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A low carbon industrial revolution? Insights and challenges from past technological and economic transformations

Peter J.G. Pearson [a,*], Timothy J. Foxon [b]

[a] Low Carbon Research Institute, Welsh School of Architecture, Cardiff University, Bute Building, King Edward VII Avenue, Cardiff, CF10 3NB, UK
[b] Sustainability Research Institute, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

HIGHLIGHTS

- ▸ Investigates lessons for a low carbon transition from past industrial revolutions.
- ▸ Explores the implications of 'general purpose technologies' and their properties.
- ▸ Examines analysis of 'long waves' of technological progress and diffusion.
- ▸ Draws insights for low carbon transitions and policy.

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ABSTRACT

Recent efforts to promote a transition to a low carbon economy have been influenced by suggestions that a low carbon transition offers challenges and might yield economic benefits comparable to those of the previous industrial revolutions. This paper examines these arguments and the challenges facing a low carbon transition, by drawing on recent thinking on the technological, economic and institutional factors that enabled and sustained the first (British) industrial revolution, and the role of 'general purpose technologies' in stimulating and sustaining this and subsequent industrial transformation processes that have contributed to significant macroeconomic gains. These revolutions involved profound, long drawn-out changes in economy, technology and society; and although their energy transitions led to long-run economic benefits, they took many decades to develop. To reap significant long-run economic benefits from a low carbon transition sooner rather than later would require systemic efforts and incentives for low carbon innovation and substitution of high-carbon technologies. We conclude that while achieving a low carbon transition may require societal changes on a scale comparable with those of previous industrial revolutions, this transition does not yet resemble previous industrial revolutions. A successful low carbon transition would, however, amount to a different kind of industrial revolution.

1. Introduction: Learning from history for a low carbon transition

Policy-makers (e.g., Huhne, 2011) and academic analysts (e.g., Stern, 2011a, 2011b, 2012) have recently argued that that a low carbon transition could take the form of a 'low carbon industrial revolution'. Two key propositions underlie this suggestion. First, that the scale of changes in technologies, institutions and practices necessary to mitigate greenhouse gas emissions and climate change is comparable with the scale of changes experienced in past industrial revolutions. Second, that the productivity gains and economic welfare benefits ensuing from a low carbon transition would be similar to those of past revolutions, making a low carbon transition economically as well as environmentally desirable. This paper aims to examine these propositions, by critically reviewing recent insights into the causes and consequences of past industrial revolutions and long-term technological and economic changes, and examining the lessons for a low carbon transition. This informs the features that a low carbon transition would need to have in order to constitute a 'low carbon industrial revolution', and examines the extent to which low carbon technologies, institutions and practices currently exhibit these features.

There are vast literatures on these issues, and so we selectively draw on what we regard as leading representatives of current

* Corresponding author. Tel.: +44 2920876617.
E-mail addresses: pearsonpj@cardiff.ac.uk (P.J.G. Pearson), t.j.foxon@leeds.ac.uk (T.J. Foxon).

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views in them. In particular, we draw on analyses which have examined the (first) industrial revolution in Britain in the 18th and 19th Centuries (Allen, 2009; Mokyr, 2009; Wrigley, 2010; Crafts, 2010a), the relations between long-term technological, institutional and economic changes (Freeman and Perez, 1988; Freeman and Louca, 2001) and the role of so-called 'general purpose technologies' in long-term economic growth (Helpman, 1998; Lipsey et al., 1998, 2005). While these analyses have developed under different academic traditions, we argue that they share many common features. It is these broad insights that are helpful in understanding the potential for, and nature of, a low carbon transition that might also be an industrial revolution. Our thinking also been informed by the literature on socio-technical transitions that has analysed transitions in systems of provision for end-user services (Geels, 2002, 2005; Grin et al., 2010), though, as argued elsewhere (Foxon, 2011), this literature has largely neglected the economic aspects which are the focus of our attention here.

The paper has the following structure. Section 2 briefly reviews some key issues relevant to a potential low carbon industrial revolution. Section 3 examines the insights to be gained from examining analyses of past industrial revolutions and the role of general purpose technologies in long-term economic growth. Section 4 draws implications for the formation of a low-carbon industrial revolution, relating to the dissemination of low carbon technologies, the technical characteristics of these technologies, the response of incumbent technologies to competition from new technologies, and the potential for macroeconomic rebound effects that could make achieving carbon emission reduction targets more difficult. Section 5 concludes by discussing the implications for research and policy on understanding and realising a low carbon industrial revolution.

2. Key issues concerning a potential low-carbon industrial revolution

Global leaders at the 2009 Copenhagen Climate Change Conference agreed a target to limit increases in global temperature due to human activities to 2 °C above pre-industrial levels (UNFCCC, 2009). The scientific evidence strongly suggests that this would require reductions in global greenhouse gas emissions of the order by 50% by 2050. As well as changes in land use and agricultural systems, this would mean a transformation in systems of energy supply and demand towards low carbon technologies and practices, i.e., a low carbon transition. The Stern Review on the economics of climate change, undertaken for the UK Government, argued that the costs of such a low carbon transition, though substantial, would be less than the costs and risks of the impacts of unmitigated climate change if high carbon technologies and practices were to continue to dominate systems for energy provision (Stern, 2007).

The UK made relatively early commitments to act on climate change (Pearson and Watson, 2012) and recently took a lead in setting a legal and institutional framework to promote a transition to a low carbon economy. This framework includes: a commitment in the *Climate Change Act* 2008 (HMG (Her Majesty's Government), 2008) to reduce the UK's greenhouse gas emissions by at least 80% by 2050, compared to 1990 levels; the Committee on Climate Change, a new institution comprising external energy and climate experts, to propose successive sets of five-year carbon 'budgets' towards the target (Committee on Climate Change, 2010); the establishment of the Department of Energy and Climate Change in 2009, and the 2011 *Carbon Plan* (HMG (Her Majesty's Government), 2011). These developments have been influenced by scientific arguments about the threat of climate change (Inter-governmental Panel on Climate Change (IPCC), 2007), and the above economic arguments of the Stern Review (Stern, 2007). On the one hand, Stern (2011a, 2011b, 2012) and others have subsequently argued that a successful low carbon transition would need to be on the scale of past industrial revolutions or 'waves' of technological transformation; and on the other hand, it has been posited that a low carbon transition would bring sustained economic benefits akin to those of previous industrial revolutions (e.g., Huhne, 2011; Rifkin 2011).

