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Marked-based Lock-in and Environmental Technologies

The Importance of Increasing Returns to Adoption

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CondEcol

Report

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CONTENTS

ABSTRACT

In many markets, technologies are characterized by increasing returns to adoption, where a technology is more attractive to potential adopters the larger the number of adopters or the larger the market share. In this case the market may become locked-in on a specific technology. The dominant technology may be inferior to alternative technology, but individual incentives to adopt the alternative technology are lacking unless it reaches a critical mass. In cases where markets were locked in at a time with low environmental concern and few environmental taxes, environmentally-friendly technologies are likely to be underrepresented among the dominating technologies.

In this paper I will discuss different mechanisms that may cause lock-in, with a particular focus on increasing returns to adoption. I will demonstrate that there are a variety of such mechanisms and that lock-in may be prevalent in many markets. When a market is locked-in a welfare improvement is possible, but not through a series of marginal changes. This poses special challenges for environmental policy.

1 INTRODUCTION

In the standard textbook version, technological change is perceived as merely a question of inventing new technologies. Once the technology is invented, the process of commercializing and marketing the new technology is seen as almost automatic. In practice, however, the latter process may pose at least as many challenges as the invention of the technology itself. Not only must the technology be developed into a product; the new product also has to be accepted by the market. In the present paper I will focus on a particular barrier to the introduction of new products or technologies in the market.

The particular barrier I will discuss arises in markets where products or technologies derive advantages from being well-known and widely adopted. I will focus mainly on the case of increasing returns to adoption, where potential adopters consider a technology more attractive the larger the share of adopters. The potential adopters may be households or other firms, depending on the case in question.

Consider a new product or technology with inherent qualities such that potential adopters would have chosen the new technology if the market share was approximately equal to the market share of existing technology. Yet with increasing returns to adoption, potential adopters may prefer the old technology as long as the new one has a low market share. We may thus have a situation in which most potential adopters would be better off if the new technology was widely adopted, but where no one has the incentive to adopt the technology until sufficiently many others have already adopted it. Thus the market may become locked-in on one particular, potentially inferior, technology.

In most of the discussion I will assume that all potential adopters have the same preferences, and hence all agree on which product is best. This clearly unrealistic assumption facilitates a presentation of the basic mechanisms involved, but as it is important to discuss the consequences of the actual heterogeneity of potential adopters, I will return to this later.

The literature on lock-in through increasing returns to adoption is not specifically related to environmental issues. However, I will argue that potential lock-in is highly relevant for environmental policy. In order to achieve a sustainable society, radical changes in lifestyle, infrastructure, technology etc may be required. It is likely that many of these changes are characterized by increasing returns to adoption, and thus no individual firm or consumer will have incentive to change. While a shift in technology may be socially beneficial, individual economic agents will lack incentives to take the first step towards the better society.

When potential adopters have no incentive to be the first adopter, this poses a challenge for optimal policy. According to the standard assumptions of microeconomic theory – in economic jargon referred to as “convex technology” – the optimum can always be reached through a series of small improvements if each economic agent maximizes private benefits. All that is required is that the prices are right, i.e. that they reflect the true social cost. With non-convexities this is no longer true. It has long been argued that non-convexities may prevail with environmental externalities (see e.g. Baumol and Bradford

1972). Baumol and Bradford's discussion of non-convexities is based on the presence of negative externalities, where one firm's production harms another firm. By contrast, the focus here will be on positive externalities in the adoption of new technologies.

From an economic point of view, a shift in the market from a lock-in on one product to a lock-in on another product or technology is a radical change, since the step is too large for any single economic agent. From a technological point of view, however, the shift may be modest. It may be the case that technologies that are radically different in a technological sense are more likely to be able to break a lock-in, but the degree of technological difference between alternative products will not be essential to the basic argument here.

This report aims to provide a background for evaluating the relevance of lock-in as a potential barrier to the new technologies considered in the cases of the CondEcol project. It is beyond the scope of the report to give a thorough discussion of these cases. The first part of the report will be rather general, presenting different mechanisms that may potentially cause markets to be locked-in on particular products and technologies. I have linked the discussion to the actual CondEcol cases only to a very limited extent. The documentation of these cases is yet at an early stage, so my knowledge of them is rather limited. Moreover, while I might be able to speculate on potential lock-in in these cases, actual documentation of such is far beyond the scope of the report. Finally, but perhaps most important, different mechanisms may apply in the different cases, and thus mechanisms that seem irrelevant to the cases I am currently familiar with may prove to be highly relevant in a case considered at a later stage. However, it may be illuminating to speculate on the economic barriers in one particular case. One of the major cases in the CondEcol project (which will be considered at the end of the report) is the technology for using CO_2 as a coolant in mobile air conditioning.

The report is organized as follows: in the following section I will survey the literature on increasing returns to adoption and technological lock-in. I will then go on to discuss the consequences for optimal environmental policy, relating my discussion to the case of CO_2 versus HFC-134a as cooler gas in mobile air conditioners. Finally, I will summarize my argument and suggest some directions for future research.

