Chapter 3
Theoretical Approaches to Dynamic Efficiency in Policy Contexts: The Case of Renewable Electricity

Pablo Del Río and Mercedes Bleda

Abstract Dynamic efficiency (or the ability of a policy instrument to generate a continuous incentive for technical improvements and cost reductions in technologies) is central to the assessment and choice of environmental and energy policies in long-run scenarios where innovation lock-in is relevant. This is also the case in instruments that support electricity from renewable energy sources (RES-E). In contrast with effectiveness and static efficiency assessment criteria, the innovation effects of such support have received much less attention from both a theoretical and an empirical perspective. Several theoretical perspectives have paid some attention to these innovation effects, including the traditional economics approach, the systems of innovation perspective and the literature on learning effects. The aims of this chapter are to provide an overview of those perspectives and to build bridges between them.

Keywords Renewable electricity • Dynamic efficiency • Innovation lock-in • Energy policy • Systems of innovation

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P. Del Río (✉)
Institute for Public Goods and Policies (IPP), Centro de Ciencias Humanas y Sociales,
Consejo Superior de Investigaciones Científicas (CSIC), C/Albasanz 26-28, Madrid 28037, Spain

Institute for Public Goods and Policies (IPP), Consejo Superior de Investigaciones
Científicas (CSIC), Serrano 117, Madrid 28006, Spain
e-mail: pablo.delrio@csic.es

M. Bleda
Institute for Public Goods and Policies (IPP), Centro de Ciencias Humanas y Sociales,
Consejo Superior de Investigaciones Científicas (CSIC), C/Albasanz 26-28, Madrid 28037, Spain

Manchester Institute of Innovation Research (MIoIR), Manchester Business School,
University of Manchester, Harold Hankins Building, Manchester, Booth Street West,
Manchester M13 9PL, UK
e-mail: mercedes.bleda@mbs.ac.uk

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3.1 Introduction

The world faces pressing challenges arising from the energy sector, including the provision of increased quantities of affordable energy needed to meet economic aspirations, limiting the economic vulnerabilities of oil dependence and reducing CO_2 emissions from fossil-fuel burning. Improving energy-supply technologies in general and renewable energy technologies in particular is a prerequisite for surmounting these challenges in a timely and cost-effective way. It is now widely acknowledged or recognised that technological advance has the potential to significantly decrease the costs of attaining societal goals such as climate change mitigation (Newell 2010).

The criterion of dynamic efficiency is central to the assessment and choice of environmental and energy policies in long-run horizons where innovation lock-in is relevant. This is also the case with instruments that support electricity from renewable energy sources (RES-E). Dynamic efficiency is understood as the capacity of a policy instrument to induce a continuous incentive for technological improvements and cost reductions in existing renewable energy technologies, facilitate the advancement of emerging technologies along the technological change pipeline and promote the diffusion of renewable energy technologies with different maturity levels.

In contrast to effectiveness and static efficiency assessment criteria, the innovation effects of this support have received much less attention from both a theoretical and an empirical perspective. Several theoretical perspectives have paid some attention to these innovation effects, including the traditional economics approach, the systems of innovation perspective and the literature on learning effects. The aims of this chapter are to provide an overview of those perspectives and to build bridges between them.

The dynamic efficiency of environmental policy instruments in general, and RES-E support schemes in particular, is a very relevant topic. Kneese and Schulze (1975) pointed out early that, besides the issue of static efficiency, the extent to which policy instruments spur new technology towards the efficient conservation of the environment is one of the most important criteria on which to judge the performance of environmental policy instruments (Requate 2005).[1]

The relative importance of the dynamic effects of alternative policy instruments on technological change (and hence long-term compliance costs) is greater in environmental problems which are of great magnitude and/or have very long time horizons. Hence, the increased attention given by scholars and policymakers to

