quantity equals demand, the managerial implication is that a green Veblen effect (the result $\frac{dP}{dq} > 0$) is compatible with the Law of Demand (the assumption $\frac{\partial P}{\partial q} < 0$).

To understand the green Veblen effect, the right hand-side of equation (17) must be better understood. As we already know $\frac{\partial P}{\partial q}$ and $\frac{\partial P}{\partial S}$, we only need to further investigate $\frac{dS}{dq}$, the total effect of quantity on stock of pollution. To determine $\frac{dS}{dq}$, both sides of (14) are divided by $\frac{dq}{dt}$. Note that, similar to the proof of Lemma 1, is the use of $\frac{du}{dq} = \frac{du}{dq}$ and $\frac{dS}{dq} = \frac{dS}{dq}$. Rearranging (14) after the division and substitutions yields

$$\frac{dS}{dq} = \frac{1}{\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S}} \left(\frac{\alpha}{\beta} \frac{du}{dq} - q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q} \right). \quad (18)$$

Equation (18) captures the intermediary role of stock of pollution between quantity and price, whose relationship defines the green Veblen effect. Note that the sign of $\frac{dS}{dq}$ directly depends on the sign of $\frac{du}{dq}$, that is of the complementarity or substitutability between abatement effort and quantity.

Proposition 5. *The relationship between price and demand, for each q , $S > 0$ is given by,*

$$\frac{dP}{dq} = \underbrace{\frac{\partial P}{\partial q}}_{-} + \frac{\overbrace{\frac{\partial P}{\partial S}}}{\underbrace{\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S}}_{\pm}} \left(\underbrace{\frac{\alpha}{\beta}}_{+} \underbrace{\frac{du}{dq}}_{\pm} \underbrace{-q \frac{\partial^2 P}{\partial q^2} - 2 \frac{\partial P}{\partial q}}_{+} \right). \quad (19)$$

Proof. Substitute (18) in Lemma 1. □

Proposition 5 offers the complete structure for the green Veblen effect to exert influence. The green Veblen effect is based on pollution dynamics, $\frac{\alpha}{\beta}$, and of the relationship between abatement effort and quantity, $\frac{du}{dq}$. As expected in the discussion of Figure 1, the green Veblen effect is also linked to the features of the inverse demand function. Indeed, it depends both on the first- and second-order derivatives of P with respect to q .

Proposition 5 is an analog to Chenavaz and Eynan (2020, Equation (14) and Proposition 4) for the green production setting instead of the advertising setting. Note that the Veblen effect is also discussed recently in Yao et al. (2022) with a consumer's environmental concern and in Mukherjee et al. (2023) with product recalls.

We now combine the previous, intermediary, results to examine the factors determining the relationship between price and quantity. Proposition 5 and Lemma 1 together show how consumer behavior, captured by the inverse demand function (2), responds to two different forces. On the one hand, quantity directly impacts the price: price decreases with quantity, $\frac{\partial P}{\partial q} < 0$, conforming with the Law of Demand assumed in (3). On the other hand, quantity also indirectly affects price through the intermediary effect of stock of pollution on the price-production relationship. Specifically, quantity influences stock of pollution, $\frac{dS}{dq}$, with further repercussions on the price, $\frac{\partial P}{\partial S}$. The two forces exert opposite influences when the indirect effect of quantity on price is positive. An increase in quantity may strongly decrease stock of pollution, due to optimal relationship between quantity and abatement effort. With sufficient decrease in stock of pollution, price will increase. Put differently, if the indirect effect is strong enough, outweighing the direct production effect, then quantity and price evolve in the same direction, and the green Veblen effect is observed.

Remark 5. *Our model does not consider the source of motivation for consumers towards less stock of pollution. Specifically, consumers may be either intrinsically (altruistic conservation) or extrinsically (conspicuous conservation) motivated to conserve the environment. The green Veblen effect appears because of the sole interest of consumers toward less stock of pollution. In other words, conspicuous conservation may explain the green Veblen effect, but it is not a necessary condition for its existence.*

5.3 Example: Linear Demand Function

This subsection uses a linear demand function as a parametric example. That is, it trades-off generality for more actionable insights.

We now examine the linear demand function, $P = m - aq(t) - bS(t)$ defined in (4), which exhibits

$$\frac{\partial P}{\partial q} = -a < 0, \quad \frac{\partial P}{\partial S} = -b \leq 0, \quad \frac{\partial^2 P}{\partial q^2} = \frac{\partial^2 P}{\partial q \partial S} = 0. \quad (20)$$

Note that the optimality conditions (10a)-(10e) are verified with the example. We substitute (20) in the previous results and obtain clear-cut managerial implications.

