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Spatially uneven development and low carbon transitions: Insights from urban and regional planning

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HIGHLIGHTS

- Nature of spatial differentiation due to low carbon transitions discussed.
- Most energy research and analysis focus on national and local level.
- A regional approach to energy can help with efficient and equitable outcomes.
- Regional science tools and methods offer untapped opportunities.
- Coordinated and concerted action can be achieved via a multi-level framework.

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ABSTRACT

The ageing of existing energy system infrastructure, the threat of climate change and uncertainty in the movement of energy prices have resulted in a widespread agreement on the need for a transition to a low carbon energy system. Yet the nature of this transition (i.e. what, when, how and where) and its socio-economic outcomes at different scales are not well understood. The interdependence of the energy sector and economic growth has been mostly studied at the national level (via some general equilibrium or econometric models) whilst sub-national studies at community or urban levels mostly focus on the governance of transitions. Hence, we suggest that a regional perspective to energy policy and research promises to integrate these two approaches by providing a more robust and comprehensive understanding of the implications of low carbon transitions, as well as contributing to the development of more effective policies. By building on recent ideas on geographical aspects of energy transitions, this article offers insights on the changing relationship between the spatial organisation of economic activities and energy systems, and identifies tools and methods from urban and regional planning to help with the delivery of efficient and equitable policy outcomes.

1. Introduction

The ageing of existing energy system infrastructure, coupled with the threat of climate change and uncertainty around the price of energy (the so-called 'Energy Trilemma' (WEC, 2013)), has resulted in a consensus around the need for a transition to a low carbon energy system, both in the UK and abroad. Yet the nature of this transition (i.e. what, when, how and where) – as well as its socio-economic outcomes at different scales – is yet to be fully understood. The interdependence of the energy[1] sector and economic growth has been mostly studied at the national level (via some general equilibrium or econometric models) whilst sub-national studies at community or urban levels tend to focus on the governance of transitions (Bulkeley et al., 2013). Introducing a regional[2] perspective to energy policy and research promises to integrate these two approaches, by providing a more robust and comprehensive understanding of the implications of changes in the energy sector on the spatial distribution of economic activities, and vice versa.

Indeed, Bridge et al. (2013) claim that the low carbon transition

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[1] With specific reference to electricity networks.

[2] We define region as an area, especially part of a country or the world having definable characteristics but not always fixed boundaries (source: http://www.oxforddictionaries.com/definition/english/region).

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is likely to lead to spatial differentiation and uneven development. These differences will be overlaid upon existing socio-economic structures which are far from homogenous, and so finding ways of managing these transitions that reduce these inequalities, rather than widen them, emerges as an important policy challenge. Yet there is a gap in the literature around how the forms of this spatial differentiation may inform the design of efficient and equitable policy outcomes. Tasked with spatial organisation of activities to reduce inequalities, the urban and regional planning discipline stands to make contributions to analyse these issues. Given the limitations of existing literature, which focuses mostly (although extensively) on the employment impacts of transitions, a systematic analysis of the interdependencies between low carbon transitions and other economic activities would address this gap. This paper therefore contributes to expanding the geographical focus of low carbon transitions beyond the community or urban level to include suburban and rural areas. To this end, we draw on insights from urban and regional planning, and previous research related to the social construction of smart grids.

This paper has two aims: (i) to discuss the changing relationship between the spatial organisation of economic activities and energy systems during the transition to low carbon economies, and (ii) to identify a number of research methods and tools from urban and regional planning to help with the delivery of efficient and equitable policy outcomes in response to these challenges. Implicit in our analysis is that focusing at local, community, or urban level does not offer a framework sufficient to understand and monitor the associated changes. In this framework, regions constitute the spatial unit of analysis for monitoring the progress and facilitating the coordination of economic and social policy objectives, both within and between regions. Our analysis builds on a review of the literature, mostly focusing on the UK, supported by international evidence where applicable.

The article is structured as follows. In Section 2, the spatial aspects of energy systems are outlined. This section is followed by a thorough discussion of the five issues related to the trade-offs between the low carbon transition and 'spatially uneven development'. Section 4 discusses these issues which are followed by concluding remarks in Section 5.

2. Energy in a spatial context

The relationship between energy and spatial systems has long been established. More than three decades ago, Nijkamp (1980) set out a research agenda for the analysis of two-way interactions between the spatial distribution of activities and the energy sector at regional level. In his editorial note, he highlighted differences in both the supply and demand of energy at regional level. While the former refers to the differences in regional production technologies, the latter focuses on differences in the sectoral composition of regions. Nijkamp identified five issues for the analysis of interactions between spatial developments and energy problems:

- impacts of changes in the energy sector on the spatial distribution of activities and vice versa;
- the examination of regional energy, economic and technological variations under a comparative standpoint;
- the exploration of different policy options, possibly via scenarios and simulation models;
- the use of a 'multidimensional approach' to shed light on the regional economic and environmental interlinkages, and;
- the analysis of 'distributional impacts' of energy issues.

Despite significant changes in energy policy goals since then, these earlier insights did not get much attention beyond the characterisation of regional energy systems in quantitative models which can be grouped in three broad categories: (i) quite detailed technology optimisation models to find the least-cost technology choices to meet certain goals, such as emissions reductions (among others, Rafaj and Kypreos, 2007); (ii) more theoretically grounded regional economy models paying particular attention to energy system characteristics (e.g. flows, prices, technologies) within the economy (Barker et al., 2007; Bohringer and Rutherford, 2013) and (iii) network models, focusing on the flow of energy from its production to its transmission and distribution to a particular location (e.g. Strbac et al., 2007).

