The Economics of Technology Diffusion: Implications for Climate Policy in Developing Countries

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Abstract

Recent efforts to forge a consensus on the role developing countries should play in reducing global greenhouse gas emissions have focused attention on climate friendly technologies (CFTs), most notably those that enhance energy efficiency. In the medium term, the effectiveness of technology-based climate strategies will depend critically on the rates at which CFTs diffuse in developing countries. This paper reviews some of the key findings of the economics research on technology diffusion and assesses the implications for climate policy. The most obvious lessons from this research are that widespread diffusion of CFTs may take decades, and that diffusion rates in developing and industrialized countries are likely to be quite different. In addition, the literature has implications for a number of strategies for promoting technology diffusion including information dissemination, factor price rationalization, and investment in human capital.

Key Words: technology diffusion, climate change, developing countries

JEL Classification Numbers: O33, O38, Q25, Q28, O48

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THE ECONOMICS OF TECHNOLOGY DIFFUSION: IMPLICATIONS FOR CLIMATE POLICY IN DEVELOPING COUNTRIES

Allen Blackman*

1. INTRODUCTION

Recent efforts to forge a consensus on the role developing countries should play in reducing global greenhouse gas emissions have focused attention on climate friendly technologies (CFTs). Developing countries are expected to supersede industrialized countries as the leading source of greenhouse gas emissions in the next thirty years. Yet their ability and willingness to contribute to abatement efforts is constrained by limited financial resources, weak regulatory institutions, and the perception that they should not have to bear the costs of mitigating a problem primarily created by industrialized countries. CFTs are seen by many as a means of surmounting these obstacles.

Many types of CFTs -- notably, energy efficiency innovations -- not only reduce emissions of greenhouse gases but also cut production costs. As a result, such technologies could conceivably diffuse spontaneously in developing countries, obviating the need for government financing and regulation. Efforts to promote the diffusion of CFTs are likely to garner widespread support since they represent opportunities to enhance productivity and abate local pollution in the eyes of developing countries, and opportunities to boost exports of equipment and expertise in the eyes of industrialized countries.

But how likely is it that technology-based strategies will have a significant impact on greenhouse gas emissions in the near to medium term? In part, the answer depends on whether, once introduced, CFTs would diffuse at a reasonably rapid pace, and whether policy makers will be able to speed the rate of diffusion.

For at least the last thirty years researchers have tried to better understand the economics of the diffusion of new technologies. This paper reviews some of the key findings of this research and assesses the implications of these findings for the ongoing debate about the technology-based climate change strategies. The paper is organized as follows. The next section identifies the key issues addressed by the literature. The third section reviews theories of technology diffusion. The fourth section summarizes the empirical evidence. And the last section develops policy prescriptions.

2. QUESTIONS ADDRESSED BY THE ECONOMICS LITERATURE ON TECHNOLOGY DIFFUSION

Though, as discussed in detail below, the evidence on some questions concerning technology diffusion is inconclusive, there is a broad consensus on two points. First, new

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technologies are never adopted by all potential users at the same time. The widespread diffusion of new technologies can take anywhere from between five to fifty years, depending on the innovation (Mansfield, 1968). Second, countless studies have confirmed that the diffusion of new technologies follows a predictable temporal pattern -- technologies are adopted rather slowly at first, then more rapidly, and then slowly again as a technology specific "adoption ceiling" is reached. Thus, a plot of the number or the proportion of adopters over time assumes a sigmoid shape. These stylized facts have prompted researchers to focus on two related questions:

- Why do some innovations diffuse more quickly that other innovations?
- Why do some firms adopt a given innovation faster than others?

The next section reviews theoretical answers to these questions.

3. ECONOMIC THEORIES OF TECHNOLOGY DIFFUSION

As discussed in Karshenas and Stoneman (1993), theories of technology diffusion fall into four categories: epidemic models, rank models, order models, and stock models.

3.1 Epidemic Models

The oldest and perhaps most influential of the four models discussed here, the epidemic model (Mansfield, 1961) is premised on the idea that the spread of information about a new technology is the key to explaining diffusion. According to this theory, initially, potential adopters have little or no information about the new technology and are therefore unable or disinclined to adopt it. However, as diffusion proceeds, non-adopters glean technical information from adopters via their day to day interactions with them, just as one may contract a disease by casual contact with an infected person. As a result, as the number of adopters grows, the dissemination of information accelerates, and the speed of diffusion increases. Eventually however, as the number adopters exceeds the number of non-adopters, the speed of diffusion falls off. Importantly, the probability of a non-adopter becoming "infected" by contact with an adopter is not the same for every technology; it depends on characteristics of the technology such as profitability, risk, and the size of the investment required to adopt.

