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Green innovation downturn: the role of imperfect competition

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We use strategic interactions to analyze the role of China's state-subsidized production expansion in the recent downturn in solar photovoltaics innovation. To that end, we develop a dynamic game model in which N solar panel manufacturers compete in price and invest in cost-reducing research. The resulting Nash equilibrium reveals an inverted U relationship between a manufacturer's market share and her research effort. In the duopoly case, with a local firm competing against a foreign state-subsidized one, we obtain analytical and numerical results that are consistent with a set of stylized facts, namely (i) the foreign manufacturer progressively expands to become the dominant player (ii) competition and innovation bring marginal costs down to zero (iii) each manufacturer's research effort follows an increasing-then-decreasing curve. At a policy level, these theoretical results suggest that national technology-push policies could affect foreign innovation, by changing the structure of global competition.

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Environmental innovation | Imperfect competition | International trade

1 Introduction

Innovation in low-carbon technologies is key to achieve climate objectives. Yet, it has followed a particular trajectory over the past fifteen years. After a fast-growing period from 2005 to the early 2010s, patenting in clean energy sources (including solar PV, solar thermal, wind, carbon capture and storage) and enabling technologies (including energy storage, systems integration, smart grids) has dropped, both at a global and at a country level. This trend was first documented by Acemoglu et al. (2019), and more comprehensively by Popp et al. (2020) and Probst et al. (2021). It also applies to private research and development spending (Pasimeni et al. (2019)).

This observation is recent and few authors have so far sought to explain it. Based on a litterature review and descriptive statistics, Popp et al. (2020) suggested several possibilities: the fall in fossil energy prices, the rise of hydrofracturing, the formation of an innovation bubble, weaker and uncertain regulatory support and the increasing maturity of these technologies might have contributed to this decline. In line with Acemoglu et al. (2012) and Aghion et al. (2016) who highlighted the path-dependent nature of environmental technical change, Acemoglu et al. (2019) developped a theoretical model providing conditions under which an exogenous shale gas boom could lead to a perpetual decline in green innovation.

Surprisingly, the role of imperfect competition has received little academic attention. Yet, China has become a major low-carbon energy player over the last fifteen years, being now the world leader in the manufacturing and installation of wind turbines and solar PV capacity (Andrews-Speed and Zhang (2018)). Focusing on the solar industry, Hart (2020) claimed that the expansion of state-subsidized Chinese panel manufacturers induced significant cost reduction, but also weakened the global industry to the point of undermining innovation.

The research question we address in this paper is precisely to what extend imperfect competition can provide an explanation for this downturn. More precisely, focusing on the solar sector, we would like to relate three stylized facts: (i) state-subsidized Chinese manufacturers have become the leading solar module producers in market share (Figure 1, left); (ii) solar module costs have fallen in all producing countries (Figure 1, right); (iii) innovation, both at each country and at a global level, has followed an inverted U-shaped trajectory (Figure 2).

To that end, we build on the work of Pillai and McLaughlin (2013) to develop a dynamic game model in which N solar panel manufacturers compete in price and invest in cost-reducing innovation. Solar electricity demand is exogenous, being mainly driven by government policies (Cadoret and Padovano (2016)). In the short run, manufacturers share this demand by engaging in monopolistic competition. Two reasons may be advanced to justify this assumption. First, solar modules can be seen as a differentiated good, varying in efficiency, durability

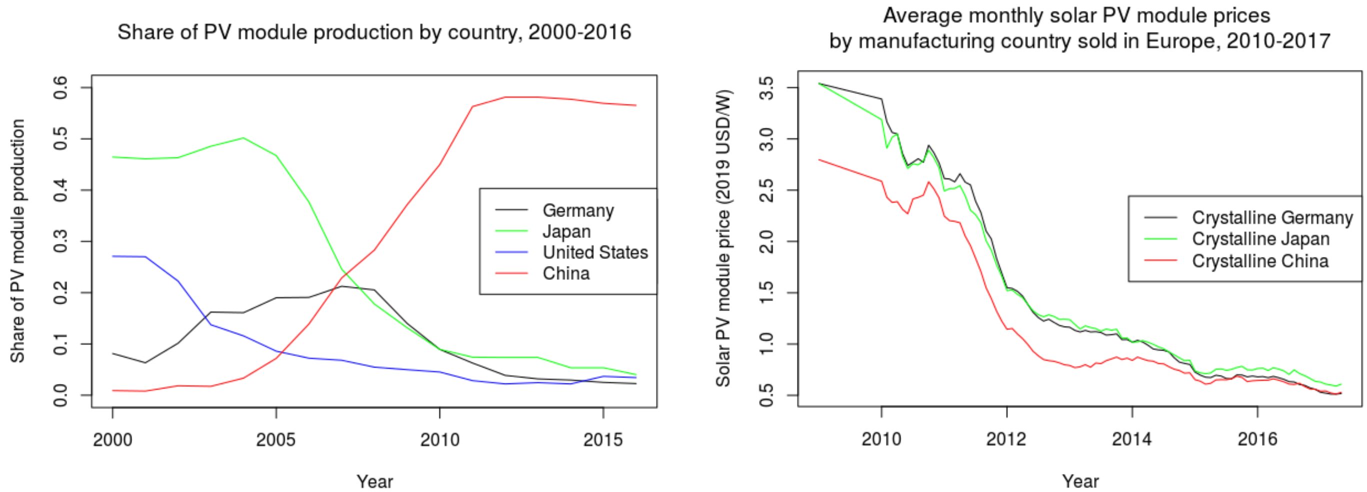

Figure 1: Left: Chinese manufacturers have become the leading solar module producers. Right: Solar module prices have fallen in all producing countries. Source: Fraunhofer Institute for Solar Energy Systems (2020), Taylor et al. (2020).

and flexibility. Second, as shown in Figure 3, solar panel companies tend to reap a similar markup, averaging around 15%, which is a typical feature of this kind of competition. In the long run, manufacturers can invest in cost-reducing R&D, which is, according to Pillai (2015), the main driver of solar panel cost reduction. However, firms differ in research costs, as some of them benefit from state subsidies. The Nash equilibrium resulting from this framework reveals an inverted U relationship between a manufacturer's market share and her research effort, which is consistent with the findings from Aghion et al. (2002) and empirical observations in the electricity sector, from Marino et al. (2019). In the duopoly case, with a local (typically American) manufacturer competing against a foreign (typically Chinese) state-subsidized one, this relationship translates into an inverted U trajectory of innovation over time. We are then, in that case, able to provide an imperfect competition rationale to the above mentioned stylized facts, and illustrate these theoretical results with a thourough calibration and a numerical application.

The underlying reasoning is as follows. At the beginning of the period, the foreign firm is assumed to be less technologically advanced than the local one. As she bears higher costs, she captures a smaller market share, and therefore innovates little -by a Schumpeterian argument (Schumpeter (1942)). But the public subsidy she receives allows her to innovate and reduce costs more efficiently than her competitor. She is thus able to progressively gain market share; as her profit increases, so does her research effort. But once she achieves a leadership position, she has less incentive to expand and innovate -which can be seen as a version of the Arrowian replacement effect (Arrow (1962)). Her research effort then declines, resulting in an inverted U-shaped trajectory of innovation. As

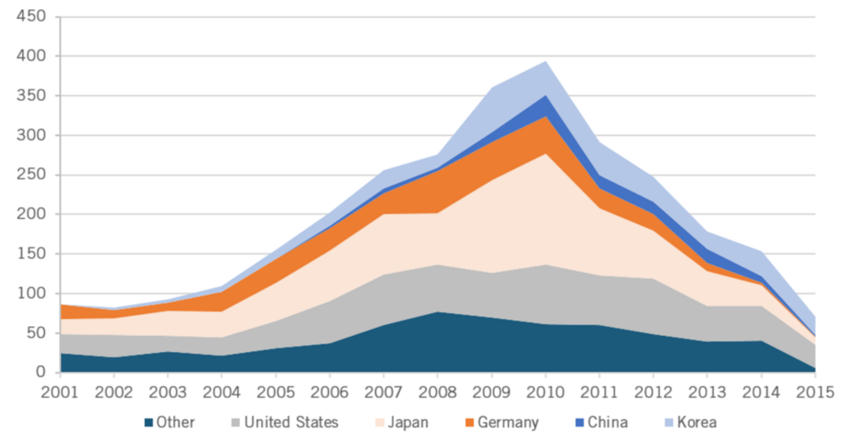

Figure 2: Innovation, both at each country and at a global levels, has followed an inverted U-shaped trajectory. Triadic patents for PV inventions by country, 2001–2015. Source: Hart (2020).

the local firm progressively loses market share, the symmetric reasoning applies and her innovation effort follows the same inverted U curve over time. Throughout this trajectory, the costs of both manufacturers continuously decline.

