ELSEVIER

Energy Policy 35 (2007) 5181–5194

ENERGY POLICY

www.elsevier.com/locate/enpol

The economics of climate change and the change of climate in economics

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Received 17 January 2007; accepted 7 May 2007
Available online 25 June 2007

Abstract

Economics is an unavoidable decision-making tool in the field of climate policy. At the same time, traditional economics is being challenged both empirically and theoretically by scholars in different fields. Its non-neutrality in dealing with climate-related issues—which is illustrated by the controversy over the "no-regret potential"—would thus call for an opening of economics to insights from other disciplines. Within that context, we show that an evolutionary-inspired line of thought coupled with a systemic and historical perspective of technological change provides a very insightful alternative to traditional economics. More particularly, it follows from that framework that the picture of the climate challenge ahead looks very different from what traditional economic analyses would suggest. For instance, the lock-in process makes it unlikely that traditional cost-efficient measures (such as carbon taxation or tradable emission rights) will be sufficient to bring about the required radical changes in the field of energy as they fail to address structural barriers highlighted in our approach.

Keywords: Climate change; Evolutionary economics; Technological lock-in

1. Introduction

Nowadays, economics has become an unavoidable discipline in the field of policy-making. From a tool supporting decision-making processes, it is now often used as the only decision-making science. Its intertwining with policy-making and the prominence of its jargon (starring words like competition, efficiency, etc.) seem deeply anchored in modern societies. This is largely due to the fact that economics is able to offer a theoretical framework that allows for a policy assessment based on metric values, which are highly appreciated by decision-makers (Maréchal, 2000).

Climate policy is surely no exception.[1] From the very beginning of international talks on this issue, up until the most recent discussions on a post-2012 international framework, economic arguments have turned out to be crucial elements of the analysis that shapes policy responses to the climate threat.[2] This can be illustrated by the prominent role of economics in different analyses produced by the Intergovernmental Panel on Climate Change (IPCC) to assess the impact of climate change on society (Toman, 2006).

Paradoxically (or maybe not), despite its political popularity, traditional economics[3] is also being challenged

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[1]The impact that the "Stern value" of €5500 billion has had on the media and decision-makers is a good illustration (the *Stern review on the economics of climate change* can be accessed on http://www.sternreview.org.uk).

[2]Among the most important decisions based on economic arguments is undoubtedly the US withdrawal from the Kyoto Protocol, based on the idea that it is "fatally flawed" and would hurt the economy (http://www.whitehouse.gov/news/releases/2001/06/20010611-2.html).

[3]We use the word "traditional" ("modern", "mainstream" or "orthodox" could also be used) to avoid the problems arising from the somewhat ambiguous use of the term "neoclassical", as shown in Colander (2000). By traditional economics, we refer to the Walrasian model of welfare economics, which can be defined as the theoretical synthesis of the Marshallian approach with marginal production theory and the rigorous precision of mechanical mathematics. It can be dated back to the second half of the 19th century with the work of economists like Alchian, Friedman, etc.

0301-4215/$ - see front matter
doi:10.1016/j.enpol.2007.05.009

as never before (see Gowdy and Erickson (2005) for a brief overview of recent sources of criticism). Its relevance has been strongly questioned by scholars from several fields—both from theoretical and empirical standpoints. Indeed, its criticisms are no longer targeted solely towards theoretical inconsistencies, but a substantial body of empirical evidence is also being gathered to demonstrate that the *Homo Oeconomicus* paradigm[4] is, to say the least, highly disputable (see the abundant empirical literature dealing with actual economic behaviour of economic agents in, for instance, Fehr and Gächter (2000); Henrich et al. (2001) as well as related ethnographic data in Richerson and Boyd (2000)).

More particularly, experimental studies in the realm of "neuroeconomics" (i.e. experimental studies expanded to include measures of biological and neural processes involved during economic activities) have shown that economic decisions are partly guided by feelings and thus emotionally coloured (Camerer and Loewenstein, 2004). In some cases, emotional processes—which are a vital part of our mental architecture (see Damasio, 1995, 2000; Muramatsu and Hanoch, 2005)—can come into competition with evolutionarily more recent processes such as planning, problem solving or language and give rise to what is referred to as economic "anomalies" (Cohen, 2005). As Dopfer (2005, p. 25) nicely puts it, this brain configuration provides the human being with "intelligent emotions and emotional intelligence".

Those studies strike a fatal blow to the traditional paradigm's assumptions of exogenous and self-regarding preferences (Bowles and Gintis, 2004), by revealing the existence of some degree of altruism (under the form of "strong reciprocity", as proposed in Gintis, 2000) and group-level influence (most particularly through culture[5]). Needless to say, this empirical evidence should be fully acknowledged in analyses that deal with the behaviour of economic agents like, for instance, in the field of energy consumption (where such "anomalies" are observed).

Yet, the traditional paradigm—which totally ignores the crucial role of emotions—still remains the dominant standard among economists and their audience (Gowdy, 2004) and thus provides the theoretical background on which policy-making is based. And this is undoubtedly the case of climate policy where strict Walrasian computable general equilibrium (CGE) models[6]—the primary tool of traditional economics—clearly dominate most of economic analysis (Laitner et al., 2000; Löschel, 2002).

The problem is that, despite the above-mentioned criticisms and the proven non-neutrality that ensues from it, the systematic use of traditional economics is not much discussed, so that its influence on policy-making still goes unhindered (which is, somewhat asymmetrically, not the case of the scientific basis underlying climate policy-making, which has been hotly debated despite the large consensus it generates among experts working under the auspices of the IPCC). This view of economics has been a key factor in designing climate policies (Toman, 2006).[7] The purpose of our paper is thus to fill this gap by providing some elements of thought based on a thorough analysis of the link between economics and climate policy.

This paper is structured as follows. The next section shows the concrete impacts of adopting the traditional paradigm on the way climate analysis is dealt with, using the illustrative case of abatement costs. In Section 3, we provide an alternative approach using evolutionary concepts with a strong focus on the issue of technological change. Section 4 deals with the implications of that approach for policy-making. Section 5 then concludes.