The attraction of the notion of a new low carbon industrial revolution, especially in today's context of financial stringency and economic stagnation, is not hard to understand. It draws on the recognition that previous revolutions not only involved new technologies supplementing and eventually displacing incumbent, less economically efficient technologies and fuels but also resulted in a continuing and widening stream of innovations and productivity improvements over many decades (Allen 2009; Mokyr, 2009; Wrigley, 2010). This suggests the value of examining the properties of the core technological innovations of previous industrial revolutions that enabled these sustained productivity gains. This might help to understand what low carbon technologies might need to emulate if they are to yield similar long run gains. In so doing, we suggest that it is also useful to examine the changing influences and circumstances that stimulated these past technological advances and helped develop and sustain the improvements they spawned. This may help to clarify the scale, scope and ambition of the challenges of achieving a low carbon transition that would amount to an industrial revolution. Not least because the low carbon transition depends on the new technologies' success in displacing existing fossil fuel-based technologies and the institutions and routines that maintain them, it is also appropriate to consider the factors that affect the relationships between new and incumbent technologies and institutions.

Before examining these issues, however, we note three key features of the low carbon transition. First, the market prospects of low carbon technologies differ from those of most of the core technologies of previous industrial revolutions. Crucially, they primarily deliver a social benefit, i.e., the public good of mitigating climate change, rather than purely private benefits to the individuals or firms adopting them. In the language of economics, greenhouse gas emissions are 'externalities' that are not fully traded and priced in markets, because their reduction as yet lacks durable, credible market value. Hence, addressing climate change is an issue for society in general and cannot be achieved solely through the responses of private markets, buyers and sellers. This suggests a much more prominent role for public policy in 'managing' this transition than in many, although not all, previous energy transitions. It also raises major questions about the roles and influence of key societal actors, especially government, market and civil society actors (Foxon et al., 2010; Foxon, in press). Second, related to this, policy strategies, actions and instruments concerned with a low carbon transition are strongly influenced by the interplay and trade-offs between climate and other energy policy objectives, such as energy security, affordability and international competitiveness. Third, the time scale for achieving a low carbon transition of the order needed to meet challenging carbon emission reduction targets by 2050 would be significantly shorter than previous comparable industrial transformations (Fouquet, 2010; Smil, 2010). These three significant contextual features influence whether and how a low carbon transition might also constitute an industrial revolution.

3. Insights from previous industrial revolutions and the role of general purpose technologies

3.1. Britain's 'first industrial revolution'

The long transformation of economy and society in Britain, known as the ('First' or 'British') 'Industrial Revolution', which saw sustained acceleration in technological progress, is widely regarded as the first instance of modern economic growth (Mokyr 2009, 4). While key aspects of it unfolded between about 1750 and 1850, some significant social, economic and technical developments in earlier centuries also influenced it and would continue to flow from it. Wrigley (1988, 2010) presents an elegant analysis of how Britain was gradually able to escape from the energy constraints on productivity and output experienced in a traditional 'organic' economy. In an organic economy, apart from what can be got from intermittent wind power and water power in fixed locations, *flows* of energy are limited to what can be captured and harnessed via plant photosynthesis from a given land area, using available technologies and knowledge. The organic material can feed people and draught animals or provide heat and other energy services. The constraints of Britain's organic economy limited its ability to deliver food, clothing, housing and energy. The growing exploitation and drawing down of *stocks* of a resource, coal, the fossilised accumulation of the residues of past photosynthesis, relaxed these energy constraints. Innovations including the development of the steam engine, new spinning and weaving technologies and cotton mills, the substitution of coal and coke for wood and charcoal in metal manufacture, along with other significant social, political, institutional and technological changes helped drive and sustain the mechanisation, urbanisation and industrialisation of this first industrial revolution. They led to dramatic reductions in the cost of direct energy services (Fouquet, 2008; Fouquet and Pearson, 1998, 2003, 2006, 2011), and enabled efficiency improvements in manufacturing and other processes that resulted in higher productivity, quality improvements and cost reductions in many other goods and services. They also led after some considerable time to much higher standards of living for the population at large.

While Robert Allen notes that the explanation of the Industrial Revolution "has been a long-standing problem in social science and has generated all manner of theories", here we consider two recent major interpretations, those of Allen (2009) and Mokyr (2009), and what they say about the role of energy.[1] We focus on these studies not least because, while their authors claim them to be competing, fellow economic historian Nicholas Crafts (2010a) argues that they offer analyses that are complementary and significant. In his review article, Crafts stresses that while Allen and Mokyr place the explanation of sustained acceleration in technological progress at the heart of their stories, they differ in their reasons: "Allen stresses that the new technologies were invented in Britain because they were profitable there but not elsewhere, while Mokyr sees the Enlightenment as highly significant and underestimated by previous scholars" (Crafts, 2010a, 153). In what follows, we draw on the works of these authors, as well as Crafts' review.

3.1.1. *Allen's interpretation*

Allen begins by analysing key socio-economic, technical and other changes, which occurred in earlier centuries and help explain the distinctiveness of Britain's economy and why it alone succeeded in industrialising when it did, in comparison with other countries. He argues that the Industrial Revolution was the result of processes of socio-economic evolution running back to the late Middle Ages; and that it was set on its path by the demographic, economic and agricultural changes that followed the Black Death in the 14th Century. The precursors included the 'agricultural revolution', with higher farm output and productivity and lower agricultural employment, the successful exports of light worsted woollen cloth (the 'new draperies') to Europe, relatively high wages and the growth of the urban, commercial economy, which "drove the English economy forward in the centuries before the Industrial Revolution" (Allen, 2009, 106). There were positive feedbacks at work. For example, more productive agriculture encouraged urbanisation, while the growth of cities and demand caused agricultural productivity to rise. In particular, London's growth was spectacular: for example, between 1500 and 1800, population grew twenty-fold, from 50,000 to 1 million. This growth and higher incomes led to higher energy demand and woodfuel shortages, which were eased by exploiting relatively cheaper coal, increasingly available from Britain's coal resources via favourably located ports. As Griffin (2010) notes, Allen memorably characterises the British economy's early success as "due to long-haired sheep, cheap coal and the imperial foreign policy that secured a rising volume of trade" (Allen, 2009, 131).

