Chapter 8

A NEO-CLASSICAL ECONOMICS VIEW ON TECHNOLOGICAL TRANSITIONS

Frank A. G. den Butter and Marjan W. Hofkes
*Tinbergen Institute and Vrije Universiteit Amsterdam, Department of Economics, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands, and Institute for Environmental Studies, Vrije Universiteit, Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, the Netherlands**[*]

Abstract: Neo-classical economics assumes rational behaviour of economic subjects. The aim of policy makers is to maximise a broadly defined concept of social welfare, which may include some measure of environmental quality. In this view government intervention is needed when, due to externalities or other reasons for market failure, individual optimising behaviour does not lead to a socially optimal outcome. Therefore, neo-classical economics provides useful insights about the reasons behind technology lock-ins, and whether technological transitions are needed to escape from such lock-ins in order to enhance social welfare in the long run. This paper gives, from the neo-classical perspective, a survey of the state of the art of economic thinking on lock-ins, technological change and the possible role of the government to correct market failures by promoting technological transitions.

Key words: neo-classical economics, economic growth, lock-in, technological change, externalities

[*] e-mail: marjan.hofkes@ivm.falw.vu.nl; fbutter@feweb.vu.nl

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1. INTRODUCTION

To some extent, environmental policy has been effective in the last decades. Environmental problems have been solved and pollution has decreased in a number of cases where the problems had a local scale and where the consequences of the pollution could be observed directly by the stakeholders. The OECD (2001) has labelled as 'green' problems that relate to traditional forms of industrial pollution, such as air and water pollution. Yet a new generation of problems that remain unsolved may have a much more fundamental impact on society than relatively simple 'green' problems. These are the 'wicked' environmental problems that are labelled 'red' by the OECD. A characteristic of these problems is that their consequences are not directly observable; due to large international externalities, they require policy co-ordination on a worldwide scale (see also WRR, 2003). The major example is the emission of greenhouse gases and the resulting global warming. Other examples are the loss of biodiversity and the possible negative consequences of the adoption of certain forms of biotechnology. Amongst environmental experts there is a general consensus that major changes in the preferences and behaviour of consumers and producers are necessary to solve these wicked environmental problems, bringing about a need for system innovations, or so-called industrial transformation.

Industrial transformation research seeks to understand complex society-environment interactions, identify driving forces for change, and explore development trajectories with a significantly lesser burden on the environment. Industrial transformation research is of an integrative and multidisciplinary character, and focuses on systems and systems change. It is based on the assumption that important changes in production and consumption systems will be required in order to meet the needs and aspirations of a growing world population while using environmental resources in a sustainable manner (see Vellinga and Herb, 1999 and Chapter by Geels in this book). 'Transition' or 'transition management' describes how such systems change can take place.

It is obvious that major changes in production and consumption systems will never take place unless they are accompanied by, and even driven by, technological changes. That is why the Dutch government emphasises, in its recent national environmental policy plan (Nationaal Milieubeleidsplan IV (NMP4), 2001), that technological transitions are required in order to arrive at a situation of sustainable development. From the perspective of government intervention, much attention is given in the plan to the possibility of managing transitions towards sustainability.

The national environmental policy plan (NMP4, 2001: section 4.5) uses a very broad concept of transition. It is seen as a long-term societal transformation process, which includes technological, other economic, social, cultural and institutional changes. These changes in the various fields of society interact and strengthen each other. During such periods of transition, policy goals should be formulated and adapted, and policy instruments are to be used in a co-ordinated manner. Transition management plays, in this view, a major role in the planning and co-ordination of the transition process. The national environmental plan thereby describes transition management as a very broad concept too. It requires as key elements process-oriented steering characterised by uncertainty, complexity and interdependence. There is, according to the plan, an explicit role for the government, which should co-ordinate, stimulate, facilitate, steer and maintain.

This article considers technological transitions and the possible role of the government in steering these transitions from the neo-classical economic perspective, and will focus its analysis by using a narrower and more precise concept of transition and transition management. The neo-classical perspective confines the definition of *transition* to a technological transition where an old and less productive technology is gradually replaced by a new, more productive technology. Consequently, *transition management* describes how the government can facilitate such a technological transition. The neo-classical perspective does not consider the interdependence among the technological transition and the cultural and social transitions, in the case of a fundamental system innovation; nor does it provide policy prescriptions on how the government should co-ordinate these interdependent transitions; but it does provide government with insights on options to correct market failures. Moreover, in the neo-classical framework preferences are considered as given, so that it does not endogenise the room for the government to interfere in the process of preference formation. However, the neo-classical look at technological transitions is related to the features of industrial transformation in taking into account the dynamic interactions and mutual interdependencies among the (socio-) economic, the technological and the environmental variables.

