Diffusion of Green Technology: A Survey

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Motu Economic and Public Policy Research

Paper presented at the 2013 NZARES Conference

Lincoln University – Canterbury, New Zealand. August 28-30, 2013

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Motu Working Paper ##-##
Motu Economic and Public Policy Research

March 2014

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Acknowledgements
We are grateful to Bronwyn Hall and Paul Stoneman for useful comments on an earlier draft. All errors of omission or commission are the responsibility of the authors.

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 ISSN 1176-2667 (Print), ISSN 1177-9047 (Online).

Abstract

This paper surveys the existing literature on diffusion of environmentally beneficial technology. Overall, it confirms many of the lessons of the larger literature on technology diffusion: diffusion often appears slow when viewed from the outside; the flow of information is an important factor in the diffusion process; networks and organisations can matter; behavioural factors such as values and cognitive biases also play a role. With respect to policy instruments, there is some evidence that the flexibility of market-based instruments can have a beneficial impact on technology diffusion, but there are also numerous cases in which regulations have forced the adoption of new technologies. There would be significant benefit to increased investment in studies that look at questions such as the role of information provision, networks and framing issues in households' and firms' adoption decisions.

JEL codes

O33; Q55; Q56

Keywords

Technology diffusion; technology transfer; policy instruments; green technology

Contents

1. Introduction

Achievement of environmental objectives, and minimisation of the cost of such achievement, are dependent on the creation and diffusion of new, environmentally more benign technologies. Market failures with respect to technological change are conceptually distinct from environmental externalities, meaning that deployment of new environmentally beneficial technologies suffers from a "double externality" that makes it an important subject for public policy (Jaffe, Newell, and Stavins, 2003; Jaffe, 2012). The creation or innovation aspect of environmentally beneficial technological change has been surveyed elsewhere (Carraro, 2010; Brunnermeier and Cohen, 2003; Cleff and Rennings, 1999; del Brío and Junquera, 2003). This paper will survey the existing literature on diffusion of environmentally beneficial technology.

The distinguishing feature of a "green" technology is that it generates or facilitates a reduction in environmental externalities relative to the status quo.[1] This reduction can be in production (e.g. SO_2 scrubbers or windmills) or in consumption (e.g. efficient appliances or hybrid cars). Some green technologies impose both new capital costs and increased operating costs on their users, so that their adoption occurs *only* because the resulting reduction in the externality is desired or required. In other cases the reduction in pollution is associated with more efficient use of material and/or energy inputs, so that operating costs are reduced along with the reduction in pollution. Because of this, some studies and public advocacy claim that large "free lunches" or even "paid lunches" are to be had through wider adoption of existing technologies that would both reduce environmental impacts and save money for the adopters (e.g. McKinsey, 2009). Economists tend to be sceptical of such claims, emphasising that the analyses frequently ignore aspects of consumer preferences and/or costs beyond the obvious installation costs that must be borne by adopters (Allcott and Greenstone, 2012). In reality, it is often difficult to distinguish empirically the extent to which the barriers to more widespread adoption are real social costs versus market failures (Jaffe and Stavins, 1994a). This paper will not take on this controversy directly, but will provide a summary of some relevant evidence.

There is a large literature on the general topic of technology diffusion. (For surveys, see Stoneman and Battisti, 2010; Hall, 2006.) In many respects, the process of technology diffusion for green technologies is likely to be similar to that for technologies more generally. We begin with an overview of the theory of technology diffusion, which emphasises the trade-off between

[1] We thus explicitly include both cases where reduction in environmental impact is the purpose of the investment (e.g., pollution control technology) and cases where it may be more incidental (energy efficiency investments).

investment cost and ongoing benefits of a new technology, the role of information transfer in facilitating diffusion, and heterogeneous characteristics of adopters that determine which agents will be early adopters. The following sections take each of these three categories of issues and discuss the empirical literature that explores them with respect to green technologies. Section VI takes up two issues that arise particularly with respect to green technologies: the choice of "end-of-pipe" clean-up technologies versus process changes that reduce emissions by using material and energy inputs more efficiently, and the role played by image and environmental values. Section VII summarises work on the impacts of different environmental policy instruments on technology diffusion.

2. The Theory of Technology Diffusion

Josef Schumpeter described the process of technological progress as consisting of three stages: "invention" – the first technical implementation of an idea; "innovation" – the first commercial introduction of a new product or business method; and "diffusion" – the gradual adoption of a new way of doing things by multiple actors (Schumpeter, 1962).[2] Thus it is through the process of diffusion that the benefits of a new technology come to be widely enjoyed.

New, intrinsically superior technologies often take a long time to diffuse widely. Further, there is tremendous variability in the diffusion rate. For example, it took about 40 years for the clothes washer to go from being present in one quarter of households to being present in three-quarters of all households, while the colour television achieved this amount of diffusion in less than ten years (Hall, 2006). The economics of technology diffusion explores the reasons why diffusion is not instantaneous, and tries to model and measure the factors that affect its pace.

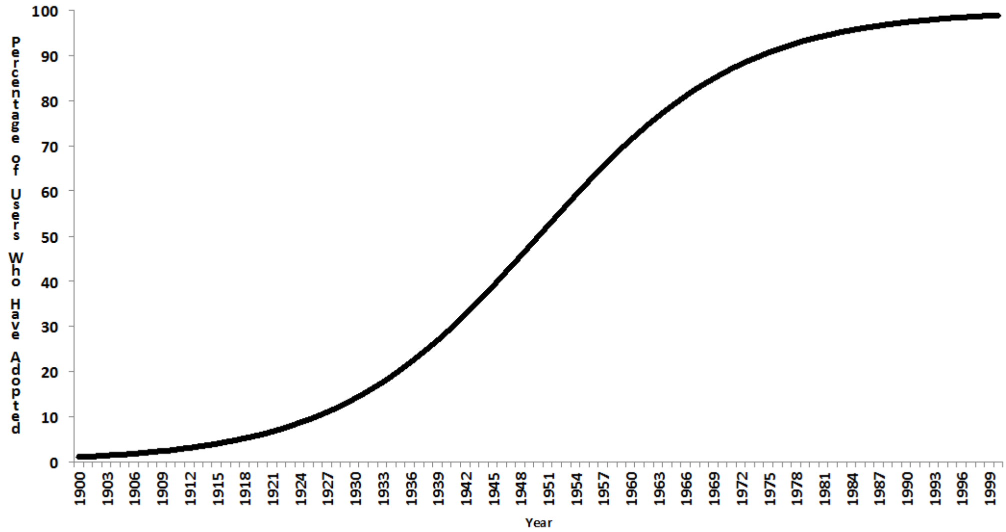
2.1. Diffusion Curves and the Epidemic Model

It has long been observed that the pattern of diffusion of a new technology can typically be described by an S-shaped function, as illustrated in Figure One. Initially, only a few early adopters try a new technology. At this early stage, both the fraction of potential users who are using the new technology and the rate of increase of that fraction are low. Gradually, both the extent of use and the rate of increase of that extent rise, leading to a take-off phase in which diffusion accelerates significantly. At some point, the extent of use becomes high and the rate of

[2] Thus technology "adoption" refers to the decision of a specific economic agent to take up a new technology, and technology "diffusion" refers to the overall process that is the result of the adoption decisions of many such agents. Depending on the context, they are often used interchangeably.

increase of that extent falls, leading to a levelling off or saturation. Depending on the technology, saturation may occur at 100% of potential users or close to it, or at some lower level.