Having addressed the pre-industrial economy, Allen focuses on what stimulated the technological breakthroughs associated with a set of famous 'macro-inventions', including the steam engine, that triggered sequences of sustained technological progress. He finds that "The Industrial Revolution, in short, was invented in Britain in the eighteenth century because it paid to invent it there" (Allen, 2009, 2). This incentive arose because the early modern economy's commercial expansion resulted in the "unique wage and price structure that Britain enjoyed in the eighteenth century. Wages were high and energy was cheap" (p. 22). This price structure, he asserts, led to the Industrial Revolution by giving firms strong incentives to invent technologies that substituted capital and coal for relatively costly labour. Britain had a high wage economy in three senses: wages were high relative to those in competing countries; they were high relative to the cost of consumer goods, so living standards in Britain were higher than elsewhere (and workers could afford a better diet, including beef, beer and bread); and, crucially for the incentive to invent coal-powered mechanised technologies in Britain, wages were high relative to the prices of both capital and energy. The high wage economy also led to a rising demand for literacy and numeracy skills and gave parents the income with which to purchase them, supplying Britain with skills for the 'high-tech' revolution.

Allen argues that in response to these stimuli, a set of 'macro-inventions' was developed that led to the supply of technologies that substituted capital and energy for relatively expensive labour, raising output per worker: Savery's and Newcomen's 'atmospheric' steam engines and later developments by Watt and others used more capital and coal to do this; cotton mills used machines to do it; new iron-making technologies substituted cheap coal for expensive charcoal produced with costly labour; and other forms of mechanisation also raised output per worker. This part of Allen's argument may be summarised as follows:

As noted above, Britain's unique price and wage structure was key. The high fixed research and development costs of developing macro-inventions into commercially viable technologies are only worth incurring where the technology is profitable to adopt (which turns on relative factor prices), *and* the market is big enough to reward the developers for perfecting the technology. Allen illustrates this argument by showing that the profitability of adopting macro-inventions, including the spinning jenny, Arkwright's mill and coke smelting, was rational at British but not at French prices. However, the widespread adoption of these technologies took time. The engineering challenges of these initially inefficient technologies, which prospered in niches such as pumping water from coal mines, stimulated their improvement via a series of 'micro-inventions'. This required research and development (R & D), which Allen suggests emerged as an

[1] Both authors have published widely on this subject. For simplicity we focus on the two recent sources cited above.

important business practice in the eighteenth century. The R & D was accompanied by the appearance of capitalist financiers and often a reliance on patents to realise returns on investment (although vigorous patent enforcement could also become an impediment to technical progress). There was also in some places a willingness to engage in 'collective invention'. This happened, for example, when knowledge sharing and cooperation among Cornish mine managers led to the reduction of the fuel consumption of their pumping engines after Watt withdrew his engineers on the expiry of his patent in 1800 and engine performance fell. Thus the macro-inventions were significantly improved over time via these processes of micro-invention, which Allen argues proved to be 'Hicks-neutral', i.e., they saved on all inputs, not just labour. Consequently, some decades later these technologies became profitable to adopt in many countries with different relative price structures - and British competitive advantage faded.

A favourable configuration of prices and wages would not on its own have been sufficient to deliver and sustain the Industrial Revolution: Allen accepts that "the rate of invention is determined by the supply of inventors as well as by the demand for new products and processes" (p. 238). However, he argues that although improved institutions, increasing knowledge of the natural world and a focus on an empirical approach to production (factors emphasised by Mokyr, as we discuss below) may have increased the supply of technology, "they would have had little impact on invention without a *demand* for new techniques" (p. 15). They were thus necessary but not sufficient conditions for the Industrial Revolution. While he does not ignore supply side developments like the growth of scientific knowledge or the spread of scientific culture, he emphasises other factors that increased the supply of technology. Here, as we have seen, he argues that it was the role of the higher real wage in making the population at large better able to afford education and training than their counterparts elsewhere, with resulting advances in literacy and numeracy, that contributed to invention and innovation. And he concludes that "because high wages and cheap energy were consequences of Britain's success in the global economy, the Industrial Revolution can be traced back to prior economic success" (p. 15).

3.1.2. Mokyr's interpretation

Mokyr argues that the Industrial Revolution is best defined as the "set of events that placed technology in the position of the main engine of economic change". His basic premise, in contrast to that of Allen, is that it grew out of "the social and intellectual foundations laid by the Enlightenment and the Scientific Revolution" (Mokyr, 2009, 5, 11). He claims that while the Enlightenment was not the sole cause of the Industrial Revolution – other influences, from a favourable location and mineral resources to a pre-existing middle-class and the skills of artisans, played a role – "the Enlightenment is the 600-pound gorilla in the room of modern economic growth that nobody has mentioned so far" (p. 487). According to Mokyr, Britain led the Industrial Revolution because it was able to exploit its favourable human and physical resource endowment "thanks to the great synergy of the Enlightenment: the combination of the Baconian program in useful knowledge and the recognition that better institutions created better incentives" (Mokyr, 2009, 122).[2] Mokyr suggests that what was needed to generate an industrial revolution "was the right combination of useful knowledge generated by scientists, engineers and inventors to be exploited by a supply of skilled craftsmen in an institutional environment that produced the correct incentives for entrepreneurs" (p. 116).

In contrast to Allen, he suggests that Britain's advantages lay mainly on the supply rather than the demand side of the economy, although growing and changing patterns of demand played a role. One of the factors that set Britain apart had been the emergence of a substantial middle class before the Industrial Revolution. They included merchants, professionals, well-off farmers and artisans, who consumed more consumer durables that required precision skills to make and so provided for the cadres of (also middle class) craftsmen whose abilities were vital if innovative ideas were to be realised successfully and reliably (p. 116). Mokyr refers also to the "fascinating hypothesis" of De Vries (1994, 2008), that the Industrial Revolution was preceded by and coincided with an 'Industrious Revolution' (p. 272). In this revolution, household members were more willing to substitute work for leisure, to work longer hours and increasingly for money rather than in the home, because the market offered more things that they liked and needed cash to pay for. Mokyr suggests that, while an exogenous change in preferences cannot be ruled out, this kind of redeployment of household resources could also have been influenced by technological changes. Manufacturers were developing growing capabilities to satisfy and encourage demand. Following Berg (2005), he suggests that producers "learned to make goods attuned to changing consumer preferences and yet were "branded" so that consumers knew what they were getting". These desirable, durable yet reasonably priced goods reflected the manufacturers' capabilities to give consumers what they wanted. And he notes that the concept of ready-made mass-marketed clothing emerged in the eighteenth century (Mokyr, 2009, 142–44).