2. Impact of analysing climate policy using traditional economics

Although traditional welfare economics has been said by Nobel-prize winner Joseph Stiglitz to be "of little relevance to modern industrial economies" (Stiglitz 1994, p. 28), it still lays the foundations of the economic guidance given to policy-makers on a variety of critical issues (Gowdy, 2004). For instance, Arrow et al. (2004) base their environmental policy recommendations on traditional welfare economics and on the idea of perfect substitutability between manufactured capital and natural capital. In addition, as preferences are assumed exogenous, the main issue is to "get the price right". The market outcome can thus be considered as the optimal allocation of resources, and consumers are left with the choice between environmental degradation and economic losses (DeCanio, 1997).

The problem with environmental amenities—like the climate—is that they are non-market "goods" for which there is no price. The climate issue is even more tricky to handle, because it is global in scope (even though its presumed impacts are geographically differentiated) and has implications that are long term (which implies dealing with intergenerational equity) and potentially irreversible. Any framework inherently favouring the short term and assuming that damages can always be financially compensated is of little use in that context (Maréchal and Choquette, 2006).

[4]This refers to the theoretical representation of the economic agent on which the traditional economic model is founded. It sees economic agents as self-interested and perfectly rational individuals who maximise their utility based on perfect information and through using their capacity to ordinate their preferences.

[5]For a good introduction to the debate on the importance of culture, see Henrich (2004).

[6]The range of models used in the Special Issue on the Kyoto Protocol (see Weyant et al., 1999) of the influential *Energy Journal* provides a clear example of the omnipresence of CGE models in economic analyses of the climate issue.

[7]The focus on flexible mechanisms and the creation of an international emission trading system are the clear results of having adopted the framework of traditional economics.

To illustrate the impact of analysing the climate issue through the paradigm of traditional economics, we can examine the crucial notion of abatement costs (i.e. the costs of reducing greenhouse gas (GHG) emissions—which are said to cause climate change).[8] In a trivial way, abatement costs depend on two elements: reduction potential and reduction effort (difference between the target and a *business as usual* (BaU) scenario).

2.1. Reduction potential and the ''no-regret'' paradox

In climate-related literature, much research has been devoted to analysing what has been termed the ''no-regret'' emission reduction potential, which triggered an extensive debate among economists (see IPCC, 1996, chapters 8 and 9 for an overview and the Special Issue of Energy Policy in Huntington et al., 1994). An emission reduction potential is said to be ''no regret'' when the costs of implementing a measure are more than offset by the direct or indirect benefits (not including climate-related benefits) it generates based on traditional financial criteria.

The most obvious non-climate benefits are those arising from reduced energy bills following, for instance, the use of appliances that are more energy efficient. Many bottom-up studies have shed light on the existence of such ''no-regret'' investments in the field of energy efficiency, and showed that their magnitude can be substantial (see Krause, 1996; Interlaboratory Working Group, 2000; Tellus Institute, 1998). Yet, even though they are highly profitable most of these investments are not implemented spontaneously, which leads to what has been termed the ''efficiency gap'' (see Jaffe and Stavins, 1994; Kirsch, 1994).

It is not surprising that the existence of a ''no-regret'' potential was first highlighted by bottom-up engineering approaches, as it is incompatible with traditional economic theory. This is the main reason why economists were quite sceptical about the existence of such profitable opportunities (DeCanio, 1998). Indeed, according to the traditional paradigm, if such a profitable potential did exist, economic agents (i.e. optimising machines) would eventually undertake the necessary investments to capture it (Sutherland, 2000).

Faced with overwhelming evidence on the ''efficiency gap'', traditional economists resorted to the existence of hidden costs (mostly transaction costs) to rescue the *Homo Oeconomicus* paradigm (see, for instance, Sutherland, 1991). However, while such costs do indeed exist, bottom-up studies have shown that they do not quite offset the benefits from identified profitable energy-efficient investments (see Brown (2001) for a survey of such studies). More specifically, transaction costs can be drastically reduced when programmes are put in place so that synergy effects arise (Levine and Sonnenblick, 1994). EU decision-makers understood this possibility quite well and launched labelling systems for electric appliances like refrigerators. In some EU regions, financial support (in the form of subsidies) is also given. Taken together, these measures allow economic agents to overcome two major obstacles hindering energy efficiency, namely, the lack of access to capital and imperfect information.

These two obstacles belong to the list of what are known to economists as ''market failures'' and which also includes distortionary taxes, unpriced costs (i.e. like environmental externalities), misplaced incentives, etc. (Jaffe and Stavins, 1994). As the market signal is erroneous (i.e. fails to give correct information), rational agents require higher rates of returns to compensate for the increased risk associated with the level of uncertainty (de Almeida, 1998). Provided the failures are corrected, excessive rates of return would no longer be needed.[9]

But again, empirical studies have shown that the picture was not as simple as thought by economists. The reason is that there are other obstacles to profitable energy-efficient investments that are of a different nature than economic market failures. These are often referred to as ''barriers'' and relate to the ''bounded rationality'' of economic behaviours (term pioneered in the work of Nobel-prize winner Herbert Simon[10]). This notion has later been developed within the field of Evolutionary Economics, among others (see Nelson and Winter, 1982), to correct the ''scientific failure'' of traditional theory in explaining why economic agents do not always act as optimising machines. In adapting to their limited capabilities, agents adopt decision ''routines''[11] to simplify their decision process and ensure satisfactory results (Nelson and Winter, 1982).

Pushing this reasoning one step further, we can consider that we are somewhat ''locked in'' our (emotionally based) consumption's routines. These routines could provide an explanation for the existence of an efficiency gap in energy.[12] This has been shown to be the case of consumers as their intrinsic (i.e. not determined by market signals) habits and preferences were important determinants of energy-inefficient choices in motor technologies (de Almeida, 1998, p. 650).[13]

This picture, highlighting the potential inertia of routines, also seems to fit with the results obtained in the study performed in DeCanio (1998) and which shows that organisational and institutional factors are atleast as important as economics arguments in explaining the

[8]This notion has indeed played a dominant role in international talks and has formed the basis on which many countries have shaped their position on climate issues.

[9]It follows that corrective measures should only be implemented if they are shown to be less expensive than the benefits arising from greater energy efficiency (see also Sutherland, 2000, p. 98).

[10]See Simon (1957).

[11]Routines are a key concept in Evolutionary Economics, which refers to regular and predictable patterns of behaviour.

[12]This is clearly in line with those authors that see energy consumption as ''the routine accomplishment of what people take to be 'normal' ways of life'' (Shove, 2005, p. 117).