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[1] However, some authors are doubtful about the relative importance of dynamic efficiency criteria compared with more traditional, static efficiency criteria. For example, Parry et al. (2003) stress that the welfare gain from innovation is sometimes not much greater than the welfare gain of efficiently abating pollutants by means of conventional technologies. Requate (2005) observes that resources to engage in R&D are scarce. Hence, environmental technological progress may crowd out other strands of welfare enhancing technological progress. Finally, Fischer and Newell (2008) argue that the underlying process of technological change turns out to be far less important than the incentives to use technology efficiently to reduce emissions.

the problem of global climate change has greatly increased the prominence of the dynamic efficiency of environmental and energy policy instruments, including RES-E support schemes (Jaffe et al. 2002). Given the ambitious targets in the RES realm everywhere (EU, USA and China), a great deal of focus has been placed on the role of innovation in lowering the costs of these non-emitting energy sources (Fischer and Newell 2008).

RES-E support schemes refer to policies aimed at encouraging the diffusion of renewable electricity technologies. Three main types of RES-E support schemes are usually considered: feed-in tariffs, quotas with tradable green certificates (TGCs) and tendering/bidding procedures. These are usually complemented with secondary instruments, including investment subsidies and fiscal incentives (del Río and Gual 2004).

3.2 Theoretical Approaches to Analysis of Innovation Effects of RES-E Support

The innovation effects of RES-E support can be analysed from several perspectives.

3.2.1 The Traditional Economics Perspective[2]

Several theoretical approaches, including mainstream environmental economics, are based on the linear model of innovation which states that technologies go through sequential stages without major interactions between them. In the environmental economics literature (Jaffe et al. 2002; Requate 2005; del Río 2009), innovation is regarded as a *black box*—into which R&D inputs flow and out of which commercial technologies diffuse into the marketplace—to the detriment of the intermediary role for supply and demand interactions (Taylor 2008). The effects on the different stages of innovation are analysed separately, disregarding the interactions between stages (Popp 2010). Assuming perfect economic rationality, decisions are based on microeconomic optimisation behaviour, triggered by price changes. The treatment of technological change is either exogenous or assumed to respond automatically to changes in relative prices as a result of exogenous developments (such as environmental or energy policies).

In turn, embracing the linear model of innovation involves the recommendation of policies based on R&D and commercialisation strategies, seeing the problem essentially in terms of a low level of R&D or carbon prices in the energy sector.

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[2] Following Marechal (2007), we use the word *traditional* to avoid the problems arising from the somewhat ambiguous use of the term *neoclassical*. *Traditional economics* refers to the Walrasian model of welfare economics, which can be defined as the theoretical synthesis of the Marshallian approach with marginal production theory (Marechal 2007).

It is assumed that technologies, once created, are optimally deployed in response to whatever policy incentives may or may not be in place (Popp 2010). The main argument derives from the theory of induced innovation (Hicks 1932): changing relative prices induce innovations. Since the hypothesis is that the rate and direction of innovation are likely to respond to changes in relative prices, changing costs for energy use (e.g. through the implementation of environmental or energy policies) are assumed to lead to incentives for future inventions and innovations (Jaffe et al. 2002; Walz and Schleich 2009; Requate 2005).

Contributions within this tradition normally analyse the cost-efficiency of RES-E deployment and support instruments by comparing them with CO_2 mitigation instruments (Palmer and Burtraw 2005; Fischer and Newell 2008). Indeed, there is a tendency in this literature to undermine the relevance of RES-E support schemes. The existence of a double externality is acknowledged: an environmental and a technological one. The former is internalised through a CO_2 price and the latter through public R&D support (Newell 2008; Jaffe et al. 2005). No RES-E policy is as cost-effective as a cap-and-trade policy for achieving carbon emission reductions (Palmer and Burtraw 2005; Fischer and Newell 2008). However, the time horizon considered is usually too short, and the mitigation targets are modest. This plays against capital-intensive technologies (with a large cost-reduction potential), such as renewables (IEA 2008). The framework adopted is usually static, disregarding dynamics and the interdependencies between institutions, actors and technologies in complex systems leading to inertia and lock-in. Furthermore, competitive pressure is regarded as the main (or exclusive) mechanism to reduce the costs of technologies, disregarding other dimensions of dynamic efficiency such as diversity. Generally, *technology-neutral* instruments are advocated.