As a matter of fact, neo-classical economics has a long-standing tradition of describing and analysing processes of technical change and the possible role of government intervention. The leading principle is that economic subjects behave rationally given their preferences. The next section of this article briefly reviews the foundations of neo-classical economics and welfare theory. It also shows how the environment has been given a proper place in this theoretical perspective. In Section 3 we focus on how technical change is analysed within the neo-classical framework. Section 4 describes why technological lock-ins may occur. The underlying reasons for technological lock-ins may give a hint of the role of the government in promoting a transition. The need for transitions and the scope for government intervention to facilitate transitions are discussed in Section 5. Section 6 takes the example of wind energy to illustrate the role of niches in an early transition process. Finally, Section 7 draws some conclusions.

2. NEO-CLASSICAL ECONOMICS AND THE ENVIRONMENT

Economics studies the production and consumption of commodities, *i.e.* goods and services. In particular, economics is concerned with the efficient use of scarce resources in production and consumption. A resource is called scarce if it is not unlimited (and freely) available. A consequence of this limited availability is that an allocation decision has to be made as to what end *casu quo* for the production or consumption of what good the scarce resource will be used. These decisions are taken by the economic actors, *i.e.* the government and private actors (producers and consumers) in so-called markets. One of the basic starting points of neo-classical economics is that economic agents behave rationally; consumers allocate their budgets in accordance with their preferences such that their utility is maximised, while producers allocate their resources in the production process such that profits are maximised.

Within the neo-classical economics school of thought one of the fields of research is welfare economics. Welfare economics focuses on the issue of the well-being of society. Pareto, who defined the concept of Pareto Efficiency, established the foundations of welfare economics. An allocation is called Pareto Efficient if no person can be made better off without making at least one other person worse off. It can be shown that in an economy where all markets are complete and competitive, the resulting allocation, which is based on individual decisions, will be welfare maximising and Pareto efficient. In such an economy there is no need for government intervention.

In the real world, however, several forms of market failures exist which give rise to inefficient allocations and thus may give cause for government intervention. In the following we will examine four forms of market failures: external effects, absence of property rights, public goods and the difference between private discount rates and social discount rates. Economists talk about an external effect if an allocation decision has an effect (*i.e.* a cost or a benefit) that is external to the agent who is causing the effect by his or her decision. In other words, the decision of one agent can affect the welfare of other agents in the economy, and this effect is not compensated for in the market. One of the underlying causes of an external effect can be the absence of property rights, as a result of which there is no market for the goods at stake.

Another form of market failure arises in the presence of public goods. A public good is a good that is non-rival (consumption by one person does not affect the amount available for others) and non-exclusive (nobody can be excluded from consuming the good). Well-known examples of public goods are defence, jurisdiction and environmental quality. As nobody can be excluded from consuming the good, nobody can be forced to pay for the use of the good, and the so-called 'free rider' problem arises, resulting in a sub-optimal allocation. Finally, a difference between the private discount rate and the social discount rate can result in inefficient market decisions. The discount rate, a concept that is used to compare the value of future money with current money, is built out of two components: time preference and a risk premium. Time preference refers to the fact that we prefer to have something today over having the same thing tomorrow. Besides pure time preference, there is another reason why having an amount of money today is preferable to having the same amount of money tomorrow. There is always the risk of losses on future amounts of money due to inflation or to setbacks in future yields. As the risk depends on the investment for which the money is used, it is obvious that there can be a difference between the social and the private risk premium, resulting in a difference between social and private discount rates. This difference can lead to inefficient market decisions.

The natural environment is a notable example of the existence of market failures, since the use of the environment in consumption and production involves external effects and/or property rights that are not (well) defined. Environmental economics focuses on the role of the natural environment in the economic process as well as on the effects of the economic process on the natural environment. Given the above-described characteristic of the natural environment in terms of a scarce resource whose allocation gives rise to market failures, conceptually the environment fits in a natural way within the neo-classical economic framework. At the same time, however, it is difficult to actually include the natural environment in the neo-classical economic framework sketched above from an operational point of view, as the natural environment has so many dimensions, both in space and in time. At least five different economic aspects of the natural environment should be distinguished:

- Environmental quality as a production factor; *i.e.* the non-extractive use of the environment in production;
- Environmental services as a production factor; *i.e.* the extractive use of the environment in production;

- Environmental quality as an (additional) indicator of economic welfare, which implies inclusion of environmental quality as an argument in the welfare function;
- The influence of abatement activities on environmental quality;
- The regenerative capacities of the environment.

So, the environment plays a role both in consumption (welfare) and production. With respect to welfare, only the stock of the environment plays a role, while with respect to production a distinction can be made between flows and stocks in the specification of the environment as a factor of production. Welfare derived from environmental services is not explicitly mentioned, as this aspect is implicit in production in the case of extractive use (*e.g.* water consumption or recreational services that lead to a degradation of the environment); and in the case of non-extractive use (recreational services that do not lead to a degradation of the environment) it is implicit in the environmental quality indicator in the welfare function. Note that extractive use of the environment in production that has negative effects on welfare — think, for example, of smoke or noise — forms part of the welfare function through the environmental quality indicator (which falls as a consequence of extractive use in production). Furthermore, abatement activities can be regarded as investment in environmental capital because they may improve the state of environment. Finally, self-regenerative capacities can (partly) offset the deterioration of the environment due to the use of environmental resources.