Thus, epidemic models hypothesize that some firms adopt later than others because they do not have sufficient information about the new technology; this information must be gleaned from adopters. Furthermore, epidemic models hypothesize that some innovations diffuse faster than others because for some technologies the chance of 'infection' is higher than for others owing to characteristics of the technology.

Epidemic models have been criticized for a number of reasons (see e.g., Davies, 1979; Stoneman, 1983). First, all firms are assumed to have an equal chance of becoming infected, an assumption that violates common sense since some firms -- for example, those with large cash reserves, higher rates of capital replacement, better managers, etc. -- would naturally seem more prone to adopt than others. Second, there is no explicit explanation for how firms' profit maximizing goals could generate the hypothesized aggregate behavior. So called "rank models" remedy both shortcomings.

3.2 Rank Models

Rank models are premised on the idea that heterogeneity among firms explains observed diffusion patterns. Firms are hypothesized to differ with regard to some critical variable that affects the expected present discounted profitability of the new technology relative to the old one -- the "net return on adoption" for short. Seven different critical variables have been identified.

(i) *Capital vintage.* Firms with older less productive vintages of capital find it more profitable to adopt than firms with newer capital (Salter, 1960).

(ii) *Firm size.* Large firms able to spread risks, access credit, and to take advantage of economies of scale associated with new technologies find it more profitable to adopt than smaller firms (Davies, 1979; David, 1975; Feder and O'Mara, 1981).

(iii) *Beliefs about the return on the new technology.* Firms whose guesses about the profitability of the new technology are overly pessimistic find it less profitable to adopt than firms with more optimistic expectations (Stoneman, 1980; Jensen, 1983).

(iv) *Search costs.* Firms that incur higher transactions costs in learning about the new technology because of their location or stock of physical and human capital, finds it less profitable to adopt than firms with lower search costs.

(v) *Input prices.* Variations in input prices across firms and input requirements across technologies imply that some firms obtain a higher return the new technology than others.

(vi) *Factor productivity.* Variations in factor productivity across firms, including variations in labor productivity due to human capital, imply that some firms obtain a higher net return on adoption than others (Kislev and Shchori-Bachrach, 1973).

(vii) *Regulatory costs.* Variations in firms' exposure or susceptibility to regulatory costs can affect the net return on adoption when the new technology has different regulatory implications than the old (Ecchia and Mariotti, 1994; Millman and Prince, 1989).

Given that firms are heterogeneous across these variables, they may be 'ranked' according to their net return on adoption. For some firms the net return on adoption will be negative. Over time, however, the net return on adoption rises for all or some firms, so that more and more firms chose to adopt. The net return on adoption is hypothesized to increase over time for any number of reasons including:

(i) *External economies of scale*. Production costs may fall as a result of, among other things, the growth of pools of trained labor and upstream suppliers that complement the new technology;

(ii) *Learning by doing*. Adopters refine and perfect the new technology;

(iii) *Falling search costs*. The costs of acquiring information about the new technology and uncertainty about it fall over time;

(iv) *Depreciation of existing capital*.

Thus, rank models hypothesize that firms adopt at different times because they because they differ with respect to some critical variable that affects their net return on adoption. For some firms this net return may be negative. Over time, however, the net return on adoption rises for all or some firms so that more and more firms adopt. Furthermore, rank models imply that innovations diffuse at different speeds either because for some technologies the distribution of net returns on adoption over the population of potential users is different than for other innovations, or because for some technologies the net return on adoption increases faster over time than for other innovations.

3.3 Order Models

Order models are premised on the idea that the order in which firms adopt the new technology determines the net return that they obtain from it, with earlier adopters obtaining higher net returns (e.g., Ireland and Stoneman, 1985; and Fundenberg and Tirole, 1985). The order effect arises from the existence of a fixed critical input into production such skilled labor for software developers or access to prime drilling sites for petroleum explorers. Because of this order effect, initially it will only be profitable for a limited number of firms to adopt. Note that this result holds even if firms are assumed to be identical. However, over time, the net return on adoption increases (for the same reasons as in rank models) so that eventually more and more firms adopt.