Equation (18) provides the total effect of quantity on stock of pollution

$$\frac{dS}{dq} = -\frac{1}{b} \left(\frac{\alpha}{\beta} \frac{du}{dq} + 2a \right),$$

which implies:

1. If $\frac{du}{dq} > 0$ (u and q complements), then $\frac{dS}{dq} < 0$,
2. If $\frac{du}{dq} < 0$ (u and q substitutes) and
 - (a) $\frac{du}{dq} > -2a\frac{\beta}{\alpha}$ (“weak” substitution), then $\frac{dS}{dq} < 0$,
 - (b) $\frac{du}{dq} < -2a\frac{\beta}{\alpha}$ (“strong” substitution), then $\frac{dS}{dq} > 0$.

Proposition 3 yields the links between the dynamics of quantity, abatement effort, and stock of pollution

$$2a \frac{dq}{dt} + \frac{\alpha}{\beta} \frac{du}{dt} = -b \frac{dS}{dt}.$$

The linear demand function results in a proportional relationship between the control and state variables. Proportional relationships tend to be easy to manage and visualize via operational rules and policies.

Remark 4 provides the green Veblen condition on the pollution-production relationship

$$\frac{dP}{dq} > 0 \iff \frac{dS}{dq} < -\frac{a}{b} < 0. \quad (21)$$

From the general demand case, $\frac{dS}{dq}$ must be sufficiently negative. In the linear demand case, the ratio $-\frac{a}{b}$ represents the maximum value of $\frac{dS}{dq}$ for the green Veblen to exist. The ratio $-\frac{a}{b}$ represents the relative impacts of S and q on price coming from the linear demand function.

Proposition 5 offers

$$\frac{dP}{dq} = \frac{\alpha}{\beta} \frac{du}{dq} + a,$$

which imposes the equivalent green Veblen condition on the abatement effort-production relationship

$$\frac{dP}{dq} > 0 \iff \frac{du}{dq} > -a\frac{\beta}{\alpha}. \quad (22)$$

The abatement effort-production relationship, $\frac{du}{dq}$, may be negative, meaning abatement effort and quantity are substitutes. However, for the product exhibit the green Veblen effect, the abatement effort and quantity cannot be “too” substitutable. It immediately follows from (22), that the product exhibits the green Veblen effect if u and q are complements, $\frac{du}{dq} > 0$, if u and q are independent, $\frac{du}{dq} = 0$, or if u and q are not too substitutable, $\frac{du}{dq} < 0$ and $|\frac{du}{dq}| < a\frac{\beta}{\alpha}$.

Remark 6. *At the end of the product life cycle, the firm cares less about the current pollution, which has two opposite consequences. On the one hand, according to Proposition 4, u monotonically decreases during the last stage of the product life cycle, see Section 6. On the other hand, the quantity produced, q , increases at the same time. Thus, u and q are very likely to evolve in opposite directions during the last stage of the product life cycle. In other words, as t tends to T , the more u and q are substitutable, and thus the Veblen effect is less likely observed.*

6 Numerical Experiments

This section provides further insights on the linear demand case, introduced in Section 5.3 via numerical examples. We solve the system made of first-order and second-order conditions, (10a)-(10e), the state dynamics (1), and the maximum principle, (10f). We also ensure that control and state variables are positive for all solutions. We find the optimal policies analytically. However, the corresponding explicit solution has a multitude of terms that themselves are difficult to examine further. As such, Mathematica (Wolfram Research Inc., 2019) plots the optimal policies. To address the continuous nature of the model, the plots use Mathematica’s internal adaptive discretization algorithm.³ The Mathematica notebook for this section is available from the authors by request.

For the numerical results below, the same set of parameters is used, except where stated otherwise.

Parameter Values 1. *As a reference case, (if not chosen, and stated, differently) there is $T = 7, c_0 = 50, c_1 = 1, \tau = 20, S_0 = 100$, and $r = 0.01$. Let stock of pollution dynamics be $\frac{dS}{dt} = \alpha q - \beta u - \delta S$,*

³Please see <https://reference.wolfram.com/language/ref/Plot.html> for details.

where $\alpha = 1$, $\beta = 1$, and $\delta = 0.3$. We use the linear inverse demand function, $P = m - aq - bS$, with $m = 300$, $a = 0.2$, and $b = 0.2$.

Although all subsequent plots use Parameter Values 1, we carry out sensitivity analysis for model parameters and find the described relationships, in the sections below, still hold.

Section 6.1, identifies the three stages of the product life-cycle. The same subsection also studies the impact of the length of the product life cycle on the length of the second stage of the life cycle. Next, Section 6.2 explores the relationship between price and quantity. The exploration provides two insights: 1) the optimal pricing policy of the firm and 2) when the green Veblen effect occurs.