As noted earlier, Mokyr views the ideology of the Enlightenment as not only successful in improving technological capabilities but also in reducing rent-seeking and promoting competitive markets, while social norms favoured "gentlemanly capitalism" rather than opportunistic behaviour. Economic growth requires an economy's social and political capabilities to adapt and the Enlightenment advocated new institutions that "cleared up centuries of mercantilist policies, regulations and social controls whose objective had been primarily to redistribute resources to politically connected groups and to enhance the interests of the Crown" (p. 486). Consequently, the enlightened age was different from the age of mercantilism both in how it accumulated, disseminated and employed useful knowledge and in how "its economic institutions operated to *create* rather than *redistribute* wealth". So the ideology of the Enlightenment had two impacts: it was conducive on the one hand to the production of more useful knowledge and reduced costs of access to it and on the other to improved incentive structures via the promotion of better economic policy and institutions.

To summarise, Mokyr argues that without the ideas of the Enlightenment, it is not possible to imagine how the wave of technological innovations after 1760 could have been transformed into what is now recognised as modern economic growth, rather than a process in which after initial flourishing the economy would have settled down in a new stationary state: "The Enlightenment, then, was indispensable not in "causing" the Industrial Revolution but in turning it into the taproot of economic growth" (Mokyr, 2009, 488).

3.1.3. A possible synthesis?

Crafts (2010a) suggests that, while they draw on various precursors in the literature, Allen and Mokyr offer greater detail and sophistication. He concludes that "Allen's analysis is theoretically defensible and his emphasis on the costs of development of a technology goes with the flow of recent growth economics", while suggesting that more quantification is needed to strengthen

[2] Here it is worth noting that Mokyr sees institutions as "the rules by which the economic game is played and the beliefs that generate these rules and people's adherence to them (Mokyr, 2009, 7).

Allen's claims. Similarly, while Mokyr's stress on the dual impact of the ideology of the Enlightenment fits perfectly with endogenous growth theory, Crafts says that "the issues that arise are not so much with the logic of the argument but its empirical validity". He judges that both authors offer important insights into "how and why a sustained and significant acceleration of technological progress took place in Britain from the late eighteenth century onwards". Their ideas are not mutually exclusive but rather potentially complementary: a combination of both claims "might produce the hypothesis that this resulted from the responsiveness of agents, which was augmented by the Enlightenment, to the wage and price configuration that underpinned the profitability of innovative effort in the eighteenth century" (Crafts 2010a, 166).

The analyses of Allen and Mokyr and those of other precursors, to which we have not done justice, demonstrate that an extraordinarily rich blend of economic, cultural, institutional and technological factors preceded, catalysed and sustained the first industrial revolution. And whilst it was far from being a 'managed' transition in the modern sense – and was about much more than simply energy – it was shaped at various times and places by the deliberate choices and agency of a range of actors and institutions.

3.2. Interactions between long-term technological change and economic growth

In addition to the roles of demand, relative factor prices and the underlying knowledge and skill base that Allen and Mokyr emphasise, other authors have argued that key technologies had attributes that enabled them to exert a strong influence on wider and enduring socio-economic change. Here, we draw on this second, parallel literature that has sought to investigate the broader patterns of interactions between long-term technological change and economic growth. This has argued that it is the innovation and adoption of new technologies that are able to stimulate wider changes and opportunities which has been a significant source of economic growth, such as that associated with the first industrial revolution. Two strands of this literature may be identified, one that argues that radical technological change has led to 'long waves' of economic development, and a second that focuses on the economic consequences of certain 'general purpose technologies'. These authors are keen to stress that these attributes of technologies do not 'determine' wider socio-economic change, but they enable co-evolutionary changes in institutions and practices that, together with the technology changes, give rise to significant macroeconomic impacts (cf. Foxon, 2011). Both of these interpretations have been somewhat controversial, but again, we suggest that the broad claims are sufficiently robust to be drawn on for our purposes.[3]

General purpose technologies (GPTs) have been defined as "a single generic technology [...] that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects" (Lipsey et al., 2005, 98; see also Bresnahan and Trajtenberg, 1995 and Helpman, 1998). Hence GPTs are said to have three key properties: (i) *Technological Dynamism:* they have the capacity for continued innovation, so costs fall and the quality of the services they deliver rise over time; (ii) *Pervasiveness:* there is a wide range of general applications; and (iii) *Innovational Complementarities*: GPT users improve their own technologies and find new uses for the GPT in combination with their technologies and practices. The steam engine, the internal combustion engine and electrification (both associated with the second industrial revolution of the late 19th and early 20th centuries), and recent information and communication technologies (ICT) (sometimes associated with a third industrial revolution) have been cited as examples of GPTs.

Broadberry (2007) notes that the idea of a GPT helps to address one of the most important questions about the first industrial revolution, why the technological progress continued rather than petering out, as in earlier growth episodes. Thus, the economic significance of GPTs is that the widespread diffusion of the GPT and its linked technologies and practices enables an increase in innovative activities, leading to the generation of mutually reinforcing productivity gains over long time periods. However, this typically requires a long acclimatisation phase, in which other technologies, forms of organisation, institutions and consumption patterns adapt to the new GPT. This has been noted by evolutionary economists, such as Freeman and Perez (1988). They argued that the widespread deployment of radical new technologies leads to structural crises of adjustment, as appropriate new institutions and industrial structures have to be developed to accommodate them. This led them to identify five 'long waves' of economic development, in which growth is driven by the development and application of new technologies and processes, such as the steam engine, electrification and mass production, but from which the full economic benefits are only realised when wider institutions and practices have had time to adapt to these technologies and processes (Freeman and Perez, 1988; Freeman and Louca, 2001). This long time lag in the economic impact of new technologies is supported by more formal statistical analyses of contributions to productivity growth. For example, Crafts (2004) argues that steam power contributed relatively little to productivity growth in the UK before 1830, and only made a significant impact after 1850, with the development of the high-pressure steam engine and its use in complementary technologies, such as railway locomotion and steamships, 80 years after the development of James Watt's first external condenser steam engine and a century and a half after Newcomen's 'atmospheric' engine.

This thinking about technological change and economic growth suggests that for a low carbon transition to become a successful low carbon industrial revolution, the key technologies would need to be able to stimulate and sustain the longer term delivery of significant, wider productivity gains and other benefits. We suggest that it is not clear that the set of currently available low carbon technologies yet demonstrate the properties necessary for this.

