Dynamic Pricing of Green Goods under Discounted Network Effects

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Introduction and Motivation

- Environmental concerns influence consumers' purchasing decisions and their willingness to pay.
- Explanations for this "green premium" include ecological and health concerns, altruism, network effects, etc.
  - Signalling effects (building a "green" reputation among the peers) and avoiding social ostracism;
  - Information transmission and word-of-mouth on the nature of the green good and the availability of possible subsidy schemes;
  - Critical mass of users may be needed for the environmentally-friendly technology to produce visible effects:
    - E.g.:Indirect network effects in EV- E.g.: availability of charging stations for EV depends on the number of users (Greaker and Heggedahl, 2010 or Greaker and Midttomme, 2016).
  - Network effects are dynamic.

Introduction and Motivation

Research Questions

- In the presence of network effects (dynamic), what is the optimal pricing policy of a dominant firm selling a green good
  $\rightarrow$ Focus on discounted network effects

- How would the network evolve under the private solution outcome versus a welfare-maximizing social planner solution?
  [With only the latter acounting for environmental externalities]

Related Literature

- Literature on network effects in the adoption of green goods:
  - Experimental
  - Empirical
  - Theoretical literature (Sartzetakis and Tsigaris (2005), Brécard, 2013; Hauck et al., 2014; **Greaker and Midttømme, 2016**)
- Liteature on pricing in markets with network effects:
  - Vast literature on this issue following the seminal contributions by Rohlfs (1974) and Katz and Shapiro (1985);
  - Recent literature on pricing dynamics in network markets (e.g. Dhebar and Oren, 1985, 1986; Xie and Sirbu, 1995; Mason, 2000; Fudenberg and Tirole, 2000; **Gabszewicz and Garcia, 2007, 2008**; Cabral, 2011; Laussel, Long and Resende, 2015)...

The model

Main ingredients

- Consider an industry in which there are 2 variants of a product: a green good (G) and a brown good (B):
  - Different emission levels,
  - Only the green good generates network benefits (E.g. E.V).
  - The green good is more costly to produce.
- The two goods are substitutes, and each consumer buys (at most) one unit of one of the variants.

The model

Main ingredients

Market structure:

- The green (brown) good is produced by a dominant firm at marginal cost $c > 0$;
- The brown good is produced by a fringe at marginal cost $c = 0$;
- Consumers have heterogeneous environmental concerns.The utility of type-x consumer (x uniformly distributed in $[0, A]$) of buying the green good is:

$$u_t^G(x) = U + xq^G + \alpha s_t - P_t^G, \tag{1}$$

- q^G- environmental quality of the green good;
- αs_t - network effect in the consumption of the green good, with α ($\alpha > 0$) measuring the intensity of the network effect;
- U stand alone utility common to both goods - it is assumed to be sufficiently high for all consumers to buy one of the goods;
- P_t^G - price of the green good in period t .

The model

Main ingredients

The relevant size of the network of the green good at time t is s_t, which is the discounted accumulated demand of the green good until period $t-1$:

$$s_t = \sum_{i=0}^{t-1} \beta^{t-i} d_t^G + \beta^t s_0, \tag{2}$$

- d_t^G represents the demand for the green good at time t;
- $\beta \in (0,1)$ is the discount factor used by consumers to evaluate the present backwards-discounted value of the network of all previous buyers;
- s_0 is the initial network size.

The model

Main ingredients

If *type* $-x$ consumes good B he obtains a utility of $u_t^B(x)$,

$$u_t^B(x) = U + xq^B - P_t^B, \tag{3}$$

- P_t^B represents the price of the brown good in period t.
- $q^B < q^G$ stands for the environmental quality of the brown good. The environmental qualities depend negatively on the level of emissions, with
$$q_i = \Omega - e_i,$$
Ω - constant parameter
e_i - production emissions i, $i = B, G$, as in Brécard (2013).
- We assume $q_G - q_B = \frac{1}{\eta}$.

The model

Main ingredients

In equilibrium, we must have $\left(P_t^B\right)^* = 0$ (marginal cost pricing by the firms on the competitive fringe), implying

$$d^G\left(P_t, s_t\right) = \eta\left(\frac{A}{\eta} + \alpha s_t - P_t\right),$$

and

$$s_{t+1} = \beta\left(s_t + d_t\right) = \beta\left[a\eta + \left(1 + \alpha\eta\right)s_t - \eta p_t\right].$$

With $a = \frac{A}{\eta} - c$

The model

Green good producer's problem

The dominant firm's one-period profit function is

$$\pi\left(P_t, s_t\right) = \left(P_t - c\right)\left(A + \alpha s_t - P_t\right) \equiv \pi\left(p_t, s_t\right) = \eta p_t\left(a + \alpha s_t - p_t\right),$$

with $a = \frac{A}{\eta} - c$ and $p_t = P_t - c$.