6.1 Evolution and Steady-State

First, the three stages of the product life cycle are defined below in Definition 3. We will use the different stages in the discussion and the remainder of the numerical experiments.

Definition 3. *The numerical experiments below indicate that the optimal evolution of the model consists of three distinct stages:*

- *introduction-growth stage: In the first stage, the firm controls abatement effort and quantity, changing the stock of pollution and its shadow price.*
- *Maturity stage: In the second stage, abatement effort, quantity, stock of pollution and the shadow price are nearly constant.*
- *Declining stage: In the last stage, abatement effort decreases, while the quantity and stock of pollution increase, and the shadow price tends to zero.*

We visualize these three stages in Figure 2. We explore the relationship between T and length of the maturity stage in Figure 3.

Note that in both Figures 2 and 3 the control and state variables, u , q , and S , are positive, whereas the shadow price, λ , is negative for the entire life cycle. From Figure 3(a) it appears that, when T is small, the maturity stage is not present. The length of the maturity stage increases with T (cf. Figures 3(b) and 3(c)). Visually, it is evident that the length of the maturity stage increases super-linearly with T .

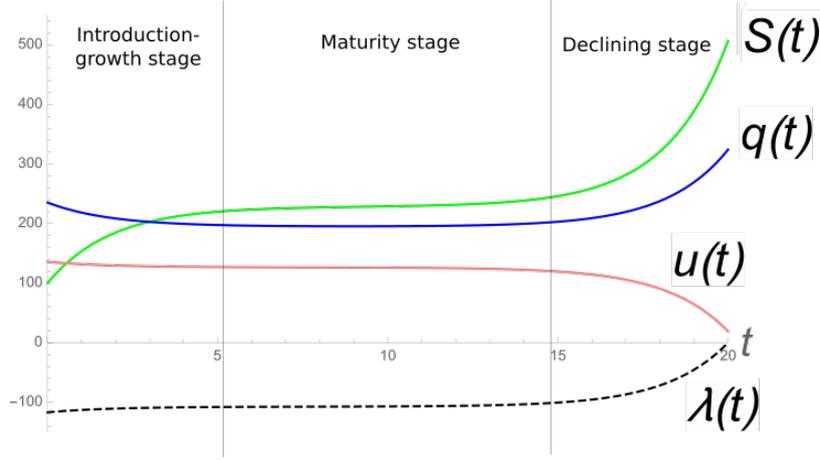


Figure 2: The three stages of the optimal evolution, $T = 20$

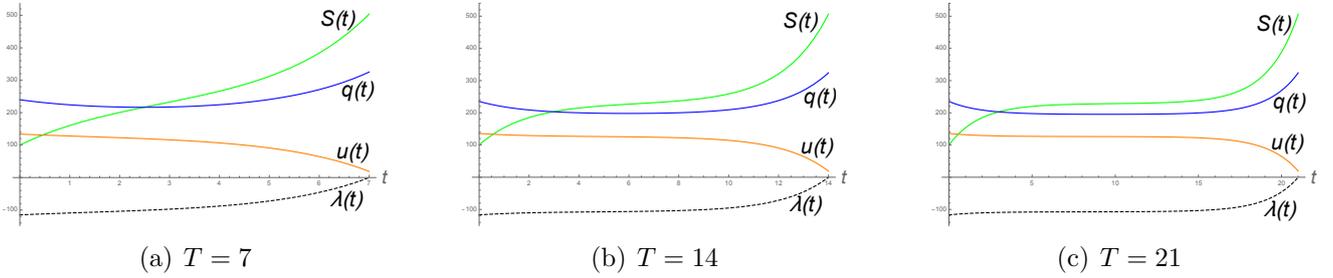


Figure 3: The impact of the length of the product life cycle, T , on the length of the maturity stage

The next section determines when/if the green Veblen effect occurs in each of the three stages. However, given the definition of the maturity stage, the green Veblen effect cannot occur during that stage. Specifically, as a linear demand function is considered, and quantity and stock of pollution are constant, then price will also be constant during the maturity stage. Constant price and constant quantity cannot result in a green Veblen effect. Given that the green Veblen effect will not be observed in the maturity stage, we set $T = 7$ and only consider the introduction-growth and declining stages in the remainder of this section.