2 MECHANISMS CAUSING LOCK-IN

The literature on technological lock-in identifies at least two meachanisms that may cause lock-in. The most important of these is increasing returns to adoption, where a technology is more attractive to the user, the larger the number of users (or the larger the market share). The second mechanism is uncertainty, where it is too costly for the user to experiment with alternative technologies, since their expected benefits are not known and are a-priori believed to be too low to justify experimenting. Common to all the cases is that the process is path-dependent, i.e. the long-run convergence is not unaffected by minor initial events. In all the case studies to be reviewed below, there are individuals that – at a time when the market was not yet locked-in on one alternative – had crucial impact on the long-run technology choice.

Increasing returns to adoption are present in all the case studies I have looked at, as well as being the factor that is most discussed in the theoretical literature. Hence I will put most emphasis on this factor. However, as the uncertain benefits of alternative technologies may play an important separate role in some applications, I will also briefly discuss that issue.

2.1 Increasing returns to adoption

The concept of increasing returns to adoption refers to the situation in which the benefits to the user of a technology depend on the number or share of other users of that same technology. In particular, the number of other users who have already adopted the technology is important, but the number of future adopters may also affect the benefits of adopting a technology. There are several reasons why there may be increasing returns to adoption, and in this respect the various case studies in the literature reviewed are rather different. I will try to point out some reasons for increasing returns to adoption using examples from these case studies. Given the dissimilarities between the different cases, I do not expect this list to be exhaustive.

One reason for increasing returns to adoption is *negative externalities from non-adopters*. The choice between pesticides and Integrated Pest Management (IPM) represents a case of this type; see Cowan and Gunby (1996). If a farmer adopts IPM, he may be harmed by a non-adopter on a nearby farm. The IPM strategy against the boll weevil, one of the major cotton pests, illustrates this problem. Implementation of IPM strategy in parts of Texas includes late planting to deprive over-wintering insects of food in the early spring. This strategy is obviously less effective if the insects find food on a nearby non-adopting farm. In this case the IPM strategy is effective only when almost all farmers use the same strategy, a quite extreme case of increasing returns to adoption.

Another reason for increasing returns to adoption is the *cost of local adaptation*. Here too the use of IPM illustrates the point. To develop an appropriate IPM strategy requires expertise in determining the appropriate natural enemy, the best-suited crop variety etc. The cost of such adaptation may be excessive for a single farmer. But the same IPM strategy would apply equally well to all farmers in an appropriately designed district, and the adaptation cost may be quite modest for a large group of farmers. In this case the adoption cost will fall with the number of adopters, and hence the net benefits for the single farmer will increase with the number of adopters.

A third variety of increasing returns to adoption is related to *technology-specific human capital*. The classic case here is the much cited QWERTY versus Dvorac keyboard (David 1985). The standard keyboard on any PC is QWERTY (the name is derived from the first row of letters: QWERTYUIOP). Originally this keyboard was designed so that the salesmen of typewriters could quickly type: "TYPEWRITER". Dvorac developed an alternative keyboard layout that was designed for easy typing, and tests have shown that typing speeds increase by 25% after some practice. But using the alternative keyboard requires training, and since people have already learned how to operate the QWERTY layout, switching entails training costs. Moreover, if I purchased and learned to use the Dvorac keyboard, I would be likely to stumble over the QWERTY keyboard every time I had to borrow someone else's machine. Thus in this case the return to investment in technology-specific human capital increases with the share of adopters of that technology. The strength of the lock-in is illustrated by the fact that the US Navy found that teaching their typists the Dvorac layout was an investment that would pay off in less than a year due to increased typing speeds. Still, David argues that individual firms did not have incentives to make the investment, as labour is mobile. At the same time, the individual typist will not make the investment unless there is a firm that will offer extra wages to pay for the investment.[1]

A final reason for increasing returns to adoption is the *learning curve of using new technologies*. This is particularly important for radically new technologies. A relevant case here is the choice of light water versus heavy water or graphite kernel in the design of nuclear power reactors. When this technology was developed in the early postwar period, there was next to no relevant previous experience to draw on. Each new reactor would provide valuable experience and help increase the quality of future reactors. Light water technology got a head start since it was chosen in the small submarine reactors for the US Navy. This contributed to a lock-in on light water technology (see Cowan 1990).

Note, however, that a plant owner will chose the technology that gives him the best plant. Since the technology to a large extent is embodied in the physical capital, the future improvement will accrue only to future investors. The individual investor will thus not have incentives to take potential learning into account in his decision. A technology that is superior at one moment in time will thus be the optimal choice for each individual investor and will thereby accrue further experience and technological improvement.

As pointed out earlier, I do not expect that this discussion contains an exhaustive list of the causes of increasing returns to adoption. It is striking how different the three cases discussed are in this respect, where mechanisms that were crucial in one case were almost absent in the other cases. With this heterogeneity within such a small sample, we should expect a rich diversity of reasons for increasing returns to adoption. Some examples immediately spring to mind: first, there are obvious increasing returns to adoption in communication. A boat with a VHF-radio can commute with any other boat that has

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[1] Those who have already invested in technology-specific human capital will not welcome a new technology that renders their investment less valuable. This group will have incentives to actively oppose the introduction of new technologies. This is not discussed in the case of QWERTY and does not seem to apply there, as the purchasers of typewriters were not the typists, at least not at the time when QWERTY was gaining its dominant market position. Such a conflict of interest may be more important in other cases, however.

installed the same technology. Persons with different computer systems – such as Windows, Mac or Linux – may experience problems in exhanging and working on the same files and documents, although this has improved, partly due to standardization.