The key strength of these models is their ability to take into account regional differences in the form of resource availabilities, economic and population growth rates, end use demand patterns and levels of energy intensity, energy infrastructure and transportation options and costs (Barazi et al., 2005). Yet, they do not offer insights into the wider social and geographical context of how and where these technologies might be deployed. All these approaches mainly focus on temporal (when and which technologies need to be deployed), 'territorial' (interaction of political power and bounded space, either national or international) or 'location' (both relative and absolute sense) aspects of energy transitions (Bridge et al., 2013).

Bridge et al. (2013) provide further insights on the geographically divergent nature of low carbon energy transitions. These can include such factors as landscape (the socio-technical connotations of energy capture, conversion, distribution and consumption), scaling (the different geographical forms in which different energy technologies can be deployed, from micro-generation to community energy schemes to large scale wind farms) and spatial embeddedness and path dependency, as well as spatial differentiation and uneven development. From generating positive externalities by attracting investment that utilises renewable resources to the clustering of low carbon technologies, the form of low carbon transitions is likely be influenced by existing regional differences, which in turn may deepen existing inequalities. We argue that regional energy policy can help us to understand the dynamics of these reciprocal dependencies and utilise them to deliver efficient and equitable outcomes. In the next section, we illustrate how spatial organisation of economic activities and energy systems might shape and reconfigure each other.

3. The changing relationship between the spatial organisation of economic activities and energy systems

Economic development, social interactions and land use patterns have always been intricately linked with demands for energy and the uses to which it is put. From agrarian communities with relatively low demands for energy, met mostly by human and animal labour and biomass, to highly concentrated industrial centres with ready access to coal or geothermal power, the economic fortunes of regions have in the past been closely tied to their natural resources. Over time, economies of scale and advances in electricity network technologies (both at transmission and distribution level) enabled increases in the size of generation facilities. As a result, a centralised infrastructure with extensive delivery networks (national or even intercontinental) and a limited number of large generators emerged in many industrialised countries. This process was reinforced further by the market push factor of high land values in population centres that resulted in the closure and re-appropriation of iconic structures such as Battersea and Bankside power stations in central London, the latter of which now houses the Tate Modern.

Looking to the future, multiple pressures raise questions around the sustainability of this centralised paradigm: the ageing of infrastructure, the impacts of climate change, energy price uncertainty and security of supply concerns. An alternative, decentralised configuration in which energy is produced at different scales from households up to community level is gaining traction in many European countries, as evidenced by a growing body of literature (including Wolsink, 2012). The existing differences and diversity in types of demand, availability of resources, preferences and acceptability of technologies, new energy services and infrastructures create opportunities and challenges for the UK's transition to a low carbon economy. In this section, we unpack what the low carbon transition may mean for spatial dynamics in the UK. In particular, we identify five issues through which low carbon transitions might lead to spatial differentiation and uneven development:

- the clustering of low carbon technologies;
- the differences in energy demand between urban and rural settings;
- the economic growth and job creation potential of a low carbon transition;
- the trade-offs between agglomeration economies and network constraints; and
- the public good problem involving different actors in liberalised markets.

For each of these issues, we present: a description, the challenges associated with their analysis, and insights on which tools for further research can be used.

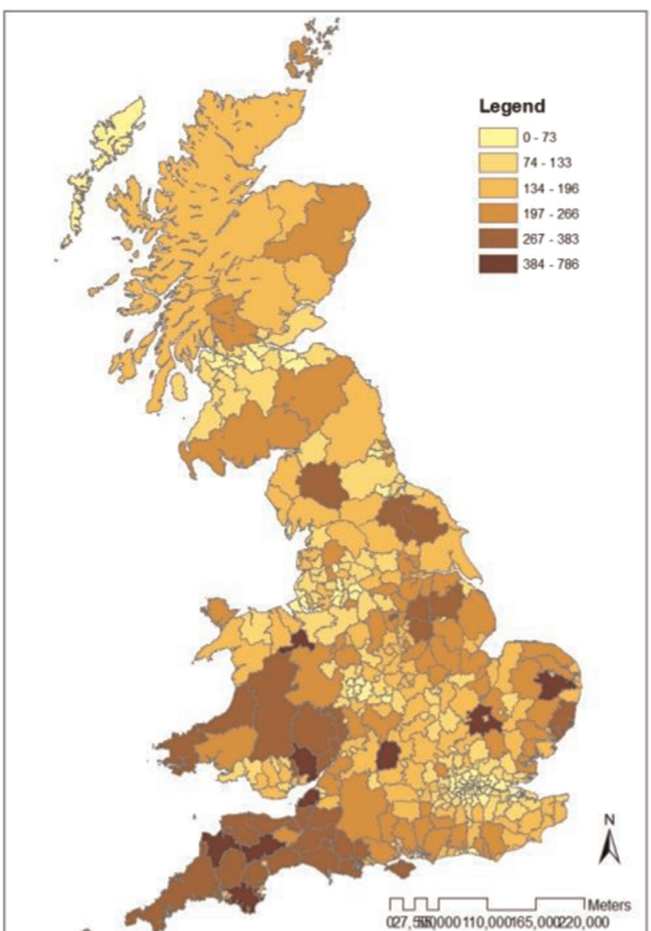

Fig. 1. Domestic solar photovoltaic panel installation by local authorities by 10,000 households in the UK. Source: Ofgem E-serve database (as of 30.06.2013).

3.1. *Clustering of low carbon technologies*

The first rule of geography stipulates that 'everything is related to everything else, but near things are more related than distant things' (Tobler, 1970, p.236). For technologies that require new infrastructures like battery charging stations for electric vehicles or hydrogen fuel cell vehicles, their spatially-dependant nature is well established (e.g. Schmidt et al., 2014). However, even in the case of technologies like solar photovoltaic (PV) panels, which do not require new infrastructure, spatial patterns are clearly visible. In the UK for example, PVs are mostly concentrated in the South West (Fig. 1).