In many aspects, the evolution of the solar panel industry, as detailed above, shares common features with the product life cycle (Klepper (1997)): prices falling by means of research, the most innovative firms dominating the market, and an increasing-then-decreasing path of innovation. Our work brings a specific contribution to this approach by focusing on the electricity sector, taking into account strategic interactions between firms in a dynamic setup, and providing an analytic formulation of the inverted U curve. Among the extensive literature on dynamic R&D games (see Cellini and Lambertini (2008) for a monography on the subject), this paper is, as far as we know, the first to explicitly account for this particular cycle.

At a policy level, our model emphasizes the double effect of research subsidies on innovation: a direct one, by reducing R&D costs; and an indirect one, by conferring on the subsidized firm a competitive advantage which, ultimately, affects the distribution of market shares. This is the main policy outcome of the paper: in addition to generating international knowledge spillovers (Griliches (1992), Grossman and Helpman (1993)), technology-push policies can also affect cross-border innovation by changing the structure of global competition. We show that this cross-border effect can be either positive or negative, depending on whether this competitive advantage tends to reduce or widen the gap between the local and foreign manufacturers. This ambivalent effect could explain why empirical studies from Dechezleprêtre et al. (2011), Peters et al. (2012), or Kim and Brown (2019), were not able to evidence any impact of public R&D funding on foreign innovation, despite the acknowledged existence of

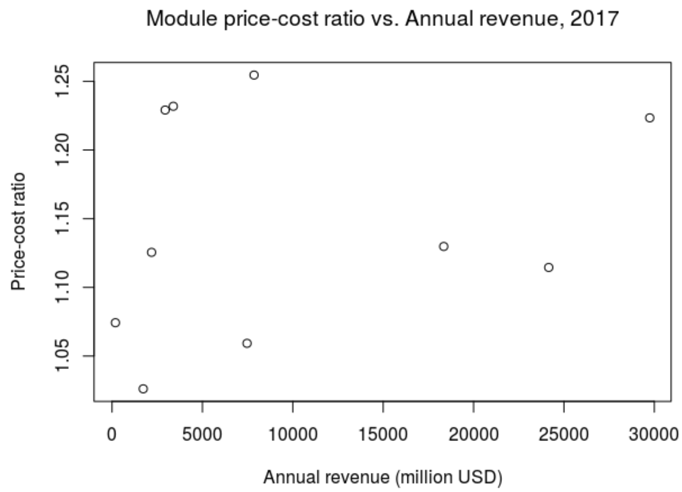

Figure 3: Module price-cost ratios vs. Annual revenues, 2017. Price-cost ratios were obtained by dividing the annual revenue of the firm by her cost of revenue in 2017. Companies displayed in the graph: Canadian Solar (2018), First Solar, Hanwha Q Cells, Jinko Solar, JA Solar, LDK, Risen Energy, SunPower, Trina Solar, Yingli. Source: Bloomberg.

international research spillovers. Our results suggest that taking into account this imperfect competition effect in econometric models could help to capture this impact with more significance.

Such an empirical evidence would make international cooperation even more critical to implement policies able to preserve global competition and foster green innovation. It could serve to design more efficient support schemes for batteries, whose market, both for supply and demand, is already highly concentrated in China (European Commission Joint Research Centre (2018)).

The paper is organized as follows. In Section 2, we describe the model, characterize the Nash equilibrium and give it an interpretation. Section 3 applies the model to the duopoly case, through which we reproduce the stylized facts and provide policy suggestions. Section 4 concludes.

2 Model

Our model is a dynamic version of the model developped by Pillai and McLaughlin (2013), which in turn derives from Smith and Venables (1988) and Atkeson and Burstein (2008). Time $t = 0, 1, 2, ...$ is discrete. Demand for solar electricity, Q_t, is exogenous, as it is essentially driven by government policies (Cadoret and Padovano (2016)). It is supplied by competitive solar power producers, who buy a variety of solar modules from oligopolistic manufacturers. In this section, we solve their respective problems to characterize and discuss the Nash equilibrium.

2.1 Solar electricity producers

We assume that solar power producers are in perfect competition and earn zero profits. They use solar modules from N manufacturers to meet the demand Q_t, with the following production function:

$$Q_t = \left(\sum_{j=1}^{N} q_{jt}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{1-\rho}} \tag{1}$$

where q_{jt} is the quantity of modules from manufacturer j at time t, and ρ is the elasticity of substitution between the different modules. In line with Pillai and McLaughlin (2013), we make the assumption that $\rho > 1$.

Competitive solar power producers face the following problem with zero-profit condition

$$\begin{cases} \max\limits_{q_{jt}} P_t Q_t - \sum_{j=1}^{N} p_{jt} q_{jt} \\ \left(\sum_{j=1}^{N} q_{jt}^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{1-\rho}} = Q_t \end{cases} \tag{2}$$

where P_t is the price of solar electricity. Solving problem (2) gives the demand for manufacturer j's modules as

$$q_{jt} = Q_t \left(\frac{p_{jt}}{P_t} \right)^{-\rho} \tag{3}$$

with the equilibrium price of solar electricity given by

$$P_t = \left(\sum_{j=1}^{N} p_{jt}^{1-\rho} \right)^{\frac{1}{1-\rho}} \tag{4}$$

2.2 Solar panel manufacturers

We now turn to the solar panel manufacturers. They are N, and there is no entry or exit. Each firm j produces one type of solar module and faces a marginal cost of production c_{jt}. This marginal cost evolves according to the following dynamics

$$\begin{cases} c_{jt+1} = (1 - \gamma_{jt+1}) c_{jt} \\ c_{j0} > 0 \end{cases} \tag{5}$$

where $\gamma_{jt} \in [0,1]$ is the R&D effort exerted by firm j at time t. The cost of running R&D activity is assumed to be quadratic:

$$C_j(\gamma) := \frac{\beta_j}{2}\gamma^2 \tag{6}$$

where β_j is a positive parameter. For simplicity, we omit spillovers effects: they would not change the main results of the paper and would yield unnecessary involved computations.

We assume that the N solar module manufacturers engage in a non-cooperative competition in price and innovation. Firms first fix their prices, and then decide about their level of research. Following Tirole (1988), their price policy is short-termist (they solve a static problem) while their innovation decisions meet long-term objectives (they solve a dynamic problem).