3.2.2 The Systems of Innovation Perspective

The systems of innovation (SI) approach (Carlsson et al. 2002) stresses that innovations are not developed and implemented in isolation but within a technological and sociocultural context. It focuses on the importance and interdependencies of actors, networks, institutions, cumulative learning processes and spatial and technological characteristics (Edquist 2005). It adopts a holistic perspective and considers phenomena such as path dependency, lock-in, interdependence, nonlinearity and co-evolution (Edquist 2005; Markard and Truffer 2008). This approach can reveal how innovation occurs in relation to particular technologies, industrial sectors and specific national contexts, what system failures may be occurring and how innovation may be influenced by incentives and policies (Foxon and Andersen 2009).

Following Unruh (2000, p. 819), technological systems are defined as “interrelated components connected in a network or infrastructure that includes physical, social and informational elements”. An innovation system consists of three elements (Malerba 2004; Woolthuis et al. 2005): technology and related knowledge and skills, networks of actors and institutions. Networks of actors develop and implement new knowledge and technology within their institutional context. For an innovation system to be successful in developing and implementing technologies, these three building blocks, which co-evolve in time, need to be aligned.

This approach has already been applied to analyse renewable energy systems (Astrand and Neij 2006; Jacobsson and Bergek 2004; Foxon et al. 2005; Jacobsson 2008; Walz and Schleich 2009, among others). These papers stress that a shift towards renewable energy technology systems is a complex process which involves changes in the aforementioned elements of an innovation system. They identify the system failures related to the development, commercialisation and diffusion of renewable energy technologies.

This perspective tries to cope with some of the drawbacks of the conventional perspective which has been much criticised for its conceptualisation of technological change. The systemic approach provides corrections to this criticism and suggests policy implications that are different from (although not necessarily contradictory to) those derived from the conventional approach:

- Feedback between stages. In particular, innovation and diffusion are not sequential phases, but learning and future innovations depend on experiences made during market diffusion. That is, the creation of a market for renewable technologies feeds back into investments in R&D**.**
- Path dependency and lock-in. One drawback of studies based on environmental economics is the fact that they do not look at system changes and interdependencies, although such system changes are necessary to reach long-term emission reduction goals (Rogge and Hoffmann 2010). In contrast, the systemic perspective acknowledges that barriers to renewable energy are systemic (also termed system failures; see Nill and Kemp 2009). These systemic barriers lead to lock-in through a path-dependent process driven by technological and institutional internal returns to scale.

Technologies are not only linked to other technologies but are also interrelated with the cultural and institutional aspects of their environment (Marechal 2007). *Carbon lock-in* has been used to denominate the persistent dominance of high-carbon technologies (in spite of the existence of low-carbon ones).[3] Unruh (2000, p. 817) defines carbon lock-in as the “interlocking technological, institutional and social forces that can create policy inertia towards the mitigation of global climate change”. This lock-in occurs through a “path-dependent process driven by technological and institutional increasing returns to scale”. Dynamic economies of scale and learning effects are a major source of lock-in. R&D investments and diffusion

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[3] A stream of the economic literature on climate change mitigation has applied an evolutionary approach with the aim of emphasising the inertia in current technological systems (Kemp 1996; Unruh 2000, 2002; Marechal 2007; del Río and Unruh 2007; Rip and Kemp 1998; Foxon et al. 2005).

provide a source of improvement and cost reductions for existing technologies. The later effect takes place because diffusion allows technologies to benefit from learning effects and dynamic economies of scale. Emerging, more expensive, technologies may fall into a vicious circle: they are not adopted because they are too expensive, and they are too expensive because they are not adopted.