Against the radical 80% carbon emission reduction target from 1990 levels by 2050 embodied in the Climate Change Act (CCA, 2008), the electrification of heat and transport emerge as cornerstones of the UK's low carbon pathways (CCC, 2008; DECC, 2009, 2011). The clustering of low carbon technologies poses a particular problem at distribution network level due to the need for reverse power flows and changes in power quality. With other technologies like heat pumps or electric vehicles, higher levels of electricity demand may cause congestion at distribution network level, where available headroom capacities at the substation level may be limited. As network investments (whether reinforcement or construction of new substations) have long lead times, the network needs to be in place before these demands can be met. Hence, an understanding of which geographical areas are more or less conducive to the deployment of these technologies is an important policy and research question.

Addressing these challenges requires a more accurate understanding of energy flows, including where it is sourced and what it is used for. Yet for many countries energy data statistics is a particular problem as they are available mostly at national level. In this regard, the UK is a leader in the provision of sub-national energy consumption statistics at fine geographical detail: the lower layer super output area[3]. Once data are accessible, urban and regional science offers tools like spatial econometrics which aim to explain the development of a phenomenon in an area by taking into account relevant neighbourhood characteristics. Behavioural insights provided in terms of peer effects in diffusion of technologies (Barabasi, 2003) are usually analysed via diffusion models (Rode and Weber, 2012) or econometric methods (a binary panel logit model by Müller and Rode (2013) and spatio-temporal model by Graziano and Gillingham (2014)). However, given that peer effects are likely to be stronger in spatially adjacent areas than more distant ones, a spatial analysis framework can capture these spillovers more robustly (Anselin, 1988; Dall'erba and Le Gallo, 2008). Spatial econometrics offers a modelling framework to incorporate behavioural insights generated in micro-level studies to be tested quantitatively using large data sets. Indeed, Schaffer and Brun (In preparation) and Balta-Ozkan et al. (In preparation) apply spatial econometric methods to analyse the determinants of solar PV panels for Germany and the UK respectively. Depending on the unit of analysis, spatial econometrics can even be used to analyse the impacts of community solar organisations (Noll et al., 2014) and their effectiveness.

3.2. *Urban and rural differences*

The lack of comprehensive energy statistics also hinders our understanding of how built environments create demand for

[3] LSOAs are small area statistical units based on measures of proximity and social homogeneity, with a minimum size of 1000 residents and 400 households, but average 1500 residents – For further details, see http://neighbourhood.statistics.gov.uk/dissemination/Info.do?page=aboutneighbourhood/geography/superoutputareas/soa-intro.htm.

energy or facilitate the adoption of microgeneration technologies, thereby reducing demand from the electricity grid. In particular, we suggest that geographical approaches need to recognise differences between urban and rural areas in three aspects: types and levels of energy demands, energy related perceptions and the potential for different types of distributed generation technologies.

An expanding literature provides insights on how differences in built environments, including housing densities, types of buildings, provision of amenities and so forth., lead to variations in demand for energy. Evidence from the US reveals that suburban and rural living is 17–19% more energy intensive than urban living (Shammin et al., 2010). More recently, Nichols and Kockelman (2014) report that suburban areas with mostly detached single family homes consume up to 320% more embodied energy as well as about 150% more operational energy, and around 160% more total life-cycle energy (per capita) than a densely developed area with mostly low-rise apartments. Similar findings have been reported in Europe. For the UK, in addition to income levels, Druckman and Jackson (2008) highlight the type of dwelling, tenure, household composition and location as key variables driving different energy consumption patterns in the UK. Wiedenhofer et al. (2013) analyse the influence of urban form, income and demographics on energy consumption patterns in Austria by combining spatially resolved household expenditure data with an input–output model. They highlight notable differences in urban, suburban and rural consumption patterns and spatial inequality. They argue that differential expenditure patterns and inequalities in income drive the differences in energy demands between urban and rural lifestyles. Heinonen et al. (2013), on the other hand, uses metropolitan, urban, semi-urban and rural contexts to document the relationship between urban form and carbon emissions in Finland. They claim that housing types, commuting distances, the availability of different goods and services, social contacts and emulation, and alternatives for pastimes are embedded in behavioural patterns, time allocation and purchasing decisions, captured by the notion of 'situated lifestyles'. Zasada et al. (2013) suggest a delineation of regions into urban, peri-urban and rural contexts, characterised by land use patterns, population distribution and density.

Another layer of urban and rural differences is due to penetration of distributed generation technologies like PVs. Graziano and Gillingham (2014), Snape (2013), and Balta-Ozkan et al. (In preparation) report higher PV penetrations in suburban and rural areas due to presence of single family housing units with larger roof space and lack of split incentives that multi-family housing units suffer. Eshchanov et al. (2013) note that residents of urban multi-storey houses have relatively limited opportunities for renewable energy applications due to the smaller surface of their rooftops and the lack of sufficient surface in the neighbourhood.

One possible contributing factor to differences in the uptake of distributed generation technologies is the variation in household energy behaviours and perceptions towards these technologies. Halder et al. (2010) report that students from urban areas have a more positive perception of bioenergy than rural ones. There are further differences between urban and rural preferences for renewable energy investments. Rural respondents not only value wildlife benefits and reductions in air pollution more highly than their urban counterparts, but also attach significant value to job creation (Bergmann et al., 2008). In contrast, in Crete, urban dwellers have higher average willingness to pay for biotope improvements and job creation than rural ones, when controlling for the effects of other covariates (Emmanouilides and Sgouromalli, 2013). Balta-Ozkan and Le Gallo (due for submission) report significant differences in energy perceptions and behaviours across self-determined categories of rural, small urban and large urban geographical contexts in Europe. People living in large and small cities are less likely to think that renewables will be one of the most used energy sources in the next 30 years compared to their rural counterparts. Both urban residents are more likely to cut down on heating and use more public transport than rural counterparts though it is the latter that who are more likely to have insulated their homes. Different attitudes towards smart homes are also reported by Balta-Ozkan et al. (2014).