Taking the above-described economic aspects of the natural environment into account, the natural environment can be given a proper and natural place within the neo-classical economics framework. The starting point of the neo-classical framework is that the market mechanism can, under specific conditions, lead to an allocation that maximises social welfare. However, in reality, economic activity can have undesired effects on the natural environment due to the existence of market failures. This, however, does not imply that markets are not suitable as a means to allocate resources in a socially most desirable way. Rather, it implies that the shortcomings of markets have to be taken into account, and that the conditions under which markets operate should be improved or that new markets have to be created. In the context of market failures that have to do with environmental issues, a whole range of policy instruments is available, ranging from taxes, subsidies and tradable permits to direct regulation and voluntary agreements.

To this point, we have presented the concept of efficiency as the leading principle in the framework of thinking of neo-classical economists. In the context of environmental issues, the concept of sustainability or sustainable development is central. According to the Brundlandt report (World Commission on Environment and Development, 1987), 'Sustainable

Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' Sustainability, which raises questions about the welfare of future generations, can in fact be viewed as a long-term variant of efficiency. In order to be able to analyse the conditions under which sustainable development is possible all the (dynamic) interactions between the environment and the economy as described above have to be taken into account. Thus, dynamic specifications of all the relationships involved should be assessed. In studying the long-term relationship between economy and ecology, technology and the development of new technologies play a crucial role. Within neo-classical economics, the analysis of technological change is studied within the field of growth theory. In the next section we will give an overview of this field of research.

3. TECHNOLOGICAL CHANGE

In neo-classical economics, the analysis of technical change is part of growth theory. Growth theory tries to explain structural developments in the economy, *i.e.* long run developments in the production structure given the preferences and, therefore, is complementary to cyclical analysis. The production function has a key role in models of economic growth. This function describes the production process as a transformation of the production factors as inputs to final production as output. The simple traditional models of economic growth have two production factors as inputs, namely labour and capital. However, in growth models that consider environmental issues as well, a third production factor is included, namely energy, which is usually considered as a practical representation of the broader concept of (the use of) environmental capital.

A production function describes a specific production technology. An increase in one of the production factors may, given the production technology, lead to more output. Hence, economic growth can be the result of an increase in input of production factors. However, for the analysis of technological change it is more relevant to consider the consequences of technical progress as a driving force for economic growth. An improvement in production technology will result in a higher output given the various factor inputs. The reason for such higher production may be an increase in the efficiency of the use of one of these inputs. For instance, given the other factor inputs, when less labour is needed to produce the same amount of output, apparently there has been an increase in the efficiency of the use of labour in the production process, which results in higher labour productivity (inputs of units of labour per unit of output). This type of technical progress is called a labour augmenting technical progress. Similarly, we may have capital-augmenting and/or energy-augmenting technical progress. Yet quite often it occurs that we are unable to ascribe the increase in the efficiency of production to one of the production factors. In that case, we have an increase in total factor productivity (TFP).

Traditional neo-classical models of economic growth do not explain why technical progress occurs. Technical progress is exogenous and, as said by Joan Robinson, given to us as 'manna from heaven by God and the engineers'. Yet, more sophisticated empirical models of the production process make technical progress endogenous by describing it as the result of investments in research and development (R&D), and, in the case of labour augmenting technical progress, as the result of an increase in human capital through learning. These models allow us to analyse the consequences of relative price changes for the production technology and for technical progress. For instance, when the relative price of energy increases as compared to the price of labour, we will see, due to the substitution effect, a decrease in the use of energy and an increase in the use of labour in the production process. It implies an increase in energy productivity and a decrease in labour productivity. Yet, as a secondary effect, more resources in research and development may be devoted to enhancing energy efficiency in production and less to the development of new labour saving technology. In other words, the relative price change, which may be an autonomous change but can also be the deliberate consequence of a green tax policy, induces a change in the bias of technical progress: technical progress becomes more energy-augmenting and less labour-augmenting (see *e.g.* Den Butter and Hofkes, 2001).

Like all models in economics, the production function is a metaphor and a very stylised representation of reality. Extending economic growth models to mimic reality more closely is needed to account for the fact that techniques are incorporated in existing capital goods. The capital goods that are installed some years ago will use an older (and less efficient) technology than new investments that can be added to the capital stock today. It is, however, necessary to use capital goods in the production process for a considerable period of time in order to earn back the investment costs. So one cannot always install the most modern and efficient capital goods and scrap all other ones. That is why in practice it is impossible to adapt the production method immediately to a change in factor prices. This way of modelling production is called 'the vintage approach' because a row of consecutive investments in capital goods is distinguished as separate vintages that build up the capital stock. In the course of time, on the one hand, investments are added as new vintages to the capital stock, whereas on the other hand, old vintages are scrapped when they become unproductive and when investment costs are earned back. In their assumed rational investment behaviour, entrepreneurs reckon with all future relative price changes and are supposed to be able to calculate the time period a vintage has to remain installed in order to earn back the investments' costs. Uncertainty and learning behaviour may complicate this calculation, however.

