WSA Working Paper Series ISSN 2050-8522

Conceptualising Low Carbon Innovation Systems: Regions, Materiality and Networks

Carla De Laurentis and Malcolm Eames

WSA Working Paper 01-2016

First published in February 2016 by the Welsh School of Architecture

Welsh School of Architecture, Cardiff University
Bute Building, King Edward VII Avenue
Cardiff CF10 3NB, Wales, United Kingdom

Tel: +44 (0)29 2087 6097
Fax: +44 (0)29 2097 4623

Email: PoortingaW@cardiff.ac.uk
Web: http://www.cardiff.ac.uk/archi/working_papers.php

WSA Working Paper Series ISSN 2050-8522

Paper Number: 01-2016

Conceptualising low carbon innovation systems: regions, materiality and networks

Carla De Laurentis and Malcolm Eames

E-mail: DeLaurentisC@cardiff.ac.uk; EamesM@cardiff.ac.uk

Disclaimer

Contents

Abstract

Over the last decade research on sustainability transitions has emerged as a dynamic frontier within the broad interdisciplinary field of innovation studies. As Coenen et al. (2012) note two conceptual frameworks, Technological Innovations Systems (TIS) and the Multi-Level Perspective (MLP), have provided the dominant analytical heuristics shaping research into the dynamics of sustainability transitions. However, both approaches have been criticised for lacking an adequate conceptualisation of space. Indeed Coenen et al. (2012) have argued that transition research needs to take a closer conceptual, methodological and empirical look both at the global networks and local clusters of transition pathways. In responding to this call this paper engages with recent research on sustainability transitions, innovation studies and geography and theoretically speculates how a deeper engagement with the concepts of materiality (following Bakker and Bridge (2006)) and the regional level could provide useful insights in exploring low carbon innovation systems. The paper, in particular, proposes a theoretical framework which is distinctive in that it draws attention to: i) the importance of regional context, not just in terms of the broader institutional, economic and governance dimensions but also the importance of the natural and built environment as a source of competitive regional advantage (and constraints) shaping low carbon innovation and transition pathways and ii) the way in which spatial and scalar processes influence actors, networks and institutions in low carbon innovations.

Key Words: Transition Studies, Territorial Innovation Systems, Technological Innovation Systems, Low Carbon Innovation, Geographies of Transition, Natural and Built Environment.

Acknowledgments

Financial support for the research underpinning this paper has come from a number of sources, including the EPSRC (Grant Number EP/1002162/1), Welsh European Funding Office (WEFO) LCRI Convergence Energy Programme, and Higher Education Funding Council for Wales (HEFCW) support for the LCRI, and is gratefully acknowledged. We offer our thanks to Prof Peter Pearson for his valuable comments.

Introduction

As the scale and complexity of global environmental problems has become ever more apparent, the notion of transition, of fundamental transformation at the scale of entire socio-technical (energy, water, waste, food, transport, etc.) systems, in order to achieve radical improvements in environmental performance, has attracted the attention of a new generation of scholars. Often used interchangeably, the concepts of transition and systems innovation (Geels, 2002, 2004; Kemp and Rotmans, 2005; Smith et al., 2010) emphasise that a system-wide approach is needed that takes into account not only sector interactions but also the complex interactions that occur between technologies, institutions, businesses and consumer behaviour (Van Den Bergh and Bruinsma, 2008). In other words, the concern over sustainable development is increasingly understood in terms of 'transitions' to more sustainable socio-technical systems, which require major changes in production and consumption supply chains, institutions and structures, and the behaviour of the actors involved (Weber and Hemmelskamp, 2005).

As Coenen et al. (2012), Smith et al. (2010) and Markard and Truffer (2008) note two conceptual frameworks, Technological Innovations Systems (TIS) and the Multi-Level Perspective (MLP), have provided the dominant analytical heuristics shaping research into the dynamics of sustainability transitions. In broad terms, TIS analysis focuses upon the emerging actors, networks and institutional structures supporting new sustainable socio-technical configurations (Bergek et al., 2008; Carlsson and Stainkiewicz, 1991). The MLP, however, draws upon historical cases and insights to focus attention on the role of niches in fostering sustainable innovation, the dynamics of competition between emerging niches and incumbent socio-technical regimes and the alignment or misalignment of niche, regime and landscape pressures (Geels, 2002, 2011a; Geels, 2014; Rip and Kemp, 1998).

We take as our starting point for this paper the argument that much sustainability transitions research, and in particular both the TIS and MLP approaches fail to provide an adequate conceptualisation of the geography of transitions (Coenen et al., 2012; Hodson and Marvin, 2009; Truffer, 2008; Truffer and Coenen, 2012) and that there is a need to develop a spatially more explicit framework for understanding the dynamics of sustainability transition processes. We review recent contributions to the literature which have sought to address this weakness, particularly those drawing upon insights from the field of economic geography. We argue that whist this cross-fertilisation of sustainability transitions research and economic geography clearly has much to offer, a number of significant gaps remain.

Turning our attention to the case of low carbon innovation, we argue that much of the sustainability transitions literature fails to interrogate and problematize critically the normative 'guiding vision' of low carbon transition, and hence to adequately differentiate the very wide range of social and technological innovations labelled under this banner. Moreover, it lacks sufficient attention to the physical geography and materiality of low carbon innovation and neglects to consider the relationship between low carbon innovation (systems) and the natural (and built) environment. And, hence it has not paid sufficient attention to the potential importance of the natural and built environment as a source of competitive regional advantage (and constraints) that shape low carbon innovation and transition pathways.

This paper therefore, builds upon recent work in the field in order to: i) propose a multi-scale conceptual framework to further explore both the relational, territorial and physical geographies of low carbon innovation systems and ii) suggest future directions for interdisciplinary research.

The paper is structured as follows. Section 2 briefly reviews how spatial and relational approaches to scale have shaped key approaches within the innovation studies literature. It goes on to discuss how the recent work, drawing upon insights from economic geography, has sought to re-embed notions of scale and place in (TIS and MLP) sustainability transitions research. Section 3 seeks to critically review and begin to unpack the notion of low carbon innovation and transition, and argues for an interdisciplinary understanding which addresses both the relational and material dimensions of low carbon (renewable energy) innovation. Section 4 argues for the importance of rematerialising regional specificities in analysing the geography of low carbon transitions and innovation systems. Section 5 outlines how our conceptual framework takes into account the importance of regional specificities and embeds the more recent research on scale in innovation and economic geography studies. Methodological and analytical challenges are also highlighted. This section also includes a few concrete examples/illustrations of what it would mean to add the extra analytical dimensions we are suggesting drawing from some preliminary research conducted in Italy. Finally, section 6 concludes this paper with a call for further interdisciplinary research that builds on the insights in the paper.

Revisiting the treatment of scale and place in innovation systems and sustainability transitions research

The notion of scale is used recurrently in innovation studies[i]. Archibugi and Michie (1997:2, emphasises added) convey that in order 'to understand technological change, it is crucial to identify the economic, social, political and *geographical context* in which innovation is generated and disseminated'. Furthermore, it is argued that knowledge creation is cumulative and evolutionary, leading towards different development paths and specialisation processes between regions and national states. In other words, the concrete socio-spatial contexts in which innovation processes are embedded play an important role. The relationship between firms and territories is exceedingly complex (Dicken and Malmberg, 2001). Whilst much innovation systems research uses three key scales based on the territorial boundaries of the global space, the nation and the region, other emerging strands of research focus on the complex networks and interactions operating across and between these scales, providing a more fluid relational account of (scale in) innovation processes. We briefly review the contribution and challenges of each of these approaches before turning to recent research on (the geography of) sustainability transitions.

There is a growing consensus that economic activity is increasingly coordinated at a global scale, and R&D and innovative activities are often seen as being part of this broad trend (Bunnell and Coe, 2001). While R&D activities of firms are being increasingly internationalised, the degree of internationalisation varies among countries (Carlsson, 2006). Most of the literature on innovation at the global scale has been concerned with the activities of firms as manifested in international trade and foreign direct investment, with R&D structures within transnational corporations (TNCs), (Bunnell and Coe, 2001) and the globalisation and internationalisation of innovation in leading multi-national companies (MNCs) (Cantwell, 1997). This literature focuses on exploring TNCs/MNCs engagement in overseas R&D, which involves both asset-exploiting and asset-augmenting R&D (Narula and Zanfei, 2005). However, international knowledge flows also move through trade, licensing, cross-patenting activities and international scientific and academic collaborations (Carlsson and Stainkiewicz, 1991; Narula and Zanfei, 2005). Archibugi and Michie (1995) identify three categories in explaining the globalisation of innovation: international exploitation of nationally produced innovations, global generation of innovation and global techno-scientific collaborations.