[13]The process leading to locked-in socio-technical regimes (see Section 3) may also serve to explain the reproduction of practices and habits.

efficiency gap in lighting. Indeed, the idea of routinised behaviours appears intuitively even more appealing when it comes to aggregate levels such as firms and institutions where sources of inertia are multiple.[14]

Non-economic barriers—which have mostly been neglected by energy economists—are thus an important part of the explanation and would require a wider range of policies (i.e. beyond those aiming at correcting market failures) to be implemented if decision-makers wish to tap the ''no-regret'' potential (Schleich and Gruber, 2006).

But this may well only be the emerged part of the iceberg. Indeed, a review of 52 case studies by Laitner and Finman (2000) has shown that the non-energy benefits of certain efficiency measures could be of the same order of magnitude as their energy benefits. This enhances the credibility of the ''Porter hypothesis'', which argues that investments undertaken to reduce environmental impacts may trigger productivity gains (Porter and Van der Linde, 1995). This seems to have been the case for British Petroleum (BP). Between 1998 and 2001, BP reduced its emissions by 18%, while gaining $650 million of net present value (BP, 2003, p. 23)—a gain that occurred because the bulk of the emission reductions came from the elimination of leaks and waste (Browne, 2004).

Contrary to what traditional economic theory would suggest, it thus seems possible in some cases to reduce GHG emissions and reap economic benefits at the same time. This has been proven to be possible in cities and companies (Climate Group, 2004), in US steel firms (Worell et al., 2003) and on a macroeconomic scale (The Allen Consulting Group, 2004).

2.2. Reduction effort

A reduction effort—such as that imposed by the Kyoto Protocol on the developed countries that have ratified it—is defined as the difference between an emission target and a BaU scenario. By convention, reduction efforts within the framework of the Kyoto Protocol are estimated with reference to 2010, the central year of the first commitment period (from 2008 to 2012). Obviously, the only unknown data are the BaU scenario that is supposed to give an estimated answer to the question ''where will we be in 2010 if we do not do anything?''. A careful analysis of these scenarios shows that the way in which technological progress is modelled is of crucial importance for the results (Maréchal et al., 2002).

This fact is not more surprising than the ''no-regret'' debate as in traditional modelling (i.e. *à la Solow-Swann*) technological change (TC) enters the production function as an exogenous variable (Mulder et al., 1999). It has to be noted that during the 1980s with the work of Paul Romer and Robert Lucas, traditional modelling of TC was enlarged to include human capital (see Mulder et al., 2001). This was a first step towards modelling TC as an endogenous variable in response to critics like those formulated in Nelson and Winter (1982). More recently, Aghion and Howitt (1998) provided a Schumpeterian type of traditional modelling. However, both of these modelling schools still fundamentally differ from the approach we will adopt in this paper.[15]

In energy-related studies, only the exogenous type of modelling was used, at least up until the mid-1990s (see Azar and Dowlatabadi, 1999; Grubb et al., 2006). This ''manna from heaven'' type of modelling takes the form of the autonomous energy efficiency improvement factor like in the model used in Manne and Richels (1992) and the famous and influential DICE/RICE model (Nordhaus, 1994). Economic modelling of climate change has obviously improved since that period. More particularly, a great deal of research has been devoted to elaborating models with endogenous technical change (ETC) as illustrated by the recent Special Issue of *The Energy Journal* on that particular matter (see Edenhofer et al., 2006). While this is undoubtedly a major step, this approach still fails to incorporate some of the main features of an evolutionary view of TC (e.g. interdependencies and heterogeneity) as we will show in our analysis. Moreover, the third generation of ETC modelling[16] appeared after major decisions (i.e. the Kyoto Protocol and the US withdrawal) were taken in the field of climate policy so that exogenous modelling of TC really had an influence on the way in which the climate challenge was posed.[17]

This is confirmed by a recent retrospective study that analysed previous energy forecasts made in the US and showed that they systematically overestimate energy consumption (Sanstad et al., 2006). This tendency is largely explained by an inappropriate way of modelling energy efficiency improvements (see also Craig et al., 2002). Varilek and Marenzi (2001) also come to similar conclusions when they compare forecasted and effective prices on the US SO_2 emissions trading market.

2.3. Economic impact of reducing GHG emissions

The fact that ''no-regret'' measures are not taken into account and that technological change is modelled as an exogenous parameter inevitably gives a pessimistic view on the possibility to tackle the climate issue at an affordable

[14]In fact, in the original work of Nelson and Winter (1982), routines are organisational (i.e. relate to firms). It is now standard practice to use the term ''routine'' for collective behaviour and the term ''habit'' for individual behaviour (Dosi et al., 2000).

[15]For a good overview of the history of the different ''induced'' TC modelling—within and outside the traditional paradigm—see Ruttan (2002).

[16]See Grubb et al. (2006) and Koehler et al. (2006) for a brief historical overview of climate modelling with ETC.

[17]We can also add that CGE domination in climate modelling makes it difficult for a widespread diffusion of ETC modelling as CGE models ''face considerable difficulties in incorporating ETC'' (Koehler et al., 2006, p. 46).

cost.[18] Traditional analysis both fails to integrate profitable energy investments and underestimates the penetration of energy efficiency (Laitner et al., 2000).

Thus, given that the main assumptions of traditional economics are strongly questioned, it seems interesting to investigate the impact that an alternative economic framework (more in line with empirical data) would have on climate policy in general, and on the modelling of technological change in particular. This is even more interesting considering that technological evolution has historically had a tumultuous relationship with environmental problems, being alternatively envisaged as their cause and their remedy (see Gray (1989) for an overview of this ambiguous relationship).

3. Impact of adopting an alternative framework

Considering the criticisms formulated against traditional economics, it seems clearly necessary to reconcile the theoretical characterisation of the economic agent with recent empirical findings, while defining a framework that allows for the integration of such a characterisation. This calls for the opening of economics to insights from other disciplines such as psychology, anthropology and biology.

Setting an entire alternative paradigm to traditional economics is beyond the scope of this paper. Nevertheless, we make the premise that an evolutionary-inspired line of thought, applied to a specific issue such as technological change modelling in energy-related issues, could provide an insightful alternative. This is due to the fact that evolutionary economics allows for the integration of concepts such as "bounded rationality" while also focusing on economic dynamics resulting from innovation, selection and accumulation, giving rise to new insights into the framing of environmental policies (van den Bergh et al., 2006). In fact, what is exogenous in traditional economics "comprises the endogenous core of evolutionary economics" (Dopfer, 2005, p. 178).