In the following, we denote by s_{jt} the market share in value of manufacturer j at time t. Equation (3) allows to get

$$s_{jt} := \frac{p_{jt}q_{jt}}{P_t Q_t} = \frac{p_{jt}^{1-\rho}}{\sum_{i=1}^{N} p_{it}^{1-\rho}} \tag{7}$$

The pricing problem. First, solar module producers solve the following short-term price problem

$$\begin{cases} \max\limits_{p_{jt}} \pi_{jt} = p_{jt}q_{jt} - c_{jt}q_{jt} - C_j(\gamma_{jt}) \\ q_{jt} = Q_t \left(\frac{p_{jt}}{P_t}\right)^{-\rho} \end{cases} \tag{8}$$

As P_t depends, due to formula (4), on the decisions of all the agents, problem (8) can be described as a simultaneous game among producers. We use the same approach as Atkeson and Burstein (2008) and assume that manufacturers take the market price P_t as given to fix their own price policy.[1] Then the problem (8) becomes a simple isoelastic demand problem, and we obtain that equilibrium prices must exceed costs by a constant factor given by

$$\frac{p_{jt}}{c_{jt}} = \frac{\rho}{\rho - 1} \tag{9}$$

Consequently, firms profits may be rewritten as

$$\pi_{jt} = \frac{1}{\rho} P_t Q_t s_{jt} - C_j(\gamma_{jt}) \tag{10}$$

[1] In addition to being consistent with empirical observations (see Figure 3 and related arguments in the introduction), this assumption is also required for the existence of a Nash equilibrium in pure strategies to problem (8). See Appendix A.

and the market share of firm j is now given by:

$$s_{jt} = \frac{c_{jt}^{1-\rho}}{\sum_{i=1}^{N} c_{it}^{1-\rho}} \tag{11}$$

We see that a firm with low marginal cost will set a lower price, in return, she will achieve a larger market share. Injecting (9) into (4), we also obtain that

$$P_t = \frac{\rho}{\rho - 1} \left(\sum_{i=1}^{N} c_{it}^{1-\rho} \right)^{\frac{1}{1-\rho}} \tag{12}$$

which shows that solar electricity price decreases as marginal costs fall.

The innovation problem. Let $T > 0$ be a large enough horizon. Long-term innovation problem writes for manufacturer j

$$\max_{(\gamma_{jt}) \in [0;1]^{T+1}} \sum_{t=0}^{T} e^{-rt} \left[\frac{1}{\rho} P_t Q_t s_{jt} - C_j(\gamma_{jt}) \right] \tag{13}$$

where $r > 0$ is the discount rate, (c_{it}) is subject to (5), s_{jt} is given by (11), and P_t by (12).

Problem (13) defines a dynamic discrete game in innovation. Firms interact through the price P_t and market shares $(s_{it})_{1 \leq i \leq N}$, which both depend on the costs of each player. As usual, we find Nash equilibria as fixed points of players' best response functions. The following proposition gives existence and uniqueness of these reaction functions, as well as an approximation when R&D costs, given by $(\beta_i)_{1 \leq i \leq N}$, are large.

Proposition 2.1. *For each firm j, optimal control problem* (13) *admits a unique solution. Moreover we have, for every $0 \leq t \leq T$, the following equivalence as β_j goes to infinity*

$$\beta_j \gamma_{jt} \underset{\beta_j \to \infty}{\sim} \max \left[c_{jt} \sum_{u=t}^{T} e^{-r(u-t)} Q_u s_{ju}^{\frac{\rho}{\rho-1}} \left(1 - \frac{\rho}{\rho - 1} s_{ju} \right) ; 0 \right] \tag{14}$$

Let us give a more precise interpretation of what a "large" value of β_j means. Proof of Proposition 2.1 in Appendix A relies on neglecting the term $e^{-rt} \beta_j^{-1} c_{jt} \lambda_{jt}$ in equation (36). To do so, β_j must be much higher than $e^{-rt} c_{jt} \lambda_{jt}$. Since λ_{jt} is of magnitude $\sum_{u=t}^{T} e^{-ru} Q_u$ by equations (32) and (33), β_j must therefore be well above $c_{j0} \sum_{u=0}^{T} e^{-ru} Q_u$. Now, on the one hand, β_j corresponds to the R&D expenditure required to bring the marginal cost down to zero in one period[2]. On the other hand, the quantity $c_{j0} \sum_{u=0}^{T} e^{-ru} Q_u$ is the discounted cost of

[2]Recall that $\beta_j = 2C_j(\gamma{=}1)$ with formula (6).

supplying all the demand, at constant marginal cost c_{j0}, over the whole period. Thus, a "large" value of β_j means that it must be cheaper for a manufacturer to continue producing at current cost, rather than to bring the cost down to zero and then produce for free.

If ρ is high enough as well, optimal research effort (14) may be further approximated by

$$\beta_j \gamma_{jt} \underset{\beta_j \to \infty}{\sim} c_{jt} \sum_{u=t}^{T} e^{-r(u-t)} Q_u s_{ju} \left(1 - s_{ju}\right) \tag{15}$$

Approximation (15) is simpler than (14), and we shall keep it in the rest of the paper. In the right term, c_{jt} and $(s_{ku})_{(k,u)\in[\![1,N]\!]\times[\![t,T]\!]}$ both depend on γ_{jt}. Together with (5), (15) therefore gives a system of $2 \times N \times (T+1)$ best-reply equations, with unknown controls $(\gamma_{kt})_{(k,t)\in[\![1,N]\!]\times[\![0,T]\!]}$. The following proposition gives an existence and uniqueness result.

Proposition 2.2. *If the $(\beta_j)_{1\leq j\leq N}$ are high enough, the system*

$$\left(\gamma_{jt} = \beta_j^{-1} c_{jt} \sum_{u=t}^{T} e^{-r(u-t)} Q_u s_{ju} \left(1 - s_{ju}\right) \right)_{(j,t)\in[\![1,N]\!]\times[\![0,T]\!]} \tag{16}$$

with (c_{jt}) subject to (5), and (s_{jt}) given by (11), admits a unique solution $(\gamma^{\star}_{jt}) \in [0;1]^{N\times(T+1)}$.

Propositions 2.1 and 2.2 thus show that if the R&D costs given by $(\beta_j)_{1\leq j\leq N}$ are large enough, our dynamic innovation game admits a unique open-loop Nash equilibrium. In the feedback version, firm j's optimal strategy $\gamma^{\star}_{jt}(c)$ is defined as the unique solution of the system

$$\left(\gamma_{jt} = \beta_j^{-1} c_{jt} \sum_{u=t}^{T} e^{-r(u-t)} Q_u s_{ju} \left(1 - s_{ju}\right) \right)_{(j,u)\in[\![1,N]\!]\times[\![t,T]\!]} \tag{17}$$

with $(c_{ju})_{u\in[\![t,T]\!]}$ subject to

$$\begin{cases} c_{ju} = (1 - \gamma_{ju}) c_{ju-1} \\ c_{jt-1} = c \end{cases} \tag{18}$$

In that case, the resulting feedback equilibrium is subgame perfect.[3]

[3] We refer to Dockner et al. (2000) for a comprehensive cover of the theory and economic applications of dynamic games.

2.3 Interpretation of the equilibrium

We now turn to the interpretation of the dynamic equilibrium. If we look at approximation (15), the left term corresponds to the marginal cost of research, and the right term to the shadow value of a unit cost decrease at time t. This shadow value is intertemporal, meaning that a research effort at a certain time has a marginal contribution on all subsequent profits. As a consequence, if the discount rate is low, optimal research effort γ_{jt} declines with time. On the opposite, if the discount rate is high, optimal effort highly depends on the quantity $\beta_j^{-1} c_{jt} Q_t s_{jt}(1 - s_{jt})$ at the same period. This quantity, which may increase or decrease over time, shows that a firm's innovation effort is inversely proportional to β_j, proportional to exogenous demand Q_t and to her current marginal cost c_{jt}, and follows an inverted U-shaped curve with respect to her market share s_{jt}.

This last relationship, related to market structure, is the consequence of a Schumpeterian and a Arrowian effect. On the one hand, following the basic Schumpeterian view of the relationship between competition and innovation (Schumpeter (1942)), a firm's research effort is positively related to her profit. There is, in this sense, a positive impact of market share on innovation. On the other hand, since demand is assumed to be exogenous, firms rely on innovation to increase their market share and capture a larger proportion of demand. This is done at the expense of a lower selling price, and large firms, which already hold a sizeable market share, are less prone to innovate. This can be seen as a version of the Arrowian replacement effect (Arrow (1962)). At the firm level, these two effects lead to an inverted U relationship between innovation and market share: small manufacturers have interest to innovate in order to expand, but capture little profits; on the opposite, large manufacturers capture more profits but have less incentive to expand. This behaviour stems from two features of our model: solar electricity demand Q_t is exogenous, and manufacturers set their price taking P_t as given.