These differences have an important implication for policy and research: differences in attitudes toward and perceptions of low carbon energy technologies can lead to uneven development with the emergence of new firms that install and maintain these technologies. Yet the literature on economic performance of these new firms is underdeveloped. Their survival rates, firm size characteristics and contributions to local economies are some of the issues that may appeal to scholars working on urban and rural economies. Nonetheless, total (i.e. aspatial) employment impacts of low carbon transitions, which we discuss next, have been studied closely. However, we also note that another line of enquiry can include development of spatial indicators to analyse the scope and nature of variation across different areas or regions (e.g. Perobelli and de Oliveira, 2013).

3.3. Economic growth and green jobs

Bridge et al. (2013) assert that the 'green economy' is economic activity undertaken with the aim of reducing energy consumption and improving environmental quality. Yet Peters (2014) notes three differences in the depiction of green jobs between academic and non-academic (including policy and governmental) studies: definition (goods and services as opposed to skills and tasks), scale (industry vs. occupation) and policy (industrial policies vs. workforce).

A large amount of research has been conducted into the employment impacts of all or part of the green economy, taken at both macroeconomic and sectoral levels. Studies have ranged from analysis of the net impact of individual policies on the Chinese power sector (Cai et al., 2011) to modelling the effects of renewable energy in Germany (Lehr et al., 2012), among others (Çetin and Eğrican, 2011; Wei et al., 2010; Blyth et al., 2014), and the scope of enquiry has varied from the national to the regional level (for the latter, Ratliff et al., 2010; Loomis and Hinman, 2009). For the UK in particular, Gilmartin and Allan (2015) analyse the regional employment impacts of marine energy on the Scottish economy using a spatial computable general equilibrium model.

Spatially uneven economic development may result in historically familiar patterns in which economic activity is concentrated in resource-rich areas, in turn giving rise to localised socio-economic characteristics. However, future patterns of development of the green economy could take any number of forms: either as remote offshore wind farms or nuclear facilities coupled with passive demand structures that do little to challenge energy-consuming conventions, or perhaps systems of highly distributed micro-generators and demand-side flexibility that give rise to new social interactions, institutions, norms, expectations and behavioural patterns at local level.

This may of course be true to various extents depending on the sector in question, and is also likely to vary depending on the unit of analysis. We may expect the employment impacts of the green building industry to be markedly different from innovation breakthroughs occurring in carbon capture and storage technologies, although these differences may be lost when assessed at an aggregated macroeconomic level. Indeed, Ernst and Young (2014) find a net job increase associated with decarbonisation in Europe (with scenarios ranging from 0–1.5%), albeit differing within sectors. Job creation would be largest under decarbonisation scenarios, especially in industries like construction and the manufacture of energy efficient equipment, whilst the change in both power sector and economy-wide employment is minimal across scenarios. The implications for inequality are therefore closely dependant on how decarbonisation is pursued: remote large-scale generation like nuclear power plants may rely on skills and expertise imported into host regions whilst exporting wealth generated to company headquarters or large financial centres in other regions, leaving the status quo largely unchallenged. Economic activity in the green economy can also be scrutinised in a range of ways: sectoral growth rates, job creation, product innovation, process innovation and so on. Chapple et al. (2010) find evidence that whilst product innovation may take place in concentrated areas, process innovation and employment opportunities may be more widely dispersed.

Likewise, the relative maturity of industries and technologies may contribute to differing spatial outcomes. Sectors that are characterised by a high degree of fragmentation, with many small actors competing for dominance, and early-stage technologies that are yet to reach economic maturity, often operate within a smaller geographic area with fewer resources. This may limit or improve their ability to innovate, again depending on the sector. Chapple et al. (2010) point to the importance of networks for innovation, concluding that their significance in the case of the green economy lies not in formal institutions like universities – well-known in the literature – but in the responsiveness of new green companies to local and regional markets.

Bridge et al. (2013) note that much of the current analysis around low-carbon transitions is either 'aspatial' or contains implicit assumptions about convergence over time, and suggest that insufficient attention has been paid to the possible spatial impacts of policy proposals. Opposed to this theory is the notion of 'circular and cumulative causation' (Myrdal, 1944, 1957, 1968 and Kaldor, 1972, 1975, 1980, cited in Stilwell and Primrose, 2010), which holds that economic, social and institutional interactions cause existing spatial inequalities to reproduce themselves, becoming more deeply entrenched over time. It is argued that targeted public investment can be used to break this vicious cycle and address a range of environmental problems, a call that became commonplace after the financial crisis of 2008 (e.g. Elliott et al., 2008, UNEP, 2009). Stilwell and Primrose (2010) argue that stimulus spending presents an opportunity to address regional inequalities in Australia, and that an awareness of the spatial impacts should be central to such policies, rather than incidental, particularly in areas with a high concentration of heavy industry.