The national scale is well captured by the notion of National Innovation System (NIS). The concept of NIS[ii] highlights the importance of 'the network of institutions in the public and private sectors whose activities and interactions initiate, import and diffuse new technologies' (Freeman, 1987:1). Further studies stress the importance of interactive learning and user-producer interaction in innovation (Lundvall, 1992) and the significance of cultural factors. Nelson (1993) suggests that there are sharp differences between various systems in attributes such as institutional set-up, organisational set up, investments in R&D and performance. He also emphasises that there is a distinctive national character, shaped by a shared historical experience and culture, which seems to pervade the firms, educational system, law, politics and government of each nation. Within the literature of territorial innovation systems, NISs are considered particularly important (Edquist, 1997, 2005) in capturing the significance of policy aspects of innovation. This is because most institutions and policies influencing innovation processes, or the economy as a whole, are still designed and implemented at the national level (Pavitt and Patel, 1999).

A country's borders normally provide the territorial boundaries for the NIS. The identification of the spatial boundaries is somewhat more complicated (and controversial, see for instance Doloreux and Parto (2005)) for the regional variant of the innovation systems approach[iii]. The notion of a regional innovation system (RIS) first appeared in the early 1990s and, according to Asheim and Gertler (2005), was to some extent inspired by the national innovation system approach. The RIS approach emphasises the important roles that place and territory specific features play in nurturing and enhancing innovation. The growing importance of the RIS framework [iv] overlaps with both: i) the success of regional agglomerations such as of clusters, industrial districts and innovative milieu in the post-fordist era (Asheim, 2000; Asheim and Cooke, 1999; Crevoisier, 2001; Maillat, 1998; Piore and Sabel, 1984; Porter, 1990, 1998) and ii) a revival of social sciences interest in the region as a learning site of economic interaction and innovation (Morgan, 1997). Moreover, the elaboration of the RIS concept, in economic geography, has represented an attempt to better understand the central role of institutions and organisations in promoting innovation-based regional growth (Asheim et al., 2003; Asheim and Gertler, 2005; Gertler and Wolfe, 2004).

Regional innovation systems scholars argue that technological trajectories are based on 'sticky' knowledge and localised learning processes. They contend that the regional spatial level is increasingly the level at which innovation is produced through regional networks of innovators, local clusters and the cross fertilising effects of research institutions (Asheim and Coenen, 2004; Asheim et al., 2003; Braczyk et al., 1998; Cooke, 1992). Accordingly it is then (often) the embeddedness of technological development processes within particular regional institutional infrastructures which explains different (regional) innovation paths.

However, it has been argued that much innovation research has been excessively focussed on these three discrete (global, national and regional) scales (Coe and Bunnell, 2003). As it has become apparent that systems of innovation are increasingly multi-scale (Hotz-Hart, 2000), and some authors have started to analyse the relationships that occurs across and between these levels. Here it has been suggested that a local-global dialectic provides a more fluid relational account of scale in innovation processes.

Recent literature on economic agglomeration and clustering processes, for example, offers important insights into the role of global-local networks and institutions that cut across and link different geographical scales (Bathelt et al., 2004; Maillat, 1998; Scott, 1998). Both Oinas (1999) and Bathelt et al. (2004) argue that the creation of new knowledge is best viewed as a result of a ‘combination’ of close and distant interactions Bathelt et al. (2004) refer to these external linkages as ‘global pipeline’ whereas ’local buzz’ implies the knowledge generated and shared locally). Whilst economic success often then has local roots, it also crucially depends on combining local and trans-local or global linkages (Asheim and Gertler, 2005; Bathelt and Glückler, 2011; Bathelt et al., 2004) [v].

This relational approach also has much in common with the heuristic framework of the global production networks (GPN)[vi]. In which, it is argued, the complexity of the global economy, especially its geographical complexity, is better understood using the concept of a network (Bunnell and Coe, 2001; Coe et al., 2008).

In this context, the work undertaken by Bulkeley and colleagues, for instance, suggests that multi-level governance perspectives might be fruitful in capturing the processes that are in place to govern climate change at the urban level (Bulkeley, 2005; Bulkeley and Betsill, 2005; Bulkeley and Betsill, 2013). Resources, competencies and powers are distributed both ‘vertically’ between different levels of government and ‘horizontally’ through multiple overlapping and interconnected spheres of authority (Hooghe and Marks, 2001). Such work on the politics of scale has provided significant insights into the socially and politically constructed nature of scale, and the ways in which processes of scaling and rescaling are intertwined, regulated and contested between different actors and networks.

Turning to the field of sustainability transitions research, as noted above it is only recently that much attention has been paid to the importance of geography in explaining the spatial unevenness of sustainability transitions. Space and place are only indirectly and implicitly addressed within both the dominant heuristics frameworks within the sustainability transitions literature (the Multi-Level Perspective (MLP) and Technological Innovations

Systems (TIS) approaches). However, both heuristics share a systemic perspective on innovation and technological change and stress the importance of networks of organisations. Recent research (Coenen and Díaz López, 2010; Markard and Truffer, 2008; Truffer, 2008; Truffer and Coenen, 2012) argues that this systemic perspective on innovation has much in common with the (global, national and regional) innovation systems approaches described above. This research suggests that exploring the complementarities between different innovation system approaches might reap the benefit of illuminating the processes of innovation and the direct interaction between technology and society in the context of sustainable development. Indeed, Coenen et al. (2012) have recently argued that 'transition research would do well to take a closer look at the global networks and local clusters of transition pathways in conceptual, methodological and empirical terms'.

Recent research has also sought to enrich the conceptualisation of space and place within both the MLP and TIS frameworks. Within the MLP literature, it is argued, path breaking innovation often occurs across located socio-technical experiments (Geels and Raven, 2006) and dedicated intermediating work at other spatial levels is needed for interactive learning to take place, expectations to develop and supportive networks to build (Raven et al., 2008; Smith, 2007). Such process, it is argued, operates on two levels, the 'local' and the 'global'. The former relates to experimentation that occurs in specific places and local contexts, supported by local networks; the latter refers to the emerging institutional field or proto regime that transcends the local contexts and that is supported by a network of global actors, which include industry platforms, user-groups and other intermediary organisations and operate partly autonomously from local experiments (Smith and Raven, 2012).

Local experimental projects (with new technologies, user preferences, infrastructures, regulations) occur in different localities and when they become supported by global actors/networks they accumulate and transcend the local contexts (sometimes this process is interpreted in terms of local or urban transitions vis-à-vis national transitions; see for instance Geels (2011b)). These references to the 'global' and 'local' processes are, however, considered highly abstract and used in a spatially decontextualised sense (Truffer and Coenen, 2012). While Hodson and Marvin (2009) emphasise that the importance of geography is often confined to 'some sort of bounded experimental local context' at niche level, Bridge et al. (2013) argue that concepts such as the local-global dialectic and landscapes are often mistaken for having a quite specific geographical meaning.

Coenen et al. (2012); Truffer (2008); Truffer and Coenen (2012) emphasise the importance of local/regional diversity and local/regional institutional contexts in explaining why niches emerge in one place and not in others. Following from these arguments, Raven et al. (2012) highlighted that a more spatially sensitive MLP leads to new questions, arguing that empirical research needs to pay more attention to regional differentiation between national boundaries in combination with the role of local/regional institutions and transnational networks.

The TIS tradition (Bergek et al., 2008; Carlsson and Stainkiewicz, 1991; Markard and Truffer, 2008) developed as a framework to analyse the interplay between the structural (actors, networks and institutions) and the functional components[vii] of innovation systems (Bergek et al., 2008; Hekkert et al., 2007) without *a priori* emphasising a specific spatial dimension. Recently, however, some scholars (Binz and Truffer, 2011; Binz et al., 2014; Binz et al., 2012; Dewald and Truffer, 2012), have started addressing this shortcoming. Binz and Truffer (2011) discuss the international level of the innovation process, emphasising the global and multi-scalar nature of TISs. They propose a new perspective that incorporates both localised and internationalised structures as part of systems innovation focussing attention on the international and multi-scalar networks of actors, localised clusters and institutions that enables and coordinates the creation, utilisation and diffusion of a new technology. They refer to a global technological innovation system, as a more detailed conceptualisation of what has in TIS studies, following Carlsson et al. (2002), been called the 'global technological opportunity set' of a specific technological field. Binz and Truffer's paper summaries the many different networks that appear in a TIS and provides a first attempt at highlighting the geographic pattern of a TIS. National and international linkages, they argue, will not only depend on the technology and the corresponding TIS in focus, but also, will vary according to the three layers of networks identified within a TIS (science and technology systems, companies and markets and institutional contexts).

