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A coevolutionary framework for analysing a transition to a sustainable low carbon economy

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Contents

Abstract

In order to address the challenge of promoting a transition to a sustainable and equitable low carbon economy, useful frameworks are needed for analysing the dynamic interactions of social and technological elements. This paper proposes a coevolutionary framework for analysing a transition to a low-carbon economy, based on the coevolution of technologies, institutions, business strategies and user practices, within a multi-level micro-meso-macro framework. This builds on and develops previous approaches to analysing long-term industrial change, that combine evolutionary understanding of how the dynamics of a system arises through processes of variation, selection and retention, with a causal account of interactions between systems, as well as on recent renewed interest within ecological economics on coevolutionary approaches.

Coevolutionary arguments have provided explanations of how significant features of current socio-economic systems have arisen: (1) how the coevolution of technologies and institutions has led to the lock-in of current high-carbon technological systems; (2) how the coevolution of physical and social technologies and business strategies has brought significant material and welfare benefits to the minority of the world's population living in industrialised countries. This paper seeks to show how a coevolutionary perspective is useful for examining how more sustainable low-carbon development could overcome this lock-in and ensure that everyone attains an acceptable level of welfare, whilst remaining within the earth's biophysical limits.

The paper argues that this approach provides a useful framework within which different types of analysis may be conducted: (1) detailed empirical analyses at a micro-meso level of the challenges relating to the innovation and adoption of particularly low-carbon technologies; (2) as a framework for analysing the multi-level interaction of social and technological elements within potential transition pathways to a low carbon energy system; (3) to assess the implications for economic growth of a transition to a low carbon economy; and (4) to assist in the development of more formal, multi-level evolutionary economic models.

Key words: coevolution, transition pathways, low-carbon economy, long-term industrial change.

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About the Author

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1 Introduction

This paper develops a coevolutionary framework for analysing a transition to a sustainable low carbon economy. Kallis and Norgaard (2010) have recently proposed that coevolutionary thinking provides a relevant and useful approach for analysing a range of critical issues in ecological economics. They argue that coevolution provides a framework for analysing the mutual causal influences between systems, which can help to overcome debates about the relative causal efficacy of different natural and social factors, and can elucidate the roles of structure and agency in changing practices. Furthermore, they contend that a coevolutionary approach naturally provides bridges between the traditional concerns of ecological economics and other intellectual streams, which can provide rich and complementary insights. Our framework exemplifies this in relation to one key challenge, that of overcoming lock-in to unsustainable high carbon systems of production and consumption, by incorporating ideas from recent thinking on socio-technical transitions, innovation systems and industrial dynamics, and evolutionary economics. We argue that a useful coevolutionary framework to address this challenge needs to incorporate the coevolution of technologies, institutions, business strategies and social practices, within a multi-level micro-meso-macro framework.

A transition to a sustainable low carbon economy will require innovation and deployment of a range of low carbon technologies for delivering energy and other services for individuals, communities and businesses, and broader change in the mix of industries for maintaining and widening economic prosperity whilst remaining within ecological limits. Analysing how a low carbon transition might occur could therefore usefully draw on advances in understanding of the processes of technological and industrial change. Evolutionary theories of innovation systems and industrial dynamics have examined how the wider social and systemic context influences these processes of change (Lundvall, 1992; Nelson, 1993; Freeman and Soete, 1997; Edquist, 2005). Recently, a multi-level perspective for understanding socio-technical transitions has been developed, which draws together insights from science and technology studies, evolutionary economics and sociology and institutional theory (Geels, 2002, 2005a; Grin et al., 2010). Other work, drawing on evolutionary economics and industrial dynamics, has explicitly used a coevolutionary approach to analyse the mutual causal influences between key evolving systems. Recent studies have analysed the coevolution of technologies, institutions and business strategies in relation to lock-in of high carbon energy systems (Unruh, 2000); to the historical development of the chemical dye industry in the $19^{th}/20^{th}$ centuries (Murmann, 2003); and to the success of the Western economic model in creating wealth and prosperity (at least for the minority of the world's population living in those countries) (Beinhocker, 2006). This range of approaches provides a rich set of analytical tools, but these are not always presented in a way that is accessible to non-specialists in these approaches. In this paper, we seek to develop a coevolutionary framework that draws on the richness of these approaches, whilst providing a useful and flexible framework for analysing topics of current theoretical and policy interest relating to a low carbon transition.

The paper is structured as follows. Section 2 reviews these coevolutionary strands of thinking, highlighting their strengths and weaknesses. Section 3 sets out our coevolutionary framework, based on coevolution of technologies, institutions, business strategies and user practices, within a multi-level micro-meso-macro framework. Section 4 provides examples of how the framework could be applied to current research and policy challenges in four areas: (1) detailed empirical analyses of the challenges relating to the innovation and adoption of particular low-carbon technologies; (2) as a framework for analysing the multi-level interaction of social and technological elements within potential transition pathways to a low carbon energy system; (3) to inform assessments of the implications for economic growth of a transition to a low carbon economy; and (4) to assist in the development of more formal, multi-level evolutionary economic models. Section 5 concludes by discussing strengths and weaknesses of the framework, and its relation to current challenges within ecological economics.

2 Coevolutionary strands of thinking

We start by reviewing different coevolutionary strands of thinking, highlighting their strengths and weaknesses. Coevolutionary approaches in ecological economics have largely focussed on the coevolution of social and ecological systems, whilst the multi-level perspective emphasises the role of social structural factors in socio-technical transitions. We also examine a range of evolutionary and coevolutionary approaches to understanding technological, industrial and economic change, and work suggesting that sociological and evolutionary approaches to analysing technological change are complementary.