A related mechanism is the selection of complementary products to consumer durables. When Microsoft Windows is the dominating operating system, most software is developed for this platform. The broad selection of software then becomes an important reason for choosing this operating system, reinforcing its dominant position. In similar fashion, a BETA type VCR can only play films in the BETA format. But eventually, the majority of VCRs were based on the VHS standard, and then few films were available in the BETA format. This illustrates a third mechanism for increasing returns to adoption: the availability of complementary goods from third party suppliers.

There is an obvious link between economies of scale and increasing returns to adoption. Here public transport systems illustrate the point. There are obvious economies of scale in public transport. The cost of running a bus route at a given frequency is practically independent of the number of passengers, and hence the cost per passenger kilometer will decline with the number of passengers. When most people own a private car and use it for commuting, public transport has a small part of the market and there will be few bus routes (operating at low frequency) since the number of customers is low. As a consequence, the service will be unattractive and those who can afford to may prefer using a private car. Still, taking congestion, road accidents and environmental externalities into account, the public transportation system may represent an improvement for most people, provided the rate of adoption is sufficiently high to make the quality of service acceptible.

A final mechanism that springs to mind is the social requirement to fit in. Wilhite (1997) reported that people participating in car-sharing systems complained about the constant need to defend their choice. Friends and relatives constantly asked them why they did not own their own car. This need to defend their decision would disappear with a sufficiently large share of adopters.

This discussion of increasing returns to adoption is not meant to be exhaustive. While some of the mechanisms are related, some are very different, indicating that there may be a vide variety of mechanisms involved. Although my discussion is not exhaustive, I hope it is sufficient to convince the reader that the question of increasing returns to adoption is not merely an esoteric issue to be relegated to footnotes.

Several of these mechanisms may be relevant for the CondEcol cases as well. A thorough analysis of potential sources of increasing returns to adoption in these cases is beyond the scope of the present report, so I will only point out some factors that seem to be of immediate relevance. An obvious factor in all cases is the cost of local adaptation, or rather more specifically: the cost of developing the required infrastructure, which is in turn related to the supply of complementary products from third party suppliers. A car manufacturer that adopts the CO_2 technology for mobile air conditioning will face the cost of training service personnel in a network of garages to maintain and repair this equipment.

2.2 Experimenting and uncertainty

Uncertainty is obviously important for potential adopters' choice of technology, but an extensive discussion of choice under uncertainty is beyond the scope of this report. Rather, I will focus on reasons why uncertainty may cause the market to be locked-in on particular technologies.

The most obvious case is the choice between a well-known, established technology and a new one. While laboratory tests can provide information about the alternative technology or product, the proof of the pudding is, as we know, in the eating. The potential adopter as the choice between a product with well-known properties and an uncertain alternative. With risk-averse adopters, the uncertainty will be a disadvantage for the new product. For a product aimed at the larger consumer market there may be adventurous consumers who are willing to try out the new product, but when the set of potential users is a small group of large firms, risk aversion may play a more important role.

Cowan (1991) argues that similar lock-in may occur even in the choice between two competing new technologies. He compares this choice to playing on "multi-armed bandits". Multi-armed bandits are hypothetical playing machines, like the one-armed bandits known from casinos, but with many arms to pull. There is a fixed cost for each time you pull an arm on a multi-armed bandit, and the probability of winning depends on which arm you pull. The optimal strategy is then to pull different arms at first, in order to learn about the probability of winning. Once the estimated probabilities are sufficiently precise it is optimal to pull only the arm which gives the highest estimated probability of winning. Note that these estimates may not be perfect, so one of the arms that are not chosen may actually have a higher probability of winning, but if the player has been unlucky with these arms initially, he will incorrectly believe that the probability of winning is low.

The argument is that new technologies share similar characteristics, with substantial initial uncertainty about their benefits. Each implementation of one technology will correspond to pulling an arm. If a developer is unlucky with the first prototypes, then agents in the economy will estimate the expected benefits from that technology to be low and find further experimenting with the technology not worthwhile.

Note that the argument presumes that there is one player pulling arms on the bandit repeatedly. This player will then receive the benefit of experimenting and learning. We are thus disregarding the problem that the benefits from experimenting are largely external, i.e. if I choose an unknown technology, others will benefit from the experience gained. By disregarding this effect, we are in essence studying the social optimum. Even so, lock-in on an inferior technology may occur.

Cowan (1991) argued as if potential adopters are queued up. When it is their turn, they have to make a choice between the different technologies available. But in many cases they would also have the option to delay the decision. Stoneman (2002) applied the real option approach (see Dixit and Pindyck 1991) to the case of technology diffusion. It may be argued that this option may be an additional barrier to adoption in many cases. When a technology is new, products are expensive and have not benefited from the improvements that derive from the experience gained by use. The individual adopter thus has incentives to delay an investment until the technology is more mature. On the other hand, the firm producing the product may sell the first generation of products based on a new technology at prices below production cost. A formal analysis is required to investigate the possibility of ways to fully internalize this external benefit of adoption.

A related issue is that of herding behavior. It is well-documented in social psychology that when uncertain about what to choose, we tend to mimic others. (See Cialdini (2001) chapter 4, for a good, popular presentation, and Banarjee (1992) for a discussion of the rationality of herding behavior.) A likely implication of herding behavior is that well-known majority products and technologies are more likely to be chosen, since this is what we observe others using.

