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Competition, Lock in and Development of Technological Variety in the Production of Solar Electricity

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Introduction

Since the beginning of the nineties the energy context is marked by the instability of petroleum's price, the ascent of environmental preoccupations and the electric market's deregulation. Renewable energies, like photovoltaic solar energy (PV), know a renewal of interest in Europe, as on behalf of public authorities or electric utilities, petroleum and gas companies. Renewable began to develop on small markets niches as the electrification of isolated rural zones. More recently installations as offshore wind farms or rooftops PV, show that some renewable sources arrive at a certain technological maturity and have more and more vocation, in industrial nations, to be integrated into the electricity's distribution network. This current flourish with the recurring subject of energy supply security leans on two new preoccupations : the will to limit greenhouse gas emissions, according to the objectives fixed with Kyoto's protocol of 1997, and the realization of figures[1] fixed by the European directive to renewable energies adopted on September 7, 2001 by the council of the European Union.

At first, this paper aims to study from the evolutionist model of technological competition of B. ARTHUR, the phenomena of increasing returns on adoption (IRA) and the situation of technological lock-in in the sector of photovoltaic solar cells intended for the production of "green" electricity. We underline that, in spite of a conceptual interest and a heuristic contribution, this type of model presents certain limits for the economic realism of some hypotheses. By throwing back the conclusion that a situation of lock-in is definitive, we show then, by taking example of competition between photovoltaic roofs and conventional electricity distributed by the network, that from markets "niches", industrial and technological public policies can support effects of interactive learnings leaning on indirect networks effects, to develop and to maintain a certain, socially preferable, technological variety.

Solar cells and technological competition

The sector of solar cells is the place of competition between "mono and polycrystalline silicon" field (*SI*), and "amorphous silicon and others thin films" (*TF*) field. For 2000, the market shares for each of two technologies became established as follows : 79,9 % for *SI* and 20,1 % for *TF*. We conclude from it that in the current state, the sector of cells solar energy presents the characteristics of a lock-in situation. Commercial sun modules equipped with *SI* cells presents interest to show an average return on conversion[2] from 11 to 15 %. However they are the most expensive because of the length their manufacturing process requiring numerous manipulations. On the contrary, *TF* cells present returns from 5 to 7 %, but they are more easily compatible with automatic manufacturing processes which allow to reduce appreciably their cost.

[1] European directive " relative to the promotion of the electricity produced from the renewable sources of energy on the domestic market of the electricity " fixes the part of renewable to 12 % of the raw consumption of energy of the Union in 2010 (against 6 % today). What represents a specific part of 22,1 % of electricity produced from renewable in the total electricity production (large hydroelectric installations inclused).

[2] The performance of a solar cell is going to translate its capacity to transform solar energy into electricity. The return is equal to the report enter the electric power which it supplies and the brilliant power which it receives. The power of a cell is defined by agreement in watt peak (Wp) : it is the maximal power that it can supply under a period of sunshine from 1 000 W / m2 to a constant temperature of 25°C.

Evolutionist approach of technical change and the B. ARTHUR's model

Evolutionist approach of technical change and innovation collects very varied works, often more additional than competitors. So, we distinguish two mains theoretical movements which deal as the creation of technological knowledge with which objective is to encircle properties and nature of these processes. (i) The movement *determinedly* evolutionist analyzes technological evolution through populations companies selected by the market (R. NELSON and S. WINTER[3]) and through the notions of technological paradigms and trajectories (G. DOSI[4]). (ii) The second in which is situated this article, is established around B. ARTHUR, R. COWAN, P. DAVID and D. FORAY and is essentially based on stochastic models with positive feedbacks studying processes of creation-diffusion of technological innovations.

These approaches, although not structuring completely the studied domain, consider any technical change as a result of continuous processes produced by diverse micro-economic agents having capacity to modify their behavior and their operations by learning. In the neo-classical approach, decreasing factorial returns and constant returns on scale allow to assure stability and predictability of an economic equilibrium as solution of a problem of optimization, but do not explain the lock-in phenomena. The evolutionist movement, as recent discipline of Industrial Economics, develops alternate paradigms of technological diffusion by insisting particularly on its dynamic and historic aspects. As underlines it B. PAULRE [1997], the central object of this approach insist on the economic study of learning, by insisting on capacity to adapt itself and to accumulate past effects of adaptation. The integration of dynamics of technological change allows to interpret increasing returns (of adoption or scale) as result of learning effects and endogenous technical change, which are leading to irreversibility and path-dependency situations.