Figure One
Typical S-shaped Diffusion Curve



One way to conceptualise this paradigmatic pattern of diffusion is based on the role of information in the diffusion process. Assume that (1) availability of information about a new technology is a key limiting factor to its adoption and (2) a key source of information about new technologies is their adoption by other economic agents. This means that when a technology is very new, and has been adopted by very few agents, it will spread only slowly, because information about it will not be widely held. But as it does begin to spread, this process will accelerate, with the process of adoption reinforcing itself by spreading information to more potential adopters. A stage will be reached where many – but not most – agents have adopted; at this intermediate stage, the *rate* of adoption will reach its maximum. But at some point, most of the agents who could adopt will have done so, so the rate of adoption then has to fall. Eventually, saturation will be achieved and at that point the rate of further adoption will tend towards zero.

From a modelling perspective, a process like this is isomorphic to the spread of an infectious disease, with transmittal of information from adopters to potential adopters operating in the same manner as the spread of an infectious agent from infected people to potential new victims of the disease. For an infectious disease, contact with an infected person creates one's chance of catching the disease, so any one person's chance of catching the disease is proportional to the number of people who already have the disease. It follows therefore that for the population as a whole, the number of *new* cases of disease in a given period will be proportional to this infection probability for a single person, multiplied by the number of potential disease victims. And this number of potential victims in any period is equal to the initial potentially susceptible population, *minus* the number of people who already have the disease and hence cannot be newly infected in the current period. That is:

$$dI/dt = A(I)(1-I) \quad (1)$$

where I is the fraction the population that is infected, and A is a parameter that is larger for more infectious diseases. The solution to this differential equation is the logistic function

$$I_t = 1/[1 + \exp(-At)] \quad (2)$$

with the characteristic shape of Figure One. Mechanically, we can think of technology as spreading like a disease, with each adopter potentially infecting other potential users with the new technology bug; thus we reinterpret I_t as the fraction of potential adopters who have adopted a new technology at time t. More concretely, we can think of the epidemic model as capturing the essence of the importance of information in the diffusion of technology. People have many sources of information about a new technology, but one of the most important sources is seeing the technology in use by others. This means that having a lot of people around me use a technology increases the chance that I will learn about it, and hence increases the chances that I will adopt it. While this story is simplistic, it does capture an important aspect of the process, and it is sufficient to generate the typically observed S-shaped diffusion pattern.

The logistic function (2) can be used as the empirical basis for estimating the factors that affect technology diffusion. If the fraction of adopters is observed across time for different markets or geographic areas, the parameter A can be made a function of characteristics of those observational units such as size and the nature of information institutions. Examples of this kind of analysis are discussed in Sections III and IV below.

The important role played by others' adoption in providing information about new technologies has potentially important normative policy implications. At a general level, markets for information are imperfect, so when one firm or household provides information to others via their technology adoption decision, they create a positive externality. There is thus at least a theoretical justification for policies (e.g. tax credits for hybrid cars) that subsidise the adoption of new technologies, over and above any broader social good that is generated by the particular technology (Jaffe and Stavins, 1994b).

2.2. Individual Economic Factors: The Heterogeneous Adopters Model

The discussion so far has treated everyone as equally susceptible to the disease or new technology. In this conception, the only reason not everyone adopts a new technology right away is that information about it spreads only gradually, and that learning is mostly generated by the diffusion process itself. An important complementary perspective on gradual diffusion starts with the insight that potential adopters are, in fact, heterogeneous with respect to the net benefits generated for them by the new technology. If we combine the reality of heterogeneous potential adopters with the observation that the new technology itself typically improves and falls in cost as it diffuses, we can generate an S-shaped diffusion curve even if information were perfectly available (David, 1966).

Suppose, for illustration, that the gross benefit from the new technology (e.g. lower operating cost or higher-quality output) is distributed across firms with a typical uni-modal distribution as illustrated in Figure Two. At a moment in time, we assume that all firms for which the benefit exceeds the cost will adopt if they have not done so before. This means that there will be a threshold benefit level, such that all of the firms for which the benefit exceeds this level will adopt (or will have adopted previously), and all firms for which the benefit is below this level will not. As shown in Figure Two, the cost will be relatively high initially, which means that the threshold benefit level will be high. Only the few firms in the upper tail of the gross benefit distribution will have adopted. But over time, the cost will fall. This makes the threshold benefit level fall. With every cost decline, more firms find the new technology attractive. If the cost falls continuously and relatively smoothly, this gradual fall will sweep out the distribution of benefits and generate an S-shaped diffusion curve.[3]

Figure Two represents the situation as the benefits of adoption being heterogeneous, while the (uniform) adoption cost falls over time. What matters, of course, is the relative benefits and costs; both the heterogeneity and the improvement over time can be on either side of the equation. An important source of heterogeneity is, in fact, on the cost side, because the cost of adopting a new technology is not limited to the purchase price of the new good. It includes also all of the costs that the user must bear in learning how to use it, and adapting existing processes and practices to it, and these are likely to be heterogeneous across potential adopters.

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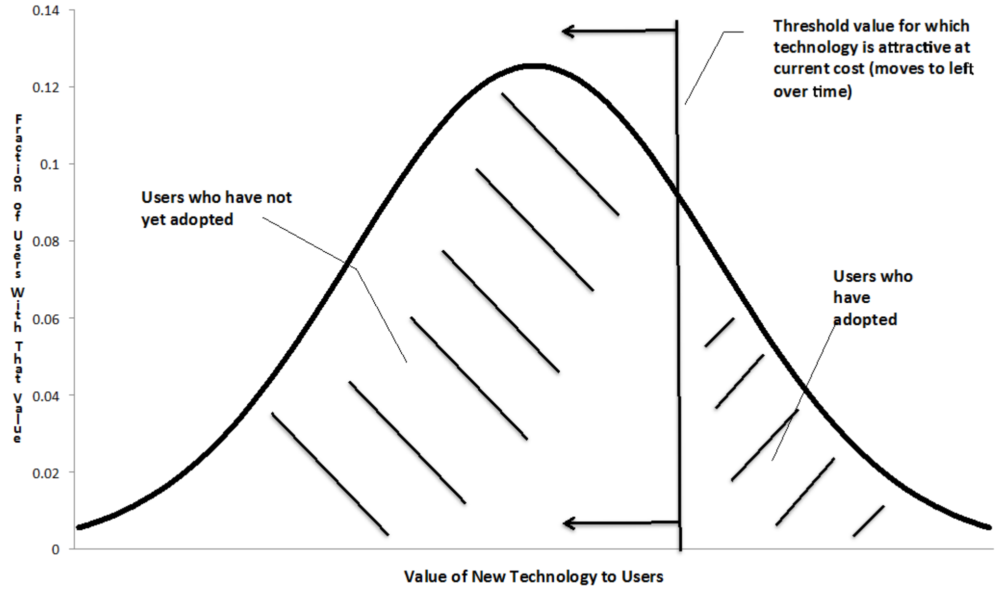
[3] This static analysis is too simple, because a dynamically optimising agent decides not just whether or not to adopt, but when. If the cost of adoption is expected to be lower in the future, then an agent for which the current present value of benefits exceeds the investment cost may nonetheless foresee overall discounted net benefit to be even higher by postponing adoption to a later period. In effect, because the adoption investment is sunk, there is an option value associated with delaying the adoption decision. This complication does not affect the qualitative story surrounding Figure Two.