The multi-armed bandit model was used to explain lock-in on a particular nuclear power plant technology, where each implementation (building a plant) is very costly and the amount of learning in each case is considerable. This does not apply to the same extent to the CondEcol cases. Moreover, the effects of risk-aversion and herding behaviour are less relevant when seeking adoption from industrial partners and not from thousands of households. Still, my understanding of these cases is imperfect, so these effects may be kept in mind for later stages of the project.

3 BREAKING OUT OF LOCK-IN

While there are many convincing studies documenting that lock-in is a very real phenomenon, nevertheless technologies do shift. The models discussed above predict that once the market is locked-in on one particular technology, the agents in the market will stick to that technology and not shift to alternative technolgies. Witt (1995), pointing out that this is a definite shortcoming of these models, suggests an alternative model, where a lock-in may be broken. The premise that no lock-in seems to be permanent is also important for the firms which want to sell their product in a market that is already locked-in on one particular product; this is particularly relevant for the CondEcol cases.

In Witt's model, he assumes that the market is initially locked-in on one particular technology. Then an alternative technology is introduced. Due to increasing returns to adoption, if the incumbent product has a 100% market share, the optimal choice for the individual will be to choose that dominant product. The new product thus requires a certain market share, the critical mass, before it will be the preferred product. When an alternative technology is introduced, consumers cannot know what market share this new technology will achieve, as there are no historical records of relative market shares to consult. Hence Witt assumes that after the new technology has been introduced, the first customers choose between different technologies more or less at random. When the market has matured the new technology will have reached some (small) market share. If the new technology has qualities that make it attractive even at such small market shares, this may be sufficient to shift the market to a new equilibrium, where it is locked-in on the new technology. In Witt's model, only technologies which even at low market shares are more attractive than established technologies can possibly enter into a locked-in market.

A natural extension of Witt's model would be to consider the case of niches. In an appropriately chosen segment of the market, the qualities of the new technology may make it attractive for potential adopters even at low market shares. In such cases, a small market share will be sufficient to reach the critical mass. If the technology is able to penetrate a fraction of the market, then adoption in the larger market may be easier.

The efficiency of the strategy of focusing on a narrow niche in the market will depend on the mechanisms causing increasing returns to adoption. When increasing returns to adoption are caused by negative external effects from non-adopters or local adaptation costs, the strategy of first focusing on a niche will most likely not help. On the other hand, when the returns to adoption are related to climbing the learning curve, the strategy may be very effective. The case of nuclear reactors is an apt illustration. Light water technology gained a crucial advantage from its use in submarine reactors in the US Navy. The experience from this niche was essential for the later use of light water in commercial reactors. While this was related to the creation of a lock-in, the same applies to breaking out of one, as the market may lock in on the new alternative technology.

While I have not been able to find economic literature that develops this point further, strategies of breaking eventual lock-in are highly relevant to the CondEcol project. A potential strategy would be to focus on segments of the market where the CondEcol technologies have particular advantages. If it is possible to penetrate these markets, this may benefit the introduction of the technologies in other markets as well. The efficiency of such a strategy to fight an eventual lock-in will depend on the extent to which more adopters in one market segment will make the technology more attractive to potential adopters in other markets. Such an effect may be due to improvements in the technology itself – based on experience in the first market segment – or a direct benefit to the potential adopters deriving from the fact that there are already a number of adopters, as discussed above.

A more direct strategy for reaching the critical mass is to target some of the major customers. Rogers (1995) discusses the use of change agents, who try to convince potential adopters by pointing out that a number of other users are considering adopting the new technology. In the case of large firms, it may be sufficient to provide a list of the other potential adopters. Thus the change agents help potential adopters to coordinate the shift, adopting the new technology only when they know that the share of adopters will be sufficiently high.

4 LOCK-IN AND PUBLIC POLICY

Public policy may have a crucial impact on technology choice and the technology that the market may become locked-in on. In the case of nuclear reactors, the US Navy chose light water technology for their submarine reactors. This choice was essential to the lock-in on that technology. In the case of pesticides versus IPM, Cowan and Gunby (1996) point out that two entomologists employed by the state were essential in convincing farmers in Bakersfield, Texas to switch from pesticides to IPM. They also report that in many instances, a part of the IPM strategy was implemented by strict regulation, e.g. by prohibiting early planting.

But why should public policy be concerned with technology choice? Would it not be better to let the economic agents choose for themselves, and hence choose the product that best serves their need? The simple answer is that individual choices do not only affect the individual. There are substantial social costs and benefits deriving from the individual choice in cases with substantial lock-in. In the following I will review some of these.

4.1 External costs and benefits with increasing returns to adoption

First, when technologies are radically new and there is next to no experience from using the different technologies, any adoption will add substantially to the accumulated experience and help make future implementations of the technology better. The individual customer may, however, benefit only marginally from these future improvements. Hence for the individual consumer it is optimal to choose the technology that is best at the moment, while from a social point of view there are substantial benefits to be gained from learning about an alternative technology with substantial potential for future improvement. The optimal economic policy would be, as with any externality[2], on any technology, issue a subsidy equal to the net social benefits from further experience with that technology.