3.1. *A brief discussion of our evolutionary view*

As long ago as the turn of the 19th century, Veblen (1898) wondered "Why economics is not a evolutionary science". Today, more than 20 years after the publication of the seminal article of Nelson and Winter (1982), evolutionary economics is a well-established branch of economics (Arena and Lazaric, 2003). Yet evolutionary economics is far from constituting a stable alternative paradigm, because internal debates still agitate those who adhere to that school of thought (Arena and Lazaric, 2003).

The approach we adopt in this paper analyses economic evolution in line with the vision adopted in Witt (2003, p. 15) and is labelled the "continuity hypothesis". This framework rests upon the idea that Darwinian type of selection has provided human beings with evolved cognitive and learning skills (Tomasello, 1999) that constitute the basis for other forms of evolution to take place (Witt, 2003). These other forms of evolution (cultural, economic, etc.) are different from biological evolution, one reason being that they take place on a shorter time scale.

What is important in our perspective is to underline the need to analyse economic evolution as a process of continuous, double (downward and upward) and interactive causation (van den Bergh and Gowdy, 2003; Corning, 1997). That is to say, what exists today is not the result of sole selection at the individual level. More precisely, some socially acquired characteristics of human beings (like the above-mentioned "strong reciprocity") are better explained by group-level analysis (Henrich, 2004).

We will show that this group-level approach (as opposed to studies analysing individual units) also applies to technological change, which is best explained through a co-evolutionary framework allowing for circular and self-reinforcing interactions between economic agents. In fact, this picture of economic evolution arises from a focus on dynamics occurring at the "meso" level, a level that is wedged between the traditional micro- and macro-scales (see the "Micro–meso–macro" approach in Dopfer et al., 2004). What is interesting about the meso-scale is that it highlights the role played by interdependencies of systems elements and the emergent nature of economic evolution. It thus provides an alternative to simple aggregation (i.e. the "representative agent" hypothesis on which the traditional framework of "general equilibrium" rests).

Furthermore, as our analysis will show, this co-evolutionary framework must be analysed at three different but connected levels (see Fig. 1): co-evolution of supply and demand, co-evolution of different technologies and co-evolution of technologies and society (see also Kemp and Reinstaller, 1999).

Needless to say, this kind of framework based on a "micro–meso–macro" approach allows for the integration of the crucial notion of *heterogeneity* which is both micro-founded (as it is the result of "bounded rationality" that results in economic agents adopting different strategies) and the "deep" macro-result of meso-dynamics. Accordingly, macro-dynamics can be seen as the emergent property of micro-diversity and meso-change.

Obviously, our approach (that clearly departs from the traditional framework) would shed a different light on energy-related issues. For instance, the above-mentioned systematic overestimation of energy forecast (Sanstad et al., 2006) can be explained by the fact that meso-analyses have been lacking in the past. Indeed, as mentioned in Schenk (2007, p. 1507), macro-level dynamics in energy-related top-down studies were unable to foresee trend-breaking events such as the decoupling of GDP and energy consumption. We have also seen in Section 2 that the notion of "bounded rationality is important in

[18] Sutherland (2000, p. 90) confirms that "most economic analyses of the cost of achieving the term of the Kyoto Protocol conclude that such costs would be high".

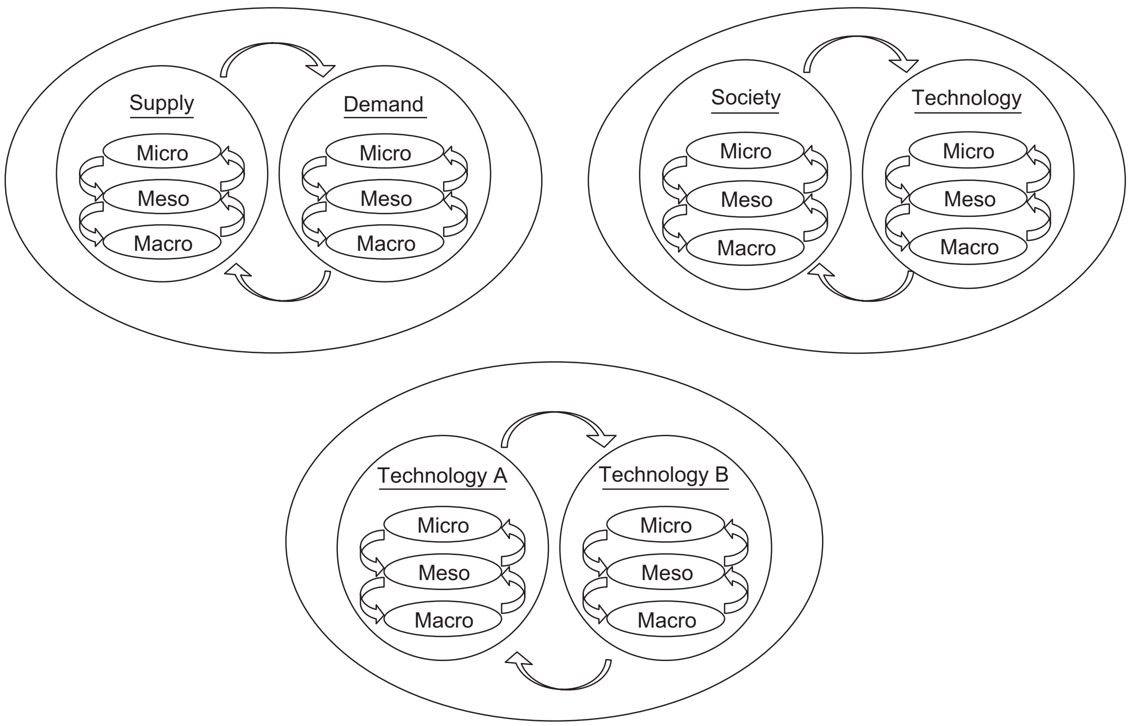

Fig. 1. Three-dimensional co-evolutionary framework of technological change.

energy-related analyses as it can serve to explain (together with other elements underlined in our approach) the no-regret paradox.

3.2. Technological change through evolutionary lenses

To define what we consider to be an evolutionary view of technological change, we start from two elements. First, we follow Foster (1997, p. 433) and identify the lack of formal historical connection as a major drawback of many analyses. This inevitably guides us towards what could be called, according to Dosi (1997), the ''David and Arthur theory'' of path dependence and lock-in and which stresses the historically contingent nature of economic change (see David, 1985; Arthur, 1989).