2.1 Coevolutionary approaches in ecological economics

The papers in the recent special issue of *Ecological Economics* (Kallis and Norgaard, 2010 and following papers) and other recent papers (Kallis, 2007a,b; Norgaard and Kallis, 2010) review and explore the range of coevolutionary approaches that are being applied in ecological economics. Kallis and Norgaard (2010) identified ‘overcoming lock-in of current unsustainable systems of production and consumption’ as one of the key challenges that could be explored using a coevolutionary approach. Within ecological economics, the focus has been on the coevolution of social and ecological systems, though coevolution of these with organisations (Hodgson, 2010) and with human behaviours (Manner and Gowdy, 2010) are also being investigated. Much of this work was inspired by the seminal contribution of Norgaard (1994), who used a coevolutionary framework to analyse how the imposition of external technologies and practices in the name of ‘development’ often undermined more local systems of production and consumption that were well adapted to their local ecological settings. Norgaard’s (1994) original framework included the coevolution of environment, knowledge, organization, technologies and values, though he later argued that this basic framework could be expanded to include other types of coevolving factors (Norgaard, 2005). Norgaard and Kallis (2010) argue that there are unavoidable tensions between the specification of a particular coevolutionary framework and a broader coevolutionary logic that suggests a more widespread coevolution between multiple systems. The choice of a particular coevolutionary framework is therefore determined by its usefulness for addressing a specific ecological economic challenge.

2.2 Socio-technical transitions approach

Understanding how a transition to a sustainable, low carbon system of production and consumption could occur at local, national and global levels is a key challenge that ecological economics seeks to address. As we shall discuss in more detail below, one way of framing this challenge is to emphasise the lock-in of unsustainable, high carbon systems. An ongoing research programme on *transitions in socio-technical systems*, pioneered by Dutch researchers, has provided great insight into this challenge and generated significant international attention and interest (Geels, 2002, 2005a; Elzen et al., 2004; Smith et al., 2005; Grin et al., 2010).

The socio-technical transitions approach draws on earlier work on science and technology studies, evolutionary economics, and sociology and institutional theory. It uses a framework for analysing socio-technical transitions based on interactions between three 'levels': *technological niches, socio-technical regimes,* and *landscapes* (Geels, 2002). The *landscape* (macro) level represents the broader political, social and cultural values and institutions that form the deep structural relationships of a society and only change slowly. The *socio-technical regime* (meso level) reflects the prevailing set of routines or practices used by actors, which create and reinforce a particular technological system, including "engineering practices; production process technologies; product characteristics, skills and procedures […] all of them embedded in institutions and infrastructures" (Rip and Kemp, 1998). Whereas the existing regime generates incremental innovation, radical innovations are generated in micro-level *niches*, which are spaces that are at least partially insulated from 'normal' selection processes in the regime, for example, specialised sectors or market locations. Niches provide places for learning processes to occur, and space to build up the social networks that support innovations, such as supply chains and user-producer relationships. *Transition pathways* arise through the dynamic interaction of technological and social factors at these different levels.

Research under the transitions approach has developed along three main lines. Firstly, the multi-level perspective is used as a framework within which *the historical dynamics of transitions* may be analysed**.** Examples include analysis of transitions from sailing ships to steam ships (Geels, 2002); systemic changes in the Dutch electricity system (Verbong and Geels, 2007); from horse-drawn to automobile transport systems (Geels, 2005b); from cesspools to sewer systems (Geels, 2006); and biogas development in Denmark (Geels and Raven, 2007). Secondly, the transitions approach has been used as a basis for developing *'transition management'*. This is a process of governance seeking to steer or modulate the dynamics of transitions through interactive, iterative processes between networks of stakeholders. This involves creating shared visions and goals, mobilizing change through transition experiments, and learning and evaluation of the relative success of these experiments (Kemp and Rotmans, 2005; Loorbach, 2007). Transition management is thus seen as a form of participatory policy-making based on complex systems thinking. A key element of this process is the creation of a 'transition arena', in which a relatively small group of innovation-oriented stakeholders can come together to engage in a process of social learning about future possibilities and opportunities (Loorbach, 2007). The third strand of research has been the use of the multi-level perspective as the basis for developing *socio-technical scenarios*, which seek to explore the potential future development of socio-technical systems through interactions between ongoing processes at the three levels (Elzen et al., 2004; Hofman et al., 2004).

The transitions approach has been described as a coevolutionary approach (Geels, 2005a), but uses a more sociological language in which “the emergence of new innovations can be analysed as a co-construction or alignment process, gradually linking heterogeneous elements together into a working configuration” (Geels, 2005a, p.61). In other words, rather than using the evolutionary concepts of variation, retention and selection, the transitions approach uses the sociological concept of alignment between different or heterogeneous elements. As described below, we follow MacKenzie (1992) in arguing that these provide different but complementary languages for expressing closely related ideas. However, the transitions approach has been criticised for providing overly structural explanations, which do not provide significant roles for the choices of actors (Smith et al., 2005). These would include individual user choice, the development of business strategies, and the role of governments. We would also argue that the transitions approach gives relatively little emphasis to economic factors, such as investment and relative prices, in influencing socio-technical change. Hence, we suggest that the socio-technical transitions approach could be usefully complemented by other strands of research with an explicit evolutionary framing.

2.3 Evolutionary approaches to technological, industrial and economic change

Evolutionary approaches to understanding technological change have emphasised both the path dependent nature of such change (Basalla, 1988; Ziman, 2000), and the role that technological change has played in contributing to economic development (Rosenberg, 1982; Mokyr, 1990). They argue that industrial innovation is constrained by shared assumptions and decisions rules, so that change follows ‘technological trajectories’ within ‘technological paradigms’ (Nelson and Winter, 1982; Dosi, 1982). These approaches emphasise that technologies evolve within particularly social and economic contexts, which are in turn shaped by the technologies that are produced and used, leading to a process of technological evolution that is *uncertain, dynamic, systemic* and *cumulative* (Grübler, 1998). Innovation systems theory provides an evolutionary-based understanding of systems and processes relating to the innovation and adoption of new technologies and modes of organisation (Edquist, 2005). This argues that firms and entrepreneurs innovate largely in response to drivers and barriers coming from the wider innovation system, including networks with other firms and suppliers and policy and regulatory frameworks (Jacobsson and Bergek, 2004; Foxon et al., 2005; Hekkert et al., 2007). It has been suggested that the technological innovation systems approach is complementary to the multi-level transitions perspective (Markard and Truffer, 2008).

