



**Designing Industrial Strategy for a Low
Carbon Transformation**

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ABSTRACT

The recent re-emergence of industrial policy as a legitimate pursuit of governments in Europe and the US has the potential to open up a new realm of policy action for climate change mitigation. This would aim to align efforts to secure national industrial opportunities with the development of low carbon industrial systems, so as to generate both socio-economic and environmental benefits. The paper discusses the role of low carbon industrial strategy in seeking to do this, thereby accelerating transitions to a low carbon economy. It sets out the elements of a more systemic low carbon industrial strategy, including providing a mission-oriented and learning-based approach, drawing on and combining insights from neo-Schumpeterian and ecological economics perspectives. The benefits for countries of implementing such a strategy are discussed, including informing approaches to analysing low carbon industrial development and assessing the effectiveness of low carbon industrial policies and policy mixes.

KEYWORDS

Low Carbon Industrial Strategy, Low Carbon Transformations, Neo-Schumpeterian theory, Mission-oriented innovation

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1. Introduction

The continuing challenging economic context in many countries, with low interest rates and bouts of quantitative easing aiming to stimulate economic activity, have led some governments to begin to articulate a 'modern' industrial strategy. In January 2017, the UK government published its plans for a new industrial strategy, in which the Prime Minister outlined "a new approach to government ... stepping up to a new, active role that backs business and ensures more people in all corners of the country share in the benefits of its success" (HM Government, 2017). At the same time, many governments are seeking to achieve substantial reductions in their projected national carbon emissions, in order to meet their commitments under the December 2015 Paris Agreement, which was signed by 175 countries in April 2016. This agreement committed countries to holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C, and to making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development (United Nations, 2015). Achieving this is increasingly recognised as requiring a transformation of the economies of both industrial and developing countries (Hermwille, 2016; International Social Science Council (ISSC) and United Nations Educational Scientific and Cultural Organization (UNESCO), 2013; IPCC, 2012).

Though some have argued that the investment needed for a low carbon transformation could provide an economic stimulus (New Climate Economy, 2016; UNEP, 2011), strategies for achieving emissions reductions are still largely formulated separately from economically-oriented industrial strategies. In this paper, we draw on and combine insights from neo-Schumpeterian and ecological economics perspectives to set out the elements of an integrated low carbon industrial strategy.

Whilst countries such as South Korea and China have long pursued active industrial plans, many Western industrialised countries (most notably the USA and UK) have, until recently, eschewed industrial strategy. The dominance of neo-classical economic thinking has led them instead to follow economic policies that emphasise market solutions to economic challenges with government 'intervention' limited to remedying market failures. However, other strands of economic thinking, inspired by the ideas of Joseph Schumpeter on how innovation and 'creative destruction' drives economic progress, provide the basis for an alternative framing on the role of government action to create and shape markets, rather than just respond to market failures (Mazzucato, 2015). We argue that this approach has synergies with arguments for strategic public action to stimulate the high levels of private investment needed for a low carbon transition (New Climate Economy, 2016). We suggest that taking advantage of these synergies could inform how a low carbon industrial strategy can help to guide near- and medium-term actions for achieving positive environmental and economic outcomes in a coherent way.

In setting out the elements of a low carbon industrial strategy, we aim to look for agreement on positive ways forward, even though there may be differences of opinion on ultimate end goals between those who support a 'green growth' approach (Bowen and Hepburn, 2014) and those who argue for the necessity of a more radical

transformation of current economic systems for achieving sustainable prosperity (Jackson, 2016). Recent political upheavals in the UK and US, which arguably relate to the lack of the spread of economic benefits to large parts of working and middle class communities, reinforce the need for practical approaches that can combine meeting environmental and socio-economic goals in a coherent way.

The paper is set out as follows. Section 2 describes the context and background. Section 3 sets out the proposed elements of a low carbon industrial strategy. Section 4 explores ways of testing the usefulness of this approach. Section 5 concludes.

2. Context and Background

2.1. Defining Low Carbon Industrial Strategy

We first draw an important distinction between industrial strategy and industrial policies. In the absence of universally agreed definitions, we take “industrial strategy” to mean a framework of ideas which influences the shaping and formulation of policies relating to economic production and consumption. An industrial strategy, therefore, includes a conceptualisation of the role of the state in the economy, and what goals industrial policies should pursue. These goals could be defined only economically, such as improving productivity, or expanded to also include social and environmental objectives. This strategic perspective draws on the idea of a policy paradigm, which shapes the way in which the problem is perceived and how it should be governed, the policy goals considered appropriate and the interventions that should be used to attain these goals (Hall, 1993; Kern et al., 2014). Drawing inspiration from Cowling and Tomlinson (2016), in this paper, we define a low carbon industrial strategy as:

The objectives and frameworks that determine how government intervenes to achieve low carbon production and consumption activities that are consistent with global goals on climate change mitigation and are in the wider public interest.