6.2 The Green Veblen Effect and Pricing Policies

This section investigates the relationship between the quantity, q , and price, P , policies throughout the product life cycle. We consider the abatement effort, u , quantity, q , and stock of pollution, S , policies to determine when conditions (21) and (22) hold. Conditions (21) and (22) determine when the green Veblen effect is observed. We observe the green Veblen effect in the introduction-growth stage and not in

the declining stage. This result is counter-intuitive, since a negative direct effect of quantity on price is assumed in (3), following the Law of Demand. We further consider when policies are complements and substitutes. Policies are complements if they evolve in the same direction, and substitutes if they evolve in opposite directions. We then discuss the pricing policies that emerge.

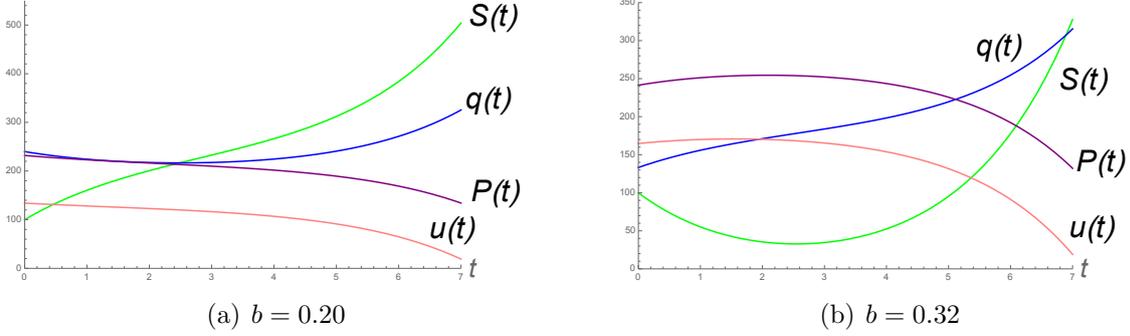


Figure 4: Impact of consumers' sensitivity to pollution, b , on price, $P(t)$ (purple), quantity, $q(t)$ (blue), abatement effort, $u(t)$ (orange), quantity, and stock of pollution, $S(t)$ (green).

Consider now each panel of Figure 4. In Figure 4(a) we set $b = 0.20$ and using Parameter Values 1, the threshold values on $\frac{dS}{dq}$ and $\frac{dq}{du}$ derive from conditions (21) and (22). Conditions (21) and (22) holding means that the green Veblen effect is observed when $\frac{dS}{dq} < -1$ and $\frac{dq}{du} > -2$. In the figure, $S(t)$ is monotone increasing and non-convex, and $u(t)$ is monotone decreasing and non-concave throughout the life cycle of the product. In addition, $q(t)$ is non-monotone and convex. Given the threshold on $\frac{dq}{du}$ and properties of $u(t)$ and $q(t)$, in the introduction-growth stage, $\frac{dq}{du} \geq 0$ implying the green Veblen effect is observed. We are able to gain additional insights from the behavior of $S(t)$ and $q(t)$. Given the structural properties of $S(t)$ and $q(t)$, the only time $\frac{dS}{dq}$ may be negative is during the introduction-growth stage. However, $\frac{dS}{dq} \geq 0$ at the end of the product life cycle meaning that the green Veblen effect cannot occur in the declining stage.

Turning the attention to Figure 4(b), set $b = 0.32$ and carry out an analysis similar to that of the previous paragraph. The derived threshold values on $\frac{dS}{dq}$ and $\frac{dq}{du}$ are $\frac{dS}{dq} < -0.625$ and $\frac{dq}{du} > -2$; the thresholds come from conditions (21) and (22), determining when the green Veblen effect may occur. Unlike, Figure 4(a), the behaviors of $S(t)$, $u(t)$, and $q(t)$ change in Figure 4(b). Specifically, $S(t)$ is now non-monotone and convex, instead of monotone increasing and non-convex. Also, $u(t)$ is now non-monotone and concave, instead of monotone decreasing and non-concave, and $q(t)$ is now monotone increasing and non-convex, instead of non-monotone and convex. Similar to Figure 4(a), the threshold on

$\frac{dq}{du}$ may be satisfied throughout the product life cycle, and $\frac{dq}{du} \geq 0$ during the introduction-growth stage. The sign of $\frac{dS}{dq}$ is the same as in Figure 4(a) throughout the life cycle, thus the same insight holds. We note that even with a larger b value ($b = 0.32$) the green Veblen effect is only present in the introduction-growth stage.

The preceding two paragraphs identify that the green Veblen effect only occurs in the introduction-growth stage, for a range of values of the price sensitivity to stock of pollution, b . Specifically, in Figure 4(a) the $P(t)$ curve is monotone decreasing throughout the life cycle and $q(t)$ is non-monotone and convex, verifying the result. Viewing the behavior of $P(t)$ through a marketing lens, one can say that the optimal pricing policy of the firm, when consumers' sensitivity to pollution is low, is a skimming policy (Kalish, 1983).