The concept of industry clustering is well-established (Porter, 1990, 1998), and growing academic and policy attention is being paid to the way in which the clustering approach to regional growth promotion might be combined with the transition to a low-carbon energy system economy (Loorbach, 2007; HM Government, 2010). Regions are increasingly pitching themselves to the business community as innovation hubs in order to draw in investment and growth. Research into attempts by policymakers to promote green energy technologies and green energy clustering has concluded that, in addition to financial incentives, these efforts are likely to benefit from greater attention being paid to social learning and social change (McCauley and Stephens, 2012). A better understanding of social responses to low carbon technologies could even be used to challenge the dominant 'technical potential' paradigm under which social science is relegated to 'barrier analysis' (Cowell, 2010).

Despite a growing literature, Masterman-Smith (2013) cautions against a lack of understanding of the dynamics of job creation potential that low carbon transitions may represent, especially in rural economies: whether there is a shift of labour across sectors or new jobs are created; where dislocation happens even if there is a net overall gain; how the characteristics of these jobs compare to the characteristics of rural communities in terms of education levels, lack of diversity in skill sets and so on. The importance of understanding the socio-economic characteristics of green jobs is highlighted by Peters (2014) as well. In particular, the quality of the jobs generated, whether they pay decent wages and are accessible to lower-skilled jobseekers are areas subject to knowledge gaps. Peters notes the under-representation of women in green jobs in the US, highlighting the importance of labour and workplace diversity in green economy in the long term.

Understanding the dynamics of job creation opportunities requires a more geographically differentiated, multi-level approach to recognise the differences between urban and rural areas. In this respect, we argue that there is a gap in the literature to combine spatially explicit network and economy models in a multi-level framework. While the links between transport flows and economic growth have been modelled in detail via econometric input–output models, the relationships between energy networks and economic flows have not been analysed to the same degree. A contributing factor here is the different temporal scales that energy network and economic models require: continuous, changing on hourly basis vs. discrete, mainly annual. A special issue on analysing the impacts of disasters in connected networks discusses some of these issues (Okuyama and Santos, 2014). Yet, other regional science tools like shift-share analysis, economic base models or location quotient approaches (for a review of these models, see Isard et al. (1998)) can be used to analyse and monitor the performance of regions over time. In the case of large infrastructure projects like nuclear power plants or carbon capture and sequestration projects, social effects on the economy through demands for new houses, schools, health facilities etc. can be analysed via Lowry models (Wilson, 2012)[4].

3.4. Agglomeration economies and network constraints

A key concept in urban economics is agglomeration economies, referring to benefits firms enjoy by being in close proximity to each other. Originating in the early 20th century, Marshall (1920) recognised that firms in close proximity to one another would benefit from the reduced costs of moving goods, people or ideas. Beyond industrial facilities, agglomeration economies can also include shopping areas, central business districts whereby transaction costs of consumers are reduced significantly by being able to visit a larger number of stores than otherwise. Ellison et al. (2010) point out that natural advantages, such as the availability of renewable resources, might also lead to a concentration of firms. Agglomeration economies therefore have two implications for energy networks: on the demand side, the concentration of firms operating in similar sectors might generate similar types of energy demand patterns. Similarly on the supply side, the availability of onshore or offshore wind resources might lead to congestion at transmission network level. Hence, the agglomeration economies concept can be used to analyse network constraints and related trade-offs.

In the deregulated electricity industry in the UK, renewable energy generators pay fees to connect to the grid depending on availability of capacity in a given network. Hall and Foxon (2014)

[4] In a nutshell, the location quotient is a measure to understand the concentration of an economic factor, say employment in a particular sector, in a region compared to its share in another region or nation. Shift-share analysis looks at a change (whether decline or growth) of a particular economic factor in a region by decomposing it into national share, industrial mix and regional share. Economic base models assume that there is a basic sector key to strengthening the local economy. The Lowry model is the first spatial interaction model to unpack the interdependencies between land use, transportation demand and other multiplier effects on the rest of the economy due to changes in population.

recognise the role of local authorities for facilitating expanded use of these new connection investments. They suggest such activities would bring in further benefits to local economies via tax and employment benefits. Similar types of demand profiles are likely to be found in central business districts where the marginal cost of energy provision can increase significantly: for example, demand for electricity on a hot day could be substantial due to air conditioning.

This points to a gap in the literature around the analysis of trade-offs between agglomeration economies and network constraints: at what level of economic concentration do the marginal costs of energy production outweigh the marginal benefits of agglomeration? The urban economies literature presents rich insights on how the lack of marginal pricing of new infrastructure developments can lead to continuous land use i.e. urban sprawl (Brueckner, 2000). Marginal pricing is a concept applied in transport in the form of peak and off-peak pricing or the application of congestion zone charging such as in central London. The application and expansion of such land use models to incorporate energy network characteristics can provide better insights for locational pricing. If such models were to include shifting demand to off-peak times via demand side response mechanisms instead of increasing the capacity of the grid, they could reveal much more realistic marginal costs of energy provision. Indeed, in an ongoing industry-led smart grid demonstration project to understand the values associated with shifting demand via dynamic price tariffs, it has been shown that peak prices might increase 16-fold (Laguna, 2014). Existing land use and transportation models (e.g. Anas and Liu, 2007) therefore provide firm foundations from which to build new models capable of exploring these issues in greater depth.

3.5. Liberalised markets and different actors: the public good problem

In deregulated industries, energy provision lies with a range of actors along the supply chain, from generators to distribution network operators to retailers. As a result, energy systems present 'vertical' and 'horizontal' complexity by relying on actors across multiple scales of a state and encompassing various types of subjects at each scale (Goldthau and Sovacool, 2012). The governance of energy is therefore 'fragmented' into a multiplicity of institutional levels: national governments, international governmental and non-governmental organisations, cross-border regional organisations and a broad gamut of other subjects ranging from 'transnational networks of advocacy to quasi-regulatory private bodies, global policy networks, and public–private partnerships' (Goldthau and Sovacool, 2012; p. 237).