Evolutionary theories of economic change reject the neo-classical economic assumptions of perfect rationality of actors and (quasi-) equilibrium analysis, and argue that actors have bounded rationality and that industrial change occurs through waves of ‘creative destruction’ (Schumpeter, 1934; Nelson and Winter, 1982). This implies that actors, both individuals and firms, are limited in their ability to gather and process information relevant to economic decisions, and so act under conditions of uncertainty within a given institutional context. Rather than being profit-maximising, firms follow routines that ‘satisfice’ rather than optimise, i.e. that give rise to satisfactory levels of profit or performance and are only changed when outcomes are no longer satisfactory, due to internal or external changes (Nelson and Winter, 1982). Structuralist-evolutionary approaches have examined the economic importance of general purpose technologies, such as steam engine, electricity and information technology, that eventually come to be widely used, to have many uses, and to have many spillover effects (Lipsey et al., 2005). Related long-wave theories have identified five waves of techno-economic development over the last 250 years, driven by key technological innovations, but also requiring significant institutional changes for the benefits of the new technology to be realised (Perez, 2002; Freeman and Louca, 2005). The role of institutions (social rule systems) in economic development has been emphasised by institutional economists (North, 1990, 2003).

Evolutionary ideas have only recently begun to be incorporated into ecological and environmental economics (van den Bergh, 2006). Six basic concepts have been identified for the application of evolutionary economic thinking to environmental policy: *bounded rationality, diversity, innovation, selection, path dependency and lock-in,* and *coevolution* (van den Bergh et al., 2006). The role of institutions in providing incentives or barriers to particular types of environmental behaviour has long been an important part of ecological economics (Vatn, 2005; Paavola and Adger, 2005). Other work applying complex systems thinking has highlighted the importance of interaction of economic agents through networks and how these interactions give rise to emergent properties at higher levels (Mitchell, 2009). In this approach, economies are identified as ‘complex adaptive systems’, differing from the standard view in at least five ways (Arthur, 1999; Beinhocker, 2006):

- *dynamics*: economies are open, dynamic systems, far from equilibrium;
- *agents*: made up of heteorogeneous agents, lacking perfect foresight, but able to learn and adapt over time;
- *networks*: agents interact through various networks;
- *emergence*: macro patterns emerge from micro behaviours and interactions;
- *evolution*: evolutionary processes create novelty and growing order and complexity over time.

Within a broad evolutionary economics tradition, the understanding of business strategies has been a core focus. The resource-based view of the firm argues that sustained competitive advantage derives from the resources, assets or competencies of the firm that are valuable, rare, imperfectly imitable and not substitutable (Penrose, 1959; Barney, 1991). These competencies include the firm’s management skils, its organisational processes and routines, and the information and knowledge it controls (Barney et al., 2001). This view was extended include how ‘dynamic capabilities’ contribute to a firm’ value creation, in relation to “the firm’s ability to integrate, build and reconfigure internal and external competencies to address rapidly changing environments” (Teece et al., 1997, p.516).

Insights from behavioural economics on the bounded rationality and habitual behaviour of economic actors have recently informed ecological economic thinking (Manner and Gowdy, 2010; Marechal, 2010). An evolutionary framework for analysing institutional change based on coevolution of economic behaviour and institutions has been proposed (van den Bergh and Stagl, 2003). The wider social and cultural context of individual behaviours is also examined in sociological work on social practices, which has also recently been applied to ecological economic issues (Ropke, 2009). This builds on the work of Shove (2003), who examines the coevolution of practices, material artifacts and sociotechnical systems using a sociological rather than an evolutionary approach.

The next section will examine coevolutionary approaches that have tried to integrate some of these strands of thinking in order to better understand socio-technical or techno-economic systems change.

2.4 Coevolution of technologies, institutions and business strategies

Coevolutionary research drawing more directly on evolutionary concepts of variation, retention and selection has sought to explain processes of economic and industrial change at meso (sectoral) and macro levels. These draw their inspiration from the pioneering work developing an evolutionary theory of economic change by Nelson and Winter (1992), and the work of Chris Freeman and colleagues providing evolutionary-based explanations of innovation processes leading to dynamic changes in industrial systems (Freeman and Soete, 1997; Freeman and Louca, 2001).

A process of technological and institutional coevolution has been used to explain the state of '*carbon lock-in*' to modern carbon-based energy systems, preventing the development and take-up of alternative low-carbon technologies (Unruh, 2000, 2002, 2006; Carillo-Hermosilla, 2006; Foxon, 2007, Marechal, 2007). This arises because both technologies and institutions benefit from path-dependent increasing returns to adoption. For technologies, *scale economies, learning effects, adaptive expectations* and *network economies* mean that, the more a technology is adopted, the more likely it is to be further adopted (Arthur, 1989, 1994; David,1985). In his pioneering work on institutional change, North (1990) argued that institutions are subject to similar types of increasing returns (positive feedbacks). For socio-technical systems, these increasing returns can be mutually reinforcing, through a process of coevolution of technologies and institutions. This applies to, for example, carbon-based electricity generation systems. Here, institutional factors, driven by the desire to satisfy increasing electricity demand and a regulatory framework based on increasing competition and reducing unit prices to the consumer, create a favourable selection environment for growth of a technological system based on large-scale centralised electricity generation, leading to a process of cumulative causation, resulting in the lock-in of high carbon techno-institutional systems (Unruh, 2000). Pierson (2000) argues that political institutions are particularly prone to increasing returns, because of four factors: the central role of *collective action*; the *high density* of institutions; the possibilities for using political authority to enhance *asymmetries of power*; and the *complexity and opacity* of politics. In particular, he notes that political power accruing to particular actors can give rise to positive feedbacks, as when actors are in a position to impose rules on others, they may use this authority to generate changes in the rules (both formal institutions and public policies) so as to enhance their own power.