Barriers to technological change are multifaceted, and the price factor is only one of the factors affecting technological changes. Technological change is endogenous to an economic system in which there are both inducement and blocking mechanisms. Changes in relative prices are only one of the inducement mechanisms. In addition to demand and technology factors, this approach underlines the importance of several factors (characteristics of innovation, actors, networks and institutions, including regulations) (Suurs and Hekkert 2009). These factors influence each other, highlighting the importance of feedback mechanisms and cumulative causation processes. Therefore, price signals are necessary albeit not sufficient to encourage innovation in new technological systems.

The implication for RES-E policy is that the inducement mechanisms need to be strong enough to overcome these interrelated barriers to RES-E and set a process of cumulative causation in motion that works in favour of the new technology.

Lately, the SI approach has been further developed following several avenues, namely, by trying to integrate it with the multilevel approach of technological transitions (Geels and Schot 2007), as done by Markard and Truffer (2008), and by identifying the functions of an innovation system (Hekkert and Negro 2009; Bergek et al. 2008).[4] With regard to this last point, different innovation systems can be assessed and compared in terms of the functions they fulfil in order to derive policy recommendations to support the development of a specific technology (Hekkert et al. 2007; Negro et al. 2007). Functions are emergent properties of the interplay between actors and institutions (Markard and Truffer 2008). The function approach identifies those properties in a technological innovation system that are needed in order to introduce sustainable energy technologies successfully (Hekkert and Negro 2009).

Cumulative causation suggests that system functions may reinforce each other over time, thereby resulting in a virtuous cycle (Hekkert et al. 2007; Jacobsson and Bergek 2004). The diffusion of renewable energy technologies into the incumbent energy system requires virtuous circles to be established between the different functions (Suurs and Hekkert 2009; Hekkert and Negro 2009). Similarly, Jacobsson and Johnson (2000) argue that there are three central issues for the emergence of a new technological system based on renewable energy technologies: variety in the knowledge base increased by experimentation, institutional change aligned to the needs of renewable energy technology and the emergence of strong actors who can promote the new technology.

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[4] Assessment in terms of system functions is one of the main approaches of the systems of innovation literature. Other innovation system studies have placed more emphasis on structural analyses (Carlsson et al. 2002; Jacobsson and Johnson 2000). Currently, some authors are concentrating on the integration of both approaches (Markard and Truffer 2008).

Such interactions may take place in a niche which can be created by public policy through, for example, RES-E support instruments. Niches allow technologies to progress and create a supportive institutional environment around it. Once they do so, technologies become a *technological regime*, as is the case for wind energy in many European countries. The SI approach points to the importance of policy interventions that support all system elements—technology and cost development as well as actor involvement—for introduction and deployment of renewable energy technologies.

The coalition of forces/actors and the cumulative causation process have not been stressed by the traditional approach but both are particularly relevant in the RES-E support realm. Although actors are embedded in an institutional context, they may also deliberately change or adapt existing institutions or create new ones (Edquist and Johnson 1997). Radical innovations are often promoted by actor networks that show little overlap with prevailing actor structures in a sector or technological field (Markard and Truffer 2008). In turn, once a coalition of forces has been formed, it is likely to organise the lobbying of changes in public support, which feeds back into the deployment of the technology. For example, wind power actors, together with biogas stakeholders, have been shown to lobby in favour of better feed-in payment conditions for renewable energy technologies (Markard et al. 2009). A coalition of forces results from the sequential interaction between support, market creation, stages of technological change and actors (Markard et al. 2009).[5]

The forming of markets is therefore a necessary requirement for setting a learning process in motion. Stimulating RES-E will create virtuous cycles between actors and stages of technological change, providing further investment opportunities and expanding the market for key technologies (Lee et al. 2009). This suggests the importance of implementing policies that result in cumulative causation processes leading to an effective deployment of RES-E in a long-term perspective.

Only public policy may break lock-in. However, not all policies are equally useful in encouraging the emergence of new technologies. The systems of innovation approach stresses the difficulties that a new technology, such as renewables, faces when penetrating a market and competing with a dominant technology which has benefited from economies of scale and learning effects and from the adaptation of the institutional environment to the existing technology. In order for renewable energy technologies to develop, the forces of inertia that prevail in the incumbent energy system have to be broken. We argue that different RES-E support instruments and design elements can exert significant influences on the direction of technological development a technological system takes.