This result is in line with the findings of Aghion et al. (2002), which emphasized an inverted U relationship between competition and innovation. Using a regulation index, Marino et al. (2019) showed that this relationship empirically holds in the electricity sector. More broadly, the debate about the role of market structure on innovation is rich and still open. While the discussion has mainly taken a macroscopic view, focusing on the number of firms (Cellini and Lambertini (2005)), their degree of collusion (Aghion et al. (2002)), or using an abstract intensity of competition index (Boone (2001)), our model, interestingly, provides a firm-level outcome by relating her market share to her incentive to innovate.

3 Application: international trade and innovation

The goal of this section is to emphasize how this model can account for the three stylized facts we identified in the introduction, namely (i) state-subsidized Chinese manufacturers have become the leading solar module producers in market share (ii) solar module costs have fallen everywhere (iii) innovation in solar photovoltaics has followed an inverted U trajectory. To that end, and to clearly illustrate the effects of imperfect competition, we study the case of a duopoly, where a local manufacturer competes against a foreign state-subsidized one.

3.1 Problem formulation

We keep using the notations from section 2. Consider a market with two competing solar panels manufacturers, denoted by L (the local one) and F (a foreign one). Assume that $c_{F0} > c_{L0}$, meaning that the local firm is initially more technologically advanced, but the foreign firm is backed by her home state and faces lower R&D costs, so that

$$C_L(\gamma) := \frac{\beta_L}{2}\gamma^2 \tag{19}$$

$$C_F(\gamma) := \frac{\beta_F}{2}\gamma^2 \tag{20}$$

with $\beta_F < \beta_L$. Assume β_L, β_F and ρ being high enough so that all the previous approximations hold.

First of all, as $s_{Lt} + s_{Ft} = 1$, equation (15) implies that for every $j \in \{L, F\}$ and $t \geq 0$

$$\gamma_{jt} \geq \beta_j^{-1} Q_t s_{Lt} s_{Ft} c_{jt} \tag{21}$$

meaning that there exists $\phi_{rjt} \geq 1$ such that

$$\gamma_{jt} = \phi_{rjt}\ \beta_j^{-1} Q_t s_{Lt} s_{Ft} c_{jt} \tag{22}$$

The following lemma gives properties of the elements (ϕ_{rjt}) that will be useful later on.

Lemma 3.1. *The following statements are true:*

1. *For all r and t, $\phi_{rLt} = \phi_{rFt} := \phi_{rt}$.*

2. *For all t, $\lim_{r\to\infty} \phi_{rt} = 1$.*

Now, in order to help the reasoning and computations along, let us consider the continuous-time analog of our discrete dynamics. State equation (5) writes

$$\frac{dc_j}{dt} = -\gamma_j(t)c_j(t) \tag{23}$$

endowed with positive initial condition $c_j(0) = c_{j0}$.

Using (22) and Lemma 3.1[4] we get, for $j = L, F$,

$$\gamma_j(t) = -\beta_j^{-1}\phi_r(t)Q(t)s_L(t)s_F(t)c_j(t) \tag{24}$$

with

$$s_j(t) = \frac{c_j(t)^{1-\rho}}{c_L(t)^{1-\rho} + c_F(t)^{1-\rho}} \tag{25}$$

Then,

$$\frac{dc_L(t)}{dt} = -\beta_L^{-1}\phi_r(t)Q(t)s_L(t)s_F(t)c_L(t)^2 \tag{26}$$

$$\frac{dc_F(t)}{dt} = -\beta_F^{-1}\phi_r(t)Q(t)s_L(t)s_F(t)c_F(t)^2 \tag{27}$$

Equations (26) and (27), endowed with the two initial conditions c_{L0} and c_{F0} (such that $c_{L0} > c_{F0}$), define a coupled system of differential equations. This sytem describes the evolution of the marginal costs of the two manufacturers, at the dynamic equilibrium. Provided that the functions Q and ϕ_r are smooth enough, it admits a unique solution. The following subsection shows how this system is able to account for the stylized facts and give them an interpretation, based on imperfect competition.

3.2 Results

As expressed in the following proposition, first outcome of system (26)-(27) is that innovation and competition bring costs down to zero. In addition, thanks to her state support, the foreign manufacturer is able to gain market share and become the dominant player. These two results account for the stylized facts (i) and (ii).

Proposition 3.1. *Assume that $Q : t \mapsto Q(t)$ is positive, continuous and bounded. Let c_L, c_F be the two solutions*

[4] The most convenient continuous-time representation for the sequences (ϕ_{rt}) and (Q_t) is a monotonic, smooth interpolation of these elements. In particular, this preserves the uniform convergence arising from the discrete and finite setup in Lemma 3.1.

of equations (26) and (27) and s_L, s_F their corresponding market shares. Asymptotically,

$$c_L(t) \to 0 \; ; \; c_F(t) \to 0$$

$$s_L(t) \to \frac{\beta_L^{1-\rho}}{\beta_L^{1-\rho} + \beta_F^{1-\rho}} \; ; \; s_F(t) \to \frac{\beta_F^{1-\rho}}{\beta_L^{1-\rho} + \beta_F^{1-\rho}}$$

We now turn to the fact (iii), related to the temporal trajectory of innovation. From subsection 2.3, we already know that a necessary condition for a non-monotonic trajectory of innovation to arise is to have a high enough discount rate - otherwise innovation steadily declines. The following proposition shows that if the elasticity of substitution is also large enough, then both manufacturers' research efforts follow an increasing-then-decreasing curve.

Proposition 3.2. *Assume that Q is constant. If r and ρ are high enough, both γ_L and γ_F admit a maximum.*

The intuition of Proposition 3.2 is as follows. Equation (24) shows that a firm's innovation level depends on costs and market shares. As costs go down, so do prices and returns on research, and this tends to slow innovation. On the opposite, as market shares converge to one half (a situation where the two firms are neck and neck and competition is fierce), innovation increases. These two interactions form a feedback loop: innovation affects costs and market shares which, in turn, impact innovation again. In our situation, the local firm, more technologically advanced, initially dominates the market. Yet the state-subsidized foreign firm innovates more efficiently and progressively expands, hence a rebalancing of market positions. When the elasticity of substitution is high, this fiercer competition effect prevails over the lower price effect, and both manufacturers initially increase their research effort. But once the foreign firm becomes the leader, she increasingly concentrates the market: as a consequence, market shares diverge, while prices continue to fall. These two effects eventually lead to a decline in innovation by both manufacturers in a second phase.

3.3 Policy implications

The inverted U curve thus stems from two counteracting imbalances: the local firm is initially more technologically advanced, but the foreign firm innovates more efficiently thanks to her state subsidy. If, instead, β_L was less than β_F, the local firm would see her initial dominance strengthen over time: there would be no rebalancing of market shares, and innovation would decline steadily. The foreign state subsidy is therefore a determining factor in the *shape* of innovation trajectory. What is its actual impact on the *level* of cost reduction?

Proposition 3.3. *Let $\beta_F < \beta_L$ and assume that r is high enough.*

(i) *For all t, $\frac{dc_F(t)}{d\beta_F} > 0$. Moreover, there exists $t_F^0 > 0$ such that for all $t < t_F^0$, $\frac{dc_L(t)}{d\beta_F} > 0$; and $t_F^1 > 0$ such that for all $t > t_F^1$, $\frac{dc_L(t)}{d\beta_F} < 0$.*

(ii) *For all t, $\frac{dc_L(t)}{d\beta_L} > 0$. Moreover, there exists $t_L^0 > 0$ such that for all $t < t_L^0$, $\frac{dc_F(t)}{d\beta_L} < 0$; and $t_L^1 > 0$ such that for all $t > t_L^1$, $\frac{dc_F(t)}{d\beta_L} > 0$.*

The effect of a subsidy on innovation is twofold: direct, by reducing R&D costs, and indirect, by changing the structure of competition between the two manufacturers. The direct effect is, by nature, always positive. The indirect effect may be positive, if it tends to push the two firms neck and neck, or negative, if it widens the gap between them. Proposition 3.3 states that for the manufacturer benefiting from the subsidy, the aggregate of these two effects is always positive. For the other, the outcome may be either positive or negative, depending on the competition effect.