Freeman and Perez (1988) argued that the widespread deployment of new technologies leads to structural crises of adjustment, as new institutions and industrial structures have to be developed which are appropriate to these technologies. Kunneke (2008) has applied this concept to analyse how coevolutionary processes lead to coherence between technologies and institutions in liberalized electricity and other network industries.

Other strands of research build on the work of Richard Nelson, who applied analysis of the coevolution of technologies, industrial structures and institutions to understanding innovation systems and processes at the meso level (Nelson, 1994, 1995, 2002, 2005) and economic growth at the macro level (Nelson and Sampat, 2001; Nelson, 2005). Analyses of coevolutionary interactions between technological development, institutional change and business strategies have been used to examine the relative success of firms in different European countries in the 19th/20th Century development of the synthetic dye industry (Murmann, 2003); the role of incumbent utilities in the recent take-up of renewable energy technologies in different European countries (Stenzel and Frenzel, 2007; Foxon et al., 2010b); and the role of sustainability-driven entrepreneurs in the take-up of renewable energy technologies in the U.S. (Parrish and Foxon, 2008).

In his work on economic growth, Nelson (2005) uses a concept of institutions as 'social technologies', i.e. ways of organising or structuring human interactions. Institutions both constrain behaviour, by defining socially acceptable ways of acting, and enable behaviour, by providing agreed-on social contexts for acting, which do not need to be continuously negotiated. An institution is then "like a paved road across a swamp" – it constrains the directions you can travel, but it can enable you to get where you want to go. He argued that prevailing institutions constrain the innovation and adoption of new technologies, and that the economic benefits of new technologies are only fully realised when institutions – modes of organising work, markets, laws and forms of collective action – evolve and adapt to these new technologies (Nelson and Sampat, 2001; Nelson, 2005). Building on this work, Beinhocker (2005) argues that the coevolution of physical technologies, social technologies and business plans has driven the creation of wealth in Western industrialised countries, crucially through the development of property-right based market economies which encourage the innovation of physical and social technologies for more efficiently and effectively meeting (and creating) consumer demands.

These coevolutionary approaches greatly illuminate processes of long-term industrial and economic change. However, they have not generally been framed within an ecological economic context and have applied a more economic understanding of the role of institutions than the 'thicker' view of social relations taken within the socio-technical transitions approach.

2.5 Linking sociological and evolutionary approaches

MacKenzie (1992) first suggested that sociological and evolutionary analyses of technological change were complementary. A key sociological concept is that of 'interpretative flexibility', meaning that different social actors may have different understandings of the 'same' idea. For example, an environmentalist may see a wind turbine as a clean and renewable form of energy generation, whereas as a 'country guardian' may see it is as an intrusive and unreliable blot on the landscape. Sociological analyses highlight how new technologies have a high degree of interpretative flexibility, and so the social networks relating to these technologies only gradually, if ever, reach a state of stability or 'closure' in which a widely shared understanding of the technology is achieved. In economic terms, this is conceptualised as new technologies having a high degree of uncertainty in relation to their costs and performance characteristics, so that shared expectations of the likely costs and characteristics influence investment choices. Analyses under the multi-level transitions perspective typically take a sociological perspective by analysing the processes of alignment between social and technical elements leading to stable socio-technical systems, such as the current dominant high carbon energy regime. Whilst this provides many useful insights, it tends to neglect economic variables which are central to policy analyses. Hence, we argue that a useful coevolutionary framework could incorporate insights from the multi-level transitions perspective, but, by using an explicit evolutionary framing, connect these to evolutionary economic understandings.

3 Coevolutionary framework

We argue that a framework for analysing long-term socio-technical and techno-economic change towards a low carbon future can usefully combine insights from the socio-technical transitions and coevolutionary approaches. The value of such a framework is that it focuses attention on the most relevant analytical categories, whilst avoiding trying to be a 'theory of everything'.

The use of the term evolution outside its original biological context often creates controversy and misunderstandings. However, much work, sometime referred to as generalised Darwinism (Dennett, 1995; Hodgson and Knudsen, 2004), has argued that any population of entities can be said to evolve, if it follows the three processes of *variation* amongst the population, *retention* of characteristics from one generation to the next, and *selection* of favourable characteristics in relation to the environment. An evolutionary analysis then needs to explain how the variation is generated, how characteristics are retained or inherited from one generation to the next, and how selection occurs of those characteristics which enhance survival or performance in a given environment (Nelson, 1995; Hodgson, 2010; Kallis and Norgaard, 2010). As in biological evolution, this does not necessarily imply progress toward any given end-point, as the environmental conditions may change, though some have argued that it leads to a general increase in complexity (Beinhocker, 2005). Two systems coevolve when they each evolve and they have a causal influence on each other's evolution. Following Murmann (2003), we can say that "two evolving populations coevolve if and only if they both have a significant causal impact on each other's ability to persist" (Murman, 2003, p.22). These causal influences can arise through two avenues: by altering selection criteria, e.g. a new incentive in the institutional structures increases the likelihood of a particular technology being adopted, or by changing the replicative capacity of individual entities, e.g. a firm adopts a new business strategy causing it to increase its investment in technological innovation relative to promotion of existing technologies.