The case of nuclear power reactors illustrates the point. The experiences gained from building and operating a new nuclear plant in the 1950s would add substantially to the experience with the chosen technology. The next power plant that was built using the same technology would benefit from these experiences. However, many of the decisions made when building such a plant are irreversible or very costly to reverse. Hence, since the plant itself would be built with the technology available at the time of building, the owners of the plant would be unable to reap most of the benefits of the new experience gained.

Since there was some experience with light water but less experience with graphite kernels, potential social benefits from gaining more experience with that technology could justify some subsidies. Note, however, that the cost difference could well exceed the social benefits from experimenting, and lock-in would occur even with optimal policy. Actually, the United States subsidized the use of light water in Europe, since they believed that it

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[2] For a brief review of externalities and public policy, see appendix.

was important for their policy objectives in the third world that US technology dominated the market (Cowan 1990)[4].

A case can be made for an industrial policy whereby the government regulates or stimulates the choice of technology. The clearest theoretical condition is discussed in Cowan (1991), where he considers a case in which the learning curve is known with certainty, and where accumulated learning is inherent in the capital equipment. In this case, future learning will not benefit a user buying the equipment now, since only current knowledge is embodied in the technology. The user will thus choose the technology that currently best serves the user's need. In cases where the short-run and long-run optimal technology are very different, the government may improve social benefits by only allowing the users to choose the long-run optimum. In Cowan's allegory, the individual will choose the hare (the technology that is quickly developed) even though the tortoise (a technology which would be superior with maturity) would be superior in the long run.

In some instances a case can also be made for direct regulation rather than taxes or quotas. The IPM strategy in parts of Texas included delayed planting in order to deprive over-wintering pests of food in the early spring. This was implemented as a prohibition of early planting. In principle, a tax for early planting – at a level corresponding to the loss an early planter would inflict on the other farmers – should also achieve the efficient outcome. Administratively, however, a simple regulation seems much easier than spending resources to determine the correct tax level.

The case is far less clear when there is uncertainty about the future potential of different technologies. The literature I have found thus far does not seem to include a thorough discussion of optimal policy with increasing returns to adoption. The literature indicates that the private incentives to experiment with alternative technologies are far less than the social benefits from such experiments, i.e. there are positive externalities from adopting a specific technology. But the uncertainty also poses a challenge to determining optimal public policy.

4.2 Uncertain Benefits and Optimal Public Policy

As pointed out above, one of the reasons for returns to adoption is that the experience gained from a new adopter is useful for further improving the technology. This is particularly valuable when uncertainties about the technology are extensive. But if this pertains, the total benefits will also be highly uncertain. Even when the technology is well known the benefits are uncertain, as the technology must be adopted in a market where yet more uncertainties abound.

A modest change in the share of adopters of a technology will have an impact on the prices and quantities of the product itself as well as of the input factors used in its production etc. Since economic conditions are constantly changing, available data will show some variations in most of the relevant prices and quantities. Hence it will be possible to estimate the economic impact of a modest shift by estimating a model from historical data. Almost by definition, radical changes take the system outside the realm of reliable data. Any assessment of benefits from radical changes will thus be highly uncertain.

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[4] Light water was the US technology. France, the UK and Canada had plants with alternative technology.

Not only is it difficult to quantify the extent of external benefits to adoption; an assessment of *public* policy also has to take into account the possibility that these external benefits are internalized by other participants in the market. For instance, if one company holds a patent on a new technology, that company may subsidize early adopters since the experience they expect to gain from early adopters will allow them to improve their technology and increase future profits. On the other hand, patents are restricted to a limited time period; moreover, other firms may eventually be able to produce similar products without violating patent rights. An assessment of external benefits relevant for public policy has to take such factors into account.

It will thus be a challenge to distinguish the cases in which net benefits will be negative – even after a radical reform – from the socially beneficial radical reforms. Due to the considerable uncertainty, there will be a substantial probability of suboptimal choices, and this has to be taken into account in the policy assessment. But in spite of all these caveats, there are cases where radical shifts are required.

I have not found a thorough discussion of the policy implications of the specific types of positive externalities discussed here, but positive externalities in general are well known from the literature. Positive externalities from research and innovation are well-known reasons for public funding of R&D, but in practise the externalities are extremely difficult to quantify, and it is correspondingly difficult to determine whether the public funding should be higher or lower than the current level.

There is also a discussion of the policy implications of positive externalities due to increasing returns to scale at the industry level. Due to agglomeration it may benefit a firm to locate a production plant in a cluster with many firms with similar production (like Silicon Valley.) This observation may be used to justify public support to “winner industries”. But on the other hand, if policy makers choose the wrong winner the support only means wasted resources and invites lobbying. Careful quantifications are required to determine which of these concerns is most important, but such quantifications have proved exceedingly difficult to generate.

In the case of increasing returns to adoption, the same kind of tradeoff is likely to pertain, and quantification is difficult but required. However, the type of externality may call for a slightly different structure of public support. While research funding typically stops once an idea is developed, positive externalities of adoption indicate that it may be optimal in some cases to extend the support to include product development and the introduction of the product on the market.

4.3 Environmental Technology and Lock-in.

As the literature on lock-in is not particularly related to environmental technology, I can only speculate on this issue here. Of the three cases I have found in the literature, only IPM versus the pesticides has a clear environmental dimension. Two questions require closer consideration: Are there particularities about environmental technologies that make lock-in on inferior technologies more likely? And, do these technologies require special policy measures?