Further work has also highlighted the importance of actors and institutions at the regional level in TISs. Dewald and Truffer (2012), for instance, demonstrate that TIS actors have to rely on critical resources that are often co-located in specific spatial contexts, mostly at the local scale. They argue that at an early phase of the TIS, important system function such as market formation depend on locally bounded conditions, such as recurrent face-to-face interactions and the availability of locally specific institutional structures. Studying the photovoltaics (PV) markets in Germany, their success and the regional differences in market dynamics, they suggest that 'locally bound market processes produced the very basis on which promotional policies (an effective national subsidy scheme) could build and without which an equally widespread market expansion would have been highly unlikely' (Dewald and Truffer, 2012).

Moreover, recent research exploring the role of cities (Bulkeley et al., 2010; Hodson and Marvin, 2010), regions (Cooke, 2010; De Laurentis, 2013; Späth and Rohracher, 2010, 2012) and power relations and social processes in influencing geographically situated regime and niche dynamics (Lawhon and Murphy, 2012) has emphasised the importance of a spatial perspective. Such perspective can provide a richer understanding of transitions processes, both in terms of explanatory power and policy advice.

This review, although necessarily selective in nature, has offered an opportunity to bring to the fore some key discussion points that are relevant for the arguments developed in the paper. In summary, whilst much innovation systems research has used the three key scales based on the territorial boundaries of the global space, the nation and the region, there is a need to consider that, often, complex networks and knowledge interactions operate across and between these scales. Hence, this review has revealed that there are already meaningful contributions that acknowledge the importance of network relationships and the issue of connectivity among actors and networks. As shown, some recent attempts to bring a stronger geographical perspective to sustainability transitions research build upon such contributions, that contrapose territorial and relational approaches in analysing economic flows (Bridge et al., 2013; Harrison, 2013; Jonas, 2012).

Nevertheless, we argue that two related problems remain unaddressed. On the one hand, as Truffer (2008) and Coenen et al. (2012) argue there is an insufficient elaboration of coupling structures between national/regional innovation systems and sectoral/technological innovation systems. On the other hand, we contend, that the absence of an effective conceptualisation of space is coupled with a lack of understanding of the importance of the regional context for sustainability and in particular low carbon, transitions. We argue that this regional context needs to be understood, more broadly, in terms of the physical geography of resource occurrence and the natural and built environment as a source of competitive regional advantage and path dependence. Before seeking to outline a conceptual framework to address these deficiencies, however, we first turn our critical attention to unpacking the notion of low carbon transition(s).

Energy Systems and 'low carbon transitions': setting the scene

The notion of a 'low carbon transition' has become a powerful guiding vision. It has provided a shared- but also often contested- narrative and moral imperative around which a broad and diverse range of societal interests – from governments, industry, business, academia, civil society and the environmental movement - can mobilise around the idea of transforming our global systems of production and consumption in order to mitigate against climate change. However, much of this guiding vision's power lies in its interpretive flexibility (Berkhout, 2006). (Berkhout, 2006); Meadowcroft (2009) for instance shows that there are many alternative ways in which transition in the energy system can be formulated, which would imply different development trajectories, mixes of energy technologies in the emergent system and orientations for policy intervention. More importantly, bringing about long-term transitions in large socio-technical systems involves political choices and political interactions that require challenging societal agreements around common goals, (re-)distributions of scarce resources and negotiation of trade-offs among potentially competing objectives (Meadowcroft, 2009). Consequently, conflicts and contestations are inherent in decision making around socio-technical transitions (Eames and Hunt, 2013; Lawhon and Murphy, 2012).

It is apparent, therefore, that there is not one low carbon transition but rather many competing (in some cases complementary) technological and social innovations and prospective pathways to a range of different low carbon futures, spanning multiple but interrelated spatial scales (from local to global) and, socio-technical regimes (energy, water, agriculture and food, mobility, housing, etc.). Moreover, each embodies particular sets of complex inter-relationships with the natural and built environment.

So for example in the domain of low carbon transport, we have seen competing expectations over the future of the automobile, around biofuels, natural gas, hybrid, battery electric, and hydrogen fuel cell vehicles (Bakker, 2011). Each of these competing sets of technological expectations is associated with the emergence of distinct but overlapping Technological Innovation Systems (TIS) and niche activities.

In the discussion that follows, we focus on innovation and prospective transitions to low carbon energy systems, which provide clear examples and evidence of both resource endowments and spatial scales. Innovations in technologies for the extraction, production, distribution, storage and end-use of energy have played a central role in transforming human society, underpinning the processes of industrialisation, urbanisation and international trade, which have shaped the global economy. For example, in recent human development, first water wheels and windmills then coal-fired steam engines powered much of the first two industrial revolutions. The development of the electric motor subsequently transformed processes of industrial production in the early to mid 20th Century. Whilst in the transport sector, first coal (railways and steam ships) and then oil and internal combustion and jet engines (the automobile, heavy trucks, shipping and aviation) have radically transformed patterns of human mobility and settlement, and domestic and international and trade (Eames and Hunt, 2013).

While, future energy transitions are highly uncertain, historical evidence has offered insights into how prospective energy transitions might unfold. Past experiences show that the broad historical context (including resource availability, industrial and household energy demands, institutions and government policies, knowledge and skills and international trade) was important for explaining specific energy transitions and that these unfolded over long periods of time (over decades and sometimes centuries) (Allen, 2009; Fouquet and Pearson, 2012; Mokyr, 2009; Smil, 2010).

In innovation studies we are familiar with conceptualising energy systems in co-evolutionary and socio-technical terms (as ‘regimes’ or ‘innovation systems’). However, it is evident (as we illustrate in section 4) that all energy systems also possess particular socio-spatial, human and physical geographies. This is equally true for low carbon energy systems, whether based on renewable technologies (such as biomass, wind, wave, solar, or geothermal, etc), fossil fuels with carbon capture and storage (CCS) or nuclear power, as it was for conventional fossil fuel based systems (coal, oil, gas, etc).

Moreover, since the surge of interest in the knowledge economy and the increasing role and significance of knowledge as an input to economic processes, innovation studies have tended to concentrate on high technology or knowledge intensive industries, (Smith, 2000). A key components, it is argued, of the knowledge economy, is a greater reliance on intellectual capabilities, while the role of knowledge (as compared with natural recourse) has become more important (OECD, 1999). However, we argue that it matters to understand low carbon innovation based on renewable energy resources as a combination of natural resource based activities with knowledge intensive-assets. It follows that low carbon renewable energy innovations will be embedded in a particular territory (where the natural resource occurs and the related human-capital resources) but also be spatially distributed (as knowledge flows across multiple-scale).

Rematerialising regional specificities in energy and the geography of low carbon transitions

Whilst the materiality and physical geography of energy systems receives relatively little attention within the MLP and TIS literature, such concerns have long been foregrounded within the broader geography literature. We therefore turn our attention to some specific features of the geography literature that could contribute to our understanding of the materiality of low carbon energy transitions. We refer specifically to i) the use of maps as an instrument in locating energy potentials and activities; ii) the role played by natural resources in regional development; iii) the influence of geography on global production networks and the 'matter' of territory.

Geography, we argue, is central to understanding and addressing current energy discourses. Zimmerer (2011), for instance, stresses that the resource systems of energy are entwined as social-environmental interactions occur across multiple-scales and energy production, distribution and consumption are grounded to the natural environment in which they occur. Moreover, Bridge et al. (2013) contend that low carbon energy transitions are geographical processes that involve reconfiguring current patterns and scales of economic and social activity. Although many energy-related issues have as yet received little attention from the geography community (Jiusto, 2009), many aspects of energy do display strong spatial dimensions (Pasqualetti, 2011).

One way to start looking at the connections between geography and energy is through maps (Pasqualetti, 2011), as these are helpful in charting energy potentials and activities. As with conventional energy resources, maps are frequently used to identify actual or potential renewable energy resources[viii] or illustrate how the distribution of such resources relates to relevant distribution and supply infrastructure, or indeed areas of demand. Maps can also be used to illustrate complex interactions between the availability of natural resources, technological performance, the built environment and energy demand (as with for example maps illustrating solar energy potential in cities, Murphy et al. (2011); Šúri et al. (2007)).