Secondly, we agree with Mulder et al. (1999) that the added value of an evolutionary approach of TC, even compared to the most recent traditional analysis based on endogenous modelling of TC, is that TC is ''contextualised'' (i.e. the circumstances of its emergence are explained), which is highlighted through a systemic vision of technologies as ''interrelated'' (see Veblen, 1915, p. 130).

As noted above, TC modelling has gone through major improvements recently, especially in the field of climate policy where models with ETC were developed (see Edenhofer et al., 2006). However, even though these models incorporate a form of learning processes with increasing returns, they still fail to integrate the main features of an evolutionary-inspired approach of TC, namely, systemic interdependencies, heterogeneity of agents and historical contingencies. For example, Koehler et al. (2006, p. 24) clearly mention the ''David and Arthur theory'', but historical contingencies are nonetheless ignored in the surveyed models. This is also the case of the heterogeneity of agents, but this is explicitly recognised as a weakness (Koehler et al., 2006, p. 49). Unsurprisingly, systemic interdependencies are not mentioned at all.[19] It is interesting to note that both systemic interdependencies and heterogeneity of agents are typical features of meso-level analyses—the ''missing link'' of energy-related studies (Schenk et al., 2007) and the ''conceptual heart of evolutionary economics'' (Dopfer et al., 2004, p. 269).

In that context, our approach to technological change can be described as a synthesis of the work of David and Arthur with an evolutionary framework in a systemic perspective. As mentioned in Dosi (1997, p. 1539), the two approaches are highly compatible. As a matter of fact, their synthesis is implicit in many recent works (Carillo-Hermosilla, 2005; van den Bergh et al., 2006; Rammel and van den Bergh, 2003; Unruh, 2000, 2002).

3.3. Our evolutionary framework of technological change

Within this framework, it is more appropriate to analyse technologies as belonging to ''technological systems'' (see Hughes, 1983). Following Unruh (2000, p. 819), technological systems are defined as ''inter-related components

[19]The need to ''understand better the underlying elements and issues in experience curves'' (Koehler et al., 2006, p. 31) can be considered as a plea for some form of contextualisation, but the systemic nature of it is still lacking.

connected in a network or infrastructure that includes physical, social and informational elements''. For example, the automobile transport system is composed of cars, roads, traffic signs, garages, etc.

If we push the systemic logic one step further, we see that technologies are not only linked to other technologies, but are also interrelated with the cultural and institutional aspects of their environment (see the example of the railway system in Kindleberger (1964) or the more general concept in Freeman and Perez (1988)). In this case, we talk about *techno-institutional complexes* (Unruh, 2000) or, more common in the literature, *technological regimes* (TRs) (Kemp, 1994).

This characterisation of technological systems composed of multiple interrelated elements sheds light on the potential inertia of such systems—an element that could not be revealed by analyses focusing on isolated technologies. In turn, this potential inertia invites us to investigate the historical conditions that lead to the emergence of a TR. This is why the notion of technological lock-in, pioneered by the work of David (1985) and Arthur (1989), has been the subject of a growing interest from scholars in different fields (Perkins, 2003). Recently, this concept has been applied in various studies that deal with environmental issues (see Carillo-Hermosilla, 2005; van den Bergh et al., 2006; Kline, 2001; Rammel and van den Bergh, 2003; Unruh, 2000, 2002; van den Bergh and Gowdy, 2003).

The notion of lock-in is linked to (and could be considered as a result of) the concept of path dependence (Arthur, 1983; David, 1985), which refers to the fact that technological systems follow specific trajectories that are difficult and costly to change. As shown in Arthur (1989), these trajectories depend on historical circumstances, timing and strategy as much as optimality (i.e. the main focus of traditional economics).

That is to say, the presence of increasing returns to adoption (i.e. a positive feedback that increases the attractiveness of a given technology when it is more and more adopted) can potentially lead to market domination (see Arthur, 1989, 1990, 1994; David, 1985).[20] This mechanism is similar to a snowball, in the sense that a given technology which, for whatever reason, obtains an initial lead will eventually exclude other competitors as its early advantage is amplified through time because of increasing returns to adoption. Thus according to this process, and contrary to what traditional economics says, the same distribution of technology and homogeneous preferences of users could lead to different technological structures, depending on how things happen in the beginning (Economides, 1996).

The lock-in literature usually identifies four classes of increasing returns (Arthur, 1994). The first two classes—namely, ''scale economies'' and ''learning economies''—are well documented and commonly used by economists who have rested on them to build ''learning curves'' (Unruh, 2000; Perkins, 2003). The impact of these two classes of economies is increased by a third type of increasing returns, namely, ''adaptive expectations'', which refer to a reduced level of uncertainty as both users and producers become more confident about the technology's general quality (Arthur, 1991). Finally, the last class of increasing returns to adoption is known as ''network externalities''.[21] It is the one most commonly associated with the lock-in literature, and clearly results from the adoption of a systemic approach for analysing technological change. According to Katz and Shapiro (1985, p. 424), positive network externalities refer to the benefits that a user derives from a technology when the number of other users increases. They arise because physical and informational networks become more valuable as they grow in size. This is obviously the case of hardware or phone networks, for example (Katz and Shapiro, 1985; Unruh, 2000).

The importance of network externalities is enhanced in our evolutionary framework, as they are thought to operate on technological systems that consist not only of multiple interrelated technologies and their supporting infrastructures, but also of technical, informational, economic and institutional relationships that enable them to work together (Perkins, 2003). This can be illustrated with the case of the automobile, whose expansion required parallel developments in supporting industries (steel, glass, etc.), infrastructures (service station, roads, etc.), academic research and lobbies (see the work of Flink, 1970, 1988).

In addition, the codified standards (e.g. html, 110 and 220 V current, litres and gallons, etc.) that are used to co-ordinate such TRs can also become a major source of lock-in (Unruh, 2000).This picture is even reinforced by the fact that, as highlighted by the notion of *technological paradigm* in Dosi (1982),[22] there is also a form of lock-in of ideas, which are shaped by the cognitive frame of actors and therefore determine exploration frontiers (see also Dosi et al., 2005). This reduced scope of investigation could explain why, as underlined in Mulder et al. (1999, p. 6), most of the technological change consists of incremental improvements rather than radical breakthroughs.