To the first question, I would argue that in cases where the market is locked-in on a particular technology, the environmentally preferable alternative is likely to be among those that are locked-out. My argument here is based on the path dependence of the outcome in such market. Minor historical events and often a single person may have a crucial impact on the technology that ends up as dominant. In this setting, new technologies face a disadvantage relative to the incumbent technology. Historically, many of the existing technologies were developed at a time with less focus on environmental concern. At best there was a focus on end-of pipe solutions. With no focus on environmental issues at the time when the lock-in was established, the environmental technologies face a disadvantage.

A closely related reason to expect a lock-in on the inferior technology is the difference between social and private benefits. The user of a less polluting technology will inflict less social cost on others, but unless this cost is reflected in prices (through taxes), an individual may find that the private benefit of the most polluting alternative is the highest, even though the social benefit of that alternative is the lowest. Such problems would be overcome with appropriate environmental taxes, but if these taxes were not in place initially, the market may have been locked in on an inferior technology before the taxes were introduced.

There may be cases in which special policy measures for environmentally-friendly technology are required. Once the market is locked in on an environmentally inferior technology, internalizing external costs (through environmental taxes) may be insufficient to break the lock-in. On the other hand, once the lock-in is broken, the external costs may be too small to justify the administrative cost of a special tax. It is futile to extend this discussion much further on a general level, as much will depend on the particularities of each separate case.

5 CO_2 IN MOBILE AIR CONDITIONING

In the particular case of HFC versus CO_2 in mobile air conditioning, the potential adopters are the major automobile corporations. Since the automobile industry has recently changed from CFC to HFC, their production lines are rather up to date. The cost of investing in new production lines for the production of CO_2 air conditioners may thus be too great to be worthwhile for the industry. As I do not have the information required for a further assessment of this point, I will turn my focus to another barrier.

As one of the main characteristics of the CondEcol project is that all the cases involve technology that represents a considerable environmental improvement compared with existing technology. While there is willingness among some consumers to pay more for greener products, this is probably limited for cars with CO_2-based mobile air conditioning. The most environmentally concerned consumers are often not fond of air conditioning at all, and air conditioning is only one component of many that together determine the environmental performance of the car. On the other hand, if environmental taxes are levied on HFC emissions, an automobile manufacturer that switches from HFC to CO_2 air conditioning will save taxes corresponding to the reduced external costs. The lack of such taxes may be a barrier to an environmentally-friendly technology. In the next section I will try to estimate the extent of these external costs. Before returning to the discussion of increasing returns to adoption, I will briefly discuss the structure of the automobile industry, where long-term relationships with suppliers may reduce the flexibility of technology choices.

5.1 External cost of HFC versus CO_2 in mobile air conditioning

Prior to the 1987 Montreal Protocol, CFC was used as the coolant for mobile air conditioners. Today the dominating coolant is HCF-134a, a gas that is less damaging to the ozone layer but which is a very potent greenhouse gas. It is estimated that the lifetime global warming potential of HFC is 1300 times that of CO_2 (IPCC, 2001) [6]. With more than 300 million vehicles equipped with air conditioning worldwide, each emitting 1.75 kg HFC over their lifetime, the global warming impact of HCF is considerable. While CO_2 is itself a greenhouse gas, it is far less potent, and the potential emissions from air conditioning systems are negligible (hence I estimate only the external cost of HFC emissions).

In my view, social costs are not well-defined. The standard approach of estimating social cost from reported willingness to pay meets with problems of how such questions are interpreted (Kahneman and Knetch 1992), and the aggregation of such willingness to pay involves distributional problems (Brekke 1997). Still, resources will be used inefficiently when different firms face different relative prices. Thus to minimize the cost of

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[6] The impact, which differs with the time horizon, is lower compared to CO_2 the longer the time horizon. The given estimate is based on the 100-year time horizon recommended by IPCC.

attaining specific emission targets, all sectors should face the same price on similar emissions. In line with this argument, social cost will be estimated using the taxes that are in place in other sectors of the economy or that would have been required across the economy to achieve central policy objectives.

In this particular case the social cost of emissions will be proportional to the global warming potential of the emitted gas over the lifetime of that gas in the atmosphere. In the following calculations I use the tax level that would have been required to reach the objectives in the Kyoto protocol prior to US withdrawal. This is the cost that other industries would face for a similar global warming effect, provided that the emission target was set at Kyoto levels. The expected price on quotas if the Kyoto protocol had been signed by all is about USD 20 per ton of CO_2, which corresponds to USD 26 per kg of HFC-134a.[7]

According to UNEP (1998), 300 million passenger cars and commercial vehicles were equipped with air conditioning in 1993. As the number of AC equipped vehicles is increasing, this is probably a low estimate of the current number. UNEP also estimates total life length to 12 years, and total lifetime emission of HFC to 1.15 kg – 1.75 kg, depending on the rate of recovery at vehicle scrap. Using an intermediate value of 1.5 kg, a tax at a level corresponding to USD 20/ton CO_2 would add USD 36 to the cost of each mobile air condition installation. This estimate is obviously sensitive to the level of taxes. To illustrate, suppose that the tax was set to correspond to the Norwegian gasoline tax, calculated per kg emission of CO_2. In this case the additional tax on a car with HFC air conditioning would be about USD 700. Note, however, that the external cost of car use (reflected in the gasoline tax) includes much more than just the CO_2 emissions.