Hansen and Coenen (2013) highlight that while relatively few contributions investigating renewable energy systems deal explicitly with the importance of natural resource endowment, some authors have started providing evidence of the importance of such endowments and the influence that they may exert on innovation processes. The success of Brazil's ethanol production is, to some extent, dependent on the favourable climate and soil conditions that allowed sugarcane production to thrive in the São Paulo and the adjacent areas (as these currently account for 85% of sugarcane currently cultivated in Brazil- see Goldemberg (2007); Solomon and Krishna (2011)). The influence of natural resources is further stressed by Carvalho et al. (2012) in their discussion of biodiesel and regional production of soya crops in Curtiba (Brazil) and also by Späth and Rohracher (2010; 2012) in their account of sustainability transition in the Murau region and the role played by the abundance of wooden biomass. A recent study by Murphy and Smith (2013) analysed wind energy projects on the island of Lewis in the north west of Scotland illustrating in detail the wider implications of issues of land ownership and tenure and infrastructure on untapped renewable resources in the Highlands and Islands of Scotland. Moreover, the growing appreciation of the scale of offshore wind (Jay, 2011), marine and tidal energy sources available to the UK (ABPmer, 2008), suggests that they are rapidly becoming valuable assets. In particular, it is stressed that the availability of relatively shallow windy waters, wave and tidal currents with centres of high demand close to the coast might facilitate resources appropriability.

Coupled with these recent studies, the natural environment, historically, has often been seen as a source of regional comparative advantage. Within the human geography literature, resource extraction (mining, oil and gas, etc.) is underpinned by the classical theory of comparative advantage in international trade as an agent of regional development (Gunton, 2003; Watkins, 1963). Although empirical evidence has led to considerable controversy[ix] asserting that resource-led growth is a high risk strategy that often does not provide sustained growth (among others: Auty (2001); Innis (1956); Mackintosh (1964); Sachs and Warner (1999)), in common with Gunton (2003), we argue that the physical geography of resource occurrence represents an important factor in economic development. Natural resource-based development is challenging, but it is the efficient management of resource development by the regional governance structure and effective investments and policy making aimed at natural resource management, on the one hand, and the long-term sustainability of natural resource-based activities on the other, that can support economic development mitigating the impediments to resource-based growth[x].

Bridge (2008) has drawn increased attention to the materiality of production networks. Bridge's work follows from a criticism that too much of the production network literature pays little attention to the institutional and geographical environments within which networks operate and are formed and shaped. He highlights, with an example from the oil industry, the influence that materiality exerts on industrial organisations. He argues that the production chain of extractive industries is territorially embedded at different points along its length and the materiality of extractive industries emphasises that dependency on natural production, location relative to markets and the existing infrastructure limits the spatial flexibility of the network.

These criticisms arise because, according to Bakker and Bridge (2006), resource and environmental geographers have predominantly conceptualised nature in physical terms, traditionally focussing on improving the flow of resources ‘from’ nature ‘to’ society through the design of institutional and territorial frameworks for procuring and managing environmental goods and services. This stands in contrast with much work on the field of political ecology (for a review see Bulkeley (2005); Neumann (2009)) and the *production of nature thesis* in which the mutual production of ‘society- nature’ relations has been central to research and analysis. Bakker and Bridge (2006) suggest that what counts as a resource depends on the interaction between its physical quality and condition (e.g. the variable grade/ quality of mineral resources, for example) and social institutions. Referencing the material, they contend (2006), is to acknowledge that ‘things other than humans make a difference in the way social relations unfold’ and brings to the fore principles of actor-network theory, such as the role of both human and non-human elements and processes of translations and negotiations (Callon, 1986; Callon and Latour, 1981; see also Murdoch, 1998; 2001).

In this sense, materiality helps us explain how natural resources are both naturally endowed (the influence that they exert vis-à-vis their physical properties and their geographical recurrence) and socially induced (e.g. recognising how a diversity of actors can construct and manipulate nature. Kaup (2008) draws a similar conclusion, indicating that the ‘material difficulties of natural gas extraction and transport have shaped the structure of Bolivia’s natural gas industry’. The extraction and transport of natural gas requires a large amount of fixed capital and technological innovation in extraction and separation processes, pipeline construction and conversion. The requirements of capital, Kaup (2008) argues, has shaped the relationships between transnational extraction firms and the people and places in which natural gas is extracted’.

The discussion presented here emphasises that natural resources, their geographical recurrence and the built environment are important features in low carbon transitions. The spatial distribution of these physical and material resources is an important aspect to bear in mind when researching low carbon transitions: geographical recurrence and knowledge flows of natural resources, together with the built environment as a source of competitive advantage (and constraints) are expected to be territorially embedded at different points in the value chains. In other words, what constitutes renewable natural resources will be contained within a particular physical territory but also be socially and politically constructed as such within and between various networks of actors at different scales. Our intention here is not to over-privilege material explanations. Nevertheless, we think that the issue of materiality, and how resources can be both materially manipulated and socially constructed, is valuable in understanding innovation processes and spatial consideration in renewable energy systems. The implications of this in studying low carbon innovations are highlighted in the next section.

Understanding scale and place in socio-technical transitions and innovation systems: towards a multi-scale systems framework of low carbon innovation

The discussion above has highlighted two issues. On the one hand, spatial scale in innovation - and environmental governance- has often been treated in hierarchical and discrete terms. The global, the national and the regional scales are often treated simply as nested spatial containers, undermining the complexity of innovation and environmental processes and overlooking the relationship that occurs between the national, the regional and the global levels (Bulkeley, 2005; While et al., 2010). Following the view that scale is a fluid, relative and socially constructed concept (Bunnell and Coe, 2001), we contend that low carbon innovation and knowledge interactions in renewable energy innovations are intertwined across a range of scales and spheres of governance that call for a better understanding of the role of actors, networks and institutions as they operate simultaneously across multiple scales.

On the other hand, the paper has highlighted that such fluid relational account of scale in innovation runs the risk of undermining the importance of the spatial context and the role that local natural resource endowment can exert and their impact on network relationships. Following Bakker and Bridge (2006), the physical properties of a resource (whether it is ubiquitous or localised, whether it requires the mobilisation of significant amounts of energy/capital and supporting infrastructures and so on) influence the political-economic relations within which the resource becomes embedded. Such material differences become significant because they might enable and constrain the social, political and economic relations necessary for resource production and innovation. Researching low carbon innovation, therefore, requires a more focussed attention on the role that geographical location and the materiality of renewable resources play.

These considerations imply that there is a need to synthetize and enrich current conceptual frameworks in order to offer a better understanding of the role that the combination of the broader and multi-level institutional, economic and governance dimensions, and the physical geography of the natural resources play in transitions processes.

The argument here is that any analysis of the geography of low carbon innovation and transitions should build upon and combine insights from recent literature that has sought to clarify and integrate emerging streams of work and theoretical perspectives that link different scales, such as those reviewed in the previous sections, enhanced by foregrounding the discussion on materiality. This will require i) a renewed attention on the occurrence and spatial distribution of natural resources and their influence on innovation processes and ii) a consideration of the role that regional, global and national spaces play in shaping the contours of the relationships (e.g. the nature and the strengths) and networks of actors that occur across spatial boundaries in innovation processes. In other words, it is important to understand the influence that regional, national and global contexts, and natural resource occurrence, exert on such relational geography.

Adopting as a starting point of the framework the regional scale, the regional lens offers a means to start unpacking the role that natural regional resources play in innovation. Defining and understanding low carbon innovation based on renewable energy resources as a combination of natural-resource based activities with knowledge intensive assets allows the identification, within the region, of the broad spectrum of renewable energy systems that might co-exist.

Within a region, there will be the co-existence of different competing and synergistic low carbon innovation systems (e.g. wind, nuclear, solar PV, solar thermal, bioenergy, CCS, geothermal) influenced by the opportunities and constraints offered by the different regional context and materiality. To clarify with an example, regions that display a well-developed grid system and port infrastructure (which are deemed to be important characteristics for the commercial success of offshore renewables), with favourable local weather conditions and local geography (e.g. accessible onshore areas suitable for assembly and maintenance) could play a determining role in the extent to which these resources become utilised (Murphy et al., 2011).