Turning the attention on Figure 4(b), one notes that $P(t)$ is a concave function throughout the product life cycle. Combining this behavior with the monotone increasing behavior of $q(t)$, the green Veblen effect is observed during the introduction-growth stage, when consumers' sensitivity to pollution is high. However, again from a marketing perspective, the optimal pricing policy is no longer skimming, but is instead an inverted-U policy (Kalish, 1983).

Combining the two behaviors of $P(t)$ in the two panels of Figure 4 helps gain additional insights. As the end of the product life cycle approaches, future stock of pollution levels become less important, and thus production quantity increases. One observes this to be indeed the case, as $\frac{dq}{dt} \geq 0$ for both cases in Figure 4. As the green Veblen effect is not observed in the declining stage, it means that $\frac{dP}{dq} \leq 0$. Non-decreasing quantity, $\frac{dq}{dt} \geq 0$ and no green Veblen effect $\frac{dP}{dq} \leq 0$, implies that $\frac{dP}{dt} \leq 0$. For products that exhibit the green Veblen effect, only skimming and inverted-U pricing policies will be observed. Meaning the other two pricing policies, U-shaped and penetration, are ruled out.

Using parameter values 1, and two values of b in $\{0.20, 0.32\}$, the green Veblen effect only occurs in the introduction-growth stage, supporting the theoretical finding in Remark 6. From the numerical exploration, it also appears that only skimming and inverted-U pricing policies are observed. We note that with other parameter values other than those used in Figure 4, the same qualitative results regarding the green Veblen effect and optimal pricing policies.

7 Discussion

Our analysis identifies when the green Veblen effect is observed; what are the drivers of the green Veblen effect, the direct and indirect effects; and how the drivers interact to induce the green Veblen effect. We now discuss the theoretical and managerial contributions of this work and conclude this section by identifying future research directions.

7.1 Theoretical Contribution

This paper introduces and formally defines the green Veblen effect. We propose a model consistent with the Law of Demand that can still exhibit the green Veblen effect. Understanding the green Veblen effect requires the analysis of the direct, indirect, and total effect of production quantity on price, shown in Lemma 1. We assume a negative direct effect of production quantity on the price under the Law of Demand. Pollution stock plays an indirect role in the impact of production quantity on price. In other words, the production quantity affects current pollution, in turn, more significant current pollution increases the stock of pollution, lowering the price due to green consumers. The total effect of production quantity on price is the sum of the direct and indirect effects. If the total effect of production quantity on stock of pollution is negative and strong enough, the green Veblen effect will appear.

Taking a closer look, the relationship between production quantity and the stock of pollution, $\frac{dS}{dq}$, within the indirect effect, may lead to the green Veblen effect. From equation (14), the sign of $\frac{dS}{dq}$ is determined by the sign and magnitude of the relationship between price and change of production quantity and stock of pollution, $q \frac{\partial^2 P}{\partial q \partial S}$. Theoretically, suppose the (non)existence of the green Veblen effect is desired in a model. In that case, an appropriate inverse demand function must be used such that $\left| \frac{dS}{dq} \right|$ is sufficiently large and $\frac{dS}{dq}$ is negative. Specifically, for the existence of the green Veblen effect, $q \frac{\partial^2 P}{\partial q \partial S}$ must not be too large $\left(q \frac{\partial^2 P}{\partial q \partial S} < \left| \frac{\partial P}{\partial S} \right| \right)$, and $\frac{\partial P}{\partial S} + q \frac{\partial^2 P}{\partial q \partial S}$ must be sufficiently small such that $\left| \frac{dS}{dq} \right|$ is sufficiently large (see equations (14) and (17)). Our structural insights will help modelers construct settings of interest when investigating the green Veblen effect in the future.

The theoretical work also addresses a pricing paradox in the classical Veblen effect. If demand increases with price, then the firm should set an infinite price to obtain unlimited demand and profit. Although a positive price-demand relationship may exist, it never results in infinite profit. Our work addresses the

pricing paradox by showing the positive price-demand relationship comes from the price increasing with demand, stemming from the green Veblen effect.

Returning to the relationship between price and production quantity, $\frac{dP}{dq}$, in the linear demand case, it appears that the abatement effort and production quantity relationship is critical in the existence of the green Veblen effect. Equation (22) reveals that having abatement effort and production quantity as complements is not the only way to observe the green Veblen effect. In fact, the analytical results reveal that a product may exhibit the green Veblen effect when abatement effort and production quantity are complements, independent, or not too substitutable.