Whilst it is hoped that competition within the industry will drive innovation and reduce costs, this multiplicity of actors becomes problematic especially if the benefits of technologies lie across parties: who is going to pay for the costs of these technologies when the benefits are of a public nature (Kim and Shcherbakova, 2011), and how can the problem of freeriding be prevented? This is particularly relevant for smart grids, whereby the application of information and communication technologies onto power networks such as sensors, smart meters, and the real-time monitoring of data and energy flows can be used to extract the value of 'flexibility capital' (Powells et al., 2014) – the ability of consumers to shift their electricity demand to off-peak times.

Whilst the mismatch between supplier-led smart meter roll-out and geographical nature of network constraints has been well-documented in the literature (Hall and Foxon, 2014), challenges in the coordination of different stakeholder priorities expand beyond national borders. In particular, there can be circumstances where improvements in infrastructure might result in positive externalities that may not be directly involved in these transactions. In Southern Europe, for example, increasing transmission capacity in Slovenia would not only contribute to the country's security of supply but also to Italy's and Europe's as well[5] (for a more detailed discussion of benefits of cross-border cooperation, please see Acke et al. (2014)). It can be argued that research on types of institutional arrangements cannot be isolated from these positive externalities. Indeed, Strbac et al. (2014) discuss the impacts of institutional and organisational arrangements on the behaviour of different transmission system operators in the UK.

In order to capture these positive externalities and associated values, Acke et al. (2014) highlight that 'regional-level approaches' would enable better use of transnational energy resources, especially in the European context, which is constituted by different national systems. Although several regional collaborative initiatives already exist, within the EU institutional architecture there is not a 'formalised' regional level of governance, which would maximise the benefits of regional collaborations (Acke et al., 2014: pp. 33–34).

Looking at other sectors where protection of the 'common good' is required, Goldthau and Sovacool (2012) suggest the presence of a global authority as a solution. However, Ostrom (2009) emphasises the importance of concerted action among different scales which she sees as a key issue for global solution to climate change. Instead, local-level solutions may engender significant benefits. The 'nested externalities' (Ostrom, 2012) across different parties and scales can be addressed via a polycentric approach. A polycentric system is the 'one where many elements are capable of making mutual adjustments for ordering their relationships with one another within a general system of rules where each element acts with independence of other elements' (see Ostrom (1999), p. 57). Despite these theories, Wolsink (2012) points out that more needs to be done to engender consumer buy in, especially for the adoption of low carbon technologies. We argue that coordination at local level (Hall and Foxon, 2014) would not only be costly but also may not take into account constraints at higher levels or that there might be conflicting goals with adjacent local authorities, yielding suboptimal results. Instead, coordination of activities at regional level would be more suitable as it would allow actors to find flexible solutions within their regions whilst still taking concerted actions with other parties involved.

Indeed, European regions can play a pivotal role in addressing energy problems: although the bulk of competencies for energy regulation rest with national governments, the regional authorities can support the implementation of state interventions (AER, 2010). The AER survey (2010: 37-38) showed that 88% of the 67 regional authorities involved in the research state that they are entitled of competencies to regulate energy consumption, whereas the scope of the regional powers in the realm of energy policy differs across European Member States. Nevertheless, the contribution of regional authorities to planning energy strategies is paramount. In this regard, it is argued that regions can assume a forefront position in energy policy, by limiting energy consumption and promoting the use of renewable energy sources (AER, 2010).

4. Discussion

Building on analysis by Bridge et al. (2013), this paper presents five processes through which low carbon transitions might lead to spatial differentiation and uneven development. These include the clustering of low carbon technologies, the differences between

[5] For a more detailed discussion, please see (accessed on 04/11/2014): http://www.eles.si/en/new-interconnection-between-slovenia-italy.aspx

Table 1
Classification of regional development modelling research.
Source: Albegov et al. (1982, p. 6).

Spatial scope	Type of model Explanatory and predictive	Planning and policy
Inter-regional or multi-regional	Input/output	Multiregional planning
	Spatial general equilibrium	Economic growth
	Central place	Transport and/or investment
	Migration	cost-minimisation
Regional	Input/output	Mathematical programming
	Basic/nonbasic	Spatial competition
	Growth pole	
Intra-regional	Urban land equilibrium	Transportation/land-use
	Transportation	optimisation
	Spatial interaction	Cost-benefit
	Lowry-inspired	Accessibility

urban and rural settings, the economic growth and job creation potential of transitions, agglomeration economies and network constraints, and the public good problem in liberalised energy markets.

A key characteristic of these processes is that they are dynamic, they change over time. Placed between national and local level, regional analysis presents a scale where these temporal and spatial differences can be analysed, interpreted and monitored over time both within (i.e. intra) and between (i.e. inter) regions. An analysis at the national level will be of limited use beyond understanding trends. It will not be able to explain **where** a particular phenomenon is taking place. Similarly, while local analysis can help with understanding where things happen, meaningful interpretation and monitoring of possible changes at such a level can be limited. Analysing phenomena at the region scale can address the limitations of both local and national analyses by providing insights that help to explain and enrich high-level trends, whilst recognising sub-national, often geographically-dependant, patterns that may be lost in an overarching country-scale analysis. Since its inception in the early 1950s, regional science has aimed to develop theory, tools and methods to reduce regional inequalities and facilitate economic growth. These tools and methods have been extensively used in fundamental social and economic policy areas, including population change, migration, economic growth and industrial specialisation. Albegov et al. (1982) classify different types of regional models into two groups depending on whether they are used for explanatory or planning mode, although this distinction is not clear: '*In many cases the same conditions may be derived from both programming and simulation models*' (p. 6). (Table 1)

A policy-relevant example of regional level analysis is the allocation of European structural funds. In order to reduce regional economic inequalities across Member States, the European Commission allocates funds to poorer regions[6] to support rural development, tourism, human capital development, infrastructure and environment (Dall'erba and Le Gallo, 2008). The European Hydrogen Energy Roadmap (European Commission, 2008, including *HyRaMP*, the European Regions and Municipalities Partnership for Hydrogen and Fuel Cells) is another policy initiative recognising the importance of regional constraints and infrastructure related preferences and conditions. Other scholars in science and technology studies literature have also adopted regional frameworks in their analysis (among others, Hodson et al. (2008) on hydrogen initiatives and While et al. (2010) on downscaling of national carbon targets).