Figure Two
Distribution of Heterogeneous Adopters Produces Diffusion as Costs Fall



Empirical implementation of the heterogeneous adopters model focuses on the individual economic agents, rather than a market or geographic area. The dependent variable is either a dichotomous variable for adoption, or else elapsed time until adoption. Characteristics of the potential adopters such as size and organisational structure/capabilities are used as explanators of who adopts when. Empirical work of this kind is discussed in Section V below.

Note that the learning/epidemic model and the heterogeneous adopters model can each generate S-shaped curves by themselves. In reality, both phenomena are typically at work, and the diffusion pattern we observe is generated by the combined effect of information spread and improvement in the technology making it attractive to more potential users over time.

2.3. Endogeneity of Technology Characteristics, Costs and Information

Any individual potential adopter takes the current and expected future path of technology cost and characteristics as given. But the aggregate scale and rate of adoption potentially contribute to the improvement of the technology as users provide feedback to producers (von Hippel, 2010), affect the incentive for R&D to continue improvement of the technology, and reduce the cost through static and dynamic "learning by doing" effects (Thompson, 2010). Similarly, the information that is available to potential adopters is potentially affected by strategic decisions of technology suppliers (Stoneman, 2013). This means that treating technology diffusion econometrically as a process driven by exogenous technology costs, attributes and information is not entirely satisfactory. Nonetheless, much empirical analysis does just this, as will be clear in the discussion below.

2.4. Network Effects and Technology "Lock-In"

Technology diffusion can be affected by network effects or technology lock-in. Such effects are present when the benefits of using a given technology depend on the extent to which others also use it.[4] A common source of such effects is a technology-specific infrastructure, which makes a given technology more economical, but which itself emerges only as the technology is widely used. The existence of network effects has both positive implications (the parameter A in Eq. (1) becomes a function of I_t) and normative implications (adoption generates an additional positive externality to the extent it fosters expansion of the network that supports all adopters). This phenomenon is important for some green technologies, to the extent that they depend on an underlying infrastructure (e.g. charging stations for electric cars) and compete with fossil-based technologies for which such infrastructure is already in place.

2.5. Technology Transfer

New technologies diffuse both within countries and across national boundaries. A form of technology diffusion that is particularly important for economic development and for the global environmental impact of green technology diffusion is the diffusion of technologies from developed countries to less developed countries, a process that is often dubbed "technology transfer." While in a sense just an aspect of a broader diffusion process, technology transfer raises particular theoretical and empirical issues. These include (1) the role of national and international rules governing protection of intellectual property rights ("IPR"); (2) the consequences of adapting technologies developed in one economic, institutional, legal and cultural milieu for use in another; and (3) the role played by trade policy, multinational corporations and foreign investment. These issues will be considered as they arise in the empirical analyses discussed below.

[4] These network effects are distinct from the information externality discussed above. They arise from an ongoing cost or benefit externality rather than the initial informational externality associated with first use.

3. Investment Cost and Annual Benefit

3.1. Findings

We expect that the pace of technology diffusion will be affected by the magnitude of the benefits and costs of the new technology relative to pre-existing alternatives. Jaffe and Stavins (1995) incorporated price and regulation effects in an epidemic-like model of variation across time and U.S. states in the extent of insulation of new homes built in the 1980s. The average "R-value" (a measure of effective insulation) was increasing in the price of energy and decreasing in the price of insulation. However, the elasticity of the R-value with respect to the insulation cost was significantly greater than the elasticity with respect to the (contemporaneous) cost of energy.

Similar results were found by Anderson and Newell (2004) for implementation of energy management practices by small and medium enterprises in the U.S. The data are from the Department of Energy's Industrial Assessment Centre (IAC) program, which has provided free industrial assessments to small-medium manufacturers since 1976. Overall, 53% of recommended projects were implemented (1981-2000). The paper estimated a fixed effects logit model, to explain the implementation decision, controlling for implementation cost, project type and plant level fixed effects. They found that firms are 40% more responsive to upfront costs than to annual energy savings .Interestingly, when they decompose the projected savings into energy quantity and energy price components, they also found that firms were more sensitive to the reduction in physical energy use, rather than its dollar value. (A 10% increase in the price of energy is associated with a 0.4% increase in the probability of adoption, while a 10% increase in the quantity of energy saved is associated with a 0.58% increase in the probability of adoption.) As discussed further below, this could reflect uncertainty about the future path of energy prices.

Bodas Freitas, Dantas, and Iizuka (2012) investigate the extent to which projects financed by the Clean Development Mechanism ("CDM") under the Kyoto Protocol incorporated renewable energy technologies. As such, it is not really a study of technology diffusion, but it casts perhaps some light on broader technology diffusion processes. They did find that factors associated with larger economic benefits of renewable energy (relative to fossil fuels) were associated with a higher rate of renewable energy projects. In particular, countries with higher population size and density had a higher renewable energy share; countries with large fossil fuel reserves had a lower share, and countries with greater freshwater and forest resources had a lower share. Popp, Hascic, and Medhi (2011) looked more directly at the diffusion of renewable energy technologies, measuring overall investment in electricity generation by solar, wind, geothermal and biomass in the OECD countries 1990–2004. The main foci of this paper are the effect of indigenous technology and policy variables (discussed below), but they also included indicators of expected benefits and costs. These variables had only limited explanatory power, with some negative effect from the prevalence of existing nuclear and hydro capacity. In this context the rate of investment appears to have been driven by policy rather than economics.

Turning from renewable energy to agriculture, Qaim (2005) surveyed the evidence on the adoption of herbicide-resistant soybeans and pest-resistant cotton in developing countries.[5] The net income gain per hectare, and the price of the genetically modified seeds both were found to affect diffusion. Regional variations in uptake also seemed to confirm the importance of the trade-off between cost and benefit, as adoption of pest resistant cotton is higher in northern and eastern China, where infestation levels of pests are highest; in the US, California, where infestation tends to be lower, had lower adoption levels than other cotton-growing states. Baumgart-Getz, Prokopy, and Floress (2012) conduct a "meta-analysis" of studies of the adoption of agricultural "best management practices" in the U.S. They found that subsidies for adoption of these practices do not have a significant effect. They describe this result as "unexpected," but do not speculate as to reasons why it is so.

Labson and Gooday (1994) estimated the diffusion curves for the adoption of electric arc furnace steelmaking technology for the USA, Western Europe and Japan, over the period 1970-1990. They fit S-shaped growth curves to data on the fraction of total steel production produced in electric arc furnaces including the input and output prices for the arc-furnace method relative to the input and output prices for traditional steel-making. Surprisingly, they find very little short run influence of these factors. Only the price of scrap iron relative to coking coal was found to influence short run adoption in Japan.