Total global annual emissions are 49 million tons of CO_2 equivalents, with external costs of USD 975 million, using the Kyoto quota price estimate as a basis. To give an idea of magnitude, total emissions of CO_2 equivalents in Norway amounted to 56 million tons in 1999. Worldwide there is currently only limited access to technology for recovery at scrap, and the number of vehicles equipped with AC has grown since 1993. Thus the likely emissions are higher and external costs are most likely more than USD 1 billion.

This estimate includes only the external cost of HFC-134a from mobile air conditioning. A complete economic analysis of the profitability for the car industry of switching to CO_2 is beyond the scope of this report (moreover, the relevant data are not available). Two obvious major issues in such an economic assessment should be mentioned, however. First is the cost of HFC versus CO_2, and second, a shift to CO_2 requires investment in new production lines.

While CO_2 is virtually free, HFC-134a costs “well over GBP 15 per kilogram” or more than 23 USD/kilogram[8]. In order to evaluate social benefits from a shift of technology, the ideal cost is not purchasing price but production cost, which is not available. If the automobile industry purchases HFC-134a at a price of about USD 23 per kg, that adds another USD 1 billion to the annual savings of a shift.

The calculations above include only the external cost of HFC and the cost of the gas itself. A shift to CO_2 air conditioning would require huge investments in the automobile

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[7] 1 kg of HFC - 134a has a global warming potential (GWP) equal to 1300 kg CO_2, or equivalently 1,3 tonnes of CO_2. A quota price of USD 20 per tonnes of CO_2 thus corresponds to USD 26 per kg of HFC - 134 a.

[8] http://archive.greenpeace.org/~ozone/hfcs/6reasons.html#b1, citing Outlook Environmental News Bulletin for APV Refrigeration and Freezer, Issue 2, October 1994.

industry, and an assessment of the profitability of such a shift is beyond the scope of this report. Instead I will focus on potential barriers that would remain even if the net present value of these investments is positive.

5.2 The structure of the automobile industry

The structural relationship between the automobile industry and its suppliers has changed considerably during the history of the industry (see Helper 1991). The most important shift from our point of view is the shift from what Helper labels an "exit" system to "voice with cheating". Under the exit structure, which was prevalent in the US automobile industry in the postwar period until the 1980s, the automobile industry would usually have several suppliers for the same kind of component. If they were dissatisfied with one of their suppliers, the automobile producer would exit, that is: stop purchasing from that supplier and turn to an alternative supplier or produce the part in their own factories. Contracts were typically short term, usually a year or less, and manufacturers often changed suppliers.

Partly in response to competition from Japan, the industry changed its relationship to suppliers in the 1980s. In this new system contracts are typically long term, and there is extensive contact between supplier and producers ("voice"). Contracts are constantly renegotiated in a system that is largely based on trust, where one part believes that if it loses on a new deal now, it will gain in the future (Helper and Levine 1992). This supplier/manufacturer system stems from Japan, where the automobile industry typically has long-term contracts with its suppliers, who are supposed to lower their production costs by about 2% annually. In the Japanese system, if a supplier has problems with price or quality, the car manufacturer will send some of its own experts to help resolve the problem.

The US manufacturers similarly adopted a system where the supplier and manufacturer enter into long-term contracts. Problems are discussed as they arise, the firms have contact on a daily basis, and contracts are constantly renegotiated, like in Japan. At the same time there are instances of what Helper (1991) labels "cheating". In such cases a supplier spends huge resources in developing a new part, but the automobile manufacturer later backs out, e.g. by deciding not to manufacture the product which required this part. It is not clear when such "cheating" is considered justifiable, but it seems clear that backing out of a contract will incur costs in terms of reduced trust, and hence this is something that is done only in rare cases.

In the specific case of HFC versus CO_2 in mobile air conditioning, the nature of the supplier relationship may be an important obstacle to a rapid shift in technology. The HFC technology was developed by Du Pont in a response to the potential regulation of CFC. The supplier industry (firms like Delphi, Visteon and Denso) has invested huge amounts in production plants for HFC-based air conditioners. These investments would only make sense if the suppliers have a long-term relationship with the automobile industry. If major automobile producers back out of this implicit long-term contract, the supplier may not be willing to undertake required investments at a later stage. Thus such conduct by the automobile industry may not be seen as a viable option.

While such contracts are long term, they are not indefinite, and once the supplier has received a reasonable return on its investment, the automobile industry may probably be able to back out without being seen as "cheating". On the other hand, the engineers in the supplier industry have invested in human capital related to the existing technology. HFC-based air conditioner are based on a low pressure technology. Engineers in the supplier industry who are used to HFC air conditionings are likely to be experts on low pressure air conditioners, while other firms may be better at the high pressure systems required for CO_2-based air conditioners. The engineers in the supplier industry will have a "voice" in the automobile industry, which gives them obvious incentives to defend the entrenched technology. This may cause lock-in over a period beyond the time required to give a decent return on long-term investments.

5.3 Increasing returns to adoption of CO_2 technology

To what extent do the different mechanisms of increasing returns to adoption apply to the choice between CO_{2-} and HFC-based mobile air conditioning? Of the mechanisms discussed above, the most relevant is the learning curve of new technologies. The CO_2-based technology works under much higher pressure than conventional air conditioners, posing new technological challenges. The technology is currently young, and the potential for improvement is correspondingly large. If the technology was adopted by a major automobile manufacturer, considerable improvements in the technology would be expected. But until some manufacturer has adopted it, the technology is less mature and hence less attractive.