Hence, a coevolutionary approach seeks to identify causal interactions between evolving systems. As noted, recent research has identified technologies, institutions, and business strategies as three key mutually evolving systems necessary to understand industrial and economic change. In our development of a coevolutionary framework for analysing technological and institutional change for a transition to a low carbon economy, we focus on these three co-evolving systems, together with a fourth relating to evolving user practices (see Figure 1). Much social science research (Bijker et al., 1987; Edgerton, 2005) has argued that attention must be paid to the social context of the use of technologies, rather than just to individual decision-making. This social context includes both the development of other activities needed to support the use of the technology, e.g. training of skilled persons to install and repair it, and also the development of shared meanings about the way in which a technology is used, e.g. primarily for business, recreational or social purposes. These processes of development are referred to as ‘societal embedding’. In our scheme, this embedding is partly reflected in the development of new institutional frameworks, and partly through the development of user practices, relating to the use of the new technology.

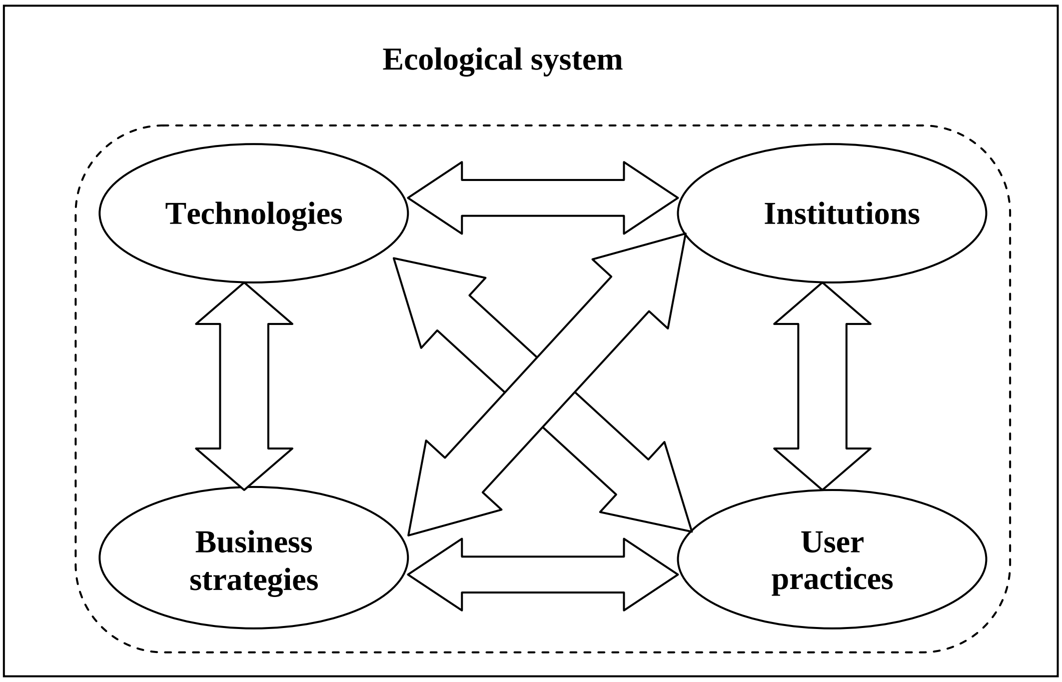

Figure 1. Coevolution of technologies, institutions, business strategies and user practices

Following Freeman and Louca (2001), we treat each of these as a system that evolves under its own dynamics, but in which this both influences and is influenced by the dynamics in the other systems through causal interactions. As noted, this differs analytically from socio-technical (and also social-ecological approaches) that emphasise the inter-connectedness and mutual dependence of social and technical (or social and ecological) aspects. We argue that a greater degree of analytical separation may be useful for some purposes, as it focuses attention on the causal influences between systems, and hence may give greater insight into how decisions made by policy-makers or other actors could affect these influences, so as to promote evolution towards more sustainable, low-carbon systems.

For clarity, we now give definitions of each of the systems. These are not necessarily definitive, but provide a starting point which is necessary for inter-disciplinary work. Technological systems are defined as systems of *methods and designs for transforming matter, energy and information from one state to another in pursuit of a goal or goals*, following Beinhocker’s (2006) definition of physical technologies. A similar notion of the application of natural process to human ends is found in the recent work of Brian Arthur on the evolution of technologies, where technologies are defined as “a collection of (natural) phenomena captured and put to use … to fulfil a human purpose” (Arthur, 2009, p.28, 50). As noted above, existing shared assumptions and decision rules constrain the evolution of technological systems. Hence, as the multi-level perspective suggests, more radical technological innovation is typically first applied in niches, where the favourable characteristics of the new technology are particularly beneficial and can be nurtured.

Systems of institutions are, arguably, even harder to define, as the term ‘institution’ is used widely and somewhat differently in different contexts and approaches. Here, we take a broad definition of institutions as *ways of structuring human interactions*. Unlike some work in new institutional economics (Williamson, 1985), here institutions are not assumed to be economically efficient ways of structuring, because of uncertainty, bounded rationality and path dependence (Pierson, 2000). This follows the institutional economics tradition of Douglass North (1990), who defines institutions as “the rules of the game”. This is taken to include, for example, formal systems of regulatory frameworks, property rights and standard modes of business organisation, as well as more informal widely-shared norms and collective conventions. It is also sometimes extended from a more social and cultural perspective to include habits, behaviours and routines of individuals or small groups of people. In our framework, we conceptualise the latter under ‘user practices’, as defined below. Nelson (2003, 2005) and Beinhocker (2006) use the term ‘social technologies’ instead of institutions. This conveys the analogy between ways of organising human interactions with ways of organising material systems for human purposes. However, this could give the misleading impression that institutions are merely a special type of technology, whereas they are an important analytic category in their own right.

