Technological Forecasting & Social Change 76 (2009) 487–496

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

A percolation model of eco-innovation diffusion: The relationship between diffusion, learning economies and subsidies

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ARTICLE INFO

Article history:
Received 19 March 2008
Received in revised form 16 April 2008
Accepted 16 April 2008

JEL classification:
C61
H23
O32
O33

Keywords:
Innovation diffusion
Learning economies
Percolation
Networks
Heterogeneous agents
Technology subsidies
Environmental technologies

ABSTRACT

An obstacle to the widespread adoption of environmentally friendly energy technologies such as stationary and mobile fuel cells is their high upfront costs. While much lower prices seem to be attainable in the future due to learning curve cost reductions that increase rapidly with the scale of diffusion of the technology, there is a chicken and egg problem, even when some consumers may be willing to pay more for green technologies. Drawing on recent percolation models of diffusion, we develop a network model of new technology diffusion that combines contagion among consumers with heterogeneity of agent characteristics. Agents adopt when the price falls below their random reservation price drawn from a lognormal distribution, but only when one of their neighbors has already adopted. Combining with a learning curve for the price as a function of the cumulative number of adopters, this may lead to delayed adoption for a certain range of initial conditions. Using agent-based simulations we explore when a limited subsidy policy can trigger diffusion that would otherwise not happen. The introduction of a subsidy policy seems to be highly effective for a given high initial price level only for learning economies in a certain range. Outside this range, the diffusion of a new technology either never takes off despite the subsidies, or the subsidies are unnecessary. Perhaps not coincidentally, this range seems to correspond to the values observed for many successful innovations.

1. Introduction

The diffusion of new technologies often depends upon the interrelations between social and technical aspects [1]. On the one hand, communication channels and social networks play a central role in the widespread adoption of innovations [2]. Information contagion and imitation effects are widely recognized as crucial factors in the process of diffusion of innovations. In the particular case of energy technologies, and especially in the case of hydrogen and fuel cells technologies, demonstration effects and increased confidence play a significant role. On the other hand, technical factors such as the degree of complexity, compatibility and special features [3] directly influence the initial cost levels of innovations. High upfront costs are among the main factors that prevent the widespread diffusion of new technologies, and this is especially true for environmental energy technologies. The degree of learning economies is of primary importance in this context. New technologies characterized by high learning cost curve reductions will have a greater chance to break into mainstream markets. If a new technology has the chance to develop first in niche markets one could then exploit cost reductions in these markets due to learning curve effects when it is introduced into the mainstream market.

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[1] We would like to especially thank Peter Kolp and Manfred Strubegger for Python programming assistance.

0040-1625/$ – see front matter
doi:10.1016/j.techfore.2008.04.010

For instance, in the case of environmentally friendly energy technologies, a potential niche for market entry might be created by the willingness of some particularly environmentally conscious and high-income consumers to pay more for products that are perceived to be green (an example is the Toyota Prius hybrid car in the US, called “Hollywood's latest politically correct status symbol” by the Washington Post[2]).

However, even if much lower prices seem to be attainable in the future due to learning curve cost reductions that increase rapidly with the scale of diffusion of the technology, there is a chicken and egg problem, even when some consumers may be willing to pay more for green technologies. It is not clear when a technology will pass the threshold that permits widespread adoption and competitive market pricing, and when it will fail. The latter seems too often to be the case without long-term subsidies.

There exist a wide variety of policy options available to decision makers to influence this process. They may be roughly divided in two categories: demand-pull and technology-push policies. Even if a mix of the two is actually necessary, especially in the case of renewable energy sources [4], we will analyze the effect of one particular policy option that belongs to the first category: adoption subsidies for consumers. According to Turkenburg [5], the innovation diffusion process can be split into two parts: early deployment in which costs decline, and widespread dissemination in which institutional barriers are overcome and investments increase. A potential policy strategy related to the first phase of diffusion is represented by temporary subsidies followed by a phasing-out policy during the period of pervasive diffusion. In practice, however, especially with regard to environmentally friendly energy technologies, we often find permanent subsidy policies because the diffusion of such innovations is frequently not self-sustainable. Thus one can ask what policy actions may be implemented to support the diffusion of a new energy technology to market maturity that are socially profitable? In other words, which kinds of subsidy policies can trigger a self-sustained diffusion of these particular technologies that ultimately justify the upfront social expenditures?