General frame of B. Arthur's model

B. ARTHUR [1988, 1989] put the foundations of his theory of technological competition by leaning at first on an idea which one can summarize simply : *« What makes competition between technologies interesting is that usually technologies become more attractive – more developed, more widespread, more useful – the more they are adopted »* (ARTHUR [1988]). From there, in a given technological domain, distribution of individual choices is at the origin of positive feedback (*increasing returns*) and increases probability that the technique adopted during period t_0 is chosen again in period t_1. Sources of increasing returns on adoption in a sector with strong technological intensity (it is the case for solar cells) helps then to explain why these can lead to a possible sub-optimal situation (in terms of welfare maximization). Dominant technology is not necessarily the most efficient. ARTHUR proposes a classification of five main causes of IRA :

1. *Learning by using* : it means that the more a technology is adopted, the more the effects of experience are going to play in favor of its diffusion and of its improvement (Cf. *learning by doing* and of *learning by using* introduced by K. ARROW[5] and N. ROSENBERG[6]) ;

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[3] NELSON R., WINTER S.[1982], « An evolutionary theory of technical change », Cambridge Harvard University Press.

[4] DOSI G. [1988], « Sources, procedures, and microeconomic effects of innovation », Journal of Economic Literature, Vol. XXVI September, pp. 1120-1171.

[5] ARROW K. [1962], « The economic implications of learning by doing », Review of Economics Studies, vol. 29, pp. 155-173.

2. *Economies of scale in production* : the more a technology is adopted, the more material elements which it incorporates will be produced in large series ;

3. *Network externalities* : a more and more adopted technology will engender direct network externalities (KATZ and SHAPIRO [1985]) resulting from increasing number of users, and from indirect network effects (CHOU and SHY [1990]) improving the characteristics of supply side (additional services) ;

4. *Informational increasing returns* : a more and more used technology will decrease risk aversion of producers and consumers (*learning about payoffs*, COWAN [1988]) ;

5. *Technological interrelations* : an established technology is going to know repercussions in settling of nearby products and affluent technologies which are going to structure its technical environment, strengthening all the more its attractiveness.

Within the framework of technological competition between the two solar cells path, existence of IRA is going to have for main effect to distort the conditions of competition, and so the exit of competition who results for the moment in a situation close to technological monopoly in favour of *SI* cells.

The basic model

If X and Y are two agents characterized by their respective natural preferences for two technologies A and B (not sponsored) introduced on a virgin market. On the market of potential users when the level of adoption of one of two technologies increases, technical progress localizes on it, what contributes to improve it and to make it more attractive for the following potential users. In the basic version of this model, after adoption, utility of the technology for an agent does not change. Agents are "nearsighted", *i.e.* their present choice is not made according to anticipations on future choices of the others.

Given the return of adoption function : $R_I^J = I_J + if(n_J)$

with R_I^J the efficiency of technology *J*, for the next agent of type *I*, considering his natural preference I_J and past behaviors of adoption $f(n_J)$, adjusted with increasing returns on adoption i ($i > 0$).

Returns associated to the use of A and B, according to natural preferences and levels of adoption can be written in the following way :

For X agents : $R_X^A = X_A + af(n_A)$ and $R_X^B = X_B + af(n_B)$

For Y agents : $R_Y^A = Y_A + bf(n_A)$ and $R_Y^B = Y_B + bf(n_B)$

[6] ROSENBERG N. [1982], « Inside the black box : technology and economics », Cambridge University Press.

With $X_A > X_B$, natural preference of X agents for A, and $Y_B > Y_A$ natural preference of Y agents for B. When returns on adoption are increasing ($a > 0$ and $b > 0$), process[7] leads with a probability 1 to the total adoption of one of two technologies. For example, if a sufficient number of X agents chose A, Y agents, in spite of their natural preference to choose B, will also opt for A, what will lead to the lock-in.

It seems to us convenient to remind now the four main properties of this type of process of competition based on the IRA :

- *Process is not ergodic (i.e. path-dependent)* : that is that the final exit of competition is conditioned with choices of the agents and events intervened in its beginning ;

- *The result of competition is not predictable* : it can not be predicted at the beginning of the process from only knowledge acquired on two technologies;

- *The possible inefficiency of the dominant technology* : at the beginning of competition, after a period of uncertainty, "small events[8]" governing the order of arrival of potential users, drive rapidly technical progress on a technology before its real capacities of development are really known. P. DAVID [1985] showed that QWERTY keyboard, nevertheless less efficient than others, had been selected as standard.

