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Experience and Learning Curves: Improving the understanding of Technology Diffusion

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Studies of experience/learning curves (Wright 1936, Arrow, 1962, Boston Consulting Group 1968) can improve our understanding of the dynamics of technology diffusion and the interplay between public R&D, markets, technology deployment and technology development (IEA 2000, IEA 2003). The purpose of this short contribution is to indicate how the interplay between market deployment and technology learning may provide technology diffusion, and point to knowledge gaps that need to be filled in order to improve our advice on technology policy issues.

Appendix A demonstrates with the help of a threshold model for technology deployment (Kemp 1997, 2003), how technology learning in three different markets leads to diffusion of photovoltaic electric system. Figure A1 shows that total installed capacity of PV systems follows the characteristic logistic curve. The early implementers within each market provide *learning investments* (IEA 2000) to bring down the price and open up the market for the followers. The same mechanism also operates between markets. Thus, markets with high willingness to pay provide learning investments, which reduces prices, improves technical performance and make the technology cost-efficient in new markets with less willingness to pay.

Usually, the first markets may be quite small and reflect the added value of a specific property of the new technology, such as reliability of fuel cells or remote off-grid electricity production of photovoltaic cells. Such *niche markets* are, however, decisive for starting the ride down the experience curve. They act as stepping stones for the technology to reach the *mass markets* which usually require low prices and standardised technical performance.

Good learning rates and potential markets do not guarantee successful diffusion. A promising new technology may not be able to attract more than the early adopters, it may not be able to cross "the chasm" (Rogers 1995, IEA 2003, p.107). In the simple model in Appendix A, this happens for PV systems in the huge third market ("Power stations EU + NA"). More optimistic assumptions on the learning rates for PV systems, on the potential in the second market, or on the distribution of investors' willingness to pay in the third market would widen the deployment-learning-deployment "virtuous cycle"[1] and help PV systems to cross "the chasm" in the third market.

[1] The term "virtuous cycle" comes from Watanabe (1999), who has analysed such cycle in detail for the Japanese photovoltaic industry.

The model in Appendix A requires more refinement and more research to provide more detailed scenarios on market chances for PV-systems. One could also add that there is more than just price that influence technology diffusion. However, price remains one of the most important decison parameters for the investor and the model captures some fundamental aspects of the interplay between market deployment and technology learning. It serves as a point of departure in discussing some gaps of knowledge of relevance to technology policy design and implementation. Below, I discuss five areas where both research and methodological developments are needed.

1. The creation of alternative technology paths.

Evolutionary economics points to the path-dependence of technology development (e.g., Cimoli and Dosi, 1995). Appendix A illustrates in a schematic way a path that PV technology could travel via different markets to reach maturity and mass production. Policy measures may influence markets to supply or deny learning investments for new technologies or clusters of technologies, thus opening up or foreclosing different developing paths. There is a need to study efficient deployment programmes for particular desirable paths leading to clean technologies (see, e.g., IEA, 2003), but also to develop methodologies to find those desirable paths, that is paths which effectively uses the scarce resource of learning investments. For energy technologies, systems engineering models such as MARKAL or Message are well suited for this purpose but need to be extended to include the effects of technology learning as described by experience or learning curves (Mattsson and Wene, 1997, Messner, 1997, Seebregts et al., 1998, Smekens, 2003). The existence of alternative technology paths is reflected in the extended models by the non-convex solution space, that is, the models have local optima. Low-cost optima which are close in cost, but differ considerably in structure represent competing alternative technology paths (IEA 2000, pp. 84-91). Such optima - "epsilon in cost, but omega in structure" - provide the policy maker with real choices. New methodologies are required that are able to identify such alternative technology paths, characterise and compare their properties, and select the feasible and desirable ones. Presently, most methodologies focus only on the global optimum which deprives the policy maker of important information.