However, the variability of regional renewable energy capabilities and of sufficient or insufficient infrastructure cannot simply explain the degree of unevenness in the way transitions unfold in one place and not another. The literature on regional innovation systems, to this end, might offer useful insights, as it is often the institutional embeddedness of technological development processes and the institutional infrastructure within particular regions that explain different innovation paths. We suggest that such emphasis on the roles that regions and the regional institutional infrastructure play in innovation allows for unfolding the institutional contexts in which cooperative practices emerge and take place and provides a better understanding of the entrepreneurial capacity, the governance and financial resources that are distinguishable at regional level. Agreeing with Kaup (2008), innovative firms and organisations ‘must not only account for the material difficulties of the resource and the physical constraints of the place, they must also negotiate the socio-political dynamics of the people in the places in which the resource is extracted from and transported through'. Nevertheless, it is important also to stress that such socio-political and economic dynamics are, at the same time, embedded and influenced by wider political-economic territorial frameworks (MacKinnon et al., 2002).

We have argued in this paper that low carbon regional innovation systems present a combination of intra-local, extra-local and transnational network connections that are influenced by the issue of materiality of natural regional resources. To investigate this further, useful insights are provided by exploring the coupling structures between territorial and technological innovation systems. The system functions developed under the TIS literature can provide a useful analytical frame to exemplify how knowledge processes unfold in a multi-scalar and spatially differentiated way displaying internal (within the same region) or external linkages (across multiple scales- global, national and regional). Recalling the discussion presented earlier in the paper the work undertaken by Dewald and Truffer (2012) on PV markets developments in Germany showed that important system functions such as market formation depended on locally bounded conditions. This highlights that internal linkages (within the region), might be more relevant for certain functions, while external linkages (that encompass the national and the global) and knowledge anchoring in different locations becomes more important for others (e.g. collaborating on R&D projects with international scientific pools or accessing external sources of capital). A particular emphasis of the framework proposed here is on the way in which energy innovation networks are organised geographically and the extent to which the physical characteristics of natural resources provide opportunities or constraints to the networks' capability to generate and capture value.

Central to this, are therefore the issues of territoriality and territorial politics (cfr. Bridge et al. (2013); Jonas (2012)), understood in terms of the way in which the social and political power that governs renewable energy systems is organised and distributed across space. This goes beyond the investigation of the deep structural trends and drivers as emphasised by the landscape concept in the multi-level perspective, and encompasses the regional institutional contexts in which cooperative practices emerge. It highlights the structure of regional governance and regional policy, the way in which this results from processes that take place at and across various scales. Such regional processes are entwined, constructed and networked to other places and people beyond any given jurisdictional territory (Goodwin, 2013).

As one might expect, there are significant methodological challenges associated with developing an analytical framework that foregrounds the physical geography and physical attributes in innovation processes. A diversity of actors, at different spatial levels, can influence and materially manipulate the physical processes and properties of nature, shaping technological and organisational structures. The critical challenge here is to deal with the complexity of understanding multi-faceted innovation processes across multiple-scales while recognising the socio-material influence of nature.

The purpose of this paper has been to speculate theoretically about how a deeper engagement with the geographical concepts of materiality and the regional level could prove to be useful in exploring low carbon innovation systems. The discussion presented here is aimed at proposing a framework that builds from past and more recent theoretical frameworks. This means that the analytical lenses adopted are those developed by previous research vis-â-vis the identification and delineation of system boundaries. Such issues of delineation of boundaries, being global, national or regional, will be especially challenging. For instance, the term region is often used ambiguously, being applied to territories as different as small countries, diverse cities and small scale industrial districts. The concept of the 'region' has dominated geographical discourse ever since the field became institutionalised (Paasi, 2010). While it is outside the scope of this paper to clarify the concept of region, it is important to stress that regions can be looked at from a variety of different perspectives, using a range of methodological approaches and this opens up a number of possibilities. The delineation of regional boundaries, and the set of spatially stretched articulations and networks (cfr. Harrison (2013); Macleod and Jones (2007)), will depend, to a large extent, on the research questions and the purpose of the analysis and will therefore be a matter for the applied reflexivity of the researcher. What the paper has shown is that such a delineation needs to be enriched by bringing to the fore issues of physical geography and the way these might shape and influence network relationships and processes of innovation that occur across a range of scales. It follows, therefore that innovation and sustainability transitions research needs to address further questions in analysing low carbon innovation processes such as: i) the extent to which the physical characteristics of natural resources provide opportunities and/or constraints to the capability of energy innovation networks to generate and capture value; ii) the influence that resource endowment exerts on the relational characteristics of low carbon innovation networks and iii) how the natural resources and their values get discursively constructed, mobilised and negotiated and by whom.

To gain explanatory power there is a need to test and supplement the discussion above with empirical work related to low carbon innovations. Social network analysis (Wasserman and Faust, 1994) has often been identified as an effective technique to identify and analyse knowledge networks at different scales. Nevertheless, we argue that although, social network analysis techniques offer insights on the geographical representation of innovation processes; it is often unsuccessful at capturing the networked relationships in the context in which they occur. Complementary approaches such as case studies, qualitative analysis and comparative methods that recognise the importance of context specificity can contribute major insights for further developing the framework.

A first attempt at operationalising the propositions brought forward in the paper is represented by recent analysis conducted to investigate the peculiarity of the greening of the regional innovation system and renewable energy policy in the Puglia region, in the south eastern heel of Italy (De Laurentis et al., 2014). The region of Puglia has endeavoured to shed its conventional image of chronically poor region -Puglia is part of the Italian South 'Mezzogiorno'- by building a reputation for itself as a region that sets a high premium on good governance, efficient public administration and regional development policies focussed on innovation and sustainability. Puglia has now outperformed the rest of the Italian regions in terms of PV installed power and wind energy and it is third in bioenergy production. The analysis conducted, and based on a deeper engagement with the physical geography attributes in innovation processes, shows that different actors can materially manipulate the physical processes and properties of nature, shaping technological and organisational structures. Since the onset of the Regional Energy Plan (PEAR, 2007), the favourable climate and natural resource endowments such as wind, solar and agricultural land were perceived as a means to overcome the current patterns of uneven development in the region. Capitalising on favourable geographical conditions meant that renewable energy developments could provide opportunities to alter patterns of economic growth and development. Breaking the old trajectory of path dependence in the region become therefore a major goal of regional energy policy in which the public sector – through a combination of green public procurement, more permissive planning regulations and the deployment of EU funds- played a significant role. Nevertheless, the easiness in which authorisations were granted has been controversial. The way the national energy policy provisions process (from the simple communication to the local authority to the much more time-consuming authorisation procedure) has been applied in Puglia has been questioned. This has caused pressures from local groups, local communities and local authorities to promote a more sustainable form of harnessing natural resources and to protect the natural 'geographical landscape' of the region. The already strong and connected regional innovation system for renewable energy was then re-directed towards micro-scale energy developments with a primary involvement of residential households and regional firms.

A further example is the region of Sardegna, where the physical constraints and peculiarity of the energy system infrastructure (such as the lack of access to natural gas infrastructure, e.g. gas pipeline and the limited distribution and transmission infrastructure) are hampering the opportunities offered by the plentiful regional resource endowments. Here, it is argued that the planned natural gas pipeline from Algeria to Sardinia and northern Italy (the GALSI pipeline) could provide an opportunity to open up the solar energy market of the north Saharian regions to Europe (Regione Sardegna, 2012a). Moreover, the installed capacity of 1.500 MW of wind power constitutes the maximum limit that the current infrastructure in the region can accept (further capacity could alter the continuity and stability of the electricity service and generate a negative effect reducing productivity of current installations (Regione Sardegna, 2012b). This example, for instance, points towards the extent to which physical characteristics of natural resources can constraint the capability of energy innovation networks to generate and capture value.

In the Toscana region, meanwhile, the discourses on renewable energy innovations and deployments are constructed around the opportunities of the region to capitalise on the rich research expertise in the regional universities, and the national and international research networks developed around the exploitation of geothermal resources (Toscana is the only Italian region with installed geothermal capacity). The importance of the innovative capacity of regional small firms within the network is also stressed, highlighting the importance of the Marshallian industrial districts' tradition (Beccattini, 1989) for the region. This reveals the sense of the relational way in which the energy networks around renewables and geothermal exceed the boundaries of the region and, at the same time, shows the influence that resource endowment may exert on such relational characteristics. While these examples are based on preliminary research underway in Italy, and further more in depth research is required, we argue that these examples highlight that there are many differences, at regional level, in the way in which the physical characteristics of resources influence low carbon innovation systems.

We are also aware that a complete understanding of the role that materiality and physical geographies can play in low carbon innovation systems will require a comparison of different regional settings in different countries. This is relevant, as it will not only allow exploring and investigating the influence that the regional, national and global contexts exert on different governance settings and innovation processes but also to contrast regions with similar and different regional resource endowments. Nevertheless, this represents the basis for further research that will be conducted comparing regions in Italy and in the UK.