Nevertheless, since the systemic perspective emphasises the wide array of barriers to RES-E, it suggests that deployment policies are only one of the factors (although a crucial one) that encourage RES-E. When this perspective has been

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[5] For example, in his analysis of wind energy deployment and policy in Denmark, Spain and Sweden, Meyer (2007) provides empirical evidence of the role of the coalition of forces in encouraging wind energy in Spain.

applied to RES-E support, several barriers have been shown to constrain RES-E.[6] Given the complexity of stages and drivers influencing technological change, it is unlikely that a single policy instrument would be sufficient to trigger major technological changes. Smits and Kuhlmann (2004) argue that system innovation processes require *systemic instruments*, that is, those that support system functions. Since RES-E support instruments cannot tackle all functions, they are not systemic instruments, although they can be made part of systemic policy packages.

In spite of the usefulness of this approach, there is a relative paucity of studies using it. Walz and Schleich (2009) review the empirical literature on RES-E support schemes and conclude that "these studies, by and large, do not analyse the effects on innovation within an integrated systems of innovation view".

3.2.3 The Literature on Learning Effects

A recent albeit abundant literature has stressed the role of learning effects in reducing the costs of technologies in general and renewable energy technologies in particular. However, this literature is not isolated from what was mentioned above since many energy-economy models that incorporate induced technological change include some learning effects and the literature on systems of innovation stresses the importance of these effects.

The specialised literature on learning emphasises two main components of technical change and energy costs: cumulative research, development and demonstration (RD&D) and cumulative installed capacity or learning-by-doing (see Sagar and van der Zwaan 2006; IEA 2008; Kahouli-Brahmi 2008). Whereas certain components of cost improve with R&D investment, others are likely to respond to increased deployment of the technology (Nemet and Baker 2010).

Learning assumes that a technology's performance improves as experience with the technology accumulates. Learning is an aggregate term that may involve a number of different mechanisms that all contribute to cost reduction over time when producing and deploying new technologies. This chapter focuses on those learning effects that are dynamic and have direct innovation effects:

- *Learning-by-doing* (Arrow 1962) refers to the repetitious manufacturing of a product leads to improvements in the production process.
- *Learning-by-using* (Rosenberg 1982) refers to improvements in the technologies as a result of feedback from user experiences of the innovation process.
- *Learning-by-interacting* (Lundvall and Johnson 1994) takes place as a result of network interactions between actors.

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[6] The assessment of Astrand and Neij (2006) shows that early inflexible steering of technology and market development, together with a lack of comprehensive, long-term strategy, lack of continuity in policy interventions and weak combinations of policy programmes and measures, have contributed to very limited wind power development in Sweden.

Often, combinations of these factors occur in each stage of the market diffusion process and the contribution of each changes over time. The importance of those learning effects varies along the technological change pipeline and for different technologies.[7] In turn, each cost element (material costs, process costs and overhead costs) is affected by different mechanisms as empirically shown by Kalowekamo and Baker (2009).

Cost reductions have been assessed through learning curves.[8] In learning curves, the experience gained with a certain technology is expressed as a learning rate (percentage at which the unit cost decreases with every doubling of cumulative installed production).[9]

These learning effects have been incorporated into energy-economy models (Kahouli-Brahmi 2008). A key message from these models is that policy needs explicitly to consider the learning potential associated with investments and accelerate abatement in order to induce cost reductions. Endogenisation of technological learning induces early investments in initially expensive technologies since future revenues offset the short-run additional investments (Kahouli-Brahmi 2008).

The extent to which instruments and design elements are able to encourage those learning effects is a main aspect of RES-E support. Obviously, learning effects only take place when deployment is increased, suggesting that there is a clear synergy between the effectiveness of a RES-E support instrument and learning effects. For socio-technical systems like the wind power system, where an important barrier to market introduction and expansion is high investment costs, policy instruments should support and accelerate the learning process (Astrand and Neij 2006).