3.2. Assessment

As expected, magnitude of investment cost and annual cost savings is generally an important determinant of the diffusion rate for green technologies that offer annual cost savings, though the tendency is not universal. The most interesting and potentially important aspect of this literature is the question of whether the under-investment in resource-saving new technologies implied by engineering comparisons of costs and benefits reflects some kind of market failure, or alternatively a failure of the engineering studies to measure costs and benefits

[5] Some might question whether the genetically modified seeds represent a green technology, but they do allow for reduced use of pesticides and other resources, and their diffusion processes may be indicative of broader tendencies that would apply to other technologies.

correctly. The evidence with respect to energy-conserving technologies that adopters are more responsive to the up-front adoption cost than they are to the magnitude of the subsequent annual savings is relevant to this issue, but unfortunately not dispositive. Perfectly informed rational decisionmakers should respond in the same way to equivalent changes in costs and benefits. Whatever the discount rate agents use to trade off current and future benefits, a given proportional change in the investment cost has the same effect on the profitability of the investment as that proportional change in the annual benefits. Thus the disproportional impact of upfront costs could be evidence of behavioural biases. Possibly relevant biases include the "endowment" effect (Kahneman, Knetsch, and Thaler, 1991) whereby people place an irrationally high cost on losing something they have, relative to how they value a potential benefit they might receive, and a "salience" bias, whereby people give too much weight to facts that are prominently visible, relative to known facts that are not as visibly present (Schenk, 2010).[6]

Of course, agents considering technology adoption are not, in fact, perfectly informed. In particular, they do not know the stream of future benefits, which bears uncertainty due both to the magnitude of the physical benefits (reduced resource use, improved product performance) and the prices associated with those physical benefits. It is entirely plausible that the elasticity of the expected stream of future benefits with respect to changes in *current* benefit measures such as energy prices is less than unity. If so, this would break the predicted proportionality between the impact of changes in adoption costs and (currently observed) adoption benefits: changes in current costs flow through precisely to costs borne by the agent, whereby changes in currently observed benefits have less impact because they are expected to be only imperfectly connected to actual benefits received in the future.[7] If this mechanism is important, than the apparently greater impact of up-front costs is a rational response to uncertainty about the future rather than a behavioural bias.

Distinguishing the behavioural-bias and optimal-response-to-uncertainty-explanations for the observed pattern has potentially important policy implications. But it is very difficult, because expectations about future benefits are not observable. One possibility is to view the possible behavioural biases in the context of the overall behavioural economics issue of "framing," and to

[6] Possible evidence for the relevance of salience bias in adoption decisions is the finding of Gallagher and Muehlegger (2011, discussed below) that a sales-tax rebate (immediately visible at the time of purchase) has much greater impact per subsidy dollar on purchases of hybrid cars than does an income-tax refund.

[7] The finding by Anderson and Newell (2004) that firms are more responsive to the predicted physical energy savings than to the future energy price hints that this might be the case.

investigate—preferably through appropriately designed policy experiments—the extent to which framing affects agents' technology adoption decisions (Allcott and Greenstone, 2012).

4. Information Mechanisms

4.1. Findings

Baumgart-Getz, Prokopy, and Floress (2012), in their meta-analysis of studies of farmers' adoption of agricultural "best management practices", found that both self-reported information levels and previous participation in agricultural extension programs were among the more robust and significant predictors of adoption. Farming experience and formal education (excluding extension training) were not significant. Networking via public agencies and local organisations were also found to be significant positive predictors of adoption.

Conley and Udry (2010) examines farmers' fertiliser practices growing pineapple in Ghana, as an example of the mechanisms and importance of social learning. Over the 1990s, the agricultural system in Ghana changed from an established mix of maize and cassava to growing pineapple for export. With this change came the need to learn how to use new agricultural technologies, such as fertilisers and agricultural chemicals. The authors find very strong effects from the practices of other farmers in a given farmer's information neighbourhood. A farm is more likely to change its use of fertiliser if a farm that used a similar amount experienced lower than expected profits. A farm will use more (less) fertiliser if another farm in their information neighbourhood had unexpectedly high profits from using more (less) fertiliser. Responsiveness to this news varied by individual farmer characteristics and the characteristics of those in their information neighbourhood. The farm's response to news was greater if it had recently changed to growing pineapple (they had more to learn). The response to news was also greater if the news came from a plot cultivated by a veteran farmer (who presumably has greater knowledge about the local conditions and the optimal amount of fertiliser to use in those conditions).

Related findings are those of Lewis, Barham, and Robinson (2011). This paper studies the adoption of organic dairy farming in southwestern Wisconsin in the years 1998-2008. They use a spatial panel dataset with information on 1800 independent dairy farms in the study area. They model the conversion to organic decision as a net present value decision that depends on soil characteristics, assessed value of structural improvements (as a proxy for size of sunk costs), the distance to a major organic cooperative, and the number of other organic dairy farms within 5 miles and between 5 and 10 miles. They find that farms closer to the cooperative are more likely to convert, and they find a positive and significant impact on the number of organic farms within a 5 or 10 mile radius on the conversion decision. Having an additional nearby organic farm increases the annual likelihood of conversion by 1.3 percentage points, where the base annual rate is itself about 1 percent.

Lee (2005) discusses the role of networks in influencing the adoption of sustainable agricultural practices in developing countries. Social-capital based connections of various types – internal and external, horizontal and vertical, top-down and two-way – have been shown to facilitate technology adaptation and adoption among those involved in sustainable agriculture.

The paper on adoption of GM seeds (Qaim, 2005) makes the point that adoption of this particular technology is easily reversible, which has important consequences for the importance of learning for the adoption decision. In the early stages of diffusion, farmers often experiment with the new technology on a small scale, and reconsider the adoption decision based on their personal experience. They present data from India, which shows that the adoption decision in this case is a reversible one. In the first season, almost half of the adopters abandoned GM crops as they were not satisfied by the results. However, the rate of dis-adoption fell over time, and a significant share of those who abandoned GM crops re-adopted later. It seems that learning-by-doing and network learning are important for the decision to adopt. Network learning or information sharing could plausibly explain why many farmers who initially abandoned the technology later readopted.

Popp, Hascic, and Medhi (2011), discussed above, also looked at the effect of prior knowledge levels (proxied by national energy R&D expenditure) on the diffusion of renewable electricity generation capacity. Overall, they found that countries with greater energy R&D investment intensity had higher levels of investment in the renewable technologies, but the effect was statistically significant only for biomass and wind investment, which are also the most prevalent technologies in the sample. The effects were small with an elasticity of renewable investment with respect to the country's knowledge stock of .26 for biomass and .06 for wind.

4.2. Assessment

Information is difficult to measure, which makes direct assessment of the importance of information transfer to the diffusion process difficult. There is, however, a variety of indirect evidence suggesting that mechanisms of information transfer are empirically important in the process of green technology diffusion:

- adoption is correlated with self-reported level of knowledge;
- use of one green technology is correlated with the use of others;

- membership in networks, organisations or programs is correlated with adoption; and
- adoption is correlated with adoption by neighbors.