The green producer's problem is then

$$\max_{\mathbf{p}=\{p_t\}_{t=0}^{\infty}} \Pi\left(\mathbf{p}, s\right) = \sum_{t=0}^{\infty} \delta^t \pi\left(p_t, s_t\right)$$

$$\text{s.t.} \quad s_{t+1} = \max\{\beta\left(a\eta + \left(1 + \alpha\eta\right)s_t - \eta p_t\right), 0\}.$$

The model

Green good's producer problem

This corresponds to a Markov-stationary infinite-horizon dynamic programming problem, whose Bellman equation writes as

$$
\begin{aligned}
V(s) &= \max_{p \in [\alpha s - c, \alpha s + a]} \left\{ \pi(p, s) + \delta V(s') \right\}. \\
&= \max_{p \in [\alpha s - c, \alpha s + a]} \left\{ \eta p (\alpha s + a - p) + \delta V[\beta(\eta a + (1 + \alpha\eta) s - \eta p)] \right\}
\end{aligned}
$$

Results

Optimal pricing policy - Private Solution

Interior

Assume that the solution is interior, i.e. $\rho(s) \geq \alpha s - c$

Assume further that $\rho = \phi + \gamma s$

Then

$$\gamma = \gamma_1 = \frac{\Delta - \left(1 - \beta^2 \delta \left(\alpha\eta + 1\right)^2\right)}{\beta^2 \delta \left(\alpha\eta + 2\right)} > 0$$

$$\phi = \phi_1 = a \frac{\Delta - \beta\delta \left(1 - \beta\right) \left(\alpha\eta + 1\right)}{\Delta - \beta\delta \left(1 - \beta\right) \left(\alpha\eta + 1\right) + \left(1 - \beta\delta\right)} \gtreqless 0,$$

with $\Delta \triangleq \sqrt{\left(1 - \beta^2 \delta\right) \left(1 - \beta^2 \delta \left(\alpha\eta + 1\right)^2\right)}$.

Note that we assume throughout that $\alpha\eta + 1 < \frac{1}{\beta\sqrt{(\delta)}}$

Results

Steady State - Private Solution

Interior

Along the optimal path, the state evolves according to the simple (Markovian) dynamic system

$$s_{t+1} \triangleq H(s_t) = \beta\big[(1+\eta\alpha)\, s_t + a\eta - \eta p(s_t)\big].$$

- If $\alpha\eta + 1 < \widetilde{\alpha} \equiv \frac{(1-\beta)+(1-\beta\delta)}{\beta((1-\beta)\delta+1-\beta\delta)}$, the steady-state network size s^* is:

$$s^* = \frac{a\beta\eta(1-\beta\delta)}{(1-\beta+1-\beta\delta) - (\beta\,(1-\beta\delta) + \beta\delta\,(1-\beta))\,(\alpha\eta+1)}.$$

Notice that the steady state satisfies the assumption for interiority if $s^* \leq \frac{\phi+c}{\alpha-\gamma} \rightarrow$ lower bound on the marginal cost.

Results

Steady state analysis - Private Solution
Interior

Proposition. *If* $\alpha\eta + 1 < \tilde{\alpha}$ and $c \geq \hat{c}$, *the following hold*

1. *There exists a unique, non-zero, steady-state equilibrium* $s^* > 0$, *with corresponding price* $P^* = c + \rho(s^*) > c$.
2. *This steady-state network size is globally asymptotically stable (for all initial states* s_0*).*
3. *For all* $s_0 \in [0, s^*)$, *the optimal sequence of network sizes* $\{s_t\} \nearrow s^*$, *and the optimal sequence of prices* $\{P(s_t)\} \nearrow P^*$.
4. *For all* $s_0 > s^*$, *the optimal sequence of network sizes* $\{s_t\} \searrow s^*$,*and the optimal sequence of prices* $\{P(s_t)\} \searrow P^*$.