3.3 Combining Different Perspectives: Points of Complementarity and Conflict

All of the approaches have their limitations, and all are approximations that miss some important phenomena underlying the complex nature of technological change, with important effects on the results of RES-E policy. For example, although the traditional economics perspective provides the seminal economic theory for the analysis of the innovation effects of environmental regulation, the approach disregards fundamental system changes and technology-related

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[7] For example, Junginger et al. (2006) show that for technologies developed on a local level (e.g. biogas plants), learning-by-using and learning-by-interacting are important learning mechanisms whereas for CHP plants utilising fluidised bed boilers, upscaling is probably one of the main mechanisms behind cost reductions. Nemet and Baker (2010) show that certain components of the costs of solar PV improved with R&D investment, whereas others responded to increased deployment of the technology.

[8] Some authors have stressed the difficulties in building learning curves for some renewable energy technologies (Junginger et al. 2006) or criticised the learning curve model itself (Kahouli-Brahmi 2008).

[9] For a recent analysis of (observed) learning rates for various electricity supply technologies, see IEA (2008) and Kahouli-Brahmi (2008), among others.

interdependencies that are necessary to reach long-term emission reduction goals (Rogge and Hoffmann 2010). The energy-related SI studies do not analyse the specific impact of environmental regulations on the innovation system; they downplay the role of competition as a source of cost reductions and technological improvements and have sometimes been criticised for not generating sufficient practical policy advice (Bergek et al. 2008; Rogge and Hoffmann 2010; Woolthuis et al. 2005). We therefore regard the aforementioned perspectives as complementary in the analysis of the dynamic efficiency of RES-E support schemes. Therefore, they should be combined in order to include all the relevant innovation effects resulting from RES-E promotion.

Thus, a combined framework may offer benefits that, for the task of analysing dynamic efficiency, go beyond the merits of each approach. In this section, we sketch the main foundations of such integration which should be improved and fully detailed in future research. Our aim is to briefly summarise a number of conceptual issues a combined framework should strive to address and the links and bridges between the different outlined approaches.

In particular, a combined approach will be highly beneficial if it meets some or all of the aspects identified as shortcomings in one of the frameworks. In order not to become overly complex or create overlaps, this framework should clarify the relevance, need and application domain of each of its conceptual elements (Markard and Truffer 2008). The integration is spurred on by two interrelated requirements: the need to broaden analytical perspectives in order to take all the relevant dimensions of dynamic efficiency into account and the need to provide lessons to promote RES-E in a dynamically efficient manner by considering those dimensions. We believe that bridges could be built between the approaches.[10] Other authors have also called for a broadening of the analytical framing regarding the set of considerations used to explain the emergence and success of innovation (Walz and Schleich 2009).

Of course, major points of disagreement exist between those approaches, but two are worth highlighting: (1) technological diversity vs. technological competition and (2) linear vs. systemic perspective of (renewable) technological change. While the conventional approach emphasises competition between technologies, the systems of innovation approach stresses the relevance of the diversity of innovations, learning effects from deployment and feedbacks from deployment to R&D. The systemic approach suggests that significant feedback loops between stages, actors and key variables may exist and that cumulative causation is crucial. In contrast, competition between innovators as a source of cost reductions and improvements in the technologies has been downplayed by the systems of innovation approach in the analysis of the barriers to RES-E deployment. While some insights or hypotheses from the traditional approach are compatible with the systemic approach (i.e. technological competition), others are certainly incompatible (i.e. the linear approach to technological change).

We propose that this integration be built on a systems of innovation approach since it provides a broader and richer picture of the innovation process in renewable

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[10] The literature seems to be too polarised in this respect, with theoretical and empirical studies following either one or the other approach. Exceptions are Rogge and Hoffmann (2010) and Walz and Schleich (2009).

energy than the conventional environmental economics approach and, thus, offers a guiding heuristic on how the RES-E support policies may influence this process.