4. Implications for the formation of a low carbon industrial revolution

In the light of the features of the low carbon transition referred to in Section 2, we can now ask what are the implications for a low carbon industrial revolution of the above insights into the socio-economic conditions and technology features that characterised past industrial revolutions. First, we need to emphasise that because mitigating climate change is a social good, it requires effective and systemic policy to promote a low carbon transition and avoid 'escape routes' associated with partial solutions (van den Bergh, 2012). Thus, a low carbon transition differs from past industrial revolutions that were primarily driven by the private economic benefits of adopting new technologies and practices (albeit sometimes supported, intentionally or unintentionally, by government and regulatory actors and institutional change). However, we argue that a better understanding both of the scale of socio-economic changes associated with past industrial revolutions and of how these delivered macroeconomic benefits to society could inform policies and choices associated with a low carbon transition. In

[3] See Verspagen (2005) for a fuller discussion of these two approaches and of the convergences and differences between them. See also Fagerberg (2002, 2003) and Broadberry (2007).

particular, if low carbon policies were to take into account the scale of the transformation needed and could be designed, as far as possible, to stimulate promotion of wider macroeconomic benefits, then this could make these policies more technologically effective, socially acceptable and politically feasible. So, we assess the extent to which conditions analogous to those that drove the first industrial revolution and the attributes of GPTs might apply to the current situation of the promotion of a low carbon transition and the attributes of currently available low carbon technologies.

4.1. Conditions for a low carbon industrial revolution

As we have seen, economic historians have argued that favourable relative factor prices driving the profitability of technological innovations, social and institutional features promoting productive innovation rather than rent-seeking, and the availability of skilled inventors and craftsmen to exploit these opportunities, all played a part in the first industrial revolution in Britain. However, they also noted that the coming together of these aspects had deep historical roots, and the consequent realisation of technological change took significant periods of time. This suggests the value of examining what may be analogous conditions for a low carbon industrial revolution and that, if these can be identified, then early action is likely to be needed to ensure that they are in place.

Allen (2009) argued that Britain's unique combination of high relative labour costs and access to cheap energy drove innovation and deployment of energy- and capital-intensive, labour-saving technologies in the first industrial revolution. Today's high-carbon energy technologies for providing power, heating and transport services have benefited from long periods of increasing returns to adoption of the technologies and supporting institutions, leading to significant efficiency improvements and cost reductions (Unruh, 2000). Though the cost of low-carbon energy technologies is decreasing with their adoption, most are not yet cost competitive with high-carbon incumbents. This supports the need for carbon pricing, in the form of carbon taxes or tradable emissions permits (Bowen, 2011), and low carbon innovation policies to internalise the carbon externality and enable low carbon technologies to benefit from positive externalities or spillover effects (Grubb et al., 2002). It also suggests that the promotion of other attributes that are complementary to the core low carbon attribute is likely to be crucial, as we discuss further below. A further insight from past techno-economic change is that improvements in the performance of incumbent technologies can be stimulated by competition from new alternatives—the so-called 'sailing ship' effect, as we discuss below.

Lessons may also be drawn from Mokyr's (2009) insights into the roles of the availability of scientists, engineers and inventors with useful knowledge and skills, and of institutions providing incentives for innovation in productive activities in the first industrial revolution. This suggests the importance of measures to overcome market and governance failures in the provision of low carbon skills, for example, by providing clear and consistent policy frameworks that signal the likely benefits for employers and employees to invest in skills training (Jagger et al., 2012). It also suggests the need for institutions and incentives to direct innovation and human capital towards productive low carbon technologies and processes, rather than, for example, towards the creation of ever more complex instruments for financial speculation.

4.2. Implications of the technical characteristics of low carbon technologies

We now turn to considering whether the characteristics or attributes of current low carbon technologies are sufficient to enhance their rapid and widespread adoption and hence their potential to contribute to other economic activities. If low carbon technologies generally offered enhanced performance to users in some way, then history suggests that they would sooner or later become widely disseminated through the action of market forces. There are two key issues here. First, as noted, currently the main benefit of low carbon technologies is the social benefit of helping to mitigating climate change, rather than the private benefits to users of these technologies. The conversion of this social benefit to a private benefit requires inter alia the imposition of a carbon price, through a carbon tax or tradable permit scheme. This is likely to be slowed or weakened by the lobbying efforts of those industries – or countries – that would suffer from a high carbon price, if they were not compensated in some way, as the experience of the EU Emissions Trading Scheme suggests. Second, the core technical characteristics of low carbon technologies mean that they are often not full substitutes for high carbon technologies. For example, renewable energy technologies require the harnessing of diffuse energy flows, rather than concentrated energy sources, nuclear power for electricity generation has significant issues with safety and waste disposal, and the use of carbon capture and storage with coal or gas involves an energy penalty and consequent lower efficiency of conversion, as well as other uncertainties that may hamper its uptake (Watson et al., 2012). These two issues create a significant challenge for the initial and speedy dissemination of low carbon technologies.

The successful initial deployment of low carbon technologies and practices lies, therefore, in their ability to compete with and displace the incumbent set of high carbon fossil fuels and/or their associated end-use technologies. A fruitful way of thinking about this competition is through the approach to consumer theory in economics developed by Lancaster (1966) and Ironmonger (1972). This 'new approach', which drew on the marketing literature, helped analyse the reactions of consumers/users to new or modified goods and services more richly than the traditional neo-classical approach. In the new approach, consumers are held to derive satisfaction not from goods, as previously understood, but from desirable combinations or 'bundles' of the intrinsic 'characteristics' or 'attributes' yielded by the goods. Thus for Lancaster, consumption is an activity or process in which goods, singly or in combination, are inputs and in which the output is a bundle of characteristics from which the consumer derives more or less satisfaction (an example would be the combination of inputs that make up a 'meal'). In contrast with the traditional theory, in which the prices of goods determine choices, here it is the (often implicit) prices of the characteristics that matter. Moreover, these objectively measurable characteristics may be physical, chemical, biological and so on. As an example, Lancaster (1966, 134) cites the choice between a grey Chevrolet and a red Chevrolet: "Here we regard them as goods associated with satisfaction vectors which differ in only one component, and we can proceed to look at the situation in much the same way as the consumer – or even the economist, in private life – would look at it." This approach, with work by Rosen (1974), offered a theoretical basis for the subsequent development of 'hedonic pricing' and the econometric estimation of the implicit prices of characteristics. Importantly, it enabled the estimation of the prices of both desirable and undesirable characteristics, for example those associated with houses in particular locations and environments.