- *Process is inflexible* : from a certain period, the lock-in on one of two technologies is irreversible. Afterward, whatever are natural preferences, user will not choose the eliminated technology.

[7] Mathematically the process here is a "POLYA's urn" and a "law 0-1". Principle is the following one : one places a black ball and a white ball in an urn of infinite capacity by settling as objective to fill it with balls of one or the other colour. At each essay a ball is pulled randomly and a ball of the same colour is added in the urn. This process will be path-dependent, that it present a stochastic character endowed with a certain shape of memory. One can represent it from a sequence of binomial choices between two events (*A*, *B*) of which the probability of appearance in n^{th} editions are respectively P_n and $(1 - P_n)$. If E_i represents event occurring in the i^{th} *essay* the probability of appearance can be written (LIEBOWITZ and MARGOLIS [1992]):

$$P_{n+1} = F\,(P_n; E_n, E_{n-1}, E_{n-2}, \ldots, E_1)$$

The property called path-dependent will be constituted by the *d* last drawing lots when function *F* of probability will take the following form :

$$P_{n+1} = F(P_n; E_n, E_{n-1}, E_{n-2}, \ldots, E_{n-d})$$, if $d = 0$ is a pure random process .

At each period the probability that the next added ball is black is equal to the proportion of black balls already in the urn. The problem which arises is then to know if these proportions vary infinitely between 0 and 1 or if they aim towards a limit, what would determine so the emergence of a structure (lock-in). G.DOSI and *alii* [1994] resumes the demonstration of POLYA that the proportion of black balls aims towards a limit X with a probability 1, X being an unpredictable variable uniformly distributed between 0 and 1. They consider then a general case in which probability is an arbitrary function of proportions of all the types of balls and show also that process converges on one of the fixed points of the correspondence between proportions and probability of adoption.

[8] B. ARTHUR call them *« small unknown events »* or *« chance »,* P.DAVID *« historical accidents ».*

Contribution of the model and solar cell path

The interest of the application of this model for the competition between two technologies is to allow at first the formulation of conditions from which a situation of technological lock-in can seem from choices realized by two economic agents' types. More exactly, as underlines it D. FORAY [1989], this method, by leaning on IRA's notion, tackles technological competition as a problem of location of technical progress and behavior of adoption of the potential users. This type of model puts well in evidence weakened and temporal equilibria.

Progress realized during technical evolution of solar cells in crystalline silicon illustrates some of IRA's types that we presented. Photovoltaic solar industry benefited from its birth of strong technological interrelations connected to the nearness of the electronic industry. As in the case of state commissions of nuclear reactors in the United-States, the first state commissions of solar cells made with the NASA in the end of 1950's correspond to what B. ARTHUR calls "small events" and R. COWAN[9] "historic accidents". They contributed very early to develop *SI* cells, creating so a sort "orbital effect" of which the set of industry has since difficulties going out, ending in the current situation of quasi monopoly. On the other hand, observation of experience curve[10] of *SI* cells allows to seize a part learning effects and economies of scale. The experience index calculated recently show average levels of 20 % (MC DONALD and SCHRATTENHOLZER [2001]). These rates are supported by a strong increase of produced quantities these last years, letting still suspect perspectives of decline of prices notably due to the automation of manufacturing processes.

The main heuristic contribution of the B. ARTHUR's model lies, as we have seen it briefly for the solar industry, in the fact that he wonders about criteria which are going to lead a technology to become dominant. It demonstrates that dominant model can be determined only *a posteriori* and that this one is potentially ineffective.

Criticisms brought to the model

Although this model presents a conceptual interest and crosses with a certain success confrontation in empirical facts, it is not exempted from criticisms notably from the point of view of economic realism of certain hypotheses. We present limits advanced by certain authors (FORAY [1989], DOSI *and alii* [1994], DALLE [1995]), including B. ARTHUR himself, around two main subjects: (i) those that concern characteristics of agents and their behavior and (ii) those that concern the inflexible character of lock-in.

(i) Model postulates at first that agents are diverse at level of their individual preferences (and not at the level of their behavior), what confers a stochastic character on initial phase of the process. Nevertheless, (strong) hypotheses made on effects of number and IRA lead then to the disappearance of initial heterogeneousness of agents. Described process becomes then strictly determinist, what seems to us open to criticism. The heterogeneousness

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[9] See R. COWAN's study [1988].