The systemic approach could easily integrate the insights from the learning literature (all learning effects). Indeed, bridges between them are inherent and/or have been explicitly built. Innovation and learning are typically activities that take place in systems (Lundvall 1992). Technological learning can be regarded as the process in which actors acquire knowledge in order to improve the performance of the technological system (Smits and Kuhlmann 2004). As Smits and Kuhlmann (2004) point out, an innovation system covers the actors who produce knowledge on the supply side, the actors who implement innovation on the demand side, as well as the actors who link supply and demand plus the actors who support the entire system. To pinpoint what is going on in the technological system, we need to describe the learning processes for all these actors precisely as well as the interaction between these learning processes.

Learning effects show two explicit points of connection with the SI approach: the interrelationships between stages and the interactions between the institutional and the technological realms.[11]

With regard to the former, Sagar and van der Zwaan (2006) note that the different forms of learning often also feedback into the technology R&D process, leading to improved technologies and products in the future. Whereas typically R&D precedes deployment, it may be advantageous to undertake them simultaneously or iteratively, so as to exploit the possible interaction between them (Sagar and van der Zwaan 2006).

As far as the second point is concerned, the presumption is that each element in the innovation system (the technology, the actors, the institutions and the cost of technology) needs to be part of the development and deployment process which could be characterised as a learning process. The learning process is essential for all elements of the system (Astrand and Neij 2006).

Learning may lead to systemic improvements, an example of which would be the institutional evolution that allows the lowering of costs in projects in which new technologies are used (Sagar and van der Zwaan 2006). This suggests a relationship between learning, R&D and institutional changes, with feedback loops between them.[12]

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[11] Indeed, learning effects introduce nonlinearities and positive feedbacks into the models in which they are used (the more a technology is used, the greater the incentive for using it more) (McDonald and Schrattenholzer 2001).

[12] Watanabe et al. (2000) convincingly showed that the political environment behind Japanese government support for PV innovation was critical in developing the interindustry partnerships basic public research and broad-based market promotion for this fledging industry which in turn led to and was a result of learning effects. The authors analysed the Japanese solar PV Sunshine Project which aimed to encourage the broad involvement of cross-sectoral industry, stimulate inter-technology stimulation and cross-sectoral technology spillover and induce vigorous industry investment in PV R&D, leading to an increase in industry's PV technology knowledge stock. They showed that an increase in this technology knowledge stock contributed to a dramatic increase in solar cell production. These increases led to a dramatic decrease in solar cell production price, and this decrease induced a further increase in solar cell production. An increase in solar cell production induced further PV R&D, thus creating a "virtuous cycle" between R&D, market growth, learning effects and price reduction.

Learning-by-interacting establishes an explicit link between learning and the systems approach. Smit et al. (2007) show that learning-by-interacting is crucial to achieving the necessary binding elements in the technology-specific innovation system. During the diffusion of the technology, the network interactions between actors such as research institutes, industry, end users and policymakers generally improve (Lundvall 1988; Junginger et al. 2006). The relationship between diffusion and learning goes in both directions: while learning-by-interacting allows the firm to benefit from external sources of learning and is greatly associated with the increasing diffusion of technology (Kahouli-Brahmi 2008), the interactions between the various actors including the research laboratories, the industry, the end users and the political decision-makers enhance the diffusion of knowledge (Lundvall 1988).

Since learning-by-interacting can take place intentionally via collaboration or through the creation of niches, there is a role for public policy in stimulating the interaction between different actors. The actors from the industrial part of the technological system should get better access to actors in academia and other actors (Smit et al. 2007).[13] Astrand and Neij (2006) empirically showed how the introduction of subsidies in the early 1990s in Sweden increased the diversity of actors involved in the development process of wind turbines and how the involvement of additional actors improved the learning in using wind turbines. The literature on *Strategic Niche Management* has also argued that whether or not a change of technological regime comes about depends, among other factors, on the occurrence of learning processes within protected spaces (or niches). Through experimentation and learning in niches (and/or between the niches and regime level), innovative ideas and technologies may *mature* and become better suited to change or replace the until then dominant regime (Van Mierlo et al. 2010).