In the low carbon context, we can think of low carbon technologies as having bundles of characteristics, from the technical to the financial, economic, environmental and social. As we have suggested, therefore, part of the market challenge for the widespread adoption of a new type of technology is whether it can offer broadly the same bundle of desirable characteristics as those of the incumbent technologies in a 'better' way and/or offer at least some additional highly desirable characteristics that have market value. The problem is that while low-carbon technologies have the unique characteristic of low greenhouse gas emissions, which as yet lacks clear market value, it is not clear that in most cases they yet offer combinations of characteristics that would be seen as superior to those of incumbent high carbon technologies. Moreover, low carbon technologies, despite desirable carbon and other characteristics, are not necessarily superior across the whole spectrum of externalities (e.g., nuclear power has waste and proliferation risk characteristics, while wind turbines, marine devices and biofuels have various other less desirable environmental and social characteristics).

Of course, a feature of many new technologies with significant potential for improvement is that in their early stages they are uncompetitive except in specialised niches, until they have had the opportunity to move down their learning curves and reduce unit cost, as the scale of output rises and experience accumulates. Both the socio-technical transitions literature (Kemp et al., 1998) and the relevant business literature (Christensen, 1997) highlight the importance of niches in initial dissemination, i.e., a geographical or market segment in which the new technology can compete against incumbent technologies because of particular features it possesses in relation to that niche; hence the role for action by market or policy actors to create and support niches. The social benefits from learning and cost reduction in niches thus provide an argument for appropriate public incentives and initial policy support for low carbon technologies, to help achieve sufficient market penetration and experience to compete with incumbent technologies that long since reaped the benefits of technological and institutional returns to scale.

We conclude that because the low carbon characteristic as yet lacks convincing market value and because, except in particular niches, they tend not yet to offer a superior combination of characteristics to those of entrenched high carbon technologies, in the near term low carbon technologies will not find it as easy to penetrate as might be expected of the core technologies of an industrial revolution.

4.3. Low carbon technologies as GPTs?

Moreover, the insights from the literature on long waves and GPTs suggest that, at least in the short term, the wider economic impacts of the currently available low carbon technologies may be limited. These insights have implications for the notion of a fourth but this time low carbon industrial revolution or a sixth 'long wave' of low carbon economic growth (Stern, 2011a, 2011b, 2012). They clearly suggest that changes on this scale would require more than merely substituting a few low carbon technologies into existing uses in the context of existing institutional structures. For wider economic benefits to be realised, low carbon technologies would need to be more like GPTs, i.e., with the capacity to be widely diffused and used; for continuous innovation and cost reduction; and to stimulate innovation in a wide range of complementary technologies. Moreover, the urgency of mitigation means that the conditions would have to exist for such GPTs to be very rapidly developed and diffused.

As noted, however, the history of GPT diffusion offers some salutary lessons. GPTs typically take a long time to diffuse and yield significant economic impacts, as Crafts (2004) showed in the case of the steam engine.[4] Their diffusion can be slowed by effects of path dependence and lock-in of earlier technology systems. In a series of papers, Unruh (2000, 2002); Unruh and Carrillo-Hermosilla, 2006) argued that high carbon technologies and supporting institutional rule systems have co-evolved, leading to the current state of 'carbon lock-in'. For example, reductions in cost and the spread of infrastructure supporting coal- and gas-fired electricity generation enabled the diffusion of electricity-using devices and the creation of institutions, such as cost-plus regulation, which encouraged further investment in high carbon generation and networks. This created systemic barriers to investment in low carbon energy technologies.

Might information and communication technologies (ICTs) perhaps offer a way forward here? The current, fifth long wave of economic development is based around ICTs. ICTs have been identified as the most recent example of a GPT, one that has diffused much more rapidly and with much greater productivity impacts than the steam engine, for example (Crafts, 2010b).[5] Significant productivity improvements have been made in ICT production and through their deployment and use. On the one hand, they have led to the rapid increase in computing power, according to Moore's law, and dramatic reductions in computing costs.[6] On the other, they have led to extensive ICT use, as firms reorganised production and supply systems to take advantage of their potential, for example, in relation to 'just-in-time' supply systems. This suggests that a major opportunity for realising economic benefits from low carbon technologies may lie in the integration of these technologies with ICTs in so-called 'smart' systems. For example, it has recently been argued that application of smart charging systems for electric vehicles, smart controls for heat pumps and use of voltage regulators in active distribution networks could significantly reduce distribution network reinforcement costs in low carbon transition pathways (Pudjianto et al., in press).

We suggest, however, that if they are to develop the properties of GPTs, then truly 'smart' developments in low carbon energy and ICT will need to go well beyond clever management of current assets, technologies and practices. In particular, such developments would need to ensure much greater engagement and 'buy in' from energy users if supply and demand are to interact in ways that make carbon emissions significantly lower than they would otherwise be. Moreover, this would require integration of incentives for low carbon innovation into ICT systems development, or there would be a danger that growing demand for ICT services would lead to increases in high carbon energy use, for example, in the development of energy-intensive data centres needed to satisfy the growing demands for internet search, data storage and other services.

We have noted that it was not the steam engine (the technology) on its own but the energy-related services that it enabled and spawned, that were economically significant in the first industrial revolution. The enhanced characteristics of previous key GPTs, such as mobility, power, flexibility and reliability, enabled the delivery better and cheaper energy services and a wider range of services (Fouquet and Pearson, 2006; Fouquet, 2008). A further lesson from previous GPTs might be that we should not be too narrowly focused on existing energy and energy-related services when we envisage future low carbon technologies. The services that new low carbon technologies

[4] See also Castaldi and Nuvolari (2003) and Edquist and Henrekson (2006). These authors also point to some of the limitations of the GPT approach.

[5] Crafts (2010b, 2011), drawing on Oliner et al. (2007), compares the impact of ICT in the US with that of steam in the UK. He states that "the impact of ICT on the rate of productivity growth throughout 1973–2006 exceeded that of steam in any period and was already close to twice the maximum impact of steam in the late 1980s," while ICT's cumulative impact on labour productivity by 2006 was similar to that of steam over the 150-year period, 1760–1910.

[6] Computing costs halved between 1950 and 2005, for example (Nordhaus, 2007), whereas the cost of steam power fell by only about 7/8ths between 1760 and 1910 (Crafts, 2004, 2010b).

might offer could be wider and could embrace much more than what we traditionally think of as energy services (e.g., the provision of edible food, satisfactory levels of thermal comfort or illumination). For example, in future these energy services could be more closely linked with the delivery of existing and new entertainment, information, or financial services. Consequently, new low carbon 'technologies' could look very different from those with which we are familiar. By the same token, they could be developed and/or provided by entities different (to a lesser or greater degree) from those that are currently big players in energy. A moot question is whether incumbents across the range of technologies associated with the ultimate delivery of energy-related services will have the flexibility to move themselves into these markets or whether they will remain locked into their established technical foundations, habits, institutions and products. And whether established regulatory systems and standards might constrain, retard or stimulate such progress.