Especially at the level of the plant or industry, vintage models provide a more elaborate representation of technological change and the adoption of new techniques than simple production functions do. Yet, new vintages of capital goods cannot be installed solely because more efficient techniques have become available or because changes have occurred in relative prices of production factors. Apart from an informational deficiency on the part of the producer, the phenomenon of 'time to build,' or to restructure, may be a reason why, in the case of so called win-win situations, where implementing new techniques can be both more environment-saving and more labour-saving than existing techniques — such new technology is not always immediately installed. So, neo-classical vintage models can explain why it can be rational that win-win situations are not (immediately) exploited by the industry. Moreover, it takes time (and money) to instruct personnel and let them become familiar with the working of a new technology. As we will discuss later, these learning processes play an important role in the path dependency of the implementation of technological innovations and are an important reason for lock-ins of existing techniques.

Indirectly and in due time, however, a change in relative prices will indeed lead to a change in the structure of production where the bias of technical progress is directed towards production factors which have become relatively more expensive. For instance, when the increase in the costs of energy exceeds the rise in wage costs, *e.g.* as a result of policy measures, entrepreneurs will select those new production techniques from the range of possible techniques that yield the highest energy efficiency. Moreover, when selecting which of the old capital goods are to be scrapped, the energy efficiency of the production process will have a greater weight in the decision than labour intensity.

Obviously, only calculations that use empirical models can show whether labour and energy savings were caused by a particular policy or by autonomous variations in factor prices. Moreover, these empirical models can also be used to calculate various scenarios for technological transitions. In such cases, policy measures (*e.g.* shifts of taxes from labour to energy) can be implemented by means of exogenous changes in the prices of energy and labour in the model. Yet alternative scenarios for transitions can also be obtained by a sensitivity analysis on the estimated or calibrated parameter values of the model. Such scenarios may represent the influence of institutional changes (*e.g*. the introduction of a system of tradable emission rights) or of changes in preferences (*e.g*. a greater weighting being given to environmental quality).

Another (and more common) interpretation of sensitivity analysis is that it provides insight into the possible range of future developments given the uncertainty about the parameter values that are used in the model's baseline projection. It should be noted that scenarios based on empirical models differ considerably from the socio-technical scenarios for transitions (see *e.g*. Geels, 2002) that are of a narrative and much broader nature.

What implications do the mechanisms described in the vintage models of economic growth have for environmental policy that aims to reduce energy use or, more broadly, for policy designed to reduce the use of environmental capital, which has to be directed at an increase in energy productivity? Given the available funds for research and development, so that the same amount is invested in the development of new technologies, and, roughly speaking, total factor productivity remains the same, such policy may lead to a relative decrease in labour productivity and/or capital productivity in comparison with the scenario without environmental policy. These changes in productivity will also lead to changes in product prices. This implies that environmentally intensive, 'dirty' products will become more expensive relative to 'clean' products, which use less environment in their production processes. This is because, in general, the possibilities for substitution in the production process will be too small to fully compensate the changes in factor prices.

Hence, in general, the products of sectors of industry with 'dirty' production methods will become more expensive in comparison to products from sectors that use clean technology. So, to some extent, the aim of the policy, namely a decrease in the use of the environment as a production factor compared to current trends, will be reached by means of a relative shrinking of the 'dirty' sectors and a relative growth of the clean sectors. This can be seen as a consequence of a general policy directed at internalising the negative externalities of environmental use in production. Therefore, in order to achieve a shift in the sectoral structure of production that leads to less damage to the environment, there is no need for (domestic) environmental policy to take specific measures with respect to 'dirty' sectors of industry.

The description above relates to the influence of environmental policy on technological change. From the neo-classical perspective, the reason for conducting environmental policy, in this case by changing the relative prices of factor inputs, is that the production using energy (or the environment more generally) as an input brings about negative externalities. These negative externalities imply a market failure, which the government has to correct in order to enhance social welfare. In this case, we assume a broad concept of social welfare with environmental quality as one of its elements (see also Den Butter and Hofkes, 1995). The policy prescription is to internalise the externality so that the users pay a socially optimal price for the use of energy (or the environment).