Nevertheless, consideration of learning effects does not involve the adoption of an SI approach, although every systemic approach has to include those effects. For example, although some energy-economy models now incorporate a form of learning processes with increasing returns (see Köhler et al. 2006), they do not include the main features of the SI approach, namely, systemic interdependencies, heterogeneity of agents (as a result of bounded rationality) and historical contingencies (Marechal 2007).

Regarding the link between Sections 3.2.1 and 3.2.3, learning effects can be regarded as a market failure in the sense of the traditional approach. As argued by Jaffe et al. (2002), the presence of increasing returns in the form of learning effects suggests that market outcomes for technologies exhibiting these features may be inefficient.

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[13] For example, in the analysis of the Dutch wind-offshore sector, Smit et al. (2007) argued that there was weak learning-by-interacting by the actors from the industrial part of the technology system, who should get better access to actors in academia and actors in the oil and gas industry. The authors showed that there were several barriers hindering this interaction process. In contrast, they also showed that in the Danish case, learning-by-interacting occurred between knowledge institutes, component suppliers, project operators and turbine manufacturers and Danish policies contributed to the formation of these interactions.

However, the combination of Sections 3.2.1 and 3.2.2 is more difficult although the systems approach, and the traditional approach may be compatible on different time frames. As argued by Faber and Frenken (2009), the policy implications that can be drawn from innovation system studies are more long term and, consequently, often rather impressionistic. As such, insights from these studies are complementary to neoclassical policy insights that apply well to well-defined, short-term problems.

Regarding the combination between Sections 3.2.2 and 3.2.3, Grübler et al. (1999) already noted that, since technological learning is a classical example of increasing returns (i.e. the more learning takes place, the better a technology's performance), the mathematical solutions are non-convex (the more investment, the lower the costs), which would be especially difficult to handle in traditional optimisation models and algorithms. However, the modelling literature on endogenous technical change related to low-carbon technologies has proved that learning effects can be introduced in traditional models without much friction (see Edenhofer et al. 2009). The insights of the conventional approach (notably, the dynamic efficiency resulting from technological competition) may/should be incorporated into a broader integrated conceptual framework. This links to the literature on RES-E support schemes which has traditionally stressed the relevance of competition between actors, particularly between equipment suppliers and RES-E generators leading to cost reductions in the technologies. This vision of dynamic efficiency is useful, although certainly not sufficient, and should be included in the integrated approach. This vision has been understated in the SI approach. This add-on is certainly not incompatible with the SI approach. Competition between those actors would be an aspect of the broader relationship between different elements of the innovation system and between those actors, institutions and RES-E support policy in particular.

3.4 Conclusions

Technological change is a complex process with different stages and barriers and drivers for each stage. The sources of technological change are also diverse, and there are several strands of thought regarding the determinants of innovative activity. Thus, the analysis of the capacity of RES-E support instruments to encourage technological changes should take this diversity into account. The dynamic efficiency of RES-E support instruments can indeed be analysed with several perspectives. This suggests that several dynamic factors are at play, that dynamic efficiency is in fact a multilayered criterion and that those different layers should be made explicit (Verbruggen 2009).

This chapter has discussed relevant approaches to the analysis of the dynamic efficiency of environmental and energy instruments and, particularly, RES-E support schemes. It has aimed to provide the first steps of an integration of approaches by building bridges between them. This is deemed highly useful in order to structure the realisation of empirical studies on the dynamic efficiency of RES-E support. An obvious avenue for further research is therefore advance in the integration of approaches. Furthermore, the few case studies that deal with energy issues with a systems of innovation approach have not analysed the implications of different RES-E support instruments and different design elements. This lack of consideration of the design elements is also a limitation of the conventional environmental economics approach. There is therefore a clear need to integrate research on the specific effects of RES-E design into a wider system of innovation approach (Walz and Schleich 2009). Therefore, a comparative analysis of different RES-E support schemes according to the complementary dimensions derived from those approaches is worth undertaking.

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