The problem with indirect evidence is, of course, that for each of these associations, it is plausible that factors other than information transmission are the true cause of the observed empirical association. People who join organisations may be generally more proactive, and hence more likely both to join organisations and to adopt new technologies, rather than the organisations being a source of information about the technologies. Correlation of adoption with adoption by neighbours could reflect unobserved attributes that favour or disfavour adoption that are themselves distributed geographically, so that the new technology is just better for all of the people in one micro-area, and not as good for people another. Overall, however, the fact that several different kinds of indirect evidence all point towards the significance of information seems to confirm that information is truly important.

5. Other Attributes of Early Adopters

5.1. Findings

Baumgart-Getz, Prokopy, and Floress (2012) found that farm size – which they interpret as an indicator of farm "capacity" to undertake adoption – was perhaps the single most important predictor of adoption of agricultural BMP. Farm capital and income are also significant positive predictors, even after controlling for farm size. This suggests that financial capability has an impact independent of size.

The analysis of GM seeds by Qaim (2005) found that the impact of farm size depends on the specific crop in question. Herbicide resistant soybean, for example, has been show to produce larger gains on large, mechanised farms. Evidence for cotton indicates that it is neutral in scale, and that productivity gains can even be bigger for smaller than for larger farms. Evidence from India shows that the difference in farm size between adopters and non-adopters is relatively small, and this difference has been decreasing over time. This paper did find that an important impediment to adoption is lack of access to finance. Farmers in developing countries tend to be more heavily credit constrained. Coupled with significant GM seed price premiums in some countries, this leads to slower adoption rates.

De Souza Filho, Young, and Burton (1999) uses duration analysis to investigate the factors influencing the decision to adopt sustainable agricultural practices (reduced chemical inputs, improved management techniques, use of locally available resources) in Espirito Santo, Brazil, based on a survey of 141 farmers in the region (64 adopters and 77 non-adopters). Adopters tended to have smaller farms, greater awareness of environmental impacts, more likely to be engaged with farmer organisations or NGO extension programs, more reliant on family labour and on-farm income than non-adopters. They also found that farm profitability had a (marginally) positive impact on adoption, and wages a negative effect, which makes sense because sustainable practices are more labour-intensive.

Lee (2005) provides a more general review of the adoption of sustainable agricultural practices in developing countries. Unlike Green Revolution farming systems, which focussed on high-yield crop varieties and the use of external inputs, sustainable agricultural systems are often location specific. As a result, local agro-climatic and biophysical conditions are key determinants in the type of sustainable agricultural practice that is adopted. While many of these technologies and practices are adopted on a relatively small scale, the adoption of zero or minimum tillage farming has been more widespread. A possible reason for this is that conservation tillage addresses a broad range of issues that are both general and location specific.

Many of these technologies are more intensive in their use of management inputs. Proxies for improved management have been shown to positively influence the adoption decision, as farmer age, experience, and education levels all make a farmer more likely to adopt sustainable practices. Information also plays a role. Farmers involved with extension programs, NGOs, farmer organisations, outreach programs and other sources of knowledge or technical support are more likely to adopt.

Kerr and Newell (2003) study the adoption of lead-reducing technology by refineries in the US, during the period leading up to the ban on lead in petrol in 1996. They find a positive effect of refinery size on the probability of adoption. Refinery size 10% larger than the mean refinery was associated with a 4% increase in the rate of adoption. However, refineries that are part of larger companies or are in regions with many other refineries have lower adoption propensities. This could be due to greater flexibility in input and output choice making adoption less profitable. They find little evidence of a learning effect among these firms.

The paper by Anderson and Newell (2004) that studied the adoption of recommendations from government energy audits investigated the reasons given by firms for not implementing projects. They classified, as best they could, these reasons into three broad categories: economic, institutional and financing. Many of the reasons seemed to reflect uncertainty around the benefits and/or costs of the project, such as changes to product quality, the need to shut down the facility, large changes to operations or the perceived riskiness of the project. Some firms gave a lack of suitable personnel, something which has come up in many firm level studies, particularly for SMEs. Others suggested that the project was initially too costly or they had a lack of cash flow to allow implementation.

5.2. Assessment

The broader literature on technology diffusion has emphasised firm size as an important determinant of which firms are early adopters (Griliches, 1957; David, 1966; Mansfield, 1961). Adoption frequently involves a trade-off between an upfront fixed cost and ongoing benefits that are scaled to the volume of output, a trade-off that is inherently more favourable for larger firms. It is, however, difficult to distinguish the fixed-cost-spreading interpretation of the firm size effect from the adoption "capacity" explanation of Baumgart-Getz, Prokopy, and Floress (2012). This general tendency towards larger firms' adopting first does have exceptions, particularly in agriculture, where details of the way in which a particular technology affects farm economics can be important.

Measures of managerial and financial capacity also seem important in explaining which firms adopt first. It is not clear to what extent these effects represent the inevitable consequence of managerial ability being a scarce resource, versus imperfections in capital markets that constrain some firms' ability to finance investments they know to be profitable. The distinction is important from a policy perspective, because the former represents a true social cost of the diffusion process, while the latter represents a market failure that policy might wish to address.

6. Issues Particular to the Adoption of Green Technologies

For many of the issues considered above, green technology diffusion appears to be simply a special case of the broader issue of technology diffusion. There are, however, a couple of issues that arise distinctly with respect to green technologies. Attitudes and knowledge about the environment – and perceptions of public attitudes and resulting image effects – may affect green technology adoption decisions distinctly. In addition, concerns about long-term sustainability have led to some investigation of the factors that affect a firm's choice between reducing emissions using an "end-of-pipe" clean-up technology and reducing emissions through process redesign.

6.1. Findings

6.1.1. Environmental Values and Image

Baumgart-Getz, Prokopy, and Floress (2012) found that environmental awareness is a significant explanator in the adoption of agricultural BMP. In particular, they found that specific knowledge about a farm's water quality consequences, and about the objectives of non-point-source pollution control programs, has a bigger impact than generic knowledge about the environment and environmental goals.

Somewhat similar results were obtained by Luken, Van Rompaey, and Zigova (2008) regarding the decision to adopt environmentally sound technologies (EST) by firms in developing countries. They focus on both pollution abatement technologies and pollution prevention/cleaner technologies. They estimate an ordered choice model of the decision to adopt either pollution abatement or prevention technologies. They find that environmental commitment, technological capabilities and ownership play a role in the adoption decision for the more complex pollution prevention technologies. A one standard deviation increase in the environmental commitment of the firms was associated with a 0.149 increase in the probability of adopting pollution abatement technologies of medium complexity and a 0.105 increase in the probability of adopting clean technologies of high technological complexity. Technological capabilities had a similar effect on the adoption of more complex clean technologies – a one standard deviation increase in technological capability increased the probability of adopting medium and highly complex clean technologies by 0.123 and 0.105, respectively. Unlike other studies, however, they find that community pressure does not play a role in the adoption decision. They posit that this is due to how the dependent variable is constructed, as it is intended to capture higher orders of technological capacity. Perhaps community pressure is a more powerful influence on the decision to adopt more basic pollution control technologies.