[10] The experience curve links unit production cost evolution of the good and evolution of its production accumulated in time. The general shape takes form of an exponential in decimal scale or a straight line in a log-log scale. The experience index is used *EI* to calculate the reduction of cost resulting from a doubling of the cumulated production. One *EI* of 25% will mean that costs are reduced by 25 % each time the cumulated production doubles. In the case of increasing cots *EI* will be lower to zero.

behavioral of agents should so be looked for. It is *indeed likely* that, at a given, moment one agent chooses the technology which does not prevail over the market. The aggregation of agents, in a simplifying purpose, by means of average individuals, makes difficult description of the effects of influence and population. A representation of agents on a *continuum* with distributions of varied probability would be preferable.

Otherwise, one can doubt the fact which agents know, at time of making their choice, the proportions of population which have already chosen one of two technologies. Asymmetries of information can here be important. Either the concerned products are not spreaded and information concerning them is rare, or they are better known and available information is contradictory because of opportunist behaviors, every user persuading others that the technology is the most wide-spread. Furthermore, model to end in presented conclusions, tend the number of agents and the time towards infinity. Now, it would seem to us more realistic to envisage a finished number of agents potentially users of a technology, established on a virtual network and benefiting, to make their decision, of ways of information of "nearness". Information of agents would become then essentially local. That is that either every agent bases his choice from observation of his own state and others agents situated inside his "horizon-perimeter", or technological information, which can have a more global character, reaches locally because agents are membership of a network.

(ii) The main criticism brought to the model aims at the irreversibility of the lock-in situation, represented in theory by an infinitely stable equilibrium in the future. This state seems indeed much stiffer than the observable forms of irreversibilities in the reality through for example technological and economic life of equipments. B. ARTHUR [1988] recognizes however that a technology practically eliminated during a competition can know a restart, what would leave the place with a technological lock-out. However, he suggests treating this break in the same terms as the external events having the status of unpredictable variables. But the initial act of a lock-out, ending for example in a change of standard, implies strategic behaviors of technological watch of agents, analytically impracticable in a context of path-dependency.

On the other hand, one can underline that technological innovations never arise simultaneously on a virgin market. As remark J.-M. DALLE [1995] one of the main interests of the ARTHUR's approach is *"to return to the economic activity a historic dimension"* but he *"does not realize that he always refers, for the rhythm of arrival of innovations or standards, to an imaginary and an original time when all the processes would have their source"*. Now, the case where a competition begins with unequal levels of adoption (that what was the case for the photovoltaics) puts particularly in evidence the advantage pull by a technology of its length of service, notably due to two IRA's sources which we have already seen : informative increasing returns and technological interrelations. D. FORAY[11] showed that in spite of the superiority of a new technology and the exhaustion of possibilities of improvement of a former technology, this last one can remain durably on the basis of these two increasing returns on adoption.

[11] D. FORAY [1985], « Innovation majeure et transformation des structures productives », *Revue économique*, septembre. D. FORAY [1987], « Innovations technologiques et dynamique industrielle », Presses Universitaires de Lyon.

Network externalities, learning and role of public policies

B. ARTHUR [1989] proposes, from the basic model on which we presented and commented, an extension in which network externalities become the main source of IRA. In that case, more realistic, agents are not nearsighted any more, their utility for the chosen technology can change after adoption. Essential change lies in the fact that agents are going not only to take into account behavior of adoption from others agents, that is they are going to observe the size of the network at the time of their choice, but they are going especially to anticipate future behaviors. In this direction, model gets closer on certain points (notably on the path-dependent character) to static technological competition models of the microeconomic theory of imperfect competition, notably those developed by J. FARRELL and G. SALONER [1985, 1986] and by M. KATZ and C. SHAPIRO [1985, 1986]. From general point of view, one notices while these currents focus both on the role of networks externalities as market failures leading to inefficiency of the processes of technological competition. That is why we would like, from these approaches, bringing a different lighting on technological dynamics, by choosing now on a "more positive", less paralyzing conception of the notion of network by associating to it learning phenomena.

One can notice from the previous technological situations of competition, that at the same moment users and producers are distinguished by a certain passivity. Even if they know how to foresee future sizes of networks in competition, users have very poor behaviors of learning or collecting information, not allowing them to anticipate emergence of a new more and efficient standard. From their part, producers would not make the necessities (promotions, convertibility offers, training…) for internalize externalities, while they should be incited to establish and to patent new one standards bearer of profit opportunities (MASSARD [1997]). Therefore neither for users, as for producers of a technology, the nature of learning is analyzed. On the other hand, interactions among producers and users are never evoked, while they often can explain constitution and development of technologies on certain market's "niches".