On the other hand, modern neo-classical theory of economic growth explains that, in the case of the development of new techniques and in the adoption of new techniques in production, positive externalities may occur. These externalities are the main reason why governments should introduce technology policy in order to enhance social welfare. In this case, market failures relate to the fact that the revenues of investment in R&D will almost never completely accrue to those who have financed the research. Research, and the implementation and adoption of technical innovations, almost always bring about positive spill-over effects to others, who may in turn use the experience in further research ('standing on shoulders') or in their own production process (taking advantage of others' learning). Technological knowledge has, in part, the character of a non-rival, public good. This is why, when investment decisions are completely left to the market, it generally results in underinvestment in R&D. It is true that the government may, by means of patents and so on, give complete property rights of the technology knowledge to those who have invested in the new knowledge. Yet, from the perspective of social welfare, such a situation is not optimal because in that case others cannot apply that knowledge and use it to further develop the technology. This is why technology policy aims to avoid under-investment in technological knowledge and tries to promote the use and diffusion of this knowledge. So we see that, from the neo-classical perspective, a good analysis of these types of market failure is essential for sound economic policy. This applies to how both environmental policy and technology policy affect technological change.

The neo-classical growth models described above are characterised by a production function with diminishing returns to the accumulation of capital, and constant returns in labour and reproducible capital together. In such a model, only continued technological progress can sustain a positive growth rate of output in the long run. Without technological progress the effects of diminishing returns eventually cause economic growth to cease, and the only feasible steady-state rate of growth that can result is a zero rate. New growth theorists have tackled this unsatisfactory property of neo-classical growth theory by endogenising the long-run rate of economic growth.

Endogenous growth can be modelled in different ways. In the late 'eighties, the first endogenous growth models appeared (Lucas, 1988; Rebelo, 1991; Romer, 1986). In Rebelo's so-called AK-model (Rebelo, 1991), endogenous growth arises because of constant returns to the reproducible factors. In this model growth is unintentional but arises as a side product of investment. Romer (1986) extends the neo-classical growth theory by accounting for production externalities. These production externalities are a consequence of knowledge spillovers in the process of human capital accumulation arising from learning by doing. In the Lucas-model (Lucas, 1988) growth arises from intentional investment in human capital. In this model, workers have to decide how much of their time they want to spend on producing goods and how much they use for learning activities. By learning, workers invest in their human capital, which leads to higher real wages.

These new developments in growth theory have also contributed to the interest in integrating the environment in economic models. In the early 'nineties, the first endogenous growth models in which the environment plays a role appeared. Gradus and Smulders (1993) analyse two endogenous growth models that incorporate the environment. Their first model is an extension of the AK-model, and their second model builds on Lucas (1988). Bovenberg and Smulders (1995) take a step further and develop a growth model with endogenous pollution-saving technology, which takes the form of knowledge of an efficient use of renewable resources. Hofkes (1996) builds on the Bovenberg and Smulders model and develops a two-sector growth model that also allows for abatement activities. Yet these models of endogenous growth do not provide much information on technological transitions and their underlying causes.

4. TECHNOLOGICAL LOCK-INS

The new growth theory that was developed in the 1990s studied the issue of sustainability, *i.e.* the question of whether sustained economic growth is compatible with conservation of the environment. The conclusion emerged that maintaining environmental quality and economic growth can go together if a steady flow of technological innovations increases the efficiency of resource use (Aghion and Howitt, 1998). Yet these new or endogenous growth models, as we discussed in Section 3, do not make a distinction between clean and dirty production technologies. If one wants to study technological transitions from dirty to clean technologies, attention has to be paid to technological diversity.

The focus on technological diversity is one of the major elements in evolutionary models. Evolutionary models typically describe a diverse set of technologies,[21] a diversification mechanism broadening the set, such as the arrival of random innovations, and a selection mechanism for the reproduction of specific technologies. The continuous diversification and selection mechanisms cause a drift (see also Chapter by van den Bergh in this book) in the characteristics of the current technology set. Those technologies that are most successful given the economic environment, the institutions, and policy regulations, are the 'fittest' and will then be reproduced. Within the context of evolutionary models, technological regimes, technological transitions, and technological lock-ins play a central role (see *e.g.* Dosi, 1982; Nelson and Winter, 1982; Arthur, 1989). Following Street and Miles (1996), a technological regime refers to 'the whole complex of scientific knowledge, engineering practices, process technologies, infrastructure, product characteristics, skills and procedures which make up the totality of a technology.' (Street and Miles, 1996: 413).

The concept of technological regimes can also be applied in the framework of the new growth theory. In the context of this framework, we will use the term 'technology clusters' instead of 'technological regimes' to indicate that the analysis in the framework of (new) growth theory takes place at a more abstract, less detailed, level. In neo-classical economic terms, the process of technology selection is characterised by increasing returns to scale and path-dependence. Typically, technology clusters, such as the fossil-fuel energy system, have their own infrastructure, and this leads to a specialisation in the following way: Innovations that improve on dominant technologies, which are technologies with a substantial market share, generate substantial profit flows, and thereby, these innovations are very valuable to the owners of the innovations, the innovators. This mechanism generates a continuous flow of innovations, which is essential to maintain high productivity levels, low production costs, and substantial market shares.