Results

Steady state analysis - Private Solution

Interior

Proposition. *The finite steady-state network size s^* is*

1. *increasing and convex in the strength of the network effect α.*
2. *increasing in the firm's discount factor δ.*
3. *increasing in the consumers' discount factor β.*

In addition, the steady-state demand $d^* = d\left(P^*, s^*\right)$ is increasing and convex in α.

Results

Optimal pricing policy - Private Solution
Boundary solution

- In this case $p = \alpha s - c$
- Note that this solution obtains if s is high, namely: $s \geq \frac{(c+a)(1-\beta\delta(1+\alpha\eta))+c(1-\beta\delta)}{\alpha(1-\beta\delta)}$
- Let $\alpha\eta + 1 > \widetilde{\alpha} \equiv \frac{(1-\beta)+(1-\beta\delta)}{\beta((1-\beta)\delta+1-\beta\delta)}$
- The steady state is $s^* = \frac{\beta(a+c)\eta}{1-\beta}$
- Universal adoption of the green good.

Welfare analysis

First-best pricing

The welfare analysis requires us to consider the environmental damage caused by the goods' production, which are not taken into consideration in the producers' private solution.

- The environmental damage function is given by $D(E) = \tau E$,
  - $\tau > 0$ measures the pollutant's propensity for environmental damage
  - $E = e^G d^G + e^B d^B$ represents the total emissions from the two goods.

Welfare analysis

First-best pricing

The one-period social welfare function is given by

$$w\left(p, s\right) = CS_t^G + CS_t^B + \pi^G\left(P_t, s_t\right) - D(E_t)$$

The social planner's problem is then

$$\max_{\mathbf{p}} \Omega\left(\mathbf{p}, s_0\right) = \sum_{t=0}^{\infty} \delta^t w\left(p_t, s_t\right)$$

$$\text{s.t.} s_{t+1} = \beta\left[a\eta + \left(1 + \alpha\eta\right)s_t - \eta p_t\right].$$

Welfare analysis

First-best pricing

The Bellman equation for this problem is

$$W(s) = \max_{p \in [0, a+\alpha s]} \{ w(p, s) + \delta W(\beta [a\eta + (1 + \alpha\eta) s - \eta p]) \}. \tag{4}$$

- Both the one-period objective function and the state equation are linear in the decision variable p and convex-quadratic in the state s.
- The value function W is anticipated to be convex in the state s
  - **Bang-bang optimal solutions** are expected - $p_1(s) = \alpha s - c$ or $p_2(s) = a + \alpha s$,
  - By making a parametric quadratic guess for the value function W, we can compare the two candidate markup policies ($W_1(s)$ and $W_2(s)$, respectively).

Welfare analysis

First-best pricing

Proposition

(i) when the negative environmental externality of the brown good is large enough, i.e, when

$$\tau \geq \widehat{\tau}$$

then $\sigma(s) = p_1(s) = \alpha s - c$.

(ii) when the negative environmental externality of the brown good is small, $\tau < \widehat{\tau}$, *then the first best price policy is*

$$\sigma(s) = \begin{cases} p_2(s) = a + \alpha s \text{ if } s_0 \leq \check{s} \\ p_1(s) = \alpha s - c \text{ if } s_0 \geq \check{s} \end{cases},$$

where $\check{s}$ *is uniquely defined by* $W_1(\check{s}) = W_2(\check{s})$.

Welfare analysis

First-best pricing

- For sufficiently high τ, the social planner encourages in a maximal way the green good's adoption by choosing $p(s) = \alpha s - c$ (green benefits) - this leads to complete market coverage by the green good.
- When τ is low, the social planner may only be interested in sponsoring the green good when a critical mass of users is reached (network effects are key to set the green market in motion).
- Public policies designed to enlarge the user base may become very relevant, in the last case.

Conclusion

Take home message

- The optimal pricing and adoption of green goods depends in important ways on the strength of network effects.
  - Early purchasers are rewarded by the dominant firm for offering critical participation in the firm's effort to build an initial consumer base.
  - For sufficiently strong network effects, the dominant firm would even be willing to subsidize earlier consumers by setting a price below to marginal cost.

Conclusion

Take home message

- When the environmental damage of the brown good is large (or the initial network of the adopters is large enough, even if the environmental damage of the brown good is not too large):
  - For sufficiently strong network effects, universal adoption may be reached. Otherwise the private solution may result in under-adoption outcomes.
  - Moreover, even when universal adoption is reached, the convergence to the steady state is slower than the first-best solution.
  - There may be room for public policy intervention (time dependent tax/ subsidy+critical network participation incentives).