While resuming the problem of penetration of photovoltaic solar energy, one can get free of the competition between fields *SI* and *TF*. We consider henceforth "competition" between these various fields of solar energy with sun roofs in a single technology and electricity produced from traditional fossil sources. Even though under certain technical aspects two technologies are additional, we consider them as directly rival. Principle of photovoltaic sun roofs allows production of electricity decentralized at the level of a house. Electricity is either consumed completely[12] on a place or the "surplus" is injected towards the network by way of a modulator which transforms it into alternating current. Except the first specific applications of solar energy for spatial industry, this shape of energy remained for a long time cantoned on narrow uses as the electrification of isolated sites or professional uses (beacons, broadcasting stations radio …) for which it often constitutes the only available electric source to satisfy a very precise need. International commitments on limitation of the greenhouse gas[13] effect aroused these last years a flourish of interest for solar energy as a clean source of electric production. PV roofs compatible in classic installations linked with the network, can be spread in large-scale on already existing houses or be directly integrated into architecture of new constructions. However diffusion of this technology, although

[12] The peak of electric production by a photovoltaic roof corresponds to the maximal period of sunshine during day. System can serve for example for feeding the cooling installation of a building.
[13] Cf. introduction.

additional but still expensive, collides with the electricity distributed by the network which totally locks the market.

It seems that uses of solar energy on evoked niches of market benefited from important learning and using effects. However separate and isolated character of these effects did not allow (or in any cases not enough) until today a development of mass improving competitiveness-price. Learning by using evokes the capacity of users to learn to clarify their necessities to translate them into specific products. It constitutes a central element in the analysis of choice of technologies and processes of standardization and allows to renew in a certain way approaches by externalities, by insisting more on tendencies to diversification (by capacities of specification of the necessities of users and producers) than on standardization. It leads us *naturally* to connect with this notion learning by interacting and to enrich the notion of network. B. LUNDVALL[14] exposed this type of learning in the analysis of producers-users networks without however clarifying his real nature and the link with the evolution of networks. It seems to us that learning by interacting can originate from indirect networks effects. These characterize the "virtual" or "metaphoric" networks (LIEBOVITZ and MARGOLIS [1994]) for which the increase of number of users of a product gets indirectly a supplementary welfare through supply externalities. The more users of a product will be numerous, the more interactions among them are going to increase. They are going to consist for example in exchanging information about the use of the technology (characteristics, advantages, limits). It's the same idea for interactions among producers and users, with for example the development of a follow-up and an after-sales services. So, one can advance that various types of learning are formed from experiences of the various agents. These social interactions (which can be localized) allow agents to acquire behaviors favoring emergence and preservation of a social order (GARROUSTE [1999]).

The possibilities of diffusion of a technology as PV roofs join well within the framework of this problem. We would like complete it by underlining the role of State's participations through technological and industrial public policies. The problem of policy makers consists in administering partially uncertainty linked to immediate advantages and to future returns on several technologies: in which direction are going their experience curves ? Technological policy is here confronted with the *"narrow window policy paradox"* (DAVID [1996]) : the action will be more effective at the beginning of process of learning, during a short period when little information about rival technologies are available. It has to administer the best relation "time-potentiality of technologies development " to press on technological competition by supporting technological options least well placed. It's a necessary condition for preserving technological variety. Various European public policies for PV solar energy and for other renewable energies help in the direction of a constitution of a "environment" favorable to learning. They are based on a range of more or less incentive instruments. One can distinguish : systems of quota (competitive bids and green certificates), fixed feed-in tariffs and fixed premium schemes of purchase established by Authorities and finally different measures of fiscal exemptions (tax credits).

To conclude, we notice that the shift of a problem based on increasing returns on adoption to a problem based on indirect network effects, and especially on phenomena of learning, allowed us to show the limits of validity of B. ARTHUR's model and to propose new

[14] B. LUNDVALL [1992], *National systems of innovation : toward a theory of innovation and interactive learning*, Londres, Pinter.

ideas to analyze technological dynamics. We showed, also by underlining the importance of the action of the State, that evolution of networks and learning kept pace. Combination of technological and relational learning leads towards endogenous technological phenomena of diffusion leaving less importance to externalities.

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