2. Niche Markets

Appendix A indicates the importance of niche markets to start the ride down the experience curve for new technologies which initially look forbiddingly expensive when viewed from mass markets. The importance of strategic niche market management has been discussed by several authors (see, e.g., Kemp, 1998). Such markets appear naturally for successful technologies but can be stimulated or even created by government technology policies (IEA, 2000, pp.64-74 and IEA, 2003, pp. 58-61 and pp.95-97). There are examples how the cool appliances industry uses niche markets created through labelling schemes to put initially expensive energy efficient refrigerators on mass markets. The interplay between technology diffusion, niche markets and experience curves need investigation, in order to find efficient policy measures which stimulate learning investments for clean technologies from private sources.

3. Public and industrial R&D and the "two factor learning curve".

The effect of Research & Development on price and technical properties is a key issue in technology policy. The price reductions are a result of *both* learning-by-doing in production *and* of technology R&D (Watanabe, 1995, 1999). Wene (1999) argues that experience curves measures market learning and the efficiency of the feed-back from market experience to production and *industry* R&D. The EU-SAPIENS project tried to separate the effect of R&D and learning-by-doing (LBD) in the two factor learning curve. They initially defined "R&D" as public+industrial R&D, but observed a strong covariance between R&D and LBD and thus had difficulties to separate the effect on R&D from LBD. Later work where only *public* R&D is considered gave more promising results (Klaasen and Schrattenholzer, 2002). Cybernetic organisation theory (Beer, 1979) emphasises the need to unfold different activities into different recursive levels and to avoid confusing levels. Following the insights from organisation theory, the conclusion is that learning in production and *industrial* R&D happens in close connection with each other, while *public* R&D emerges on a separate level. Distinguishing between public R&D on one side and LBD and industrial R&D on the other side should therefore be a more promising approach for a two factor learning curve. Considering the policy implications of being able to separate the effects of public R&D and technology learning through market deployment, continuing work on understanding the factors behind the experience/learning curve appears very important.

4. Global learning but local deployment.

The calculations in Appendix A assume that learning through deployment in one market is immediately transferred to the other markets. Deployment is local but to which extent is learning global? Learning is most probably global for the PV modules, but to what extent is the assumption true for the Balance of System? Governments need to consider the effects of deployment programmes both inside and outside the country (see for instance the discussion of Japan's PV Roof programme in IEA(2000, pp. 71-74). Learning investments can go both to industries inside and outside the country. To what extent do government need to align their technology policies in order to make them effective? Do patent rights hinder or foster global learning? The effect of globalisation on technology learning need to be studied, both to understand what is happening and to adjust policies.

5. Government deployment programmes and over stimulation of markets.

Two much growth creates scarcity cost and prices become larger than those expected from the experience curve. Studies of high and low growth periods indicate correlations between deviations from the experience curve prices and deviations from expected (historical) growth rates.[2] However, policy measures that lead to over stimulation of the market and poor price reductions are inefficient and need to be corrected. The situation become more complex when the over stimulation is due to government programmes in different countries, set up and working independently but together overheating the market. Studies of correlations between growth and deviations from the experience curve can help the policy maker to development

[2] Introducing such correlations in the model in Appendix A would adjust the growth, which is generated internally by the model. The model would then reflect what is expected in a real market situation. However, over stimulation caused by policy measures may not have this built-in auto correction.

more efficient deployment programmes. But ultimately, in a globalised market, national policy measures need to be aligned with each other.

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APPENDIX A:
Price-induced market deployment and experience curves create technology diffusion

Consider a three-market model for one single technology, where investments at each time t in each of the markets, M, is described by the threshold model and the price, P, for the technology is the same in all markets and described by the experience curve for the technology. We have the following equations

$$\begin{cases} X(t) = \sum_{M=1}^{3} N_M/\sigma_M/\sqrt{(2\pi)} * \int_{P(t)}^{\infty} \exp[-(P-P_M)^2/2/\sigma_M^2] * dP & \text{(Eq. 1)} \\ P(t+dt) = P_0 * X(t)^{-E} & \text{(Eq. 2)} \end{cases}$$

We thus assume that the willingness-to-pay in each market is distributed around an average value P_M with a standard deviation of σ_M. N_M is the potential sales in market M. The learning rate is

$$LR = 1 - 2^{-E} \qquad \text{(Eq. 3)}$$

We also assume that the cumulative sales of the technology, X(t), at time t determines the price of the technology at time t+dt, i.e., time for feed-back from market experience to improved technology is dt. In solving the equations we will put dt = 1 year. P_0 is a constant.