7.2 Managerial Contribution

We define the green Veblen effect with price and production quantity evolving in the same direction, similar to the classical Veblen effect. However, the classical Veblen effect's causality is different from the green Veblen effect's causality. Indeed, with the classical Veblen effect, an increase in price drives demand because of conspicuous consumption (not pollution concern). In contrast, when a product is sold to green consumers, the price may increase with production quantity, leading to the green Veblen effect. Recall green consumers are willing to pay more for a product with lower pollution emissions. We show that if a product follows the Law of Demand and is sold to green consumers motivated to conserve either intrinsically or extrinsically (conspicuously), the green Veblen effect may be observed. This fact may be leveraged by firms when designing or marketing products. Further, one identifies that experiencing the green Veblen effect does not depend on the product's characteristics, but on the stage of the product life-cycle. More precisely, when sold to green consumers, any product may experience the green Veblen effect only during the introduction-growth stage; no product exhibits the green Veblen effect during its life cycle's maturity and declining stages.

Proposition 2 teaches that price and abatement effort evolve in the same direction. This result allows for determining when the green Veblen effect will not occur. Abatement efforts will decrease at the end of the declining stage, as current pollution has less importance on future sales. Naturally, if abatement effort decreases, then so does the price. At the end of the declining stage, the firm is more concerned with the immediate impact of price on demand than current pollution. As further highlighted in the numerical exploration, the firm will lower the product price to induce demand. Lowering price, due to

lower abatement effort, at the end of the declining stage results in only one of two pricing strategies, inverted-U or skimming. One insight for managers is that the green Veblen effect will only be observed by products following the inverted-U or the skimming pricing policies, as these policies are the only ones with the price decreasing at the end of the product life cycle. For industry analysts, knowing the pricing trends of a product now informs the likelihood of the green Veblen effect. Specifically, having a U-shaped or penetration pricing policy means the product will not exhibit the green Veblen effect.

The green Veblen effect gives firms a unique pricing opportunity when selling a product to green consumers. A firm may capitalize on the green Veblen effect, similar to what *Beyond Meat* did in 2019, by raising prices. However, a firm should conduct a careful market analysis to determine if their consumers are sufficiently green to expect the green Veblen effect to appear.

In the numerical experiments, it appears that the green Veblen effect only appears at the beginning of the product life cycle, when abatement effort and production quantity are complements or not too substitutable, as discussed in the theoretical contributions section. Our results highlight that the green Veblen effect is not a permanent fixture and disappears during a product's life cycle. Specifically, a policy implication is that firms selling a product exhibiting the green Veblen effect follow an inverted-U pricing policy when possible. The exact shape and structure of the inverted-U pricing policy is a direction for future research, discussed below.

Perhaps the most exciting aspect of this work is that it explains the green Veblen effect observed at the early stages of the *Beyond Meat* burger (Reinicke, 2019). During that time, the number of units sold increases as does the price, showing the green Veblen effect. Looking at *Beyond Meat* end-of-year statements via Bloomberg's terminal, the 2019 fiscal year is the best yet with the highest revenues, profits, and margins. It seems that, knowingly or unknowingly, *Beyond Meat* is capitalizing on the green Veblen effect.

7.3 Implications for Theory and Practice

The concept of the green Veblen effect is an important one for managers to be aware of when designing or marketing products. The green Veblen effect is a phenomenon where an increase in price leads to an increase in production quantity, as opposed to the classical Veblen effect, where an increase in price leads to a rise in demand. This rise occurs when a product sells to green consumers willing to pay more for a

product with lower pollution emissions.

The study shows that the green Veblen effect may appear if a product follows the Law of Demand and is sold to green consumers. This fact can be leveraged by firms when designing or marketing products. Furthermore, the study also shows that the product life-cycle stage is essential in determining when the green Veblen effect will occur. Specifically, the green Veblen effect only occurs during the introduction-growth stage of the product life-cycle.

In terms of practical implications, the study highlights that firms can capitalize on the green Veblen effect by raising prices, similar to what Beyond Meat did in 2019. However, firms must conduct a careful market analysis to determine if their consumers are sufficiently green to expect the green Veblen effect to appear. Additionally, the study suggests that firms selling a product exhibiting the green Veblen effect should follow an inverted-U pricing policy when possible.

Overall, this study provides valuable insights for managers, industry analysts, and policymakers on how to approach pricing strategies for products sold to green consumers. It highlights the importance of understanding the green Veblen effect and its relationship with the product life-cycle stage. Furthermore, it suggests that firms can capitalize on the green Veblen effect by raising prices when selling products to green consumers. Still, they should also conduct a careful market analysis to determine if their consumers are sufficiently green to expect the green Veblen effect to appear.