Concluding remarks

This paper suggests that to fully understand processes of low carbon energy transitions there is a need to address two major shortcomings identified in the two conceptual approaches that have provided the dominant analytical heuristic that has shaped research into the dynamics of sustainability transitions. Investigating complementarities between different innovation systems approaches and reviewing the recent literature that has emerged investigating the ‘geography of transition’, we argue that a spatial perspective on sustainability transition is certainly meaningful. In particular, the paper contends that much of recent research in both innovation and transition studies has concentrated on the importance of the institutional, economic and governance dimensions at different spatial scales. Although these contributions have been fruitful, much of this research has treated scale in hierarchical and discrete terms (the global, the national and the regional). While some authors have started to scrutinise the increasing complexity of innovation processes and the relationship that occurs between the national, the regional and the global levels proposing a more fluid relational account of scale in innovation, the paper argues that there is a further need to consider regional specificities in a way that includes the physical geography of resource occurrence and the natural and built environment as a source of competitive regional advantage and path dependence. The arguments in the paper show that, drawing from recent geography literature, the geographical location and materiality of renewable resources helps explain the influence that natural resources might exert vis-à-vis their physical properties, their geographical ubiquity or concentration, the requirement to mobilise substantial amounts of investment and capital and the provision of supporting infrastructures and so on. The paper also stresses that a diversity of actors, networks and institutions located at global, national and regional levels are able to construct, influence and manipulate such resources.

An understanding of the broader institutional, economic and governance dimensions as they are represented at different geographical scales, in combination with an appreciation of spatial differentials in natural resources occurrence of energy, and renewable energy in particular, can provide fruitful insight in explaining processes of low carbon innovation and transitions.

The framework proposed builds on many nested levels of analysis that derive from recent contributions from innovation studies, economic and human geography literatures, which illuminate the increasing complexity of innovation systems. In this sense, the framework does not claim to be novel but it stresses the importance of the institutional, economic and governance dimensions at different spatial scales, as stated in much recent research in both innovation and transition studies. The framework aims to accommodate the view that innovation processes become intertwined at different spatial levels and those spatial scales, and their material differences, influence the social, political and economic relations of resource production and innovation. While further research is required to foreground the role of materiality and physical geographies, the paper has presented some preliminary evidence from research underway in Italy that highlights the many differences, at regional level, in the way in which the physical characteristics of resources influence low carbon innovation systems. This preliminary evidence points towards the fact that these are issues that warrants further critical and empirical enquiry.

This is a research agenda, which is of wide political, and policy relevance and which deserves much greater interdisciplinary attention from the sustainability transitions research community.

References

ABPmer, 2008. Atlas of UK Marine Renewable Energy Resources Report to the Department for Business, Enterprise and Regulatory Reform (BERR). ABP Marine Environmental Research Limited, London.

Archibugi, Michie, 1997. Technological globalisation and national systems of innovation: An introduction, in: Archibugi, D., & Michie, J. (Ed.), Technology, Globalisation and Economic Performance. Cambridge University Press, Cambridge, pp. 1-23.

Archibugi, D., Michie, J., 1995. The globalisation of technology: a new taxonomy. Cambridge Journal of Economics 19 (1), 121-140.

Asheim, B., Coenen, L., 2004. The Role of Regional Innovation Systems in a Globalising Economy: comparing Knowledge Bases and Institutional Frameworks of Nordic Clusters, Druid summer Conference, Industrial Dynamics, Innovation and Development, Denmark.

Asheim, B., T., , Isaksen, A., Nauwelaers, C., Tödlting, F., 2003. Regional Innovation Policy for Small-Medium Enterprises Edward Elgar Publishing, Cheltenham.

Asheim, B.T., 2000. Industrial Districts: the contribution of Marshall and beyond, in: Clark, G., Feldman, M., Gertler, M., (Ed.), The Oxford Handbook of Economic Geography. Oxford University Press, Oxford, pp. 413-431.

Asheim, B.T., Cooke, P., 1999. Local learning and interactive innovation networks in a global economy, in: Malecki, E., Oinas, P. (Eds.), Making Connections: Technological learning and regional economic change. Ashgate, Aldershot, pp. 145-178.

Asheim, B.T., Gertler, M., 2005. The geography of Innovation, Regional Innovation Systems, in: Fangerberg, J., Mowery, D., Nelson, R (Ed.), the Oxford Handbook of Innovation. Oxford University Press, New York.

Auty, R., M., , 2001. Resource Abundance and Economic Development. Oxford University Press, Oxford.

Bakker, K., Bridge, G., 2006. Material worlds? Resource Geographies and the 'matter of nature'. Progress in Human Geography 30 (1), 5-27.

Bakker, S., 2011. Competing Expectations, the case of the hydrogen car. University of Utrecht, Utrecht.

Bathelt, H., Glückler, J., 2011. The Relational Economy. Geographies of Knowing and Learning. Oxford University Press, Oxford.

Bathelt, H., Malmberg, A., Maskell, P., 2004. Clusters and knowledge: local buzz, global pipelines and the process of knowledge creation. Progress in Human Geography 28 (1), 31-56.

Beccattini, G., 1989. Sectors and/or districts, in: Goodman, E., Barnforth, J. (Eds.), Small firms and industrial districts in Italy. Routledge, London, pp. 120-133.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Research Policy 37 (3), 407-429.

Berkhout, F., 2006. Normative expectations in systems innovation. Technology Analysis & Strategic Management 18 (3-4), 299-311.

Binz, C., Truffer, B., 2011. Technological Innovation Systems in multiscalar space, Analyzing an emerging water recycling industry with social network analysis Geographica Helvetica 66, 254-260.

Binz, C., Truffer, B., Coenen, L., 2014. Why space matters in technological innovation systems-Mapping global knowledge dynamics of membrane bioreactor technology. Research Policy 43 (1), 138-155.

Binz, C., Truffer, B., Li, L., Shi, Y., Lu, Y., 2012. Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China. Technological Forecasting and Social Change 79 (1), 155-171.

Braczyk, H.J., Cooke, P., Heidenreich, M., 1998. Regional Innovation Systems: the role of governance in a globalized world. UCL press, London.

Bridge, G., 2008. Global Production Networks and the Extractive sector: Governing Resources-Based Development. Journal of Economic Geography 8 (3), 389-419.

Bridge, G., Bouzarovski, S., Bradshaw, M., Eyre, N., 2013. Geographies of energy transition: Space, place and the low-carbon economy. Energy Policy 53, 331-340.

Bulkeley, H., 2005. Reconfiguring environmental governance: Towards a politics of scales and networks. Political Geography 24 (8), 875-902.

Bulkeley, H., Betsill, M., 2005. Rethinking Sustainable Cities: Multilevel Governance and the 'Urban' Politics of Climate Change. Environmental Politics 14 (1), 42-63.

Bulkeley, H., Betsill, M.M., 2013. Revisiting the urban politics of climate change. Environmental Politics 22 (1), 136-154.

Bulkeley, H., Castán Broto, V., Hodson, M., Marvin, S., 2010. Cities and Low Carbon Transitions. Routledge, London.

Bunnell, T.G., Coe, N., M.,, 2001. Spaces and Scales of Innovation. Progress in Human Geography 25 (4), 569-589.

Callon, M., 1986. Some elements of a sociology of translation: Domestication of the scallops and fishermen of St. Brieuc Bay, in: Law, J. (Ed.), Power, action and belief: a new sociology of knowledge? . Routledge, London, pp. 196-223.

Callon, M., Latour, B., 1981. Unscrewing the big Leviathan: how actors macro-structure reality and how sociologists help them to do so in: Knorr-Cetina, K., Cicourel, A. (Eds.), Advances in social theory and methodology: towards an integration of micro- and macro-sociology. Routledge & Kegan Paul, London, pp. 227-303.

Cantwell, J., 1997. The globalisation of technology: what remains of the product cycle model?, in: Archibugi, D., & Michie, J. (Ed.), Technology, globalisation and economic performance. Cambridge University Press, Cambridge, pp. 1-23.

Carlsson, B., 2006. Internationalization of innovation systems: A survey of the literature. Research Policy 35 (1), 56-67.

Carlsson, B., Jacobsson, S., Holmen, M., Rickne, A., 2002. Innovation systems: Analytical and methodological issues. Research Policy 31 (2), 233-245.

Carlsson, B., Stainkiewicz, R., 1991. On the Nature, Function, and Composition of Technological Systems. Journal of Evolutionary Economics 1 (2), 93-118.