Business strategies are defined as *the means and processes by which firms organise their activities so as to fulfil their economic purposes*. For most commercial firms, their primary economic purposes would be to make a profit and to provide a return to their shareholders or other owners, though uncertainty and bounded rationality mean that firms will be profit-oriented rather than profit-maximising. The delivery of goods or services to consumers would be seen as a means towards these ends, though social factors, such as reputation of the firm, would have an influence on the ability of firms to fulfil their economic purposes. This wide definition in terms of economic purposes would also include social enterprises which are more explicitly oriented at delivering useful goods and services to citizens and communities, and may or may not have the aim of delivering a profit or financial return. Because of our interest in economic outcomes, we focus on firms’ strategies, but this category could be broadened to include organizations with a wider range of social purposes, such as public sector organizations. The coevolution of organizations, including firms, and their social environments has been explored within organizational science (Baum and Singh, 1994; Porter, 2006).

Finally, user practices may be defined as *routinised, culturally embedded patterns of behaviour relating to fulfilling human needs and wants*. Practices are conceptualised as ways of meeting social needs, such as cleaning, cooking or washing, using particular technologies, in which individuals have agency but this is constrained by social structures (Spaargaren, 2003). This may be regarded as a generalisation of the concept of routines or habits. Though the concept of practices comes from sociological theories, the analysis of how practices change over time by competing to recruit practitioners suggests that it would be amenable to being framed in explicit evolutionary terms. Ropke (2009) has suggested that study of more sustainable consumption patterns should examine the coevolution of domestic practices with systems of provision, supply chains and production. Here, particular practices may be enabled or constrained by prevailing systems of technologies, institutions and business strategies, and so will co-evolve with these.

So, our framework suggests that key events in the transition to a sustainable low carbon economy may occur through technological changes, forming of institutions, revisions to business strategies or changes in user practices. Each of these types of change involves a role for agency, i.e. for actors to actively influence change, though the consequences of any individual action will always be uncertain, as it is mediated through the interaction with existing structures within the four systems. This process of influencing change is referred to as ‘path creation’ (Garud and Karnoe, 2001; Geels and Schot, 2008).

As with any evolutionary approach, to gain explanatory power, our coevolutionary framework needs to be supplemented with empirical content in order to investigate the particular causal influences at work in a particular context. However, the framework provides a way of organising such empirical insights and examining how these causal influences are playing out in a dynamic context. Drawing on insights from the multi-level transition perspective and evolutionary economics, the framework includes interactions at micro, meso and macro levels, as illustrated in the applications below. We would argue that the framework is related to, but more flexible than the multi-level transition perspective, in that it enables more explicit consideration of the role of actors within a transition. As we argue below, it may also provide new insights for the development of evolutionary economic models.

4 Applications of the coevolutionary framework

We argue that this coevolutionary framework can provide a useful framework for undertaking analysis of dynamic processes contributing to a transition to a low carbon economy at multiple levels. In this section, we describe early applications of our coevolutionary framework and potential future research directions. These applications seek to address key research and policy challenges relating to a transition to a low carbon economy: (1) to inform detailed empirical analyses of the implementation of energy and climate policies to promote innovation and take-up of low carbon technologies (Parrish and Foxon, 2008; Foxon et al., 2010b); (2) to develop a framework for analysing the interaction of social and technological elements within potential transition pathways to a low carbon energy system (Foxon et al., 2010a); (3) to inform assessment of the implications for economic growth of a transition to a low carbon economy; and (4) to assist in the development of more formal, multi-level evolutionary economic models. As these applications are further pursued, this will feed back into the further development and specification of the framework.

4.1 Analysing innovation of low carbon energy technologies

The first micro-meso level challenge is to inform the mix of policy measures needed to promote the successful innovation and diffusion of low carbon technologies that are challenging the existing fossil fuel dominated energy regime. A key dilemma facing policy-makers is how to maintain appropriate levels of diversity amongst different low carbon options, whilst ensuring that promising options benefit from increasing returns and learning effects so as to be able to challenge the dominant technologies (Foray, 1997; van den Bergh et al., 2006, 2007; Gross, 2008). As these authors note, this issue is barely addressed by mainstream economic analyses. A coevolutionary approach argues that there is no simple resolution to this dilemma. The concept of creating and maintaining an 'extended level playing field' has been proposed to keep all chosen options open and to give them a fair chance (van den Bergh et al., 2007). The coevolutionary approach proposed here could provide a framework for systematic analysis of what this implies in particular situations and circumstances (Foxon et al., 2008).

Previous research used an earlier version of our coevolutionary framework to analyse the role of incumbent utilities in the take-up of renewable energy technologies in Germany, Spain and the UK between 1990 and 2005 (Stenzel and Frenzel, 2007; Foxon et al., 2010b). The business strategies of these incumbent firms covered both investment in technological innovation and also institutional engagement in the process of development of regulatory frameworks and incentives for renewables. This led to a process of coevolution between the technological systems, the institutional frameworks and the business strategies relating to renewables development. This showed that relatively small initial differences in institutional contexts in the three countries led to incumbents pursuing different strategies and hence to radically different levels of take-up of wind energy by incumbents in the three countries. For example, in Spain, a supportive institutional framework in the form of a 'feed-in' tariff system providing price support for renewables give rise to selective pressure for investment in wind farms by incumbents, development of relevant technological capabilities by these firms and lobbying by them for further enhancement of the feed-in system. This shows that coevolutionary processes can give rise to 'virtuous cycles' of cumulative causation, that have been identified as key emergent patterns of the interaction of technological and social factors necessary for successful innovation (Garud and Karnoe, 2003; Jacobsson and Bergek, 2004; Suurs and Hekkert, 2009).