In contrast, industrial policies describe the specific interventions that government uses to implement the strategy.

Thus, a low carbon industrial strategy consists of two parts. First, it should specify the strategic objectives both in relation to carbon emissions and the wider public interest e.g. maximising economic growth or improving societal welfare, whilst also indicating types of economic activities that are expected to enhance these goals. Second, it should set out a framework that defines how the problem is perceived, what solutions should be sought, and how this needs to be governed.

In terms of carbon emissions, any strategic objective needs to recognise the global nature of the problem, whilst also providing clear targets for domestic action. We therefore argue that a strategic approach is needed in which international targets are translated into national carbon emissions reduction targets. This has been done by the UK in terms of setting five-yearly carbon budgets, 15 years in advance, towards an 80% reduction by 2050, under the Climate Change Act (2008), and, in Germany, in the national emissions reduction targets towards 2050 under the Energiewende. What constitutes the wider public interest is clearly the subject of many differing

interpretations. Whilst usually within industrial strategy it has been narrowly interpreted as enhancing economic growth, many other goals are possible including regional or sectoral rebalancing of the economy, increasing employment and improving other indicators of social welfare.

Moving to the second element, the frameworks that guide a low carbon industrial strategy are, to a significant extent, shaped by the nature and extent to which government intervention is seen as desirable. Colebrook (2016) develops a typology of industrial strategy based on the role of government that extends from command and control (most direct involvement), through co-ordinated capitalism, liberal capitalism plus, to liberal capitalism (least direct involvement). Germany and South Korea are typical examples of co-ordinated capitalism approaches to industrial strategy, and this is reflected in their approach to low carbon development. The German Energiewende is arguably a product of integrated industrial and energy strategy rather than simply energy policy (Rutten, 2014), and its effects have so far done more to stimulate the renewables industry than to reduce carbon emissions. Its implementation in policy has focused on developing the low carbon sector, whilst protecting energy intensive industries from price increases. South Korea is frequently held up as an example of industrial strategy successfully fostering the growth of competitive industries (Rodrik, 2014). In recent years, South Korea has aligned its industrial strategies with a low carbon agenda, launching a National Strategy for Green Growth in 2009, with specific focus on sectors including renewables, nuclear energy and transport (UNEP, 2010), and building on historical strengths in electronics as the basis of a new smart grid industry (New Climate Economy, 2014; Skillings and Smailes, 2017).

While it is clear that no consensus exists on the role of government, and both command and control and liberal capitalism have been experimented with, most developed democracies now lie somewhere on the co-ordinated capitalism (e.g. Germany) to liberal capitalism plus (e.g. the United States) spectrum. In the remainder of this paper, we are not prescriptive as to the precise role of government, but assume that some form of interventions compatible with capitalism are acceptable, and propose theoretically grounded elements for low carbon industrial strategy on whose basis interventions can be justified.

2.2. Creating and Shaping Markets

In order to define a strategic framework to guide a low carbon industrial strategy, we need to draw on theoretical understanding of industrial systems change. We argue that this is provided by neo-Schumpeterian theories that characterise economies as evolving systems in which innovation is driven by both public and private actors interacting through networks to create new technologies, institutions, business models and user practices (Foxon, 2011). This approach implies that a low carbon industrial transformation would involve an active role for governments in creating and shaping markets, not just fixing market failures (Mazzucato, 2015), and helping to identify key industrial sectors that can drive the transition in similar ways to previous long-term techno-economic system changes (Perez, 2013).

The idea that industrial strategy should be about seeking to create and shape markets (Mazzucato, 2015) breaks from the mainstream economics framing in two important ways. Firstly, it claims that the idea of a single optimal path of economic development that is followed by a perfect market is false. Economic development can follow many different possible trajectories that are subject to patterns of lock-in and path dependence (Fouquet, 2016; Unruh, 2002). Secondly, it argues that the 'optimal' choice of possible outcomes of different economic development pathways is necessarily normative, can vary over time and space, and must be politically negotiated (Lütkenhorst et al., 2014).

This line of argument draws on a long history of understanding economic development and structural change as the result of innovation processes (Schumpeter's (1939) 'creative destruction') governed by innovation systems (Freeman, 1974; Perez, 1985). The neo-Schumpeterian approach describes technical innovation as a process that takes place in an institutional context and involves the dynamic interaction of multiple agents of change including researchers, suppliers, distributors and consumers (Perez, 2009). First described by Lundvall and Freeman as a 'national system of innovation' (Freeman, 1987; Freeman et al., 1995; Lundvall, 1988), this conceptualisation encompasses the full life-cycle of technological innovation from basic research and invention, through early adoption, to market diffusion (Wilson et al., 2012).