4.4. Sailing ship effects

The difficulties faced by low carbon technologies might also be exacerbated by the potential of high carbon technologies to continue to improve their competitiveness, whether through falling fuel costs (for example, if larger discoveries of shale gas prove to be extensively exploitable at low market cost, along with other non-convention fossil fuels, such as oil sands), through improvements in their characteristics or via increased regulatory protection or higher barriers to entry.

We have suggested that the role of incumbents will be an important influence on the successful penetration of low carbon technologies. For example, even if the 'new' low carbon technologies have essentially the same bundle of characteristics as the existing technologies, apart from being low carbon, if the existing technologies are both mature and already under pressure, then the low carbon technologies could be aiming at a moving target. Thus, for example, those producing internal combustion engines and vehicles running on fossil fuels are already under considerable pressure from environmental and fuel efficiency regulations, fuel prices and alternative fuels and technologies. Perhaps not surprisingly, therefore, we have seen considerable recent developments in the performances of petrol and diesel engines, as well as reductions in vehicle weight and improved aerodynamics. This has made it much harder for electric and future hydrogen and fuel cell powered vehicles to penetrate.

This tendency of improvements in incumbent technologies to be stimulated by competition from new technologies is known as the 'sailing ship' effect or the 'last gasp' effect of obsolescent technologies (Rosenberg, 1976; Utterback, 1994; Snow, 2010). In addition to the improvements in the performance of sailing ships due to competition from steam ships (Geels, 2002), it has been suggested that this effect has been observed in other cases, such as the adoption, after initial reluctance, of the much more efficient Welsbach gas mantle in response to the competition faced by the gas lighting industry from new developments in incandescent electric lighting in the late nineteenth century. Although there is some debate as to whether cited instances of the sailing ship effect always stand up to closer scrutiny (Howells, 2002), the proposition that industries or technologies whose ascendancy is threatened by new competition tend to respond, carries some weight. It also suggests that actors, such as large energy companies, with substantial investments in the current system and its technologies, and relatively strong political influence, are likely to act to frustrate the implementation of institutional changes that would support the implementation of low carbon technologies (Pierson, 2000). This could be seen, for example, in the efforts of large utilities in Germany in the 1990s to lobby for the repeal of the feed-in tariff law supporting the deployment of renewable energy technologies (Jacobsson and Lauber, 2006; Stenzel and Frenzel, 2007).

An effect analogous to that of the sailing ship effect may occur in the form of what has been called the 'green paradox' (Sinn, 2008; van der Ploeg, 2011). This is that incumbent primary energy suppliers could be stimulated by reductions in the cost of low carbon energy sources to accelerate the extraction of fossil fuels, in order to enhance their exploitation of economic rents. The foregoing arguments suggest that policy will need actively to stimulate substitution away from fossil fuels alongside the promotion of low carbon alternatives.

4.5. Rebound effects

Most scenarios of how global greenhouse gas emissions reductions of the order of 50% by 2050 could be achieved project that this will require not only widespread dissemination of low carbon energy technologies, typically including a range of renewables, nuclear power and coal and gas with carbon capture and storage, but also significant improvements in the efficiency with which energy services are delivered and used (e.g., International Energy Agency (IEA), 2009). It is widely argued that energy efficiency improvements tend to lead to direct rebound effects, in which the resulting effective reduction in the cost of energy services leads to some increase in demand for those services (Sorrell, 2007).[7] For example, improvements in the fuel efficiency of vehicles effectively reduce the cost per distance travelled, which could lead to users choosing to travel further, leading to the loss of some of the expected emissions reduction. Similar arguments have been advanced in the case of efficiency improvements in lighting (Fouquet and Pearson, 2011). Moreover, some have argued that there can also be a macro-economic rebound effect from the widespread dissemination of efficiency improvements and technological change, as they free up economic resources to be invested in creating new ways of meeting growing end-user demands via increasing output.

One way of thinking about the dissemination of GPTs is that they have the potential to create exactly this type of macro effect, as well as direct rebound effects. Technologies that have GPT-like properties have a good chance of stimulating further demand, both because of the cost reductions they experience and because of their capacity to enhance productivity, output and incomes in the wider economy. This means that, to the extent that low carbon technologies do not become 'zero' carbon, there could be potential for some direct and macro rebound effects on energy use and the carbon emissions associated with their widespread dissemination, making those technologies less effective at reducing carbon than they otherwise would be. Stringent and increasing emissions caps or carbon prices might then be needed to ensure that carbon emissions reductions benefits could be maintained at the overall economy level.

5. Discussion and conclusions

In this paper, we aimed to explore two propositions about the low carbon transition: that on the one hand, a successful

[7] 'Rebound' occurs where potential energy savings from greater energy efficiency are reduced (e.g., 20% rebound means only 80% of expected savings actually occur). 'Backfire' is said to occur if energy consumption rises with efficiency. Rebound effects can be direct (e.g., substitution and income/output effects) and indirect (embodied energy and secondary effects), and as noted there can be economy-wide macroeconomic effects. For a review and classification, see Sorrell (2007) and Sorrell and Dimitropoulos (2007).

transition would need to be on the scale of past industrial revolutions or 'waves' of technological transformation; and on the other hand, that it would bring sustained economic benefits akin to those of previous industrial revolutions. We recognise that the foregoing analysis might be read as highlighting a range of challenges that make the achievement of a low carbon transition unlikely. This is not our intention. More constructively, we argue that this longer run perspective and these challenges illustrate both the complexities and the opportunities of which key decision-makers need to be aware when formulating strategies and policies to promote the innovation and dissemination of low carbon technologies and practices. And we suggest that they support and reinforce the Stern Review's analysis that the innovation and deployment of low carbon technologies requires at least three types of policy measure: a carbon price, through a carbon tax or tradable permit scheme; direct support for demonstration and early stage commercialisation of low carbon technologies; and measures to remove institutional and non-market barriers to the uptake of energy efficiency and low carbon options (Stern, 2007).