Carvalho, L., Mingardo, G., Van Haaren, J., 2012. Green Urban Transport Policies and Cleantech Innovations: Evidence from Curitiba, Goteborg and Hamburg. European Planning Studies 20 (3), 375-396.

Coe, N., M.,, Bunnell, T.G., 2003. Spatialising knowledge communities: towards a conceptualisation of transnational innovation networks. Global Networks 3 (4), 437-456.

Coe, N.M., Dicken, P., Hess, M., 2008. Global production networks: debates and challenges. Journal of Economic Geography 8 (3), 267-269.

Coenen, L., Benneworth, P., Truffer, B., 2012. Toward a Spatial Perspective on Sustainability Transitions. Research Policy 41 (6), 968-979.

Coenen, L., Díaz López, F., 2010. Comparing Systems Approaches to Innovation and Technological Change for Sustainable and Competitive Economies: an Explorative Study into Conceptual Commonalities, Differences and Complementarities. Journal of Cleaner Production 18 (12), 1149-1160.

Cooke, P., 1992. Regional Innovation Systems: competitive regulation in the new Europe. Geoforum 23 (3), 365-382.

Cooke, P., 2010. Regional innovation systems: development opportunities from the 'green turn'. Technology Analysis & Strategic Management 22 (7), 831-844.

Crevoisier, O., 2001. L'approche par les milieux innovateurs: état des lieux et perspectives. Revue d'Economie Régionale et Urbaine 1, 153-165.

De Laurentis, C., 2013. Innovation and Policy for Bioenergy in the UK: A Co-Evolutionary Perspective. Regional Studies.

De Laurentis, C., Morgan, K., Eames, M., 2014. The role of regions in low carbon transitions dynamics: the ‘Greening’ of Puglia Region, 9th International Conference on Regional Innovation Policies, Stavanger.

Dewald, U., Truffer, B., 2012. The Local Sources of Market Formation: Explaining Regional Growth Differentials in German Photovoltaic Markets. European Planning Studies 20 (3), 397-420.

Dicken, P., Malmberg, A., 2001. Firms in territories: a Relational perspective. Economic Geography 77 (4), 345-363.

Doloreux, D., Parto, S., 2005. Regional Innovation Systems: Current discourse and unresolved issues. Technology in Society 27, 133-153.

Eames, M., Hunt, M., 2013. Energy justice in sustainability transitions research, in: Bickerstaff, K., Walker, G., Bulkeley, H. (Eds.), Energy Justice in a Changing Climate. Zed Books, London, pp. 46-60.

Edquist, C., 1997. Systems of Innovation: Technologies, Institutions and Organisations. Pinter, London.

Edquist, C., 2005. Systems of Innovation, Perspectives and Challenges in: Fangerberg, J., Mowery, D., Nelson, R. (Ed.), The Oxford Handbook of Innovation. Oxford University Press, New York, pp. 181-208.

Freeman, C., 1987. Technology, Policy and Economic Performance: Lessons from Japan. Pinter, London.

Geels, F., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31 (8-9), 1257-1274.

Geels, F., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Research Policy 33 (6-7), 897-920.

Geels, F., 2011a. The multi-level perspective on sustainability transitions: Responses to seven criticisms. Environmental Innovation and Societal Transitions 1 (1), 24-40.

Geels, F., 2011b. The role of cities in technological transitions. Analytical clarifications and historical examples, in: Bulkeley, H., Castán Broto, V., Hodson, M., Marvin, S. (Eds.), Cities and low carbon transitions. Routledge, Abingdon, pp. 13-28.

Geels, F., Raven, R., 2006. Non-linearity and expectations in niche-development trajectories: ups and downs in Dutch biogas development (1973–2003). Technology Analysis & Strategic Management 18 (3-4), 375-392.

Geels, F.W., 2014. Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective. Theory, Culture & Society 31 (5), 21-40.

Gertler, M., Wolfe, D., 2004. Ontario's Regional Innovation System: The Evolution of Knowledge-Based Institutional Assets, in: Cooke, P., Heidenreich, M., Braczyk, H.J. (Eds.), Regional Innovation Systems, 2 ed. Routledge, London, pp. 91-124.

Goldemberg, J., 2007. Ethanol for a sustainable energy future. Science and Public Policy 315 (5813), 808-810.

Goodwin, M., 2013. Regions, Territories and Relationality: Exploring the Regional Dimensions of Political Practice. Regional Studies 47 (8), 1181-1190.

Gunton, T., 2003. Natural Resources and Regional Development: An Assessment of Dependency and Comparative Advantage Paradigms. Economic Geography 79 (1), 67-94.

Hansen, T., Coenen, L., 2013. The Geography of Sustainability Transitions: A literature review. Centre for Innovation, Research and Competence in the Learning Economy, Lund University, Lund, pp. 1-24.

Harrison, J., 2013. Configuring the New Regional World': On being Caught between Territory and Networks. Regional Studies 47 (1), 55-74.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R., 2007. Functions of innovation systems: a new approach for analysing technological change Technological Forecasting and Social Change 74 (4), 413-432.

Hodson, M., Marvin, S., 2009. Cities Mediating Technological Transitions: Understanding Visions, Intermediation and Consequences. Technology Analysis & Strategic Management 21 (4), 515-534.

Hodson, M., Marvin, S., 2010. Can cities shape socio-technical transitions and how would we know if they were? Research Policy 39 (4), 477-485.

Hooghe, L., Marks, G., 2001. Multi-level Governance and European Integration. Rowman & Littlefield Publishers, Inc, Maryland.

Hotz-Hart, B., 2000. Innovation Networks, Regions, and Globalization, in: Clark, G., Feldman, M., and Gertler, M. (Ed.), The Oxford Handbook of Economic Geography. Oxford University Press, Oxford, pp. 432-450.

Innis, H., A.,, 1956. The fur trade in Canada, An Introduction to Canadian Economic Industry. University of Toronto Press, Toronto.

Jay, S., 2011. Mobilising for Marine wind Energy in the United Kingdom. Energy Policy 39 (7), 4125-4133.

Jiusto, S., 2009. Energy transformations and geographic research, in: Castree, N., Demeritt, D., Liverman, L., Rhoads, B. (Eds.), A Companion to Environmental Geography. Blackwell Publishing, Oxford, pp. 533-551.

Jonas, A.E.G., 2012. Region and place: Regionalism in question. Progress in Human Geography 36 (2), 263-272.

Kaup, B.Z., 2008. Negotiating through nature: The resistant materiality and materiality of resistance in Bolivia's natural gas sector. Geoforum 39 (5), 1734-1742.

Kemp, R., Rotmans, J., 2005. The Management of the Co-Evolution of Technical, Environmental and Social Systems, in: Weber, M., Hemmelskamp, J., (Ed.), Towards Environmental Innovation Systems. Springer, Berlin, pp. 33-55.

Lawhon, M., Murphy, J., 2012. Socio-technical regimes and sustainability transitions: insights from political ecology. Progress in Human Geography 36 (3), 1-25.

Lundvall, B., A.,, 1992. National Innovation Systems, towards a theory of innovation and interactive learning. Pinter, London.

MacKinnon, D., Cumbers, A., Chapman, K., 2002. Learning, innovation and regional development: a critical appraisal of recent debate. Progress in Human Geography 26 (3), 293-311.

Mackintosh, W.A., 1964. The Economic Background of Dominion- Provincial relations. McClelland and Stewart, Toronto.

Macleod, G., Jones, M., 2007. Territorial, Scalar, Networked, Connected: in what sense a 'Regional World'? Regional Studies 41 (9), 1177-1191.

Maillat, D., 1998. Innovative Milieux and new generations of regional policies. Entrepreneurship and Regional Development 10 (1), 1-16.

Markard, J., Truffer, B., 2008. Technological Innovation Systems and the multi-level perspective: towards an integrated framework. Research Policy 37 (4), 596-615.

Meadowcroft, J., 2009. What about the politics? Sustainable development, transition management, and long term energy transitions. Policy Sciences 42 (4), 323-340.

Morgan, K., 1997. The learning region: institutions, innovation and regional renewal. Regional Studies 31 (5), 491-503.

Murdoch, J., 1998. The Spaces of Actor-Network Theory. Geoforum 29 (4), 357-374.

Murphy, J., Lynch, K., Serri, L., Airdoldi, D., Lopes, M., 2011. Site Selection Analysis For Offshore Combined Resource Projects in Europe, Offshore Renewable Energy Conversion - Co-ordinated Action, . ORECCA, Brussels.