Thus, order models hypothesize that firms adopt at different times because the net return on adoption is negative for firms that are slow to adopt relative to their rivals. Over time, however, the net return on adoption rises so that more and more firms adopt. Furthermore, order models imply that innovations diffuse at different speeds because for some technologies, the order effect is stronger than for others (because, for example the pool or trained labor is smaller for some technologies than for others) and/or because for some technologies, the net return on adoption increases faster over time than for other technologies.

3.4 Stock Models

Stock models are premised on the idea that the net return on adoption for any firm depends on the total stock of firms that have adopted, with the net return on adoption declining as the stock increases (e.g., Reinganum, 1981; Quirmbach, 1986). Stock effects are hypothesized to arise when the adoption of a new technology by a subset of firms in the industry lowers their average production costs to such an extent that output prices fall. Lower output prices in turn, reduce the net return on adoption. Given this stock effect, initially it will only be profitable for a certain number of firms to adopt. Note that this effect does not depend on heterogeneity among firms or on the order in which firms adopt. However, as in both rank and order models, the net return on adoption increases over time so that more and more firms adopt.

Thus, stock models hypothesize that firms adopt at different times because the net return on adoption falls as the stock of adopters grows. Over time, however, the net return on adoption rises so that more and more firms adopt. Furthermore, stock models imply that innovations diffuse at different speeds because for some technologies, the stock effect is stronger than for others (because, for example, the new technology has a larger impact on firm costs and therefore on output prices) and/or because for some technologies, the net return on adoption increases faster than for other innovations.

3.5 Other Considerations: Technology Suppliers and Research and Development

In addition to the factors that play a role in models described above, two others have received some attention in the theoretical literature: the role of technology suppliers and the role of research and development (R&D). All of the models described above focus on the demand for new technologies by end-users and simply assume a perfectly elastic supply of the new technology. But, obviously this is an oversimplification -- supply-side considerations like the competitiveness of markets for the new technology could clearly affect the diffusion process. Several researchers have incorporated supply-side considerations into diffusion models (for a review see Stoneman, 1991).

In addition, a number of researchers have argued that firms' expenditures on adapting new technologies to their particular circumstances and on searching for new technologies -- i.e., R&D expenditures -- are closely linked to diffusion. Diffusion of new technologies stimulates R&D, and R&D undoubtedly stimulates diffusion (Stoneman, 1991; Cohen and Leventhal, 1989). There is a considerable economics literature on R&D that is relevant. However, for the most part it has not been integrated into the diffusion literature.

3.6 Conclusion

What then does the economic theory of technology diffusion tell us about why some firms adopt earlier than another and why some innovations diffuse faster than others? First it is important to note that the models described here do not necessarily offer competing explanations of diffusion. They generally incorporate only one explanation at a time for the sake of tractability. Nevertheless, in many, if not most, respects, these models are not inconsistent with each other. There is no reason why diffusion of a given technology could not be influenced by some combination of epidemic, rank, order, stock and supply-side effects. In fact, this is likely to be the case in the real world (though, in certain circumstances, one type of effect may dominate). Thus, the most accurate -- though perhaps unsatisfying -- conclusion to this section on theory is that a broad range of factors are likely to affect technology diffusion. The factors emphasized in the theoretical models include:

> *Information and learning.* A critical factor in each of the models described above. The dissemination of information about the new technology drives diffusion in the epidemic model. In the rank, order, and stock models, learning by doing and the spread of technical information cause the net return on adoption, and therefore the proportion of adopters, to increase over time. Finally, in some versions of the rank model, differential access to information about the new technology determines which firms adopt and which do not in the initial period.
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> *Characteristics of potential adopters.* Differences in firm-specific characteristics that affect the return on the new or old technology drive diffusion in the rank model. These characteristics include: capital vintage, firm size, beliefs about the return on the new technology, search costs, input prices, factor productivity, and regulatory costs.
>
> *Characteristics of technology*. In every model discussed above, characteristics of the new technology such as risk, average return, and intellectual property restrictions affect the net return on adoption,.
>
> *Fixed resources.* Limitations on the supply of a critical input into the new technology drive diffusion in order models.
>
> *Effect of adoption on output prices ("general equilibrium" effects).* The effect of adoption on reductions in average production costs and on the price of output drives diffusion in stock models.