From our evolutionary perspective, the last two centuries can be described as a succession of three dominant TR: from 1800 to 1870, the dominant TR was composed of steam, iron and canals; then over the 1850–1940 period it was progressively replaced with coal, railways, steel and industrial electrification; and this last cluster has in turn been shifted to a TR made of oil, roads, plastics and mass electrification between 1920 and 2000 (see Grübler, 1998).[23]

[20]Arthur's theory of self-reinforcing mechanisms can be compared to the famous ''Polya-urn'' process (see Arthur et al., 1987, p. 295).

[21]See the pioneer work of Frankel (1955) based on the concept of ''interrelatedness'' in Veblen (1915) and, for more recent formalisations, Katz and Shapiro (1985, 1986) and Farrell and Saloner (1986).

[22]This notion is inspired by the ''scientific paradigm'' of Kuhn (1970).

[23]Note that all three regimes are built around and dependent upon a specific source of energy that highlights the relevance of evolutionary concepts for energy-related studies.

If it can be said that the existence of such clusters has long been acknowledged by economists (Perkins, 2003), the idea that the aforementioned lock-in process can lead to the dominance of an inferior design is highly disputed. The following examples give a brief overview of the debates and show how they evolved along with the different documented stories of technological lock-in.

The suggestion that locked-in design could be inferior has first been made in David (1985) using the example of the QWERTY keyboards—an example sometimes considered to be the "Founding Myth" of path-dependence literature, as mentioned in Ruttan (1997, p. 1523). Indeed, the QWERTY keyboard is said to have been locked-in through the above-described process and to the detriment of superior keyboard designs (i.e. the Dvorak keyboard).

Because of its acquired status in the literature, the alleged superiority of QWERTY has been strongly disputed, most notably by Liebowitz and Margolis (1990, 1994, 1995) who called it a "Fable". Their critics of the second most popular story, the "Betamax vs VHS" case (Arthur, 1990), were even more vehement, as they claimed that VHS came to dominate the market due to a real advantage: its longer playing time (Liebowitz and Margolis, 1994, p. 148). It is beyond the scope of this paper to present the details of the controversy over this symbolic case, but an analysis of the well-documented study performed in Cusumano et al. (1992) would tend to contradict this version and give credit to Arthur's version.[24]

Still, this controversy underlines the main problem with the "lock-in of inferior designs" hypothesis: the difficulty of empirically proving the superiority of "locked-out" alternatives (Cowan and Foray (2002) talk about the "counterfactual threat"). For instance, when confronted with the idea that the gas-powered internal combustion engine might not be the best design (Arthur, 1989, p. 127), Liebowitz and Margolis (1994, p. 148) only oppose that they find this claim "difficult to take seriously". However, in line with Mokyr (1990, p. 191) or Unruh (2000, p. 821), existing studies again clearly show that Arthur's claim is at least worth analysing (our claim is based on a proper analysis of various papers: Arthur, 1989; Cowan and Hulten, 1996; Foray, 1997; Foreman-Peck, 2000, 2001; Kirsch, 1994; Mowery and Rosenberg, 1998).

The case of the emergence of the light water reactor in nuclear plants, as explained in Cowan (1990), provides a more solid empirical example of the lock-in of an inferior design.[25] Even more robust yet is the evidence gathered in Scott (2001), which describes the lock-in of the British railway into a system of small wagons that was undoubtedly less profitable than the larger wagons system almost universally adopted in other industrialised nations.

It seems to us that all these examples[26] make a case important enough to further investigate the lock-in process and identify some insights it could bring for policy-making in the field of energy and climate-related issues.

3.4. The common background of the various "lock-in" stories

In all the aforementioned cases of suspected lock-in of inferior designs, we may distinguish two different periods in the lock-in process (Foray, 1997, p. 740). The initial period, whose duration may vary, exhibits very low increasing returns to adoption and thus reflects preferences,[27] which may be deliberate or not. This first period also varies in terms of the number of decisional events involved before a distribution of choices can be observed. In the nuclear example of Cowan (1990), there was one such event, whereas in the battle of the motors (Cowan and Hulten, 1996) or in the battle of the videotape recorders (Cusumano et al., 1992), a succession of events was involved.

Then, the second period of the "lock-in" process starts with the appearance of dynamic complementarities, that is, positive feedbacks that are introduced in the system and tend to amplify the initial distribution of choices (see Foray, 1997, p. 740). These can take the form of complementary goods, like pre-recorded tapes in the VCR case (Cusumano et al., 1992); technical interrelatedness as in the case of the automobile (Flink, 1988); or triggering events, like those car races in France that undoubtedly had an impact on the selection of the gas-powered internal combustion engine (Foreman-Peck, 2001).

In line with the work of Veblen (1915, p. 130), complementarities are also important in that they provide an explanation for the persistence of obsolete intentions, as in the QWERTY case, whose design originated from the need to hinder typing speed to avoid type-bar clashes—a need that is no longer relevant to computer keyboards (Foray, 1997, p. 745). Interrelatedness generates an analytical bias known as the "profit gap" (see Frankel, 1955, p. 306), which helps explain the persistence of locked-in technologies (like, for instance, small wagons in Britain, even though they were substantially less profitable, as shown in Scott (2001, p. 371)). Technological lock-in can even persist without increasing returns if other elements are in place (Balmann et al., 1996).

[24]As the Betamax's playing time had been extended well before the crucial arrival of the pre-recorded tape (see Cusumano et al., 1992).

[25]The choice of the LWR technology—which is found to have emerged through a decision from captain Rick Hoover that was not grounded on any scientific consensus—is recognised as suboptimal for civil applications compared with other nuclear technologies (Foray, 1997, p. 739). Interestingly, this example is not even mentioned in Liebowitz and Margolis (1994, 1995).

[26]See also the "Battle of the current" case in Hughes (1983) and David and Bunn (1988).

[27]It could be argued that these preferences are already historically determined.

The bulk of lock-in stories that can be found in the literature also highlight the relevance of adopting a systemic approach to technology, as they all demonstrate how essential it is to take into account the unavoidable interactions that exist between related technologies, as well as the role played by related institutions, whether public or private. In fact, taking technological systems into consideration makes it difficult to circumvent historical contingencies, as their importance turns out to be fundamental (see Carlsson, 1997). A detailed analysis of four different technological systems in Sweden shows that, though these four systems were very different in terms of economic success, evolution trajectory, etc., in all cases their evolution and configuration could not be rightly understood without analysing initial conditions and path dependence (Carlsson, 1997, p. 796).