On the other hand, innovations in technologies with minor market shares are less valuable, and thus the incentive to improve on the technology is less powerful so the minor technology maintains a low productivity level, high costs, and a minor market share. In short, the positive feedback from market shares to innovations, to productivity, to market shares, strengthens the position of existing dominant technology clusters, and cuts the competitiveness of alternative, new technologies. This phenomenon is known as increasing returns to scale, and it leads to path dependence. The economy will specialise in technologies typical of the dominant cluster. This phenomenon of specialisation can in the end lead to a situation of lock-in.

[21] This technological variety may be embodied in firms, sectors or countries. For example, in (Nelson and Winter, 1982), the set consists of firms that possess different capabilities, procedures, and decision rules.

Increasing returns can be classified into three broad types: network externalities, learning effects, and economies of scale. Network externalities refer to the fact that the existence of networks (interrelations) between technologies, infrastructure and users of technologies can give rise to positive externalities, as the networks become more valuable as they grow larger. An example is telephone networks that become more valuable the more subscribers they have, since more people can be reached through them. Learning effects occur if, as a consequence of knowledge accumulation, the costs of using a technology decrease (and/or the performance of a technology improves). Finally, economies of scale can arise if, as a consequence of high fixed costs, the costs per unit decrease if production increases. In all cases, a mechanism may come into force where increasing returns lead to specialisation, and eventually to a situation of lock-in.

Gerlagh and Hofkes (2002) show that in an economy which takes into account environmental quality and where spillovers occur, three different types of externalities may exist: an investment externality, a 'choice-of-technology' externality and an environmental externality. Investment externalities result from the existence of spillovers between firms (See Section 3). This leads to the investment externality situation where investments fall short of the social optimum, which is in fact equivalent to the network externalities discussed above. The 'choice of technology' externality has to do with the fact that, due to path dependency, the distribution of investments over different technology clusters may be sub-optimal from a social welfare point of view. Finally, the environmental externality arises from the fact that there is no proper market for the environment. It is important to distinguish these three types of externalities, as only taking away the environmental externality does not imply that situations of lock-in will no longer occur. In Section 5 we will look at government policies with respect to the different types of externalities, and discuss the question of how government intervention may induce an escape from an undesired situation of lock-in.

We complete this section by looking at an example of technological lock-in. One of the most discussed and pressing examples of technological lock-in is the lock-in of industrial economies into fossil fuel-based technological systems. Despite the availability of carbon-saving technologies that have environmental and economic advantages, carbon-based energy technologies are still being widely applied. There appear to be barriers to the diffusion and adoption of the alternative carbon-saving technologies. These barriers can, at the micro-level, be explained by myopic micro-economic decision-making. Above that, at the macro-level there are forces that create systematic barriers to the adoption of carbon-saving technologies. These forces can be understood in terms of path-dependence, which comes about as a result of positive feedbacks into the economy (increasing returns). As a consequence, dominant designs are continuously being refined and firms incrementally develop their know-how. Examples of inferior technologies becoming locked-in as dominant designs are the QWERTY keyboard and the VHS video tape technology.

5. TRANSITIONS AND GOVERNMENT INTERVENTION

In principle, neo-classical economics describes technology transitions as processes of gradual technical progress, which is the eventual result of rational behaviour. Three consecutive steps can be distinguished when entrepreneurs make investment decisions in technological development. The first choice is to decide what part of the available factor inputs, labour in particular, is utilised for actual production, and what part is assigned to investments in R&D that leads to increases in technology capital through the design and implementation of a more efficient production technology. Important in this decision is the trade-off between foregone production now, when investing in the development of a new technology, and expected future increases in production, when the newly developed technology becomes operational. The second decision is about the type of these investments in R&D. Here the entrepreneur has to decide about the bias of technical progress. Should research be directed at the development of a more energy-saving technical progress, or will the focus be on enhancing the efficiency of labour in production? This choice determines the type of vintages that can be installed in future. The third decision relates to new capital investments, namely whether new vintages are installed to improve on existing technologies or whether the new capital investments use a new technology. The latter case would represent the start of a technological transition. According to neo-classical economics, relative prices and expectations about relative prices, uncertainty, and the costs of learning processes are the main determinants of decisions on these three choices.

As noted in Section 3, government policy will interfere with these choices in so far as the policy aims at correcting market failures. We have seen that environmental policy relates to negative externalities in the use of energy in production, and technology policy relates to positive externalities because of spillovers in the design and adoption of technology capital. Both types of policies may, through the mechanisms described above, contribute to technological transitions. However, neo-classical theory does not leave much scope for additional transition management by the government. In fact, if the government is to promote technological transitions, it must have good reasons to do so. An essential prerequisite for transition management is that production in a broad sense has to be trapped in a technological lock-in, which, from a long-run perspective is considered unfavourable. In other words: for transition management to be successful it is necessary to know both the reasons that have caused technological lock-in (see the previous section) and to have a clear indication that the lock-in is socially sub optimal in the long-run. These are harsh conditions that limit the scope of transition management much more than the broad concept in the national environmental policy plan (NMP4, 2001), and in the proposals for transition management following this plan (see *e.g.* Aubert *et al.*, 2001, RMNO, 2003). From the neo-classical perspective the rules for policy intervention are also stricter than suggested by evolutionary economics (see also chapter by van den Bergh *et al.*, in this book).