We suggest that the foregoing analysis offers some further insights into the interpretation of a low carbon transition as requiring and/or leading a new industrial revolution:

First, the literatures on long waves of economic development and GPTs show that the introduction of new technologies that have widespread potential uses, the scope for further cost reductions as they are deployed and the potential for stimulating complementary innovations, has historically contributed significantly to enduring productivity gains and the spread of economic benefits. For the low carbon transition to resemble an industrial revolution, at least some of its technologies would need ultimately to have properties like these. In our view, some low carbon technologies have the potential for these properties to emerge and hence to give rise to a new wave of dynamic, innovative and creative activity that would be economically as well as socially and environmentally beneficial, as Stern (2011b) suggests. As yet, however, unlike many previous GPTs, they do not offer significant private benefits to users beyond the social benefits of lower carbon emissions (and elements of energy security). This is in striking contrast with the new kinds of benefits that the steam engine or the availability of electricity delivered to a wide range of economic sectors. Addressing this would not only require the social benefit to be internalised through a sufficiently high and credible carbon price; it would also require space for the creation of innovations complementary to the core low carbon characteristic. This is no mean challenge. And it means a difficult 'balancing act' for policy makers—on the one hand, creating sufficient incentives to promote innovation in low carbon technologies and their substitution for high carbon technologies in *current* uses, whilst, on the other hand, doing this in a way that also gives incentives to and enables innovators and citizens to discover and benefit from opportunities for complementary innovations and *new* uses and practices.

Second, and related to this, the current lack of superiority of the bundles of characteristics offered by some low carbon technologies, the extent of carbon 'lock in' and the potential for sailing ship/last gasp effects in high carbon technologies mean that policy makers cannot assume that low carbon technologies will automatically, smoothly and acceptably substitute into current uses on the timescales needed to meet climate change mitigation targets.

Third, it is inappropriate to view a low carbon transition mainly in terms of narrow economic substitution, for two reasons. First, the literature on previous industrial revolutions shows that they involved profound, long drawn-out, interacting changes not simply in technology but also in markets (and trade), institutions, culture and society, much of whose complexity we have barely touched on but whose significance we acknowledge. Second, as Mokyr confirms, by the mid-nineteenth century Britain had started to discover the limits of liberal ideology and the free market economy, as it ran into the hard reality of inequality and market failures. Thus Edwin Chadwick, whose 1842 *Report on the Sanitary Condition of the Labouring Population of Great Britain* sold over 100,000 copies (Chadwick, [1842], 1965), and other concerned Victorians faced the "dilemma that the free market would not solve the hard problems of congested urban areas, unhealthy work and living places, adulterated food, and above all, issues of public health" (Mokyr, 2009, 479). Late 19th Century developments in clean water supply, public and private sanitation and sewerage infrastructure (e.g., Bazalgette's system for London), and health (e.g., the changes that flowed from Pasteur's development of processes to avoid the spread of bacteria borne diseases) were important features of the second industrial revolution, creating major gains both for society and for private actors (Gordon, 2000). The challenge of climate change may have more in common with these sorts of developments for the public good than with more narrowly framed technological challenges viewed mainly in the context of private markets. For both these reasons, for the low carbon transition to really 'work', it may prove necessary to transform our energy and related systems and institutions in more profound ways than we have yet acknowledged. In this sense, it may be that we do need societal changes on a scale and breadth akin to those of previous industrial revolutions, if conditions conducive to such a radical transformation are to obtain.

Fourth, more sophisticated analysis is required in order to better understand what constitutes a distinctively *low carbon* transition or revolution. It is not enough just to invoke vague comparisons with past industrial revolutions. After all, the first and second revolutions were *high carbon* industrial revolutions. As we have seen, their success was built on the exploitation, largely unconstrained by environmental or other regulatory concerns, of fossil fuel stocks that freed the economy from constraints it would otherwise have faced. As one of us has argued elsewhere (Foxon, 2011; Foxon and Steinberger, 2011), there has been a tendency to neglect or misunderstand the role that the availability of cheap, high quality, carbon intensive energy sources has played in the co-evolutionary developments in technologies, related institutions and business strategies that have underlain the unprecedented economic growth and creation of wealth in Western countries over the last 250 years (Beinhocker, 2006). This does not mean that valuable insights cannot be gained from this past experience. But it does mean that we cannot assume that previous largely unmanaged high carbon transitions are direct historical analogues for a managed low carbon transition. Consequently, it matters to develop a richer understanding of the ways in which a transition to low carbon energy in today's world presents different challenges – and opportunities – from those involved in the high carbon transitions of previous eras.

Here we are conscious that the discussion of GPTs in this paper might be taken to imply that a low carbon transition is 'all about' technology, which is not what we intend. Nevertheless, as noted, it has been widely argued (e.g., Broadberry, 2007) that the idea of a GPT helps to address one of the key questions about the first industrial revolution—why the technological progress continued rather than petering out, as was the case for previous technology-induced growth spurts. Moreover, we argue that the three key properties of a GPT, which indicate the capacity of new technologies to deliver on the supply side, together with considering the demand for desirable bundles of characteristics necessary for low carbon technologies to be seen as generally superior substitutes for fossil technologies and fuels, throws light on what might be required for a low carbon transition both to succeed and to resemble previous industrial revolutions. Of course, this does not, of itself tell us how to create the conditions that would promote and nurture a low carbon industrial revolution.

We suggest that the paper informs the challenges facing policy-makers and others aspiring to promote a low carbon transition intended to deliver economic and wider benefits commensurate with those of previous industrial revolutions. It also emphasises the scale of the challenges involved, including the time dimension, since the larger benefits of earlier revolutions took decades to emerge, while climate science supports the urgency of large scale rapid greenhouse gas mitigation. This suggests that, to reap the climate and other benefits from a successful low carbon transition sooner rather than later, implies remarkably active efforts to build new enthusiasm, technology, infrastructure, forms of organisation and institutions, in order to escape the ongoing shackles of path dependence and carbon 'lock-in' and turn over the high-carbon capital stock. This will demand considerable political vision, skill and determination, in the face of high levels of socio-technical and economic risks and uncertainties. It will also demand better understanding of the co-evolutionary relations between changes in technologies, institutions, business strategies and user practices, the dependence of these relations on the availability of high quality energy sources, and how these co-evolutionary developments are both a driver and a consequence of economic and social change.

To conclude, the challenges of achieving a low carbon transition may well require societal changes on a scale comparable with those of previous industrial revolutions. However, the low carbon transition does not yet amount to another industrial revolution, in terms of its technologies and practices, their desirable bundles of characteristics and their ability to stimulate enduring long-run productivity and output gains of the kind previously experienced. It might, however, yield remarkable and unprecedented welfare gains if it were to succeed in avoiding the extreme human, environmental and economic impacts of climate change. This would then amount to a different kind of industrial revolution.

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