We choose PV-systems connected to the electric grid to illustrate solutions to the equations (1) and (2). The learning rate for the PV-systems are assumed to be 0.18 (18%) and the price in 2000 is set at 5.5 US\$/W_p. Total cumulative sales in year 2000 was 1 GW_p. The three markets are centred at P_1 = 3 US\$/W_p, P_2 = 1.1 US\$/W_p and P_3 = 0.5 US\$/W_p, and can be thought of as representing niche markets for residential PV-systems, and power systems in Japan and East Asia, and European Union and North America. EU is assumed to use electricity from power stations situated in North Africa. σ_1 is set to reproduce the year 2000 values for price and cumulative sales. The distribution of the willingness-to-pay need to be very broad in markets 2 and 3 in order for the PV-systems to be deployed in these markets, otherwise they do not proceed beyond the small market 1. Figure A1 shows a solution with σ_M at 1 and 0.8 US\$/Wp. It should be emphasised that this solution is chosen only to illustrate the arguments in the paper. Other scenarios are possible, e.g., distinguishing more markets and/or assuming a greater potential for distributed generation of electricity.

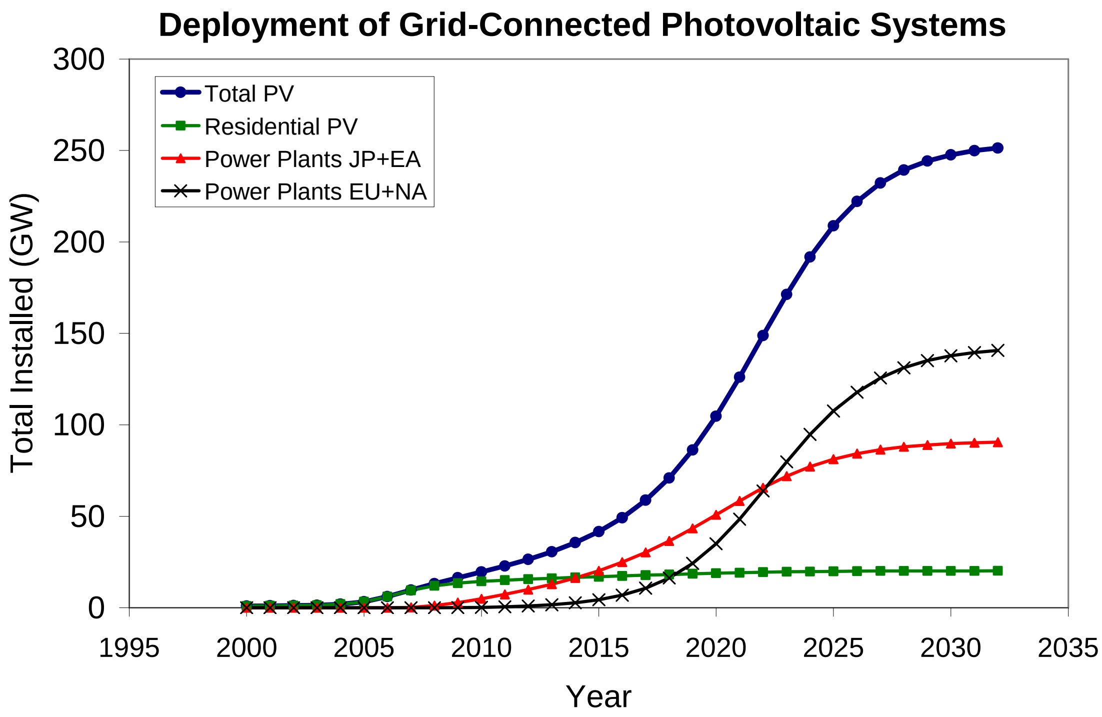

Figure A1. Market scenario for diffusion of PV systems.