To better understand this proposition, let us emphasize that, for $t > 0$ and $j, k \in \{L, F\}$, $dc_j(t)/d\beta_k > 0$ (resp. $dc_j(t)/d\beta_k < 0$) means that $c_j(t)$ decreases (resp. increases) as β_k decreases. Remember that a lower value of β_k reflects lower research costs for firm k, and thus higher financial support from state k. In our situation, the foreign firm is initially laggard, and then becomes the leader. Raising the foreign subsidy, i.e. reducing β_F, would always increase the level of cost reduction of the foreign firm ($dc_F(t)/d\beta_F > 0$ for all t). In the short run, it would narrow the gap between the two firms and, therefore, increase the level of cost reduction of the local firm ($dc_L(t)/d\beta_F > 0$ for $t < t_F^0$). However, in the long run, this competitive advantage would strengthen the dominance of the foreign firm, and reduce the cumulated research of the local firm ($dc_L(t)/d\beta_F < 0$ for $t > t_F^1$). Symmetrically, taxing the revenues of the foreign firm, i.e. increasing β_F, would always diminish her level of cost reduction. In the short run (resp. long run), it would reduce (resp. raise) that of the local one. Applying the same reasoning, as long as $\beta_F < \beta_L$, increasing the local subsidy would have a positive effect on the cost reduction of both manufacturers in the long run.

This analysis emphasizes the cross-border effect, through imperfect competition, of technology-push policies. A large number of empirical studies showed the positive domestic influence of such policies on innovation, focusing on solar PV (Watanabe et al. (2000), Peters et al. (2012)) and other renewable energy technologies (Klaassen et al. (2005), Johnstone et al. (2010)). However, their cross-border influence is more ambiguous. Although it is known that innovation generates international knowledge spillovers (Griliches (1992), Grossman and Helpman (1993)), no empirical study has been able to find any significant cross-border positive effect of technology-push

Table 1: Calibration choices.

Parameter	Symbol	Value	Source
Solar panel demand	Q_t	2 GW per month in average	BP (2021)
Initial production costs	$c_{L,2005}$ and $c_{F,2005}$	$c_{L,2005} = 3500$ USD/kW $c_{F,2005} = 6100$ USD/kW	Authors' estimations based on Taghizadeh-Hesary et al. (2018)
R&D costs	β_L and β_F	$\beta_L = 300$ G.USD $\beta_F = 270$ G.USD	Authors' estimations
Elasticity of substitution	ρ	7.5	Authors' estimation
Discount rate	r	15%	Moore et al. (2007)
Time horizon	T	20 years	Arbitrary

policies (Dechezleprêtre et al. (2011), Peters et al. (2012), Kim and Brown (2019)). Proposition 3.3 suggests that this effect can be either positive or negative, depending on the state of international competition.

3.4 Numerical illustration

We give here a numerical illustration of the results obtained in the previous subsections. To do so, instead of simulating the continuous-time equations (26)-(27), we directly solved the discrete system (16) in the duopoly case, assuming that "F" represents a Chinese manufacturer and "L" an American one.

Our calibration choices aim to reflect the evolution of cost, market share and innovation in these two countries. They are summarized in Table 1. As solar innovation took off in 2005 (Figure 2), the period considered for the simulation is 2005-2025. Time is monthly. For simplicity and to emphasize the effects of imperfect competition, we took Q_t constant, equal to the monthly average of global solar capacity installation, China excluded,[5] between 2005 and 2020. Initial production costs, $c_{L,2005}$ and $c_{F,2005}$, were estimated using equation (9) with price data coming from Taghizadeh-Hesary et al. (2018). We determined β_L and β_F to match numerical outputs of marginal costs and market shares with actual values, given in Figure 1. Elasticity of substitution was computed based on values shown in Figure 3 and formula (9). Finally, the discount rate was set to 15%, a standard value in private R&D (Moore et al. (2007)).

Figure 4 shows the numerical results, focusing on the effects of the discount rate, elasticity of substitution and foreign subsidy on the dynamic equilibrium. We simulated several configurations: $r = 10\%$, $r = 15\%$, $r = 20\%$; $\rho = 5.0$, $\rho = 7.5$, $\rho = 10.0$; and $\beta_F = 270$ G.USD, $\beta_F = 210$ G.USD (with, each time, other parameters as given in Table 1). In the base case ($r = 15\%$, $\rho = 7.5$ and $\beta_F = 270$ G.USD), we find the three stylized facts: expansion of the foreign firm, falling costs and an inverted U shape of innovation trajectory. Interestingly, the

[5] The Chinese solar market was specifically designed for domestic manufacturers, as a result of an intense local lobbying (Huang et al. (2016)). In our model, this competitive advantage is captured by β_F.

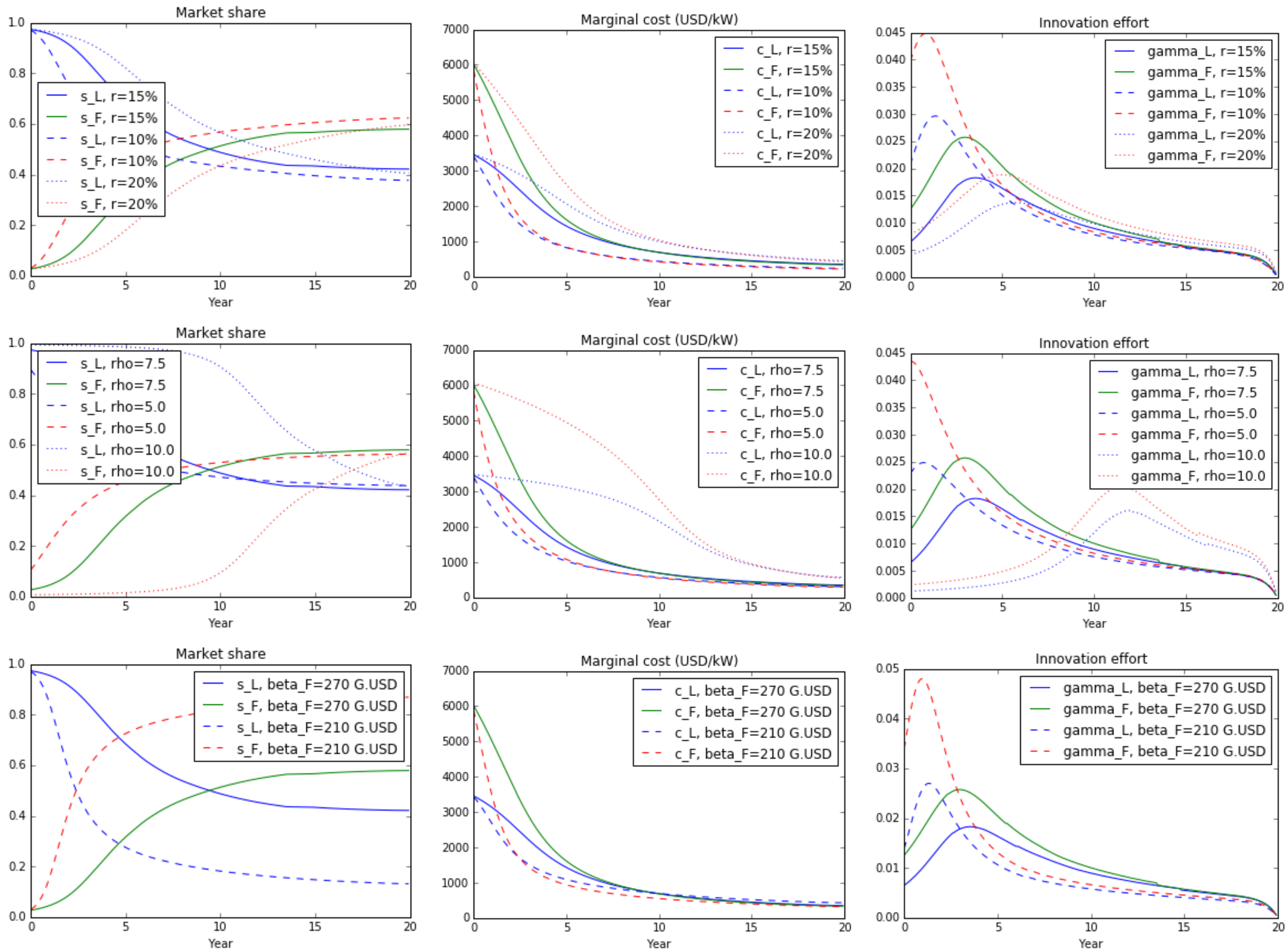

Figure 4: Dynamic equilibrium in market share, cost and innovation, for different values of r, ρ and β_F