7.4 Future Research

Our model focuses on controlling pollution on the production side. That is, consumers are concerned with pollution generated during the production of the product. However, pollution on the consumption side- when the consumer uses the product- may also be a concern for other products.

Hybrid vehicles, LED lights, and energy-efficient appliances are examples of such products with pollution on the consumption side. Although these products may be more expensive than their non-green counterparts, they typically come with price savings during consumption. For example, LED light bulbs tend to have higher upfront costs than incandescent bulbs, but because they use 25-80% less energy and last 3-25 times longer, switching just five traditional light bulbs to LEDs can save consumers \$75 USD per year (*U.S. Department of Energy, 2020*). In other words, consumers may be willing to invest in these green products, not because of their concern for the environment, but for the cost savings acquired during

use. Thus, cost savings associated with green products are important to incorporate into future models for the green Veblen effect.

Air travel also looks at pollution on the consumption side. According to *CNN* (2020), the airline industry is facing pressure from environmentally-conscious consumers concerned with the emissions associated with air travel. This pressure has prompted Delta Air Lines to plan for carbon neutrality by 2030, through the use of carbon offsets, to help attract green consumers (*CNN*, 2020). Additional fixed and variable costs may be incorporated into the presented model to account for firms managing pollution on the consumption side. The anticipated insights from this updated model are unknown and warrant future research.

Nevertheless, evidence suggests that cost savings or consumers' care for the environment are not always consumers' motivations behind purchasing green products. *The New York Times* (2007) reports that in a survey, the top reason consumers cited for why they purchased the Toyota Prius was "it made a statement about me." Sexton and Sexton (2014) estimate that consumers are willing to pay a premium between \$430-\$4,200 for the Prius to signal their environmental concern and go "green to be seen." The Toyota Prius is a clear example of conspicuous conservation and the green Veblen effect. Explicitly accounting for conspicuous conservation within the model will be of interest as it may lead to increasing the range during which the green Veblen effect may be observed; currently, the model does not distinguish between intrinsic and extrinsic conservation.

Though this work provides insights into the previously paradoxical pricing and demand relationship of *Beyond Meat* identified by Reinicke (2019), there are multiple avenues of additional research. First, it needs to be clarified what additional factors lead to the observed behavior. Second, a qualitative survey or interview approach interfacing with the firm will provide additional insights into if the firm knowingly leveraged the green Veblen effect or if it is a fortunate happenstance. Finally, the role of *Impossible Foods*, an up-and-coming *Beyone Meat* competitor, in the pricing decisions of 2019 is unclear; *Impossible Foods* became commercially available during the last quarter of 2019 (Capritto, 2020). Exploring this case from quantitative and qualitative perspectives are natural directions for future work.

We model a monopolist selling a product and show the green Veblen effect may occur. However, it is unclear if a competing product, either green or regular, mitigates the green Veblen effect's potential or magnitude. Similarly, a symmetric information setting is assumed. In an asymmetric information

setting, greenwashing, misrepresenting a product's greenness, may occur, further reducing the likelihood of observing the green Veblen effect. Investigating competition, green and non-green, and greenwashing as a strategy are future research directions on the green Veblen effect.

8 Conclusion

This article examines the dynamic production and pollution management of a firm facing green customers. More specifically, the firm decides on the production quantity and the pollution abatement effort (i.e., investment in a cleaner production process), determining the pollution stock. In the optimal control model, production quantity and abatement effort are the control variables, and the stock of pollution is the state variable. We analyze this model analytically and numerically to gain theoretical and managerial insights.

A key result is that with green consumers and polluting production, a new product may exhibit the green Veblen effect at the beginning of its life cycle while conforming with the Law of Demand. The reconciliation of the green Veblen effect with the Law of Demand rests on the distinction between the direct and the total effects of price on demand, related via the *indirect effect* of price on demand. We also find that production quantity and pollution abatement policies are complements at the beginning of the product life cycle and substitutes at the end. Our result highlights how firms self-regulate their emissions at the beginning and disregard pollution at the end of the product life cycle. Lastly, the numerical results indicate that of the four popular pricing policies, only skimming and inverted-U policies emerge. That is, the firm only selects pricing policies that decrease at the end of the product life cycle.

A critical insight from this work is that similar to luxury products, green products may be Veblen. In the case of luxury products, demand increases with price as consumers use the product to show their wealth or status. In the proposed case, the green Veblen effect is observed as green consumers desire a less polluting production process.

This research focuses on pollution on the production side, i.e., pollution emitted by the firm in the production process. A natural research question from this work would be to consider pollution on the consumption side. When it comes to products such as electric cars (e.g., Toyota Prius), consumers may be more concerned with the pollution linked with driving the vehicle as opposed to its production. The

distinction between pollution on the production- and consumption-side warrants further investigation.