Del Río González (2005) surveyed 46 Spanish pulp and paper firms to find which factors influence their decisions regarding the adoption of environmentally friendly technologies. The technologies that are adopted are for reducing wastewater discharge (and water consumption), solid residues and energy consumption. Most of the technologies adopted were end of pipe or incremental clean technologies (involving small changes to the production process). 55% of the technologies adopted were incremental clean technologies and 36% were end of pipe. 8% were radical clean technologies (substantial changes to the production process). The main reasons given for adopting environmental technologies were improving the corporate image, and pressure from regulation. Economic motives (cost savings or increased revenues) were relatively unimportant.

Blackman and Bannister (1998) examined diffusion of propane as an alternative, clean production technology among traditional brickmakers in Mexico. An NGO lead a coalition that introduced a scheme to introduce clean burning propane to the brickmakers in the early 1990s. A probit adoption model was estimated on data from a survey of 76 brickmakers. It included predictors such as experience, education, whether they believe burning propane is healthier, input costs, capacity of kiln and measures of their financial resources. The main result is the role that local community groups can have in influencing the adoption decision. Local community organisations affiliated with one of the main political parties placed pressure on the brickmakers to adopt propane. However, their estimates are sensitive to the inclusion of neighbourhood fixed effects, so this result is suggestive.

Popp, Hafner, and Johnstone (2011) analyses the role that policy and consumer demand played in the innovation and adoption of chlorine-free bleaching technologies in the pulp and paper industry. They found that consumer demand and policy both affected the adoption decision, with consumer demand apparently generating regulations on chlorine that eventually forced adoption, but with some plants responding to the public pressure by beginning the modification process before regulations were in place.

Kahn (2007) tests whether or not self-proclaimed "environmentalists" have consumption patterns consistent with their beliefs. Most relevant to this survey, he finds that the fraction of registered Green Party voters within a community has a statistically and quantitatively significant positive correlation with registrations of hybrid and other "green" vehicles. Looking at specific hybrid vehicle types, an increase in green voter registrations from 0 to 4% of voters is associated with a 2- to 4-fold increase in local market shares. Overall, a 1 percentage point increase in green voter registrations is associated with a reduction in annual fuel use of over 10%, and a reduction in the likelihood of SUV ownership of 2.2 percentage points.

Gromet, Kunreuther, and Larrick (2013) demonstrates a potential opposing effect, namely that promoting the environment can negatively affect the adoption of energy efficiency in the US. Because the environment is seen as a political issue, the authors hypothesised that agents with conservative ideology would respond negatively to environmental messages. And indeed politically conservative individuals were less likely to purchase a more expensive, energy efficient light bulb *when it was labelled with an environmental message*, than when it was unlabelled.

Though operating in the opposite direction than is normally investigated, this effect confirms that ideological or image-related considerations do play a role in green technology diffusion.

6.1.2. "End-of-pipe" Versus Process Redesign

"End-of-pipe" technologies mitigate pollution impacts by treating an effluent stream to reduce or remove pollutants and either neutralise them or redirect them to less harmful disposal. An example is "scrubbers" that remove oxides of sulphur and nitrogen from combustion gases resulting from burning of fossil fuels. In some cases alternatives to such end-of-pipe treatment modify the underlying process to reduce or eliminate the creation of the undesirable substances. While end-of-pipe treatment is cost-effective in many cases, process redesign is seen as potentially more desirable, because it offers the possibility of eventually eliminating or reducing pollution without the ongoing cost of operating the end-of-pipe technology. For this reason, there has been interest in trying to understand the factors that might affect the deployment of process redesign as opposed to end-of-pipe solutions.

Hammar and Löfgren (2010) analyses the factors influencing the adoption of environmental protection investments by 181 firms across pulp and paper, chemical, manufacture of basic metals and energy and heating in Sweden over the period 2000–2003. They distinguished between investments in "clean technology" and those in "end of pipe" technologies. Comparing first those firms that invested in either of these categories (141 firms) with those who had invested in neither (67 firms), the green investors tended to have higher energy intensity and tended to be heavier polluters. Contrasting those who chose clean technology with those who chose end-of-pipe, firms that invested in "green" R&D were more likely to choose clean technology, although the difference was not large. An important factor for the decision to adopt end-of-pipe technologies was energy expenditure and this effect is stronger for more energy intensive firms.

An interesting question they considered is whether clean technologies and end of pipe solutions are substitutes or complements in emissions reductions. They find some evidence that the two are in fact complements; firms that invest in one type are more likely to invest in the other, although the effect is small and is weakened in attempts to control for potential endogeneity of investment in the other type of technology. Nevertheless, they never find that the two types of investment are substitutes.

Frondel, Horbach, and Rennings (2007) use firm or facility level data on firms from 7 OECD countries (USA, Japan, Germany, France, Canada, Norway, Hungary) to examine the factors that influence investment in end-of-pipe technologies vs. cleaner production technologies. The data are derived from a survey of manufacturing firms with more than 50 employees. They estimate a multinomial logit model, where the choice outcomes are: invests in end of pipe technology, invests in cleaner production technology or does not invest in either. Their explanatory variables include: expectations around image improvements, cost savings, potential to avoid environmental incidents, the existence of market based or regulatory instruments, information programs, subsidies, regulatory stringency, various management systems (both environmental and non-environmental), the influence of pressure groups and facility characteristics. These variables are all derived from the survey responses.

They find that cost savings have a positive relationship with adoption of cleaner technologies, but not for end-of-pipe technologies, which seem to be driven by regulatory constraints (see below). They use environmental R&D spending as a measure of the technical capabilities of the firm, and find that this variable is positively associated with investment in cleaner technologies but not end-of-pipe technologies.

They also find a positive association between a desire to prevent or control environmental incidents and investment in both types of technologies. Environmental management tools were found to be positively associated with investment in clean technologies, but less important for end-of-pipe technologies.

Del Río González (2005) found that environmentally proactive firms were more likely to adopt radical clean technologies, for reasons such as improved image, market variables and cost savings. Smaller firms were less likely to adopt radical clean technologies due to the limited financial, human and technical resources of these firms. This stands somewhat in contrast to a study of Swedish manufacturers. Hammar and Löfgren (2010) found that larger firms were more likely to invest in end-of-pipe technologies, while firm size had no affect on investment in more radical "clean technologies."

6.2. Assessment

While the coverage is somewhat idiosyncratic, there is evidence from a number of different choice settings (farms, manufacturing firms, the "informal" sector, individuals/households) that environmental attitudes of decisionmakers and their perceptions of community attitudes can have an impact on adoption of green technologies. It is difficult to assess the quantitative significance of these effects relative to other factors, and in some contexts it is hard to distinguish the effects of attitudes per se from the effect of policies or regulations that represent or implement those attitudes.

It is more difficult to summarise the results regarding "end-of-pipe" versus more radical or more systemic clean technologies. This probably reflects a reality that these choices are very technology-specific. There is some evidence that end-of-pipe technologies are driven by regulatory mandates, while broader environmentally beneficial technology adoption is influenced by a broader set of factors that can include, depending on the technology, cost savings, technical capability and environmental attitudes.