There is also an element of technology-specific human capital. As pointed out above, experts in supplier industries have a vested interest in retaining the technology where they have developed their expertise, and they have a voice in the automobile industry. Beyond this, there is technology-specific human capital in the maintenance sector as well. Just as typists learn to use the dominant keyboard, mechanics at local garages will have incentives to learn maintenance and repair of the dominant system of air conditioners. Thus, a car owner with an unconventional air conditioning system may encounter difficulties in finding skilled persons to fix the system once there is a problem. As automobile producers are dependent on satisfied consumers in the long run, they will have few incentives to change to a radically different system.

Note that the critical mass required to make an alternative technology preferable to the old one will depend on the inherent qualities of the different technologies. The likelihood of a CO_2-based technology breaking a possible lock-in on HFC-134a will depend on the quality of the services the new technology can provide. In this connection it should be noted that CO_2-based and HCF-based mobile air conditioners do not serve identical functions. The CO_2-based systems may more appropriately be used for heating the car as well. As the main engine in the car becomes more energy efficient, there will be less residual heat available, and hence the need will arise for separate heating systems. Here the CO_2-based technology can provide services that the alternative technology cannot provide. This may be essential for the possibility of breaking a lock-in.

6 CONCLUSIONS

A review of case studies from economic literature has identified a series of mechanisms that may cause a market to be locked-in on a particular technology. In particular, lock-in may obtain in markets with increasing returns to adoption. The different cases show that increasing returns to adoption may prevail in very different contexts and often for different reasons. Thus it seems likely that lock-in may be observed in many markets.

The mechanisms discussed may be relevant to several of the CondEcol cases. A comprehensive discussion of how these mechanisms apply in the CondEcol cases is premature, as the cases have not been mapped out yet. The purpose of this report has been to present a survey of the literature as input for further research on the different CondEcol cases.

I have also briefly discussed the particular case of CO_2 versus HFC as the coolant gas in air conditioning. Due to lack of data, this analysis identifies only a few major issues. While the alternative (CO_2) technology may be socially superior to the existing HFC technology, both the lack of environmental taxes and lock-in may be barriers to the adoption of the new technology. In this case lock-in may be a consequence of steep learning curves. As high pressure air conditioning is a new technology, the technology would benefit considerably from the experience gained from adoption by a major automobile producer. But no producer may have incentives to adopt the technology until the necessary experience has been gained.

Lock-in represents a classic situation where the design of optimal policy is particularly challenging; that is when radical changes (in the sense of involving coordinated actions from large groups of actors) are socially beneficial, while marginal changes in the same direction are not. Almost by definition, a radical change takes us to a situation where we have little experience, and hence the uncertainties about potential benefits are particularly great. This uncertainty creates an arena for lobbying by interest groups. Groups or firms with special interests in the choice of one technology will argue for the benefits of a particular choice, often with highly specialized knowledge that policymakers will lack the capability to assess. For this reason, care should be taken to avoid spending public resources to serve private interests. On the other hand, there are situations where radical changes are beneficial and where the market will not implement the change, even with environmental taxes set to let prices reflect social costs.

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APPENDIX: PIGOUVIAN TAXES

As a background for the discussion of public policy implications, I present a brief and rather crude review of the basic theory of optimal economic policy in the presence of external costs or benefits. Adam Smith argued that when everyone pursued his own interest, the market outcome would be to the best of everyone. The basic intuition behind this claim is that if it were possible to make someone better off without harming anyone else, it would be possible for this person to realize the potential gain through a transaction with someone else that both parties find in their interest. This presumes, however, that the transaction does not affect anyone not involved in the transaction, since if a third party was harmed by the transaction, the benefit for one party would harm someone else. This is typically the case for environmental effects: if I buy and use a car, the pollution it causes harms other persons who have no interests in the car company or petrol stations. The harm imposed on others is labeled "external costs", or if others benefit, it is a question of external benefits.

To cope with this, Pigou (1920) suggested the use of "Pigouvian taxes". Suppose first that all parties that are affected by the production and use of a product are compensated by the producer or user. Now, if it is possible to make someone better off without making anyone else worse off, there will always be a transaction that is beneficial to both parties involved, even after everyone affected has been fully compensated for the harm inflicted on them. When all potentially beneficial transactions are exhausted we reach the market equilibrium, where it will be impossible to make anyone better off without making someone worse off. Furthermore, the same applies if those who suffer from the external costs are not directly compensated, but the parties in the transaction have to pay a tax equal to the amount it would take to fully compensate all affected parties. The latter would of course lead to an income distribution that is different from the case where all parties are actually compensated.

This is a very crude description of the status of theory almost a century ago. Pigou's argument has been much elaborated, and the conclusion will be modified if we account for asymmetric information, search costs or transaction costs, just to mention a few. Even so, external costs and benefits remain the most valid justification within economic theory for taxes or subsidies or other sorts of public support or restraints on economic activity. In the text I have focused mainly on the extent to which support to specific technologies may be justified in terms of external benefits, also pointing out the instances where alternative policies, such as direct regulation, are likely to be more suitable than the traditional economic instruments.