Focusing on low carbon transitions in particular, there are more specific reasons why a regional analysis is needed. The inherently geographical nature of low carbon transitions points to the emergence of further spatial and temporal energy inequalities. Spatial inequalities can stem from differences in the availability of renewable resources to socio-economic differences or elsewhere: for example, 30% of UK households are tenants, who do not often have the capacity or incentives to improve the energy efficiency characteristics of their dwellings. There could also be instances where spatial and temporal inequalities overlap and reinforce each other. For example, whilst dynamic and differentiated tariffs can help to extract flexibility capital from householders who are able or willing to shift their demand to off-peak times, due to lifestyles, socio-economic or physical network constraints some may not be able to do so.

The other side of the coin is that diversity and differences in types of household demand profiles, resource availabilities, and infrastructure characteristics could actually offer opportunities to use existing energy infrastructure much more efficiently. In particular, the transition to a smart grid where the cost of providing each extra unit of energy is more reflective of actual costs should enable a better fit between consumers' demand and tariffs that suit their lifestyles in a perfectly competitive market. Under the state ownership model on which UK energy infrastructure has operated in the past, energy was conceptualised as a public good and investment decisions were taken accordingly. Its subsequent privatisation and the introduction of regulatory mechanisms marked its re-conceptualisation as something between a public and private good. The complex involvement of (and interaction between) numerous public and private institutions means that reconfiguration of energy infrastructure towards a low carbon future will hinge upon concerted and coordinated action to utilise system benefits that are distributed across these different actors.

In particular, given the multiplicity of parties and scales involved and the regulated nature of energy systems, the incentivisation of efficient behaviours emerges as another challenge either across the countries or within a country. Some thorny questions emerge: should a European region put the benefits of European connections in front of national priorities and concerns? Or within a country, should benefits from demand side management be used for resolving local network constraints or national balancing? How can consumers be assured that they get the best value? Who decides where these benefits can accrue? A regional level analysis will not only help with coordination of activities, but also analysis and monitoring of the impacts of systematic and nested externalities.

Planning decisions should also be seen to be made legitimately and democratically despite the inevitable emergence of winners and losers, which brings into question the political level at which such decisions ought to be taken. In the UK conflict has already emerged in this area, in practise between the coalition government's commitment to devolve more powers to local authorities – which have powers to block planned developments – and the simplification of regulation found in the National Policy Planning Framework, which seeks to encourage major infrastructure projects such as new nuclear power stations. In addition to economic and social inequalities, therefore, there are additional political inequalities to consider, such as the extent to which the demands of local residents, especially those located in rural areas with less economic and political influence than large population centres, can be overruled to meet wider public needs, such as energy security.

[6] A region is defined poor if its average per capita GDP was 75% below of the European average. In the allocation of funds, the Commission uses Nomenclature of Territorial Unit Statistics (NUTS) regional classification system. There are three hierarchical levels of NUTS regions where sometimes the levels do not necessarily correspond to administrative divisions within a country. There are 139 NUTS3 regions in the UK.

Given these challenges, a review of existing literature analysing regional energy issues reveals that the number of studies focusing on the interdependencies between spatial organisation of economic activity and energy systems has increased in recent years (Table 2). These studies are assigned into five key themes as closely as possible.

Table 2 reveals that while green economy and jobs have been studied most extensively, few studies use spatial econometrics to analyse the clustering of low carbon technologies, yet other studies focus on analysing regional energy system characteristics and differences. Overall, two observations can be drawn from this table: a number of studies use scenario approaches to deal with uncertainty. Indeed, the five issues we have identified can follow different trajectories across time and space. Rather than deterministic approaches, using and developing methods to deal with these nested uncertainties is an important challenge for analysts as well as policy makers. Such scenario-based approaches can facilitate the negotiation and alignment of planning policy and solutions across different scales (from national to regional to local) as well as different policy departments and actors (Wilson, 2009).

Secondly, current tools do not seem to take into account geographical differences across the urban-rural gradient. There is a need for a new set of multi-level models that can capture interactions between macroeconomic and network structures at different spatial scales and within different regulatory and market environments. Partly linked with the public good problem, Zhang (2010) reports how fiscal arrangements can drive the focus of local authorities to pursue economic growth at the expense of environment if the allocation of resources between central and local government is not responsive to local needs.

5. Conclusions and policy implications

We argue that existing policy and academic interest in national or local energy issues does not offer a framework for understanding and addressing the challenges associated with the geographically divergent nature of low carbon transitions. Whilst the employment impacts of low carbon transitions have received ample scrutiny, there are other issues that can lead to spatial differentiation and uneven development. In particular, these include the clustering of low carbon technologies, urban and rural differences in the built environment, agglomeration economies and network constraints, and liberalised energy markets with different actors.