7. Evidence on Policy Instruments

In general, diffusion of new technology involves both social costs and social benefits, so in principle one should try to identify factors affecting the *optimal* rate of diffusion (Ireland and Stoneman, 1986), rather than presuming that faster diffusion is always socially desirable. It is often assumed, however, that it is preferable, all else equal, if environmental policy encourages diffusion of new technology. This preference could be based on an implicit assumption that the total costs of achieving a given environmental goal will be lower if it is achieved through technology diffusion. Further, as noted above, the role of information in the technology diffusion process creates a positive externality associated with the adoption of new technology. This means that there is a basis for a general expectation that technology diffusion occurs more slowly than would be socially optimal, so that it is a desirable feature of any possible to encourage diffusion. In this section we discuss research that compares different environmental policy instruments with respect to their effect on technology diffusion.

7.1. Findings

7.1.1. Direct Regulation and Market-based Instruments

Popp (2010) studies the link between innovation of NO_X pollution control technologies and their adoption by US coal fired power plants. The paper finds that the key explanatory variable for adopting pollution control technologies is environmental regulations. The author does find that technological advances are an important determinant in the decision to adopt existing combustion modification techniques. For the newest post combustion control technologies, however, adoption only seems to occur when needed to comply with strict emissions limits. The study of Spanish pulp and paper firms (del Río González, 2005) found that regulation was an important factor in adopting environmentally friendly technologies, particularly for smaller firms. The study of environmental technology adoption in manufacturing in seven OECD countries (Frondel, Horbach, and Rennings 2007) found that the adoption of end-of-pipe technologies was driven by regulatory constraints.

Kerr and Newell (2003) studied the adoption by refineries of a technology to produce unleaded gasoline (pentane-hexane isomerisation technology) under various policy regimes. They found a large, positive influence of regulatory stringency on the adoption of the technology: a 10% increase in the stringency of regulation was associated with a roughly 40% increase in the probability of adoption by refineries. They also found a divergence in behaviour of refineries with different compliance costs under different regulatory regimes. When market based instruments were employed, the relative adoption propensity of low versus high compliance cost refineries was significantly higher than under individually binding regulations. Thus, the expected efficiency benefit of the tradeable permit regime was realised, as it shifted compliance actions from high-compliance-cost to lower-compliance-cost firms.

Popp (2006) explores how differences in the stringency and timing of environmental regulations affect the development and diffusion of SO_2 and NO_X abatement technology across countries. Using data on pollution control patents and citations among those patents, he finds that a country's adoption of regulations increases the rate of patenting of pollution control technologies, and also increases the rate of citation from that country's patents to other country's pre-existing pollution control patents.[8] He interprets these findings as suggesting that each country must adapt international technology to its own circumstances, and that regulation stimulates the development of these local technologies, which are built in part on technologies that are imported from abroad.

Frondel, Horbach, and Rennings (2007) found that policy stringency and regulatory measures are associated with investment in end-of-pipe technologies, but not cleaner production technologies. They interpret this result to mean that adoption of cleaner production technologies is driven by factors other than command and control. They find no impact of market-based instruments on investment in either type of technologies. They suggest this could be due to a lax implementation of these instruments.

Newell and Siikamäki (2013) evaluated the effectiveness of different energy information labels for consumers on appliances. The implications for information policies are discussed below, but their finding that information on yearly operating costs was the single most important

[8] This builds on the earlier work of (Lanjouw and Mody 1996), who found substantial evidence of developed world patents for pollution control technologies being subsequently registered in developing countries.

factor influencing consumer choices also has implications for the potential affect of market-based instruments on technology adoption.

Gallagher and Muehlegger (2011) explores the role of policy incentives and petrol prices in the adoption of hybrid cars in the US from 2000–2006. They find that tax incentives are positively associated with hybrid vehicle adoption. When they examine the impacts of a sales tax waiver vs. an income tax credit, they find that a sales tax waiver has a much larger impact on hybrid vehicle sales than an income tax credit. A sales tax waiver equal to 1% of the retail price is associated with an 8.3% increase in sales; an income tax rebate of comparable size is associated with a 0.6% increase in sales. Thus the sales tax waiver has a statistically and economically significant impact, while the effect of the income tax waiver is small and not statistically distinguishable from zero. (Chandra, Gulati, and Kandlikar 2010) examine the effect of tax rebates on hybrid purchases in Canada. They find that a $1000 increase in the tax rebate increases the share of hybrid vehicles among all new cars by approximately 34%. The actual rebates offered are in the range of $500-$3000, so this is a significant percentage increase, but the base of hybrid penetration at the time was quite small (less than .5% of the overall market).

7.1.2. Information Policies

Anderson and Newell (2004) examined the U.S. Department of Energy's Industrial Assessment Centre (IAC) program, which has provided free industrial assessments to small-medium manufacturers since 1976. This involves assessors visiting these plants and assessing energy usage and efficiency, and making recommendations on how energy efficiency could be improved. Over 10,000 assessments have been conducted since 1981, which recommended over 70,000 individual projects. Overall, only 53% of the recommended projects were actually adopted, despite estimated payback periods of 1 to 2 years. This suggests either that the analyses did not fully account for the costs to the firms, or else that information is not in many cases the limiting factor to the adoption decision.

Newell and Siikamäki (2013) evaluated the effectiveness of different energy information labels for consumers on appliances, using a choice experiment in which respondents were asked to assume that they needed a new water heater, were given various information about different choices, and then asked to choose. The authors estimate a mixed logit model to estimate willingness to pay for energy efficiency (reduced operating costs). If households were cost-minimising, then there would be a 1:1 trade-off between operating costs and installation costs (i.e. should be willing to pay $1 more for a water heater with $1 lower present value of operating costs). This parameter is estimated as a function of the information treatment. This allows the authors to assess which type of information is most important in guiding behaviour.

Their results show that simple economic information (yearly operating costs) is the most important factor guiding cost-efficient energy efficiency investment decisions. An energy star label (which indicates a particular model is among the most energy efficient) and an energy efficiency grade label (e.g. 5 star) also induced energy efficient behaviour. Physical energy use and CO2 emissions played an incremental role. They found that households tended to display cost-minimising behaviour on average – placing equal weight on energy savings and upfront costs.

7.1.3. The Clean Development Mechanism ("CDM") and Joint Implementation ("JI") Projects

The Kyoto protocol established the CDM and JI projects as a way for advanced economies to undertake greenhouse-gas emission reductions taking advantage of potentially low-cost reduction opportunities in less developed countries. The goal of these policies is reduction in emissions, not technology diffusion, but a number of papers have investigated the extent to which they have, in fact, fostered transfer of lower-emission technologies and the diffusion of those technologies within less developed countries.

Dechezleprêtre, Glachant, and Ménière (2008) considers the role of the CDM in technology transfer using data on 644 CDM projects registered up to 1 May 2007. They find that, of the 644 CDM projects, 279 (43%) involved technology transfer. These projects accounted for 84% of the expected CO_2 emissions reductions. For technology types, 69% of end-of-pipe projects involved transfer, while 36% of projects installing new production units involved transfers. 33% of projects involving switching inputs involved transfer while 20% of the projects that altered the production process involved transfer.