A major question when the government considers intervention in a dominant technology is whether there are alternative technologies that, for some reason, did not succeed in becoming dominant. It seems that the government should be very cautious in promoting the transition to such existing alternatives. An example is the promotion of public transport at the cost of private transport. Apparently both technologies co-exist and there is no reason, other than internalising the negative externalities of private transport, for the government to favour a shift to public transport. Both technologies co-exist because they are imperfect substitutes and even, to some extent, complementary to each other.

From the neo-classical perspective, a reason for additional government intervention in promoting technological change can be that initiating the development of a complete new technology is very costly because, at that early stage, it is very uncertain whether it will become the dominant single technology where the investment costs are earned back. In fact, it is the imperfect working of the capital market that provides a reason for such government intervention. Here the role of transition management is to facilitate the development of new technologies in niches where they are, in an initial period, protected from harsh competition. Yet, after this period of variation facilitated by the government comes a period of selection. The scope for the government to interfere in this selection process is very limited. The government, by no means has a lead in information on which of the alternative new technologies will yield the highest social welfare in a technological transition. Therefore, the government should not try to pick winners. The government, however, may interfere when letting the market do its work seems to lead to a suboptimal technology (but, again, who decides what is suboptimal?). Government intervention may also be needed when, due to network externalities, the economy gets trapped in an unwarranted lock-in of a technological monopoly, or, on the contrary, in a technology split that is socially suboptimal because network externalities are not fully exploited. An example of the latter is the simultaneous introduction of the 'chipper' and the 'chipknip' as two competing forms of plastic money by two bank consortia in The Netherlands. During the co-existence of both technologies, hardly any transition took place to this new payment technology.

All in all, from the neo-classical perspective it seems that the traditional policy instruments of environmental policy and of technology policy still constitute the basic tools in transition management. Yet when there is a clear indication that an escape from an existing technology is needed, it can be important to put the existing system under pressure by means of levies and regulation. This makes the old system more expensive and enhances the incentives for the development of, and the transition to, a new system. Such transition policy requires both a solid knowledge of the reasons for the lock-in and of the market failures that prevent adoption of a new technology in a socially optimal way. However, unlike evolutionary economics, no further policy prescriptions can be given to the shape and timing of stimulating transition trajectories. Moreover, there is another reason why the policy of making the old system more expensive is to be preferred to a policy of general subsidies for the development of new technologies. Subsidies may cause early adoption of a new technology, whereas, with the benefit of hindsight, it would have been better to wait and adopt a more efficient technology later. As a matter of fact, general subsidies for development and adoption of new technologies (or to improve on existing technologies) bring about high 'deadweight' losses, *i.e.* a large number of entrepreneurs would have developed or adopted the new technology without subsidies.

6. TRANSITION TO WIND ENERGY: AN EXAMPLE

An obvious way to achieve more sustainable use of energy would be a transition from fossil fuel-based production methods to wind as a means of energy production. Although the use of wind as a source of energy has a long tradition, the technology of large-scale production of electricity by means of wind turbines has only recently gathered (new) momentum. Development of wind turbine technology is ongoing, especially with respect to electricity production, and various routes are still open. Wind turbine technology can thus be regarded as an example of technological transition at an early stage, where various alternative technologies still co-exist and the selection of a dominant technology has not yet taken place. In principle, two different roads are open for the adoption of wind technology: namely, production by relatively small windmills on the premises of individuals, farmers, in most cases, and on a larger scale in windmill parks owned by major electricity-producing companies.

Klaassen *et al.* (2003) report on how government policy, with respect to subsidising the development of wind turbine technology and the adoption of that technology, has been different in Denmark, Germany and the United Kingdom. Differences in policy have resulted in different outcomes with respect to the extent of wind energy production in these countries; so the case can be seen as a kind of natural experiment in transition management, although neo-classical economists would look at it from a different perspective, seeing it as a lesson in what incentives government can use to promote the development and adoption of a new technology. Learning curves and their exploitation play a major role in the design of government policy to speed up a warranted technological transition.