What we also see is that such a systemic reasoning has often been lacking in the decision-making process of crucial economic actors. This can be illustrated by the non-anticipated exponential growth of the sales and rentals of pre-recorded tapes in the VCR story (see Cusumano et al., 1992). Most of the time, deliberate choices cannot be qualified as ''irrational'', even in terms of financial profitability, but rather *systemically myopic* (or *systemically* ''boundedly rational'', to use the term coined by Herbert Simon). David (2000, p. 14) adds that even Thomas Edison's business strategy in the ''Battle of the currents''—and especially its withdrawal from the flourishing electricity supply market—failed to correctly take into account the systemic aspects of his decision, even though it was driven by rational economic considerations (see also Rosenberg, 1982, p. 60).

It is obviously rather complex, if not nearly impossible, for an individual decision-maker to forecast all the complementary developments to his technology, and to make decisions that are optimal for the whole system built around it. For instance, it would not have been easy to foresee the explosion of the American pre-recorded tape market, as market surveys indicated that only 8% of VCR owners found this product to be important (Klopfenstein, 1985 quoted in Cusumano et al., 1992).

The analysis of railway gauges performed in Puffert (2002) is interesting because it adds one element—the spatial dimension—to the ''lock-in of inferior designs'' debate, and sheds complementary light on the type of processes involved. It is also a very insightful analysis to deal with the dilemma of ''standardisation vs diversity'' (to which we will come back in Section 4). Puffert (2002, p. 285) provides convincing evidence for the existence of an initial period during which the ''lock-in'' process—including the making of path-dependent choices and the occurrence of positive feedback mechanisms—is clearly at play.

However, this study also shows that, even if the process never completely breaks free of early contingencies, in later stages the dynamics of choices are based on a rather systematic rationalisation (Puffert, 2002, p. 291)—which we could even call ''systemic'' rationalisation, as those later stages are driven by a quest for improved co-ordination and facilitated compatibility of neighbouring networks. The contrasted examples of the Netherlands and Spain (which does not use the most common gauge—the ''Stephenson'' one) provided in Puffert (2002, p. 285) underline the role played by conversion costs, which could also serve, for instance, to explain the persistence of the British system of standard weight and measures in the US (see Unruh, 2000, pp. 822–823).

In the example of the ''Stephenson'' gauge, however, the historically produced inefficiency does not really come from a wrong choice of dominant design—the ''Stephenson'' gauge is considered to be close to the optimal size—but rather stems from the persistence of other, non-compatible systems. The spatial dimension thus provides a complement to the model in Arthur (1989), as it allows for the lock-in of a dominant design (concept coined by Abernathy and Utterback, 1978) in parallel with the persistence of various small systems that are geographically spread out.

A modelling exercise performed in Jonard and Yildizoglu (1998) shows that diversity can be sustained even in the context of increasing returns to adoption. It all depends on the importance of ''spatially localised learning'' with respect to ''network externalities'' (Jonard and Yildizoglu, 1998, p. 47). Small ''network externalities'' can be a source of diversity (Jonard and Yildizoglu, 1998, p. 49). Therefore, lock-in can only arise if network externalities are strong enough. As mentioned by David (2000, p. 3), this shows that empirical enquiries remain necessary in order to determine what proportion of economic change can be understood more adequately through the approach adopted in this paper.

Yet, the most interesting result of the modelling exercise is that the biggest inefficiency comes from a reduction in the level of technological progress when ''lock-in'' effects dominate as, in this case, the technological space is not fully explored (Yildizoglu, 1998, p. 47). This is in line with the aforementioned concept of ''technological paradigm'', by Dosi (1982).

4. Policy recommendations

The importance of historical contingencies, coupled with the impossibility of foreseeing future developments, is not without implications for public policies dealing with technological progress, including those related to climate change. As emphasised in David (2000, p. 14), this does not imply that governments should pick up the winners instead of letting markets decide—a choice that would involve a risk of locking-in a ''dead-end'' technology, as highlighted in Sanden (2004, pp. 327–328). On the contrary, as mentioned in Foray (1997, p. 748), public authorities should pursue the objective of securing a good balance between diversity and standardisation, knowing that the gains from each are variable in time (see also David and

Rothwell, 1996). As Foray (1997, p. 748) puts it, a technology could emerge too early, or it could become too deeply entrenched.

Wisdom would thus require governments to delay their commitment to an inextricable future, in order to allow for the availability of sufficient information on any given option (David, 2000). In other words, governments should act to maintain a diverse range of technological options open (Berkhout, 2002, p. 3). For instance, in the "Battle of the motors", US engineers were able to switch from electric to gas-powered vehicles because they "did not put all the eggs in one basket, nor were they irrevocably committed to any particular technology" (Foreman-Peck, 1996, p. 9). This allowed them to deal with conversion costs that were not as prohibitive as they were for Spain in the case of railway tracks (see Puffert, 2002).

Furthermore, if we acknowledge that we are locked into an undesirable trajectory (as climate analysts could deem to be the case of our economies which strongly rely on the use of exhaustible fossil fuels[28]), then it follows that we must find ways to unlock out of it (see Unruh, 2002). After all, such shifts have happened in the past (see Berkhout (2002, p. 3) and the three above-mentioned major TRs of history from Grübler (1998)).

Of course, unlocking ourselves from an undesirable trajectory is not a task that can easily be undertaken as it is quite difficult to identify the solution that would yield the best outcome. We must also bear in mind the risk inherent to what has been called the "paradox of entrenchment"—that is, the need to create conditions for the lock-in of a desired new technology to overcome the lock-in of an incumbent one (Walker, 2000). Unruh (2002, p. 323) adds that this risk increases when action is delayed, which implies that extreme measures must be implemented quickly.[29] The new locked-in technology could then prevent superior technologies or designs from developing, as might be the case of solar energy technology, where crystalline silicon photovoltaics are possibly locking-out thin-film photovoltaics (Menanteau, 2000).