timing and amplitude of the peak are consistent with empirical observations (Figure 2). We now turn to the comparative dynamics. First, as explained in subsection 2.3, lowering the discount rate leads firms to give more consideration to the intertemporal return of their innovations and, therefore, to raise their initial research effort: as a consequence, marginal costs decline more steeply, and the shape of innovation trajectory gradually shifts from an inverted U to a declining curve. Second, lowering the elasticity of substitution has two effects: it tends to even out the distribution of market share and makes it less elastic to cost variations. The result is an increased initial research effort (because $s_L(t)$ and $s_F(t)$ get closer to one half), but firms are, thereafter, less prone to raise it (because of a lower market share sensitivity to cost reductions); here again, the shape of innovation curve shifts from an inverted U to a declining one. Third, in line with Proposition 3.3, we see that a higher foreign subsidy, i.e. a lower β_F, reduces the marginal cost of the foreign firm over the whole period. It also reduces that of the local firm in the short run, but slightly raises it in the long run, after around ten years. In terms of cost reduction, the short-term gain seems much higher than the long-term loss -but this would require a further welfare analysis.

4 Conclusion

In this paper, we proposed an interpretation in terms of strategic interactions of the recent downturn in green innovation, focusing on the case of solar photovoltaics. As the foreign firm, benefiting from a state subsidy, progressively gains market share, the structure of competition evolves and, consequently, so does the intensity of research. The result is an initially rising, then falling trajectory of innovation. This suggests that technology-push policies, such as public R&D fundings, can contribute to shape international competition and therefore impact cross-border innovation.

This work opens several avenues of research. A first step would be to test empirically, beyond the stylized facts, these theoretical results. The model could aslo be extended to assess how factors other than pure strategic interactions can affect innovation; for example, one could add uncertainy in the R&D process, or incorporate fossil fuel price fluctuations into the exogenous renewable demand function. It could also be used to address the problem of the regulator, that is how to balance between demand-pull and technology-push policies in a way that preserves national industrial competitiveness while achieving environmental objectives.

Proofs

On the Nash equilibrium in pure strategies to problem (8): a non existence result

Lemma. *There is no Nash equilibrium in pure strategies to problem (8), with P_t given by (4).*

Proof. If there was an equilibrium $(p^\star_{jt})_{j\in[\![1,N]\!]}$, it would satisfy the first-order condition for $j = 1, ..., N$

$$(p^\star_{jt} - \rho(p^\star_{jt} - c_{jt}))P_t^{\star 1-\rho} + \rho p_{jt}^{\star 1-\rho}(p^\star_{jt} - c_{jt}) = 0 \tag{28}$$

Dividing by $P_t^{\star 1-\rho}$ we obtain the corresponding price-cost ratio as

$$\frac{p^\star_{jt}}{c_{jt}} = \frac{\rho(1 - s^\star_{jt})}{\rho(1 - s^\star_{jt}) - 1} \tag{29}$$

Injecting (29) into (8) gives the resulting profit of firm j as

$$\begin{aligned}
\pi_{jt}(p^\star_{jt}) &= p_{jt}^{\star 1-\rho} P_t^{\star\rho} Q_t - c_{jt} p_{jt}^{\star -\rho} P_t^{\star\rho} Q_t \\
&= P^\star_t s^\star_{jt} Q_t - P^\star_t s^\star_{jt} \frac{c_{jt}}{p^\star_{jt}} Q_t \\
&= P^\star_t s^\star_{jt} \left(1 - \frac{c_{jt}}{p^\star_{jt}}\right) Q_t \\
&= \frac{P^\star_t}{\rho} \frac{s^\star_{jt}}{1 - s^\star_{jt}} Q_t
\end{aligned}$$

In this last equation, $P^\star_t$ and $s^\star_{jt}$ are functions of $p^\star_{jt}$. Now,

$$\frac{\partial \pi_{jt}}{\partial p_{jt}}(p^\star_{jt}) = \frac{s_{jt}^{\star \frac{\rho}{\rho-1}}}{1 - s^\star_{jt}} \left[1 - \frac{\rho}{\rho - 1} s^\star_{jt} - (\rho - 1)s^\star_{jt}(1 - s^\star_{jt})\right] \tag{30}$$

which is non zero except when $s^\star_{jt}$ is zero or equals a singular value that only depends on ρ. As a consequence, in the general case, there is no Nash equilibrium in pure strategies to problem (8) with P_t given by (4). □

Proof of Proposition 2.1

The problem is discrete and of finite horizon. Dynamics (5) and firm j's payoff function (13) are continuous in c_j and γ_j. Moreover, at each period t, the control γ_{jt} lies in the compact $[0; 1]$. This yields the existence of an optimal control path to (5) – (13).

The Hamiltonian function of firm j's problem writes

$$H(\gamma_{jt+1}, c_{jt}, \lambda_{jt+1}) = (1 - \gamma_{jt+1})c_{jt}\lambda_{jt+1} + e^{-rt}\left(\frac{\beta_j}{2}\gamma_{jt+1}^2 - \frac{1}{\rho}P_tQ_ts_{jt}\right) \tag{31}$$

with $(\lambda_{jt}) \in \mathbf{R}^T$ the adjoint sequence subject to the following dynamics

$$\lambda_{jt} = (1 - \gamma_{jt+1})\lambda_{jt+1} - e^{-rt}\frac{\partial(P_tQ_ts_{jt})}{\partial c_{jt}} = (1 - \gamma_{jt+1})\lambda_{jt+1} + e^{-rt}Q_ts_{jt}^{\frac{\rho}{\rho-1}}\left(1 - \frac{\rho}{\rho-1}s_{jt}\right) \tag{32}$$

for $0 \leq t < T$, and the following transversality condition on T

$$\lambda_{jT} = -e^{-rT}\frac{\partial(P_TQ_T/\rho)}{\partial c_{jT}} = e^{-rT}Q_T\ s_{jT}^{\frac{\rho}{\rho-1}}\left(1 - \frac{\rho}{\rho-1}s_{jT}\right) \tag{33}$$

As optimal control γ_{jt+1} solves $\max\limits_{\gamma} H(\gamma, c_{jt}, \lambda_{jt+1})$, we have

$$\gamma_{jt+1} = \max\left(e^{rt}\beta_j^{-1}c_{jt}\lambda_{jt+1}, 0\right) \tag{34}$$

Gathering (5), (32), (33) and (34) characterizes uniquely the optimal control trajectory.

For the second part of the proposition, we need the following lemma.