4. EMPIRICAL EVIDENCE ON TECHNOLOGY DIFFUSION

Empirical tests of technology diffusion have used data at the level of the firm, sector, and country. Firm-level data has been used to test for the impact of firm characteristics on either adoption or time to adoption. Sector-level data has been used to test for the impact of sector characteristics (usually average characteristics of firms in the sector) on the speed of diffusion (usually the slope parameter of an estimated diffusion curve for a given sector). Sector-level data has also been used to test for the impact of the characteristics of the new technology on the speed of diffusion. Finally, country-level data has been used to test for the impact of sector and macroeconomic characteristics on the speed of diffusion.

Since most of the sector-level research uses average firm characteristics to explain diffusion, the majority of the empirical research on technology diffusion boils down to an examination of how firm characteristics affect diffusion. This research can be thought of as a test of the rank model described above.[1] This section is mainly devoted to describing the findings of this research. In addition, I provide a brief description of the findings of the two other types of studies: those of the impact of the characteristics of a technology on diffusion and the impact of macroeconomic characteristics on diffusion.

4.1 The Impact of Technological Characteristics

Perhaps because the data requirements are daunting, there are a relatively small number of studies on how the characteristics of technologies affect diffusion. Mansfield (1961) is the most widely cited. Using data on nine different innovations in four industries, Mansfield tests for correlation between the speed of diffusion on one hand and the average profitability of the innovation (measured as the average *ex post* payback period) and the average initial investment required for adoption, on the other hand. Not surprisingly, he finds both of these variables to be significant. Using data on the diffusion of twenty two process innovations in the UK, Davies (1979) finds significant differences between the diffusion patterns of relatively cheap and simple innovations and more expensive and complex ones. He finds that the simple innovations a diffused relatively quickly during the beginning of the observation period, and more slowly at the end.

4.2 The Impact of Firm and Sector Characteristics

Among firm and sector characteristics that impact on diffusion, researchers have devoted the most attention to firm size and market structure. In addition, they have examined the impact of factor prices, factor productivity, infrastructure, vintage of capital stock, macroeconomic variables, R&D expenditures, and institutional differences.

Firm size. Almost all empirical studies of diffusion test the Schumpeterian hypothesis that large firms in concentrated industries are both more innovative and faster to adopt new technologies than small firms. Considerable evidence supports the second part of the

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[1] To my knowledge, there has only been one attempt to test order and stock models empirically, perhaps because these models are relatively new. Using data on the diffusion of numerically controlled machine tools in the UK, Karshenas and Stoneman (1993), find that epidemic and rank effects, not order or stock effects, best explain observed diffusion patterns. Though some early empirical papers are billed as tests of the epidemic model (e.g., Romeo 1975), most do not actually focus on the impact of the information spreading mechanism that is at the heart of the epidemic model. Rather, they use the logic of the epidemic model to rationalize the choice of a measure for the speed of diffusion.

hypothesis -- that large firms adopt earlier, e.g., Antonelli and Tahar (1990a), Globerman (1975), Romeo (1975), Davies (1979), Feder, Just and Zilberman (1985), and Karshenas and Stoneman (1993). However, these findings beg the question of why large firms adopt faster. A number of hypothesis were offered in Section 3.2. Some research has attempted to test these underlying hypotheses. For example, Rose and Joskow (1990) control for the fact that large firms turn over capital faster than small firms, and still find a significant correlation between firm size and adoption. This suggest that large firms adopt earlier because of economies of scale, superior human capital, or easy access to credit.

Market structure. The evidence on the impact of market structure on diffusion is inconclusive. For example, Hannan and McDowell (1984) and Sommers (1980) find that concentration is positively correlated with the adoption of new technologies, while Romeo (1975) finds the opposite. Other studies find market structure has no observable impact on the speed of diffusion. According to Davies (1979) the reason that the evidence is inconclusive is that market concentration proxies for two countervailing effects. On one hand, the number of firms in concentrated industries tends to relatively low, which facilitates information flows and speeds diffusion. On the other hand, firm size in concentrated industries tends to be quite variable which slows diffusion.

Factor Prices. There is considerable evidence to support the hypothesis that faster diffusion is correlated with relatively low prices of inputs used intensively by adopters (e.g., Jarvis, 1981). Some studies have found a direct relationship between wage rates and the speed of diffusion of labor saving technologies (e.g., Antonelli and Tahar, 1990b).