In any case, when defining their position in the face of several competing technologies, public governments should bear in mind the need to manage the risk of committing to inextricable trajectories, but they should also promote the type of measures that have been proven successful in overcoming lock-in situations (see the set of necessary conditions in Windrum (1999, p. 31) and the key aspects identified for regime shifts in Mulder et al. (1999, p. 9) and in Cowan and Hulten (1996, p. 65)). This invites us to go one step further than the model of Arthur (1989), and to depart from its example of a competition between contemporaneous technologies (Windrum, 1999, p. 6). What is needed in the case of climate policy is a technological succession (Windrum and Birchenhall, 2005), which is considered as a necessary condition for attaining a low-carbon society (Koehler et al., 2006, p. 18).

The example of the gas turbine shown in detail in Islas (1997) is very interesting as it illustrates both the need to create niches (i.e. a limited space where new technologies can mature[30]) and the possibility of overcoming lock-in with hybrid technologies. In that example, niches (namely, aeronautics and peak power plants) allowed the gas turbine technology to improve through a process of increasing returns to adoption (Islas, 1997, p. 63). Then the emergence of gas turbines into the bigger electrical base market occurred through hybridisation between the incumbent steam turbines and auxiliary gas turbines–the latter eventually becoming the main component (Islas, 1997, p. 64).

In line with our described framework of TC highlighting the existence of a somewhat locked-in TR and with Rosenberg (1982), a substantial body of literature focuses on "strategic niche management" (see Kemp, 1994; Schot et al., 1994) in order to identify the key aspects that must be promoted for niches to be successful in overcoming incumbent lock-in—a concern that arises because capturing a niche does not automatically lead to subsequent wider diffusion (see the example of the electric car in Mulder et al., 1999, p. 15). As mentioned in Unruh (2002, p. 322), niches are also an attractive policy target since incumbent producers do not fiercely defend them, removing some of the resistance towards new entrants.

Niches are even more important within our co-evolutionary framework as they facilitate learning not only about the performance of a given technology but also about social acceptance and users needs in general (Kemp and Reinstaller, 1999).[31] They help create a virtuous circle to build a supporting network and serve as an incubator for new technologies (Kemp and Reinstaller, 1999, p. 23).

5. Conclusions

Our analysis shows that adopting an evolutionary approach to study technological progress could substantially alter the policies recommended by economic analysis, away from the current focus on the sole notion of efficiency.[32] Particularly, the lock-in process makes it unlikely that traditional cost-efficient measures (such as carbon taxation or tradable emission rights) aimed at

[28]See Unruh (2000) or Arentsen et al. (2002).

[29]This might soon become the case of climate measures as global emissions have been continuously rising ever since the signature of the Kyoto Protocol in 1997 (IEA, 2005).

[30]When there is a protection (whether public or not), a niche is said to be technological. If not, it is called a market niche (Mulder et al., 1999, p. 11). For instance, the internet was developed within a technological niche whereas railways grew within a market niche (Windrum and Birchenhall, 2005, p. 125).

[31]The failure of the milk cart is another example that illustrates the need to take a user's acceptance into account and not just focus on technical aspects.

[32]An evolutionary perspective requires one to also concentrate on the efficacy of interactions (Dopfer, 2005) or functional compatibilities (Windrum, 1999).

internalising external costs will be sufficient to bring about the required radical changes in the field of energy, because they fail to address structural barriers (del Rio and Unruh, 2006, p. 14). Climate policy should instead create conditions enabling the use of cumulative and self-reinforcing character of technological change highlighted by evolutionary analyses (Mulder et al., 1999) and take into account the current lock-in of our economies in the fossil-fuel era.

By requiring a broader change (to include change of, for instance, the institutional environment), "strategic niche management" fundamentally differs from simple "technology-push" policies, particularly in the role that states are to undertake. "Strategic niche management" is larger than simple niche promotion in that niches are managed (i.e. created, developed and then phased out), taking into account the broader context in which niches evolve (i.e. acknowledging that social and institutional factors do contribute to reinforce the locking-in of the incumbent technological system). For instance, policies in Denmark were eventually more successful than those in the US in promoting wind energy because they were built upon ongoing socio-technical dynamics rather than simple subsidies, as shown by a comparative analysis in both countries performed by Kemp and Reinstaller (1999).

The existence of an untapped "no-regret" reduction potential, as shown in Section 2, further illustrates the importance of enlarging the picture to also look at demand-side aspects. Indeed, as it comes out of our approach, the existence of a "locked-in" carbon-based socio-technical regime means that changing people's behaviour would inevitably "be the result of collective, contingent and emergent processes of socio-technical co-evolution" (Shove, 2005, p. 119). Focusing solely on "bringing in" more efficient technologies could turn out to be counterproductive if it serves to sustain unsustainable patterns of consumption (one such counterproductive effect being the well-known "rebound effect"[33]). It is thus important to take into account the evolution of routines, habits and practices that go along with technical change.

Altogether, this confirms the need to look at technological change through the aforementioned three-dimensional co-evolutionary framework (shown in Fig. 1).[34] Analysing technical evolution through this type of perspective shows the importance of contingencies, feedbacks and dynamic interactions and thus renders inevitable to acknowledge the emergent, complex and uncertain nature of economic evolution. Accordingly, policy-makers should thus try to influence the selection environment and create conditions under which the evolutionary process defined in the previous sections would lead to the desired outcome (i.e. climate protection in our case).

For all those reasons, adopting an evolutionary approach to treat the climate issue would give a different picture of the challenge ahead from what traditional analyses tend to suggest. For instance, Castelnuovo and Galeotti (2002, Section 5) show that the costs of reducing greenhouse gas emissions are reduced by a factor of 3 or 5 when technological progress is modelled in a structurally endogenous way with respect to the outcome obtained using the same model but with exogenous modelling of technological change. Thus, as claimed by Koehler et al. (2006, p. 19), the absence of endogenous technological change biases policy assessment in the field of climate protection. Still, as mentioned earlier, modelling TC as endogenous is only the first step towards a better representation of technological evolution according to the framework we adopted in this paper.

It thus appears that, in order to deal with climate change in an appropriate way, economics must adapt. Most certainly, this calls for a better understanding of the key factors that explain how and in what context technological change arises in order to adequately design climate policies aimed at promoting climate-friendly technologies. As our analysis has shown, an evolutionary-inspired line of thought coupled with a systemic and historical perspective of technological change provides a very insightful alternative to traditional economics.

[33]See, for instance, Berkhout et al. (2000).

[34]The case study on the comparative diffusion of totally chlorine-free pulp bleaching technologies in the US and Sweden stresses the crucial role of co-evolution of technology and endogenous preferences (see Reinstaller, 2005).

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