Drawing on recent percolation models [6–9] of diffusion, which combine the contagion aspect (e.g., epidemic models) with the heterogeneity of agent characteristics (e.g., Probit or heterogeneous threshold models), we develop and analyze a model of new technology diffusion. While this model is clearly applicable to a more general category of (perhaps all?) innovations that start out with a disadvantage with respect to incumbent and competing technologies, it is especially applicable to the case of eco-innovations, where there may be strong ecological externalities justifying their diffusion but market forces may initially be unfavorable. While regulation or very high permanent subsidies may break this deadlock, we are particularly interested in the minimal policy interventions that could ‘kick-start’ a market-based diffusion process. Using agent-based simulations (ABS) we explore when a limited subsidy policy can trigger diffusion that would otherwise not happen. As a main result we find that subsidies are not helpful both when learning economies are too low (and thus reasonable temporary subsidies fail to trigger diffusion), and when learning economies are too high, (and diffusion would take off anyway). However, for a certain range of learning coefficients a temporary subsidy policy may indeed trigger self-sustained diffusion provided that the level of subsidies is high enough.

The article is organized as follows. Section 2 gives a brief overview of the existing literature on percolation diffusion models, learning curves and subsidies. The details of the model and the methodology are discussed in Section 3. In Section 4 we present the results. Interpretations and conclusions are discussed in Section 5.

2. Extending standard models of diffusion by introducing percolation, learning curves and subsidies

Innovation diffusion has been investigated using different approaches [10]. In particular, the S-shaped diffusion models and the epidemic models stem from two lines of research originating in Griliches' empirical investigation [11] and Mansfield's contributions [12,13]. In general, diffusion models can be classified as epidemic models, Probit models, legitimation and competition models, and information cascades models [14]. In what follows we focus on the first two categories: epidemic and Probit models. While the former emphasizes the effects of information contagion, it usually presupposes agent homogeneity. The latter is especially relevant in stressing the effects of agent heterogeneity but it neglects a description of the interrelations among individuals. The percolation model developed in the present paper incorporates both information contagion and agent heterogeneity. Agents interact on a specific network structure called the *Ising* network [2]. According to Stauffer and Aharony [15], percolation was originally applied by Flory and Stockmayer during the Second World War to describe critical phenomena for the process of gelation. Broadbent and Hammersley introduced the name percolation theory in 1957. Percolation explains, for example, how a fluid can traverse a porous material. But it has been applied to other cases, like the investigation of forest fires or stock market bubbles. As a simple example we explain the simple case of an atemporal site-percolation model. In a two-dimensional square lattice, assign randomly either 0 or 1 to each site. The values are stochastically independent and P is the probability for the realization of value 1, $1-P$ for value 0. Percolation is said to occur if there exist at least one unbounded cluster of sites with value 1. It can be shown that there is a critical value P_c, such that for $P<P_c$ percolation will not occur. On the contrary, if $P>P_c$ percolation will occur with probability 1 (for the two-dimensional site lattice we use in this paper, it can be shown numerically that $P_c \approx 0.592743$). Percolation theory has been applied to social science [7] as well as to the economics of technology diffusion [8,9].

The process of diffusion of new products and technologies often occurs on different time scales. It often starts with a few early adopters, followed by an increasing cumulative number as time passes. Moreover, it often follows an S-shaped path of diffusion. The market price may have to fall below some threshold level, however, before this process of diffusion can take off.

[2] *The Washington Post*, June 2, 2002, p. C01.