Human Capital. There is also considerable evidence to support the hypothesis that firms with higher levels of human capital have been early adopters. Much of this evidence concerns that adoption of agricultural innovations (e.g., Lin, 1991, Pitt and Sumodiningrat, 1991).

Regulation. Recently, a number of researchers have found some empirical evidence of a link between formal regulatory pressure and clean technological change (e.g., Lanjouw and Mody, 1993; Jaffe and Stavins, 1995). Notwithstanding this theory and evidence, the link between regulation and technological change will obviously dissolve if enforcement is lax. This is often the case in developing countries. However, a growing body of recent research shows that community pressure -- also known as "informal regulation" -- applied by private-sector groups such as neighborhood organizations, non-governmental organizations, and trade unions can substitute for formal regulatory pressure (e.g. Pargal and Wheeler, 1996). Blackman and Bannister (1998) find that informal regulation is correlated with the adoption of a clean technology.

Infrastructure, Capital Vintage, and Research and Development. Research has verified that early adoption of new technologies is directly related to R&D expenditures (Romeo, 1975) and the existence of complimentary infrastructure (Hastings, 1976; Minami and Makino, 1983) and is inversely related to capital vintage (Oster, 1982).

4.3 International Differences in Diffusion

Though studies of international differences in diffusion are relatively rare, their findings echo those of single country, sector-level studies. Using data on the diffusion of synthetic rubber in twelve countries, Swan (1973) finds that faster diffusion was correlated with industry growth, exports, and date of adoption.[2] A number of studies have sought to explain the relatively slow diffusion of the basic oxygen furnaces (used in steelmaking) in the United States *vis a vis* other countries, namely Japan. While some have argued that inefficiency caused by trade barriers slowed diffusion (e.g., Adams and Dirlam, 1966), others have argued that differences in factor prices and industry growth rates in the two countries have been determinative (e.g., Maddalla and Knight, 1967; Lynn 1980). Otsuka et al. (1988) argues that differences in human capital explained the fact that ring spinning diffused faster in Japan than in India. Antonelli et al. (1990b) argues that international differences in the diffusion of shuttleless looms in fifteen countries was explained by, *inter alia*, differences in sectoral rates of growth. Nabseth and Ray (1974) bring together a collection of studies of the diffusion of ten process technologies in six countries. Though for at least one technology (numerically controlled machine tools) wage rates seem to have had the greatest impact on diffusion, according to Stoneman (1983), "If anything is to come from these studies it is that the different production programs, product mixes, and institutional characteristics of firms are key factors in the diffusion process." Finally, some studies have sought to explain international differences in diffusion rates with macroeconomic statistics such as GDP and money supply (e.g., Lucke, 1993; Blackman and Boyd, 1995). While these studies have found that macroeconomic characteristics are indeed correlated with speed of diffusion, explanations for these correlations are necessarily ad hoc.

4.4 Conclusion

To sum up this section, empirical investigations have, by in large, used firm-level and sector-level data on the diffusion of a single technology in a single country. These investigations may be considered test of the rank model discussed above. There is good evidence that adoption and/or the speed of diffusion is directly related to: firm size, human capital, regulatory costs of the old technology, complimentary infrastructure, industry growth, and R&D expenditures, and is inversely related to the prices of factors used intensively by the new technology, and capital vintage. Despite considerable research, the evidence on the impact of market structure on adoption and diffusion is inconclusive.

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[2] These findings are likely to have been corrupted by endogeneity.

In addition to the above research, the literature includes investigations of international differences in diffusion and of the impact of the characteristics of the new technology on diffusion. The latter finds that the speed of diffusion is directly related to its profitability and is inversely related to the size of the investment required and the complexity of the technology (in the early stages of the diffusion cycle). The findings of literature on international differences in diffusion echo those of the single country studies.