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A Shadow Price, Price and Abatement

The shadow price of stock of pollution, λ , represents the net benefit of relaxing the dynamic constraint in (9), written in (1), by one unit of additional pollution. It corresponds to the additional profit (at time t) of one additional unit of pollution. As such, λ affects the intertemporal trade-off between current and future profits. It thus warrants greater examination. We find the following for the value of λ over time:

Lemma 2. *The value of λ over time writes for each t in $[0, T]$ as:*

$$\lambda(t) = \int_t^T e^{(\delta-r)(x-t)} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx. \quad (23)$$

Proof. We first rewrite the first order differential equation (10f) in standard form, which gives $\frac{d\lambda}{dt} + \lambda(\delta - r) = -q \frac{\partial P}{\partial S} + \delta(\tau - c_1)$. We then multiply both sides of the equation by the integrating factor $e^{(\delta-r)t}$, which yields $e^{(\delta-r)t} \left(\frac{d\lambda}{dt} + \lambda(\delta - r) \right) = \frac{d(\lambda e^{(\delta-r)t})}{dt} = -e^{(\delta-r)t} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right)$. Thus, $d(\lambda e^{(\delta-r)t}) = -e^{(\delta-r)t} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dt$. Therefore, $\int_t^T d(\lambda e^{(\delta-r)x}) = -\int_t^T e^{(\delta-r)x} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx$, which yields $\lambda(T)e^{(\delta-r)T} - \lambda(t)e^{(\delta-r)t} = -\int_t^T e^{(\delta-r)x} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx$. Applying the transversality condition, $\lambda(T) = 0$, yields $-\lambda(t)e^{(\delta-r)t} = -\int_t^T e^{(\delta-r)x} \left(q \frac{\partial P}{\partial S} - \delta(\tau - c_1) \right) dx$. Dividing both sides by $-e^{(\delta-r)t}$ proves the result. \square

The shadow price of stock of pollution, λ , increases with quantity, q , and the price sensitivity to stock of pollution, $\frac{\partial P}{\partial S}$. It decreases with the degradation of pollution, δ , and the difference between the pollution tax and the pollution sensitivity of cost, $\tau - c_1$. Consequently, both the demand-side, with green consumers, and the supply-side, with a polluting process, impact the shadow price of pollution, and in turn future profits.

Lemma 3. *The sign of λ over time for each t in $[0, T]$ is given by*

$$\lambda(t) \leq 0.$$

Proof. Immediate from Lemma 2, noting that $q \frac{\partial P}{\partial S} \leq 0$ and $-\delta(\tau - c_1) \leq 0$. □

Consequently, more stock of pollution decreases the intertemporal profit for two reasons. First, the price that green consumers accept to pay falls ($\frac{\partial P}{\partial S} \leq 0$). Second, the net cost of current pollution increases ($\tau - c_1 \geq 0$). Eventually, if consumers do not value the environment ($\frac{\partial P}{\partial S} = 0$) and the tax rate equals the pollution sensitivity of the marginal production cost ($\tau = c_1$), then the shadow price is zero ($\lambda = 0$).

Lemma 4. *The value of $u(t)$ and $P(t)$ over time, for each t in $[0, T]$, is*

$$u = \beta(\tau - c_1 - \lambda), \tag{24a}$$

$$P = -\frac{\partial P}{\partial q} q + c_0 + \alpha(\tau - c_1 - \lambda), \tag{24b}$$

with λ given by Lemma 2.

Proof. Equations (24a) and (24b) follow immediately from conditions (10a) and (10b). □

Based on the two first-order conditions (10a)-(10b), we can obtain only two independent equations. We choose to express u and P , instead of u and q , as price is more informative than quantity when investigating the green Veblen effect. Of course, a rearrangement of (24b) would give q as a function of P .

As λ is the shadow price of $\frac{dS}{dt}$, and λ appears in (24), it follows that current pollution, $\frac{dS}{dt}$, exerts a dynamic influence on the control variables, u and P . Indeed, current pollution feeds future stock of pollution, affecting the future price that green consumers will accept to pay, and thus influencing profits. A distinguishing characteristic of the model is that current pollution also drives a static influence (i.e., current pollution impacts current profits). On the one hand current pollution negatively impacts future price, as green consumers prefer less overall pollution. On the other hand, current pollution decreases immediate marginal production cost, $\tau - c_1$. As such, the firm must trade-off immediate profits for future profits. However, if $\tau = c_1$ there is no benefit from immediate pollution, then there is no longer the need

for making any trade-offs. Lemma 4 also verifies Remark 3, according to which τ and c_1 exert influence in opposite directions.

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