A second case study focussed on the role of sustainability-driven entrepreneurs in the take-up of renewable energy in the U.S. (Parrish and Foxon, 2008). In this case, an innovative business strategy enabling investors to capture the future benefits of selling 'green electricity' helped to overcome technological and institutional selective pressures for lock-in to existing systems, and enable the adoption of small-scale renewable energy by local communities. In turn, this contributed to the emergence of an institutional niche around putting a market value on reducing carbon emissions, favouring the selection of other business strategies for creating economic benefit in low-carbon ways. Thus, these entrepreneurs helped to catalyse a transition to a low-carbon economy by exemplifying and legitimising alternative business strategies.

The innovation of low carbon energy technologies and related institutions, business strategies and user practices is clearly crucial to a low carbon transition. This has been a focus of much analysis within economic, organizational and sociological literatures, but there has been a relatively limited cross-fertilization of ideas between these approaches. We argue that analysis of low carbon innovation using a coevolutionary framework can facilitate this by linking economic issues of value creation, organizational issues of firms' strategies and capabilities, and sociological issues of the roles of structure and agency.

4.2 Analysing transition pathways to a low carbon economy

The second application of our coevolutionary framework relates to the exploration of transition pathways to a low carbon economy. Looking beyond the innovation and deployment of individual technologies, a key challenge is to improve understanding of the processes by which systemic change in systems of energy technologies and supporting institutions could occur, including the roles of 'small' and 'large' actors in these processes. This is being pursued by the author and colleagues in a project analysing the interaction of social and technological elements within potential transition pathways to a low carbon energy system for the UK (Foxon et al., 2008, 2010a). The project is developing and analysing a number of potential transition pathways for the evolution of UK electricity systems, applying the socio-technical scenarios strand of the multi-level transitions perspective, supplemented by our coevolutionary framework. In this context of long-term systemic change, understanding of the role of the multiple levels of 'landscape', 'regime' and 'niche' is particularly important. In our coevolutionary framework, these may be viewed as emergent, stable sociotechnical structures.

Thus, the current dominant regime in a country like the UK for meeting lighting, heating and power-related services represents a stable, coevolved configuration of technologies, institutions, business strategies and user practices. The technological system is dominated by a set of large-scale, mainly fossil-fuel generation technologies, a transmission and distribution network and a set of end-use technologies operating within a build infrastructure. The institutional system is based on competitive markets for generators and suppliers, supplemented by particular regulatory constraints and incentives, such as support for increasing deployment of renewable generation. The business strategies of the small number of dominant large energy companies include managing uncertainty by investing in a diverse range of generation technologies, including coal, gas, nuclear and renewables, whilst mainly competing on price rather than other attributes in customer supply. The user practices of consumers assume the reliable provision of electricity at affordable prices, for an increasing number of end-use devices. These systems have co-evolved to produce a relative stable electricity regime that generally meets consumer needs, whilst providing profit for the companies. However, the regime is under pressure from cultural changes at the landscape level, including growing public awareness of climate change, and concerns over security of primary energy supplies. These are leading to institutional changes relating to incentives for the much more rapid deployment of renewable generation technologies and for companies to invest in building new nuclear power stations, as well as the (partial) internalisation of the costs of carbon emissions through an emissions trading scheme. At the niche level, a range of large-scale and small-scale renewables technologies, including offshore wind, wave and tidal power, tidal barrages and biomass co-firing, local energy crops, photovoltaics, solar heating and heat pumps, are competing for resources and building advocacy coalitions for further public support and private investment. At the same time, large energy firms have successfully lobbied for greater active government support for both new nuclear build and demonstration of carbon capture and storage (CCS) technologies, which may be seen as attempting to enhance the replicative capacity of the current dominant regime, as these large-scale technologies require investment from the incumbent firms. The coevolution of technologies, institutions, business strategies and user practices, involving interactions between these multiple levels, could give rise to different transition pathways to a low-carbon electricity regime (Foxon et al., 2010a).

As we have noted, our coevolutionary framework needs to be supplemented with empirical content for any particular analysis, and it is likely that the multi-level coevolutionary dynamics would play out differently in different national institutional contexts. Further case studies are needed of the dynamics in different countries to illustrate both generic patterns and special cases, and to combine insights from understanding of long-term systemic changes using sociotechnical (Grin et al., 2010) and structuralist-evolutionary economic (Lipsey et al., 2005) approaches.

4.3 Implications for economic growth and prosperity of a transition to a low carbon economy

A meso-macro level challenge is to assess the implications for economic growth and prosperity of a transition to a low carbon economy. Conventional macro-economic modelling estimates that a pathway to achieve a 80% reduction in global greenhouse gas emissions by 2050 would result in around a 1-2% reduction in global GDP in 2050 (Stern, 2007), but provides relatively little insight into how such a transition could be achieved. A coevolutionary approach could complement such modelling work by (a) providing a more realistic view of the difficulties faced in overcoming the technological and institutional lock-in of existing regimes; (b) informing the strategies needed for, and benefits of, a radical shift in energy investment portfolios towards low-carbon technologies and processes. As noted in Section 2.4, it has been argued that a process of coevolution of physical technologies, social technologies (institutions) and business strategies has underpinned Western economic development by stimulating innovative new ways to meet (and create) end-user demands (Beinhocker, 2006). If, as some ecological economists argue (Victor, 2008; Jackson, 2009), maintaining and widening prosperity means abandoning traditional models of economic growth, then a coevolutionary approach could help to understand how to stimulate more ecologically-beneficial forms of innovation that contribute to growing prosperity.

4.4 Development of more formal, multi-level evolutionary economic models

The above examples have taken the form of appreciative theory (Nelson, 2005). The fourth application of our coevolutionary framework is to assist in the development of more formal, multi-level evolutionary economic models. The development of formal evolutionary economic models has so far been relatively limited. Following the pioneering evolutionary model of economic change expounded by Nelson and Winter (1982), some ‘history-friendly’ models of industy evolution have been developed (Malerba et al., 1999), as well as interactive selection-innovation dynamics models drawing on modelling in theoretical biology (Safarzynska and van den Bergh, 2008), and agent-based simulation models (Carillo-Hermosilla, 2006). Our coevolutionary framework should assist in this endeavour by providing a general approach, within which additional layers of complexity can be applied, depending on the research question and the situation being analysed.