5. POLICY PRESCRIPTIONS

What does the theoretical and empirical research suggest for technology-based climate change policy? Two implications are immediately obvious, if facile. First, even if CFTs that significantly lower production costs can be transferred to developing countries, diffusion will not be immediate. If past evidence is an accurate guide, near complete penetration will take from five to fifty years. The theoretical models reviewed above offer a wide range of explanations for lagged adoption. Second, and relatedly, CFTs will not necessarily be rapidly adopted in developing countries simply because they reduce production costs in industrialized countries. We have seen that a broad range of firm-, sector-, and country-level characteristics can determine whether or not and how quickly new technologies are adopted. These include: firms size, factor prices, human capital, infrastructure, the profitability of old capital, the turn over of old capital, learning by doing, the scarcity of inputs vital to the new technology, search and transactions costs associated with adoption, miscellaneous institutional factors, and path dependency. There are likely to be systematic differences between developing countries and industrialized countries in nearly all of these characteristics. To give one example, labor is generally much more costly relative to capital in developing countries. Therefore, labor saving technology that is profitable in industrialized countries will not necessarily be profitable in developing countries.

In addition to these two rather obvious points, it is important to note that, as Stoneman and Diederen (1994) make clear, faster diffusion of a technology is not necessarily welfare enhancing. Diffusion may be "too fast" if firms adopt a technology before it is profitable to do so, or if firms adopt a new technology today that effectively preempts the adoption of a superior technology in the future.

Having made these three points we may now proceed to a discussion of the policy levers that are available to influence the speed of diffusion of CFTs in developing countries. Given the theory and evidence presented above, there would seem to be seven types of policy levers available -- those concerning: information, factor prices, regulation, credit, human capital, infrastructure, research and development and intellectual property rights.

5.1 Information

As discussed in Section 3, the dissemination of information about the new technology is a critical determinant of diffusion in each of the theoretical models; it drives diffusion in the epidemic model and raises the return of adoption over time in the rank, order, and stock models. That paucity of empirical support for the importance of information probably stems from the difficulty of measuring information flows.[3] As Stoneman and Diederen (1994) point out, government intervention to enhance the dissemination of technical information is likely to justified since information is bound to be imperfect. Firms may acquire information about new technologies in three ways: through the costless day to day contact with other firms emphasized in the epidemic model, through active search as described in some rank models, and through the advertising of technology suppliers. Each of these mechanisms is subject to imperfections. In the first mechanism -- casual contact -- early adopters supply information about the new technology to later adopters, but do not capture any of the benefits from this information transfer themselves. As a result, they do not have proper incentives to make this information available to their rivals. In the second mechanism -- active search -- firms operating independently, will engage in inefficient duplication of search efforts. And in the third mechanism -- advertising -- technology suppliers who are concerned about market share, not the diffusion of the technology, have incentives to oversupply technical information, which may lead to too rapid diffusion of intermediate technology.[4]

Policy options for enhancing the flow of information about new technologies include: demonstration projects, advertising campaigns, the testing and certification of new technologies, and subsidies to technological consulting services. Have such mechanisms had a verifiable impact on diffusion? Demonstration projects have received wide application in the context of developing country agriculture. There is some evidence that they have been quite effective. Many industrialized countries have set up regional information clearinghouses to provide consulting services to small and medium sized businesses that presumably can least afford search costs associated with adoption. For example, the US Department of commerce sponsors a network of "Manufacturing Technology Centers." Similar networks have been established in the United Kingdom (the Advanced Information Technology Programme, and the Regional Office Technology Transfer Programme) and in Europe (Centres Regionaux d'Innovation et de Transfer de Technolgie in France, and the SPRINT programme in the European Union). As yet evaluations of these programs have been limited.

5.2 Factor Prices

Both theory and evidence attest to the important role that factor prices play in the diffusion of new technologies. In particular, energy prices clearly have a critical impact on the adoption of energy saving technologies. In many developing and reforming economies, energy is highly subsidized (World Bank, 1992, 69). Removing or significantly scaling back energy

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[3] But see Lester and McCabe (1993).

[4] Despite these market imperfections, Stoneman and Diederen (1994) sound a cautionary note about attempts to mitigate them. They point out that information-based polices may actually retard diffusion by fostering the expectation that improved technologies are forthcoming, and therefore creating incentives to defer adoption. Also, they argue that public provision of information about new technologies may crowd out private information.

subsidies in these countries would create incentives to adopt energy saving technologies.[5] In countries where energy prices are not subsidized, taxing energy to raise its effective price above the market price would clearly have the same effect as removing subsidies.