Turning to their regression results, they find that the size of the project increases the likelihood of technology transfer; they suggest that larger projects can better exploit economies of scale in technology transfer. The presence of a buyer for the emission reduction credits generated by the project also increases the likelihood that a project will involve technology transfer. Technology transfer is also more likely if the technology is going to a company that is a subsidiary of a company from an Annex 1 country. The effect of being a subsidiary is much larger than that of having a credit buyer. The probability of transfer was lower if there were a large number of similar projects in the country. More open economies are more likely to receive technology transfers, although the share of FDI in GDP had little impact. Overall technical capacity increased the likelihood of transfer; however, the effect varied by sector. Technical capabilities had a strong positive influence on transfer in the energy and chemicals sectors, but a strong negative impact in agriculture. They discuss two opposing effects of technological capabilities. On one hand, higher technical capacity promotes transfer as the receiving country has the skills required to implement the technology. On the other hand, a higher technical capacity increases the likelihood that a similar technology is already available locally.

Bodas Freitas, Dantas, and Iizuka (2012) examined CDM projects in the "BRICS" countries. They found that the majority of the projects involved mature technologies that had already begun to diffuse locally; less than 20% of the CDM projects they examined involved exploiting foreign technologies. Rather than promoting the diffusion of new technologies between countries, the Kyoto mechanisms seem to have fostered the use of locally available technologies and capabilities. The authors speculate that CDM and JI projects may be promoting a lock-in effect, where locally available technologies are used, because these represent the "low hanging fruit" that can easily generate emission reduction benefits.

7.1.4. Other Policy Issues

Perkins and Neumayer (2005) investigate the effect of openness to trade and FDI on technology transfer, looking at the international diffusion of continuous steel casting, shuttleless textile weaving looms and digital telephone mainlines. They find that trade openness is positively related to the rate of diffusion for all three technologies. They did not, however, find an influence of inbound FDI on the rate of diffusion into countries.

An earlier paper looking at the effect of trade policy on green technology diffusion in the steel industry is Reppelin-Hill (1999). This paper uses a partial adjustment model to estimate the extent and speed of diffusion of electric arc furnace ("EAF") technology, using data from 30 countries over the period 1970–1994. It uses several proxies for trade openness in the estimation: share of trade in total GDP, value of taxes on trade as a fraction of total trade value, value of import duties as a fraction of total import value, value of export duties as a fraction of total export value, total value of steel imports as a fraction of apparent steel consumption (steel production plus imports less exports) and the value of steel exports as a fraction of total steel production. These measures include both the importance of trade to the economy and the steel industry, and also the level of trade restrictions imposed. The measures of trade openness all have the expected sign; countries with lower trade barriers or higher levels of trade all adopt EAF technology at a faster rate. The results indicate that trade taxes appear to have the biggest influence on the rate of diffusion; the author concludes that trade distortions can have a substantial detrimental effect on the speed of technology diffusion.

Popp, Hascic, and Medhi (2011) looked at the effect of a number of different policy settings on the rate of investment in renewable electric generation capacity 1990–2004. The only factor found to be significant was ratification of the Kyoto Protocol. The authors suggest that ratification signals a suite of policies whose broad aim is to decrease carbon emissions. This view is supported by the result that increased nuclear or hydro generation capacity reduces investment in renewable sources.

Hall and Helmers (2013) study the effect of the donation of environmental technology patents to the Eco-Patent Commons, which was established in January 2008 by IBM, Nokia, Sony and Pitney Bowes, in cooperation with the World Business Council for Sustainable Development. Since January 2008, Bosch, DuPont, Xerox, Ricoh, Taisei, Dow Chemical, Fuji-Xerox, Hewlett Packard and Hitachi have joined. Firms "pledge" patents to the commons, meaning that these patents are available for use by third parties free of charge, while the ownership of the patent remains with the firm that pledged it to the commons. The paper examines the extent of subsequent citation of these patents as an indicator for the diffusion of the underlying technology. It uses a difference-in-difference approach, comparing the citations to the donated patents to those of a control group constructed to have the same priority year, application authority and technology class as the pledged patents. They find that pledged patents are cited less than the control group, both before and after they are pledged. They find no discernible impact on the diffusion of the technology embedded in the patents after they are pledged to the commons. They suggest that removing patent protection may have little impact on the diffusion of previously protected green technologies. However, because their analysis is based on relatively few post-pledge observations, these findings are more suggestive than conclusive.

7.2. Assessment

It is clear that binding regulatory constraints can induce firms to adopt environmental control technologies that they would not otherwise utilise. The more interesting question is how different policy instruments affect the firms' choice of which technology to utilise (along with the related question of the effect of the instruments on innovation as opposed to diffusion, which is beyond the scope of this paper). The theoretical literature emphasises that the flexibility of market-based instruments will allow for technology choices that may be superior from a long-run overall social cost perspective (Jaffe, Newell, and Stavins, 2003). The empirical literature, while limited by the number of appropriate "natural experiments" available for study, tends to confirm this expectation. Specific market-based policy instruments have been shown to affect technology adoption. Further, there is some evidence that regulatory instruments are most effective at inducing end-of-pipe adoptions, while more systemic environmental improvements are influenced by a wider range of factors, including economic considerations that can be manipulated with market-based policies.

The overall importance of information to the diffusion process calls for analysis of the extent to which specific government programs aimed at the information problem are actually effective. The glass seems to be half full: information provision policies do increase technology adoption, but they do not necessarily solve the "problem" of incomplete adoption of apparently beneficial technologies. This is consistent with the view that adopters are heterogeneous and their individual circumstances have important impacts on their adoption decisions.

There is some evidence that the Kyoto Protocol and the Clean Development Mechanism did have some impact in technology transfer and technology diffusion. It seems likely, however, that these effects were not large relative to what would have occurred anyway driven by the underlying trends.

While the number of studies is modest, there is a consistent finding that openness to international trade fosters technology transfer of green technologies. This is consistent with the wider literature on trade and technology transfer (Keller, 2004).

There is widespread concern that enforcement of intellectual property rights will limit technology transfer of green technologies (Derclaye, 2008; Rimmer, 2009). At a theoretical level, this involves a trade-off between the possibility of such enforcement raising the cost or limiting access to specific protected technologies with the tendency for such protection to serve in general to foster trade and foreign direct investment, which in turn are important mechanisms for technology transfer (Branstetter, Fisman, and Foley, 2006; Lee and Mansfield, 1996). Hall and Helmers (2013) suggests that a "patent commons" for eco-patents may not be a meaningful answer to this dilemma.

8. Conclusion

The literature surveyed here is very heterogeneous and somewhat haphazard in its coverage. Overall, it confirms many of the lessons of the larger literature on technology diffusion: diffusion often appears slow when viewed from the outside; the flow of information is an important factor in the diffusion process; networks and organisations can matter; behavioural factors such as values and cognitive biases also play a role.

Different policy instruments do have different impacts. There is some evidence that the flexibility of market-based instruments can have a beneficial impact on technology diffusion, but there are also numerous cases in which regulations have forced the adoption of new technologies. Most likely the impacts of different instruments are inherently somewhat context dependent, but it would be desirable to have more research that attempts systematically to compare different instruments.

Given the importance of the behavioural issues, there is a relative scarcity of work applying behavioural economics techniques in this area, compared to other arenas such as finance and health care. In the long run, faster diffusion of green technologies is central to the achievement of environmental policy objectives, so there would be significant benefit to increased investment in studies that look at questions such as the role of information provision, networks and framing issues in households' and firms' adoption decisions.

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