Lemma 4.1. *Denote by $(\lambda_{jt}^{\beta_j}) \in \mathbf{R}^T$ the adjoint sequence for a certain $\beta_j > 0$. For every $t \in [\![0, T]\!]$ and $j \in [\![1, N]\!]$, $\bar{\lambda}_{jt} := \lim\limits_{\beta_j \to \infty} \lambda_{jt}^{\beta_j}$ is finite and verifies*

$$\bar{\lambda}_{jt} = \bar{\lambda}_{jt+1} + e^{-rt}Q_ts_{jt}^{\frac{\rho}{\rho-1}}\left(1 - \frac{\rho}{\rho-1}s_{jt}\right) \tag{35}$$

Proof. Consider that $\bar{\lambda}_{j(T+1)} := 0$ by convention. Then (33) gives the result at time T. Now consider that Lemma 4.1 holds at time $1 \leq t \leq T$. If $\gamma_{jt+1} = 0$, then taking the limit in (32) leads directly to the result. Else, injecting (34) into (32) gives that

$$\lambda_{j(t-1)} = \left(1 - e^{rt}\beta_j^{-1}c_{jt}\lambda_{jt}\right)\lambda_{jt} + e^{-r(t-1)}Q_{t-1}s_{j(t-1)}^{\frac{\rho}{\rho-1}}\left(1 - \frac{\rho}{\rho-1}s_{j(t-1)}\right) \tag{36}$$

We then just have to take the limit to get

$$\bar{\lambda}_{j(t-1)} = \bar{\lambda}_{jt} + e^{-r(t-1)} Q_{t-1} s_{j(t-1)}^{\frac{\rho}{\rho-1}} \left(1 - \frac{\rho}{\rho-1} s_{j(t-1)}\right)$$

and lemma 4.1 is proved by induction. $\square$

Taking the limit $\beta_j \to \infty$ in (34) and using (35) concludes the proof of the proposition.

Proof of Proposition 2.2

The map

$$\begin{aligned}\Gamma :\ [0;1]^{N\times(T+1)} &\longrightarrow \mathbb{R}^{N\times(T+1)} \\ (\gamma_{j,t})_{(j,t)\in[\![1,N]\!]\times[\![0,T]\!]} &\longmapsto \left(\beta_j^{-1} c_{jt} \sum_{u=t}^{T} e^{-r(u-t)} Q_u s_{ju} (1 - s_{ju})\right)_{(j,t)\in[\![1,N]\!]\times[\![0,T]\!]}\end{aligned}$$

is differentiable. If the $(\beta_i)_{1\leq i\leq N}$ are high enough, Γ is a contraction and $\Gamma\left([0;1]^{N\times(T+1)}\right) \subset [0;1]^{N\times(T+1)}$. By compactness of $[0;1]^{N\times(T+1)}$, Γ admits a unique fixed point.

Proof of Lemma 3.1

1. (15) and (22) give

$$\gamma_{jt} = \beta_j^{-1} Q_t s_{Lt} s_{Ft} c_{jt} + \beta_j^{-1} c_{jt} \sum_{u=t+1}^{T} e^{-r(u-t)} Q_u s_{Lu} s_{Fu} = \phi_{rjt}\ \beta_j^{-1} Q_t s_{Lt} s_{Ft} c_{jt} \tag{37}$$

Then,

$$\phi_{rjt} = 1 + \frac{\sum_{u=t+1}^{T} e^{-r(u-t)} Q_u s_{Lu} s_{Fu}}{Q_t s_{Lt} s_{Ft}} \tag{38}$$

which shows that ϕ_{rjt} does not depend on $j = L, F$.

2. Is obtained by taking the limit $r \to \infty$ in (38). Note that the convergence is uniform as $[\![0, T]\!]$ is finite.

Proof of Proposition 3.1

Market share of the local firm, s_L, is solution of

$$\begin{aligned}\frac{ds_L}{dt} &= \frac{\partial s_L}{\partial c_L}\frac{dc_L}{dt} + \frac{\partial s_L}{\partial c_F}\frac{dc_F}{dt} \\ &= -\frac{\partial s_F}{\partial c_L}\frac{dc_L}{dt} + \frac{\partial s_L}{\partial c_F}\frac{dc_F}{dt} \\ &= \phi_r(t)Q(t)(\rho-1)(s_L(t)s_F(t))^2\left(\beta_L^{-1}c_L(t) - \beta_F^{-1}c_F(t)\right)\end{aligned}$$

Besides, $\beta_1^{-1}c_1$ and $\beta_2^{-1}c_2$ are solutions of the same differential equation, namely, for $j = L, F$

$$\frac{d[\beta_j^{-1}c_j]}{dt} = -\phi_r(t)Q(t)s_L(t)s_F(t)[\beta_j^{-1}c_j]^2$$

As $\beta_L^{-1}c_L(0) < \beta_F^{-1}c_F(0)$, Cauchy-Lipschitz theorem gives $\beta_L^{-1}c_L(t) < \beta_F^{-1}c_F(t)$ for all t. Therefore s_L is nonincreasing and, thanks to formula (11), minored by $\frac{\beta_L^{1-\rho}}{\beta_L^{1-\rho}+\beta_F^{1-\rho}}$. Then it converges to a positive limit $l \geq \frac{\beta_L^{1-\rho}}{\beta_L^{1-\rho}+\beta_F^{1-\rho}}$.

Given equations (26) and (27), c_L and c_F are nonincreasing, minored (by zero) and so converge as well. As their derivative must tend to zero, we get $c_L, c_F \to 0$.

Now, c_L and c_F are also solutions of

$$\frac{d(c_1/c_2)}{dt} = \phi_r(t)Q(t)\frac{s_L(t)s_F(t)}{c_L(t)^2}\left(\frac{\beta_F^{-1}c_F(t) - \beta_L^{-1}c_L(t)}{c_L(t)c_F(t)}\right) \tag{39}$$

As s_L converges in $]0,1[$, then (c_L/c_F) converges to a positive limit, and its time derivative tends to zero. As c_L goes to zero, we must have

$$\frac{\beta_F^{-1}c_F - \beta_L^{-1}c_L}{c_Lc_F} \to 0$$

Or equivalently

$$\frac{\beta_L^{-1}}{c_F}\left(\frac{\beta_Lc_F}{\beta_Fc_L} - 1\right) \to 0$$

which implies $\beta_Lc_F(t) \underset{t\to\infty}{\sim} \beta_Fc_L(t)$ given that c_F converges to zero. Applying formula (11) then gives the limits of s_L and s_F and concludes the proof.

Proof of Proposition 3.2

We write the proof for γ_L only, a similar one applies for γ_F.

For $r > 0$, let $\gamma_L^r(t) = -\beta_L^{-1}\phi_r(t)Q(t)s_L^r(t)s_F^r(t)c_L^r(t)$, where c_L^r and c_F^r are solutions of (26) and (27). Using Lemma 3.1, as r goes to infinity, ϕ_r uniformly goes to one and γ_L^r uniformly converges to γ_L^∞ such that for all t,

$$\gamma_L^\infty(t) = -\beta_L^{-1}Q(t)s_L^\infty(t)s_F^\infty(t)c_L^\infty(t) \tag{40}$$

where c_L^∞ and c_F^∞ are solutions of

$$\frac{dc_L^\infty}{dt} = -\beta_L^{-1}Q(t)s_L^\infty(t)s_F^\infty(t)c_L^\infty(t)^2 \tag{41}$$

$$\frac{dc_F^\infty}{dt} = -\beta_F^{-1}Q(t)s_L^\infty(t)s_F^\infty(t)c_F^\infty(t)^2 \tag{42}$$

with $c_j^\infty(0) = c_{j0}$ and $s_j^\infty(t) = \frac{c_j^\infty(t)^{1-\rho}}{c_L^\infty(t)^{1-\rho}+c_F^\infty(t)^{1-\rho}}$ for $j = L, F$.