Murphy, J., Smith, A., 2013. Understanding transition–periphery dynamics: renewable energy in the Highlands and Islands of Scotland. Environment and Planning A 45 (3), 691-709.

Narula, R., Zanfei, A., 2005. Globalisation of Innovation, The role of multinational enterprises in: Frangerberg, J., Mowery, D., Nelson, R., (Ed.), The Oxford handbook of innovation. Oxford University Press, New York, pp. 318-345.

Nelson, R., 1993. National Innovation Systems: a comparative analysis. Oxford University Press, Oxford.

Neumann, R., P.,, 2009. Political Ecology: theorising scale. Progress in Human Geogrpahy 33 (3), 398-406.

OECD, 1999. The Knowledge Based Economy: A set of facts and figures. OECD, Paris.

Oinas, P., 1999. Voices and silences: the problem of access to embeddedness. Geoforum 30 (4), 351-361.

Paasi, A., 2010. Regions are social constructs, but who or what 'constructs' them? Agency in question. Environment and Planning A 42 (10), 2296-2301.

Pasqualetti, M., J., , 2011. The Geography of energy and the Wealth of the World. Annals of the Association of American Geographers 101 (4), 971-980.

Pavitt, K., Patel, P., 1999. Global corporations and national systems of innovation: who dominates whom? , in: Archibugi, D., Howells, J., Michie, J. (Ed.), Innovation Policy in a Global Economy. Cambridge University Press, Cambridge and New York, pp. 94-119.

PEAR, 2007. Regional Plan for Energy and Environment (PEAR) Regione Puglia. Regione Puglia, Bari.

Piore, M., Sabel, C., 1984. The second industrial divide: Possibilities for prosperity Basic Books, New York.

Porter, M., 1990. The competitive advantage of nations. Macmillan, London.

Porter, M., 1998. Clusters and the new economics of competition. Harvard Business Review 76 (6), 77-90.

Raven, R., Schot, J., Berkhout, F., 2012. Space and scale in socio-technical transitions. Environmental Innovation and Societal Transitions 4, 63-78.

Raven, R.P.J.M., Heiskanen, E., Lovio, R., Hodson, M., Brohmann, B., 2008. The contribution of local experiments and negotiation processes to field-level learning in emerging (niche) technologies: meta-analysis of 27 new energy projects in Europe. Bulletin of Science Technology and Society 28, 464-477.

Regione Sardegna, 2012a. Piano d'azione regionale per le energie rinnovabili Sardegna Documento di indirizzo sulle fonti energetiche rinnovabili Regione Autonoma della Sardegna, Cagliari, pp. 1-57.

Regione Sardegna, 2012b. Piano energetico ambientale regionale al 2020, Rapporto preliminare di scoping Regione Autonoma della Sardegna, Cagliari, pp. 1-26.

Rip, A., Kemp, R., 1998. Technological change, in: Rayner S., M.E.L. (Ed.), Human choice and Climate Change. Battelle Press, Washington, pp. 327–399.

Sachs, J., Warner, A., 1999. The Big Push, Natural Resources Booms and Growth. Journal of Development Economies 59 (1), 43-76.

Scott, A., 1998. Regions and the World Economy: The Coming Shape of World Production, Competition, and Political Order. Oxford University Press, Oxford and New York.

Smith, A., 2007. Translating sustainabilities between green niches and sociotechnical regimes. Technology Analysis & Strategic Management 19 (4), 427-450.

Smith, A., Raven, R., 2012. What is Protective space? Reconsidering niches in transitions to sustainability. Research Policy 41 (6), 1025-1036.

Smith, A., Voß, J.P., Grin, J., 2010. Innovation studies and sustainability transitions: The allure of the multilevel perspective and its challenges. Research Policy 39 (4), 435-448.

Smith, K., 2000. What is the 'knowledge economy'? Knowledge intensive industries and distributed knowledge bases, Innovation Policy in a Knowledge-Based Economy. European Commission, STEP Group, Oslo.

Solomon, B., D., , Krishna, L., 2011. The Coming sustainable energy transition: history, strategies and outlook. Energy Policy 39 (11), 7422-7431.

Späth, P., Rohracher, H., 2010. 'Energy regions': The transformative power of regional discourses on socio-technical futures. Research Policy 39 (4), 449-458.

Späth, P., Rohracher, H., 2012. Local demonstrations for global transitions - Dynamics across governance levels, Fostering socio-technical regime change towards sustainability. European Planning Studies 20 (3), 461-479.

Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy 81 (10), 1295-1305.

Truffer, B., 2008. Society, technology, and region: contributions from the social study of technology to economic geography. Environment and Planning A 40 (4), 966-985.

Truffer, B., Coenen, L., 2012. Environmental Innovation and Sustainability Transitions in Regional Studies. Regional Studies 46 (1), 1-21.

Van Den Bergh, J., Bruinsma, R., 2008. The Transition to renewable energy: background and summary, in: Van Den Bergh, J., Bruinsma, R. (Eds.), Managing the Transition to Renewable Energy: theory and Practice from local, regional and macro perspectives. Edward Elgar, Cheltenham pp. 1-11.

Wasserman, S., Faust, K., 1994. Social Network Analysis, Methods and Applications. Cambridge University Press, Cambridge.

Watkins, M., H., , 1963. A Staple Theory of Economic Growth. Canadian Journal of Economics and Political Sciences 29 (2), 141-158.

Weber, M., Hemmelskamp, J., 2005. Merging Research Perspective on Innovation Systems and Environmental Innovation: An Introduction, in: Weber, M., Hemmelskamp, J. (Eds.), Towards Environmental Innovation Systems. Springer, Berlin, pp. 1-8.

While, A., Jonas, A.E.G., Gibbs, D., 2010. From sustainable development to carbon control: eco-state restructuring and the politics of urban and regional development. Transactions of the Institute of British Geographers 35 (1), 76-93.

Zimmerer, K., S.,, 2011. New Geographies of Energy: Introduction to the Special Issue. Annals of the Association of American Geographers 101 (4), 705-711.

---

[i] Our focus here is necessarily selective, given that our goal is not to survey the literature in its entirety but rather to introduce some key discussion points that will be reappraised later in the paper.

[ii] The NIS is often defined as all important economic, social, political, organisational, institutional and other factors that influence the development, diffusion and use of innovations at national level (Edquist, 1997).

[iii] The three perspectives- national, regional and sectoral- are often seen as variants of a single ‘generic’ systems of innovation approach and these different variants, co-exist and complement each other (Edquist, 2005); often the regional and sectoral variants of the generic SI approach complement each other and are, often, considered as parts or in relations of national ones.

[iv] A regional innovation system is defined as set of institutions, both public and private, which produces pervasive and systemic effects that encourage firms within the region to adopt common norms, expectations, values, attitudes and practices, where a culture of innovation is enforced and a learning process is enhanced.

[v] In the context of this paper it should be noted that Bathelt and Glückler (2011) also called for attention to be paid to natural resources through their suggested relational economic geography perspective.

[vi] The GPN approach, building from the global commodity chain and global value chain literature (GCCs/ GVCs), reflect the structural and relational nature of how production, distribution and consumption of goods and services are organised. The GPN literature contends that the value-chain relationship developed around certain types of products, industries or technology fields have become more complex and spread-out to include a growing number of firms in different stages of production process and located in an increasing number of countries throughout the world.

[vii] In recent years, the identification and assessment of functions of innovation systems has received particular importance. Functions are emergent properties of the interplay between actors and institutions and a series of empirical as well as conceptual articles have identified (Bergek et al. (2008)or Hekkert et al. (2007) for an overview) a series of functions. These are: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resource mobilisation, creation of legitimacy and development of positive externalities. The purpose of the different functions is to emphasise- and allow for comparison and appraisal- the important

processes that need to take place in innovation systems to lead successfully to technology development and diffusion (Hekkert, et al., 2007).

[viii] These potentials are often socially constructed based upon, among others, assumptions of cost, technological performance and variability in natural systems

[ix] Bridge (2008) highlights that two schools have emerged – i) the dependency school with its pessimistic conclusion that resource-led growth is high risk strategy that cannot provide sustained growth and ii) the comparative advantage school in which extractive resources are an important asset in economic development- provides a portfolio of present and historical examples in support of the positive and negative effects of resource-led development. California, Germany, Sweden, Canada, Australia and Norway represent examples of successful resource-led development and, on the contrary, Bolivia, Guyana, Angola, Zambia, Zaire, Guinea, but also South Wales represent examples of dependency and 'resource curse'.

[x] Gunton (2003) argues that the key to successful management revolves around the ability of natural resources to generate rent.