5 Discussion and Conclusions

This paper responds to the call for the application of coevolutionary approaches within ecological economics, focussing on the theme of overcoming unsustainable lock-in to carbon-based systems of production and consumption (Kallis and Norgaard, 2010). It argues that a useful framework for analysing a transition to a sustainable low carbon economy should integrate ecological economic thinking with insights from recent work on socio-technical transitions, innovation systems and industrial dynamics, and evolutionary economics. So, we propose a framework for analysing the coevolution of technological systems, institutions, business strategies and user practices, within a multi-level macro-meso-micro approach. These coevolutionary processes are examined by analysing causal mechanisms by which activities within one system influence the selection criteria and replicative capacity within other systems. We argue that this gives a single framework within which both micro-meso and meso-macro level analyses can be carried out, and so offers the potential for further analysis of the relations between phenomena at these different levels. Initial and potential further applications of this framework were described relating to: (1) detailed empirical analyses of current policy challenges relating to the implementation of measures to promote the innovation and take-up of renewable energy technologies; (2) analysis of the interaction of social and technological elements within potential transition pathways to a low carbon energy system; (3) analysis of the implications for economic growth of a transition to a low carbon economy; and (4) the development of more formal, multi-level evolutionary economic models.

We now discuss the strengths and weaknesses of our framework in relation to the open questions for any coevolutionary approach raised by Kallis and Norgaard (2010). Firstly, in relation to *levels of coevolution*, our framework explicitly includes micro, meso and macro levels as three key emergent levels in relation to coevolution dynamics. As noted, we argue that evolutionary processes are occurring within each of the four systems, but that the evolutionary dynamics in one system causally influences that in the other systems. To take a concrete example, a transition to a low carbon energy system will involve the innovation and deployment of low carbon technologies, business strategies relating to investment in these technologies and market and regulatory frameworks that encourage such investment. It will also involve changes to practices relating to energy use, for example changing the time of use of appliances to suit variations in supply or allowing the external control of these appliances through some form of ‘smart grid’. It is clear that there will be many causal influences relating the evolutionary dynamics in each sub-system at multiple levels.

Secondly, in relation to *boundaries and geography*, our framework is flexible in relation to the application to local, regional, national or global scales. We argue that this is a strength, as the framework can be supplemented with empirical content relating to the relevant scale of application. One point to note is that our coevolutionary framework focuses on the coevolution of technological and social systems, and natural systems are not given a central role in the framework. We argue that this is both a strength and weakness of the framework. It is a strength because it enables an ecological economic analysis of the conditions and processes for a low carbon transition to draw on a wide range of work that analyses long-term industrial and economic dynamics, as we have described. Indeed one of the motivations for setting out this framework is to provide a means by which this range of work can enrich ecological economic analysis. It is a weakness in that ecological economic analyses start from the recognition that human economic systems are situated within natural environmental systems that provide the services of resource provision and waste assimilation. Though, as noted, coevolutionary analyses can be used to examine the interactions between social and ecological systems on shorter timescales, for the long-term socio-technical changes that our framework seeks to address, we argue that it is more appropriate to treat changes in ecological systems as part of the exogenous environment. For example, though the impacts of climate change will undoubtably affect future social and technological changes, these impacts have so far had relatively little direct influence on innovation of mitigation technologies, except through a general raising of the acceptance for the need for mitigation. Nevertheless, it would be of interest to relate the framework presented here more closely to other approaches to coevolution of natural and social systems (Gual and Norgaard, 2010).

Thirdly, in relation to *power and inequalities*, as Kallis and Norgaard note, this remains undertheorised in evolutionary economics. Nevertheless, as noted, the application of ideas from institutional economics, e.g. Pierson (2000), enables the incorporation of some power dynamics into selection processes. In particular, lobbying by firms for changes in regulatory frameworks to support particular business strategies and/or technological applications can form an important causal influence (Murmann, 2003; Stenzel and Frenzel, 2007; Foxon et al., 2010b). The framework can thus reveal how the use of power can influence dynamics, though deeper analysis would be needed to understand how different actors become powerful.

Fourthly, in relation to *rates of change and crises*, it is important to understand that an evolutionary explanation does not necessarily imply gradual, incremental change. Evolutionary processes do imply that change is path dependent and that innovation proceeds by combining the elements at hand in any given situation. However, as the multi-level transitions perspective has shown, innovative activity occurring in niches may enable the rapid spread of a new technology or business strategy when learning effects and other positive feedbacks enable it to out-compete a previous dominant alternative. Crises, precipated by social, economic or ecological changes exogenous to the system of interest, may also affect evolutionary processes.

In conclusion, we hope that this framework will contribute to further research in relevant areas of ecological economic thinking. In particular, arguably the greatest challenge is how to achieve growing and widely shared prosperity whilst remaining within ecological limits. Recent work in this area has challenged the mainstream economic idea that continuous economic growth, measured by increasing GDP, is possible or desirable within an ecologically 'full' world, and argued that broader understanding and new measures are needed of the social and economic factors leading to greater prosperity (Victor, 2008; Jackson, 2009). However, some economists have argued that the levels of innovation and investment needed to achieve a low carbon transition would be economically beneficial (Stern, 2007; Bowen et al., 2009). As the type of coevolutionary framework proposed here to inform understanding of a low carbon transition has also been used to explain the success of the Western economic model in creating wealth and prosperity (Beinhocker, 2006), we hope that it may be further developed and applied to inform how a low carbon transition could help to achieve growing and widely shared prosperity whilst remaining within ecological limits.

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