5.3 Regulation

As discussed in Section 4, empirical research supports the hypothesis that firms that pay higher environmental regulatory costs are more likely to adopt clean technologies, including CFTs. The opportunities for and barriers to effective regulation in developing countries have received considerable attention, especially in the last ten years. Even a brief synopsis of this literature is outside the scope of this paper (for reviews see World Bank, 1992; Blackman and Harrington, 1999). Two points may be worth emphasizing, however. First, the use of market-based incentives such as pollution taxes and marketable permit systems is analogous to raising the price of a critical factor of production -- environmental services, and therefore, the same arguments about the link between factor prices and technology adoption are applicable. Second, as mentioned in Section 4, even when institutional and financial constraints make formal public-sector-led regulation problematic, private-sector-led "informal" initiatives can be an effective substitute.

5.4 Credit

As discussed in Section 4, empirical studies of the adoption of new technologies in developing countries have often identified lack of access to credit as a critical barrier to adoption. Subsidizing credit for specific types of investments has been has been a common policy response. Thus far these programs -- both public and private -- have had very mixed results. Chronic problems include the diversion of loans by borrowers to non-targeted activities, low repayment rates, the creation of financially unsustainable lending institutions, and the undermining of existing credit markets (Adams and von Pische, 1992). Given the growing consensus that the costs of 'targeted' credit outweigh the benefits, a wiser approach to overcoming financial barriers to technological innovation is to focus on improving financial intermediation which, in developing countries, is often hamstrung by unstable monetary policy, interest rate restrictions, and weak property rights (Fry, 1988).

5.5 Human Capital, Infrastructure, and Research and Development

The policy implications of the literature that identifies human capital and infrastructure as key predictors of early adoption is obviously to promote education and technical training and to build and maintain infrastructure. This needn't be a broad-brush and long-term strategy if investments are focused on greenhouse gas intensive sectors such as energy production. Given the close link between R&D and diffusion, policies that promote R&D

[5] In addition it would reduce greenhouse gas emissions directly by reducing the quantity of energy demanded.

will also benefit diffusion. However, a review of the extensive literature on R&D policy is outside the scope of this paper.

5.6 Intellectual Property Restrictions

Intellectual property restrictions such as patents and licenses have countervailing effects on technology diffusion. On one hand, they stimulate R&D, which in turn stimulates diffusion. Perhaps more important for developing countries, they are likely to encourage foreign investment, which can be a significant source of new technologies. But on the other hand, intellectual property restrictions attach significant costs to adoption of new technologies which retards diffusion. In many developing countries, adaptation of existing technologies, rather than the creation of substantially new ones may account for the bulk of productivity growth. Therefore, there is reason to suspect that the negative impact of intellectual property restrictions on diffusion in developing countries could be substantial.

5.7 Conclusion

To summarize briefly, this section argues that the theoretical and empirical literature on technology diffusion suggests the following:

(i) There is no guarantee that new technologies that have successfully diffused in industrialized countries will diffuse widely or rapidly in developing countries, or that they will diffuse at all. To be successful, new technologies must be "appropriate" to developing countries.

(ii) The dissemination of information about new technologies is critical to diffusion but is likely to be imperfect, and therefore, there exists a presumptive argument for subsides to activities that improve information flows such as demonstration projects, testing and certification of new technologies, consultancy services, and science parks. However, we know little about the effectiveness of such policies.

(iii) More stringent regulation of polluting activities and reductions in energy subsides are likely to speed the dissemination of energy efficient and CFTs.

(iv) If past experience is a guide, targeting credit for investments in CFTs is likely to be costly and ineffective. A better way to overcome financial barriers to diffusion is to improve the financial intermediation.

(v) Investments in human capital and infrastructure in the energy sector will likely speed of the diffusion of CFTs.

(vi) Intellectual property restrictions have countervailing effects on the diffusion of new technologies.

Of the broad range of policy options presented here, which are likely to be politically practical? As mentioned in the introduction, technology-based strategies will generate political support to the extent they represent obvious "win-win" opportunities for the parties involved. All of the policies described above fit this description to some degree. Information, human capital and infrastructure policies will enhance productivity; rationalizing energy prices will boost allocative efficiency; improving financial intermediation should stimulate saving and investment; and strengthening regulation should produce environmental benefits. However, some of these policies involve up-front economic costs that are more immediate and payoffs that are more delayed than others, making them unattractive to decision makers with short time horizons. For example, though investments in financial intermediation, human capital (broadly defined) and environmental regulation may have tremendous benefits in the long run, they involve substantial up-front costs. Thus, the most practical policy options discussed here would seem to be investments in improved information, energy infrastructure, and the rationalization of energy prices.

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