The Danish policy to promote the development and use of wind turbines for electricity production has been most successful. Klaassen *et al.* (2003) conclude that in Denmark, R&D as well as demonstration projects, in conjunction with investment subsidies, favoured the development of reliable small wind turbines. In that country, the careful balance and timing of R&D and procurement support have been important to promote both innovation and diffusion of wind energy. Denmark started to promote wind energy in the mid 1970s. In 1991, wind turbines provided around 3% of Danish electricity consumption. It appears that the success of the Danish policy can be ascribed both to an early start in promoting these developments ('first movers' advantage') and to good insights into the learning processes so that the adoption of reliable windmills by farmers on a small scale was favoured. The European Commission (1997) reported another aspect that may have contributed to this Danish success: the first large market for the modern wind industry was California, USA, in the early 1980s. The growth of this market, a good example of an early niche for a new technology, stimulated the development of wind technology in many other countries. In the years from 1986-1990, the market in California declined, causing major financial difficulties in the wind industry. Many companies went bankrupt, but the simple Danish, 3-bladed stall-regulated design survived and was even up-scaled to provide more cost-effective units. This early selection process thus favoured Danish windmill technology.

By contrast, German R&D programs that started also in the 1970s, but aimed at developing large-scale wind energy production, failed. Yet the development of small wind turbines, where various subsidies provided an incentive for product and process innovation, has been rather successful in Germany, although overlapping subsidies might have resulted in efficiency losses. Moreover, due to knowledge spillovers, small German windmill manufacturers were able to benefit from Danish expertise. According to Klaassen *et al.*, the UK has been least successful in promoting wind energy. Here, support for renewable energy only started in 1989 with the passing of the electricity Act. R&D expenditures were insufficiently geared towards the type of turbines being installed. The UK subsidy scheme thus contributed to driving down the costs but not much capacity has been installed.

The example of wind energy shows that, with the benefit of hindsight, part of the developments can be explained by means of neo-classical economic theory. It is documented how price incentives (through various types of subsidies) influenced the adoption of new technologies, and how learning curves played a crucial role. Yet more sophisticated neo-classical models should be developed to explain more of the transition to wind energy. More attention should be paid to the total adoption costs of the alternative new technologies. These consist not only of learning costs and investment costs, but depend also on the societal preferences and acceptance with respect to the various types of windmills. It appears that large-scale windmill parks may bring about more societal costs than small windmills used by individual farmers, due to the impact on the landscape. However, such preferences may eventually change. Environmental valuation methods could give more insights into these indirect societal costs.

7. CONCLUSION

Neo-classical economics has a long-standing tradition with describing processes of technological change. This perspective is very much related to what environmental policy-makers nowadays call ‘technological transitions.’ Therefore, neo-classical economics offers an excellent methodological framework for the design and evaluation of policy prescriptions with respect to technological transitions and transition management. The arguments are based on formal models of production processes where, through the market economy, price incentives lead to the development, adoption and use of socially optimal production technologies. Changes in preferences, *e.g.* towards a higher weighting of the environment in the welfare function, result in changes in price incentives which promote the gradual adaptation of existing equipment to the technology which is optimal under the new preferences. Ideally, in their R&D investments, entrepreneurs anticipate these preference changes so that producers can avail themselves of the new technologies in due course.

In this formal neo-classical theory, the role of the government is limited. Government intervention is needed in the case of market failures, *i.e.* when rational behaviour of individual consumers and producers does not lead to a socially optimal outcome. In most cases (positive and negative) externalities will be the reason for market failure. The appropriate policy is to correct these market failures by internalising the externalities. There are various ways to do so, but from the neo-classical economics perspective it is essential that government intervention should be based on an extensive analysis of the types of market failures. Here the favoured choice of government intervention is through prices. Yet when the markets do not work perfectly, *e.g.* the capital market fails to finance highly risky R&D investments in new technologies, other types of government intervention may be justified.

To justify such government intervention, policy-makers should always see to it that the benefits of repairing market failures outweigh the costs of government intervention. Therefore, the government should be very cautious when conducting transition management that goes beyond traditional environmental policy to correct the negative environmental externalities, as well as traditional technology policy, which copes with positive externalities caused by knowledge spillovers in R&D and new technology adoption. Here, it appears that for the promotion of technological change, more emphasis is needed on adoption as compared with technological innovation (see *e.g.* Mulder, 2003).

When there is general consensus that an escape from a technological lock-in is needed and that only a fundamental system innovation can resolve a 'wicked' environmental problem, a solid analysis should be made of the causes of the lock-in. These causes relate to the path dependence and the increasing returns with respect to adoption and use of dominant technologies, such as the fossil fuel-based technological systems of industrial economies. In that case, it is the subtle interaction between the design of new technologies and the learning processes with respect to implementing these new technologies about which the government should collect information in order to facilitate the escape from a technological lock-in.

In sum, in the neo-classical view of industrial transformation and transition management, the emphasis is on the co-ordination between environmental and technology policy, where the government should reckon that diversification of new technologies can be hindered by capital market imperfections and that societal costs with respect to environmental preferences can play a major role in the adoption of new technologies. The scope of transition management is limited, however, in the sense that final decisions about the development and adoption of new technologies should be left to entrepreneurs.

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