Although energy systems were developed over centuries in incremental steps through interactions between technologies, organisational structures and socio-economic conditions, a rapid and radical system change is needed in response to the energy trilemma. Past transitions have produced enormous and complex social and economic change as well as differences in the distribution of the associated costs and benefits. A major challenge for policymakers is to find ways of utilising these differences to ensure that any such changes do not deepen existing inequalities. This applies to the quality and price of power provision but also the economic opportunities that are gained and lost as a result of a move away from fossil fuels. Although the potential of the low carbon transition to reduce inequality has been widely touted, its spatial and economic form is still emerging, and so little is known about both the type and degree of inequality that may arise.

More specifically, our analysis highlights five key issues that are relevant for policy makers:

Table 2
Review of existing methods to analyse low carbon transitions.

	Aim	Geographical scope	Method
Clustering of low carbon technologies			
Balta-Ozkan et al. (In preparation)	Understanding spatial patterns of photovoltaic deployment and its determinants	United Kingdom	Spatial econometrics
Schaffer and Brun (In preparation)	Understanding spatial patterns of photovoltaic deployment and its determinants	Germany	Spatial econometrics
Green economy and jobs			
Barker et al. (2007)	Analysing macroeconomic effects of efficiency policies for energy-intensive industries	United Kingdom	Multi-region econometric input–output model
Bohringer and Rutherford (2013)	Analysing impacts of European climate and energy policy goals on the economy	Poland	Multi-region computable general equilibrium model
Cai et al. (2011)	Analysing direct and indirect employment impacts of climate policies in the power section	China	Both analytical and input–output models
Lehr et al. (2012)	To analyse the labour market implications of large renewable energy investments	Germany	Econometric input–output model (PANTA RHEI model)
Çetin and Eğrican (2011)	Investigating the employment impacts of the solar energy industry	Turkey	Literature review and use of capacity targets
Wei et al. (2010)	Presentation of an analytical job creation model for the US power sector from 2009 to 2030	USA	Meta study and analytical calculation under different scenarios
Ratliff et al. (2010)	Analysis of state-level economic impact of wind power	Utah, USA	Input–output model, JEDI
Loomis and Hinman (2009)	Analysis of the economic impact of wind energy	Illinois, USA	Input–output model, JEDI
Gilmartin and Allan (2015)	To understand the regional employment impacts of marine energy	Scotland	General equilibrium approach
Regional differences and inequalities			
Perobelli and de Oliveira (2013)	Development of an indicator to calculate regional energy development potentials	Brazil	Factor analysis for the development of the indicator and an exploratory spatial data analysis
De Almeida et al. (2010)	Analysis of the linkage between transport and equity at regional level as well as between economic performance and regional equity	Minas Gerais, Brazil	Spatial computable general equilibrium model
Santos et al. (2013)	Assessment of the regional effects of tariff policy on the electricity sector	Brazil	Interregional Computable General Equilibrium model
Gomi et al. (2010)	Analysis of future carbon pathways	Kyoto, Japan	Export-base approach
Liang et al. (2007)	Understand future energy requirements under different scenarios	China	Multi-region input–output model

- The need for a radical, system-wide change raises questions around how such a transition can be managed effectively and potential risks avoided or mitigated. The range and variety of possible outcomes is baffling, and a systemic way of monitoring progress and assessing whether we are following a trajectory consisting with our goals would benefit the industry by contributing to the long-term policy stability. The development of a set of indicators to gauge the level of change occurring within and between regional economies on a variety of fronts, such as fundamental changes in the structure of the economy and changing levels of inequality, could be sufficient for this, and could bring together government departments to tackle cross-cutting policy issues. The regular updating of these indicators over time and space will help to monitor the direction of change and any potential interventions that are needed along the way.
- The development and use of such indicators can also help with the development of policies that take into account wider socio-economic and infrastructure differences. This could include identifying regions with high penetration of electric vehicles or heat pumps and development of region-specific financial incentives to initiate demand side response to reduce network reinforcement costs where possible. Regional oversight would also help to monitor the effects of such policies in neighbouring regions. Coordinated efforts such as these may help to analyse regional trade-offs more explicitly and contribute to the development of more effective policies to deliver optimum system benefits, which may not emerge from a national analysis.
- Policy-makers may also wish to attempt to assess the possible impacts on inter- and intra-regional inequality, through careful analysis of the industries likely to contract or expand as a result of low carbon policy. Such analysis could include projections of the types of jobs created, their long-term sustainability, whether wealth generated will stay in local economies or flow outwards. Policies could then be tailored to local areas to take such issues into account or be designed centrally to include flexibility in implementation, in addition to promoting the economic potential of regional hubs as a way of revitalising poorer regions.
- No matter what the shape of the future energy system (whether a centralised, upstream decarbonised or more decentralised and local), green jobs would be affected. However, the current focus on green economy and jobs needs to be expanded further to include their socio-economic characteristics and location as well as their implications for other social policy goals around equality and workplace diversity.
- Finally, rather than deterministic approaches, the use of scenarios can help facilitate the alignment of policy goals at different scales and across different actors, as well as analysing the impacts of policies as a whole more systematically.

Over the years regional science has developed a number of research tools to monitor and analyse regional inequalities. Research tools such as shift share analysis, social accounting matrices, or spatial computable general equilibrium models stand to provide a better understanding of regional interdependencies and their impacts on inequality (De Almeida et al., 2010; Santos et al., 2013). The challenge for research here is to develop tools and methods that capture the diversity of actors as well as differences in socio-economic structures across space, all within a multi-level framework. The need for a new set of multi-level models that can capture the interactions between macroeconomic and network structures at different spatial scales and within different types of regulation and market environments is clear and urgent. While different temporal scales and data availability are likely to be key challenges, regional science offers a good starting point to address these issues. Exploration of further synergies between energy studies and urban and regional planning can only help to manage the diversity and differences in energy networks to deliver equitable outcomes for years to come.

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