Differentiating (40) using (25) gives

$$\frac{d\gamma_L^\infty}{dt} = (Qs_L^\infty s_F^\infty)^2\left[-(\beta_L^{-1}c_L^\infty)^2 + (\rho-1)(s_L^\infty - s_F^\infty)\beta_L^{-1}c_L^\infty(\beta_F^{-1}c_F^\infty - \beta_L^{-1}c_L^\infty)\right] \tag{43}$$

γ_L^∞ is continuous, asymptotically goes to zero thanks to Proposition 3.1, and $\gamma_L^\infty(0)$ is positive. As a consequence, if $\frac{d\gamma_L^\infty}{dt}(0) > 0$, then γ_L^∞ admits a maximum. Now, given that $\beta_F < \beta_L$, $c_L^\infty(0) < c_F^\infty(0)$ and $s_L^\infty(0) > s_F^\infty(0)$; we have

$$(\rho-1)(s_L^\infty(0) - s_F^\infty(0))\beta_L^1 c_L^\infty(0)(\beta_F^{-1}c_F^\infty(0) - \beta_L^{-1}c_L^\infty(0)) > 0$$

Formula (11) gives $\lim_{\rho\to\infty} s_L^\infty(0) = 1$ and $\lim_{\rho\to\infty} s_F^\infty(0) = 0$, therefore

$$\lim_{\rho\to\infty}\left[-(\beta_L^{-1}c_L^\infty(0))^2 + (\rho-1)(s_L^\infty(0) - s_F^\infty(0))\beta_L^{-1}c_L^\infty(0)(\beta_F^{-1}c_F^\infty(0) - \beta_L^{-1}c_L^\infty(0))\right] = +\infty$$

Then, given equation (43), there exists a minimal $\rho_0 > 0$ from which $\frac{d\gamma_L^\infty}{dt}(0)$ becomes positive. Thus γ_L^∞ admits a maximum when $\rho > \rho_0$. As γ_L^r uniformly converges to γ_L^∞, one can show by contradiction that there exists $r_0 > 0$ (depending on $\rho > \rho_0$) such that for all $r > r_0$, γ_L^r admits a maximum.

Proof of Proposition 3.3

We write the proof for (i) only, a similar one applies for (ii). Using the notations of the proof of Proposition 3.2, we have

$$\frac{dc_L^r}{dt} = -\beta_L^{-1}\phi_r(t)Q(t)s_L^r(t)s_F^r(t)c_L^r(t)^2 \tag{44}$$

$$\frac{dc_F^r}{dt} = -\beta_F^{-1}\phi_r(t)Q(t)s_L^r(t)s_F^r(t)c_F^r(t)^2 \tag{45}$$

Therefore,

$$\frac{1}{c_F^r(t)} = \frac{1}{c_F^r(0)} + \beta_F^{-1}\int_0^t \phi_r(u)Q(u)s_L^r(u)s_F^r(u)\mathrm{d}u \tag{46}$$

$$\frac{1}{c_L^r(t)} = \frac{1}{c_L^r(0)} + \beta_L^{-1}\int_0^t \phi_r(u)Q(u)s_L^r(u)s_F^r(u)\mathrm{d}u \tag{47}$$

Differentiating w.r.t. β_F^{-1}, and after a few computations, we get

$$\frac{\mathrm{d}[1/c_F^r(t)]}{\mathrm{d}[\beta_F^{-1}]} = \int_0^t Q(u)s_L^r(u)s_F^r(u)\left[\frac{\mathrm{d}\phi_r(u)}{\mathrm{d}[\beta_F^{-1}]} + 1 - \left(1 - \frac{c_F^r(u)}{c_{F0}}\right)(s_L^r(u) - s_F^r(u))\right]\mathrm{d}u \tag{48}$$

$$\frac{\mathrm{d}[1/c_L^r(t)]}{\mathrm{d}[\beta_F^{-1}]} = \frac{\beta_F}{\beta_L}\int_0^t Q(u)s_L^r(u)s_F^r(u)\left[\frac{\mathrm{d}\phi_r(u)}{\mathrm{d}[\beta_F^{-1}]} + \left(1 - \frac{c_F^r(u)}{c_{F0}}\right)(s_L^r(u) - s_F^r(u))\right]\mathrm{d}u \tag{49}$$

Assuming that $\frac{\mathrm{d}\phi_r}{\mathrm{d}[\beta_F^{-1}]}$ uniformly vanishes as r goes to infinity, $\frac{\mathrm{d}[1/c_F^r]}{\mathrm{d}[\beta_F^{-1}]}$ and $\frac{\mathrm{d}[1/c_L^r]}{\mathrm{d}[\beta_F^{-1}]}$ then uniformly converge, respectively to

$$\frac{\mathrm{d}[1/c_F^\infty(t)]}{\mathrm{d}[\beta_F^{-1}]} = \int_0^t Q(u)s_L^\infty(u)s_F^\infty(u)\left[1 - \left(1 - \frac{c_F^\infty(u)}{c_{F0}}\right)(s_L^\infty(u) - s_F^\infty(u))\right]\mathrm{d}u \tag{50}$$

and

$$\frac{\mathrm{d}[1/c_L^\infty(t)]}{\mathrm{d}[\beta_F^{-1}]} = \frac{\beta_F}{\beta_L}\int_0^t Q(u)s_L^\infty(u)s_F^\infty(u)\left(1 - \frac{c_F^\infty(u)}{c_{F0}}\right)(s_L^\infty(u) - s_F^\infty(u))\mathrm{d}u \tag{51}$$

The right member in equation (50) is positive, therefore for all t

$$\frac{\mathrm{d}[1/c_F^\infty(t)]}{\mathrm{d}[\beta_F^{-1}]} > 0 \tag{52}$$

Now, given that $s_{L0} > s_{F0}$, we have, for ε small enough,

$$Q(\varepsilon)s_L^{\infty}(\varepsilon)s_F^{\infty}(\varepsilon)\left(1-\frac{c_F^{\infty}(\varepsilon)}{c_{F0}}\right)(s_L^{\infty}(\varepsilon)-s_F^{\infty}(\varepsilon))>0 \tag{53}$$

Therefore there exists $t_F^0 > 0$ such that for every $t \in (0; t_F^0]$,

$$\frac{\beta_F}{\beta_L}\int_0^t Q(u)s_L^{\infty}(u)s_F^{\infty}(u)\left(1-\frac{c_F^{\infty}(u)}{c_{F0}}\right)(s_L^{\infty}(u)-s_F^{\infty}(u))\mathrm{d}u>0 \tag{54}$$

i.e.

$$\frac{\mathrm{d}[1/c_L^{\infty}(t)]}{\mathrm{d}[\beta_F^{-1}]}>0, \quad \text{for } t\in(0;t_F^0] \tag{55}$$

In addition, given Proposition 3.1,

$$Q(u)s_L^{\infty}(u)s_F^{\infty}(u)\left(1-\frac{c_F^{\infty}(u)}{c_{F0}}\right)(s_L^{\infty}(u)-s_F^{\infty}(u)) \underset{u\to\infty}{\sim} Q(u)\frac{\beta_L^{1-\rho}\beta_F^{1-\rho}(\beta_L^{1-\rho}-\beta_F^{1-\rho})}{(\beta_L^{1-\rho}+\beta_F^{1-\rho})^3} \tag{56}$$

and the right term is negative. Thus, there exists $t_F^1 > 0$ such that for all $t \geq t_F^1$,

$$\frac{\beta_F}{\beta_L}\int_0^t Q(u)s_L^{\infty}(u)s_F^{\infty}(u)\left(1-\frac{c_F^{\infty}(u)}{c_{F0}}\right)(s_L^{\infty}(u)-s_F^{\infty}(u))\mathrm{d}u<0 \tag{57}$$

i.e.

$$\frac{\mathrm{d}[1/c_L^{\infty}(t)]}{\mathrm{d}[\beta_F^{-1}]}<0, \quad \text{for } t\geq t_F^1 \tag{58}$$

From (52), (55), (58) and uniform convergence, we obtain that there exists $r_0 > 0$ such that for all $r > r_0$,

$$\frac{\mathrm{d}[1/c_F^{r}(t)]}{\mathrm{d}[\beta_F^{-1}]}>0 \text{ for all } t$$

$$\frac{\mathrm{d}[1/c_L^{r}(t)]}{\mathrm{d}[\beta_F^{-1}]}>0 \text{ for } t\in(0;t_F^0]$$

$$\text{and } \frac{\mathrm{d}[1/c_L^{r}(t)]}{\mathrm{d}[\beta_F^{-1}]}<0 \text{ for } t\geq t_F^1$$

which concludes the proof.

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