Perez analyses the development of new techno-economic paradigms (Perez, 1985, 2002), where a paradigm describes a collective, shared, best practice model for the effective use of new technology that influences new and existing industries and the institutional context. According to this approach, previous waves or surges of economic growth have been driven by the deployment of new techno-economic paradigms, following periods of installation and upheaval as institutions and practices are re-oriented to enable the benefits of the new paradigm to be realised. Perez has argued that the current deployment phase of the ICT (information and communication technologies) paradigm could be strengthened by combination with a clear 'green' direction for this deployment, leading to a new surge of 'green growth' (Perez, 2013; Perez et al., 2016).

Mazzucato builds on the techno-economic paradigm concept to argue for 'mission-oriented' innovation (Mazzucato, 2015; Mazzucato and Penna, 2015; Mazzucato and Perez, 2014). This work highlights the crucial role of the state in directing and driving innovation. Technologies including GPS, shale gas extraction and the internet were created following government agency investment (Mazzucato, 2014). On this basis, the state is described as taking an entrepreneurial role and going far beyond fixing market failures to creating markets and investing in specific industries and technologies. There are complementary roles for public and private state actors, and a more dynamic, learning approach is needed. This conception of the role of the state calls for an active industrial strategy with appropriate investment in government capacity and the establishment of collaborative innovation institutions (Mazzucato and Penna, 2015).

2.3. Integrating Low Carbon and Economic Objectives

Developing a low carbon industrial strategy requires identifying the scale of the transformation needed to achieve climate change mitigation targets, and setting strategic goals that would help to realise this type of transformation in the most socially and economically beneficial way.

To be consistent with achieving the Paris target of a maximum 2°C temperature rise, with a likely chance of success (66-100%), requires global greenhouse gas emissions to be reduced by between 40% and 70% from 2010 levels by 2050 (IPCC, 2014). Scenarios suggest that this requires a massive expansion of low carbon energy sources (some combination of renewables, nuclear power and coal and gas with carbon sequestration) and significant improvements in efficiency of energy conversion and use, as well as negative emissions technologies (such as biomass energy with carbon capture and storage). These would substitute for unabated coal, gas and oil sources, enabling extensive reserves of these fossil fuels to be left in the ground. Given that fossil fuels are currently the source for around 80% of the energy used for household, industry, services and transport uses, and that increases in the availability of these sources and in the efficiency of their conversion to useful energy have been a key enabling factor in previous long waves of economic growth, this transformation has large implications for how economies can deliver economic benefits. Nevertheless, as the Stern Review (2006) and subsequent studies have argued, the economic costs of inaction, as unchecked climate change would lead to severe environmental and social impacts, are likely to be much higher than the economic costs of action to realise a transformation to a low carbon economy.

The neo-Schumpeterian approach identifies innovation as the principal driver of economic dynamics and development (Hanusch and Pyka, 2007). Novel technologies and organisational forms in production techniques are described as leading to cost reductions in key inputs (such as energy and raw materials) and intermediary products, and co-evolve with institutional and social innovations that promote the adoption of those products. These novelties are not created continuously but display patterns of punctuated equilibrium, and the resulting economic dynamics have strong non-linearities, explaining past surges of economic growth punctuated by periods of stagnation (Perez, 2002). The recent cost reductions in some renewable energy sources give grounds for optimism that these could help to promote a new surge that would deliver similar types of economic benefits to these past surges. Writing about “The irreversible momentum of clean energy”, President Barack Obama recently stated that he is:

“confident that trends toward a clean-energy economy that have emerged during my presidency will continue and that the economic opportunity for our country to harness that trend will only grow”. (Obama, 2017)

However, in recognising innovation competition rather than price competition as the principal coordinating mechanism of the economy, neo-Schumpeterian theory also suggests that restricting government action to only ‘fix’ market failures associated with the carbon externality is misguided. Reliance on an ‘efficient market’ with endogenised

externalities to drive the transition to a low carbon economy is based on an inappropriate theoretical framework, and therefore blind to the wider institutional changes that are needed to support the mechanisms of low carbon innovation. Carbon taxes may create a more favourable market for low carbon technologies, but they do not address the lock-in of fossil fuel industries (Unruh, 2002) or the lack of finance for innovations to cross the “valley of death” from demonstration to market diffusion (Gallagher et al., 2011). Institutional changes relating to the creating and shaping of markets to promote innovation in low carbon technologies and systems are likely to be needed. In the next section, we set out six elements of a low carbon industrial strategy that would promote these technological and institutional changes in a way that helps to stimulate low carbon production and consumption activities that are in the public interest.

3. Elements of a Low Carbon Industrial Strategy

As discussed above, the formulation of low carbon industrial strategy can draw on a wealth of insights from low carbon transitions, innovation systems and economic literature. In the following, we synthesize important elements of a low carbon industrial strategy from these literatures. The six elements we discuss relate both to changes in the structure and operation of the economic system that should be targeted, and to the governance system required to achieve this. They are:

- 1) A mission-oriented approach from government,
- 2) Promotion of renewable energy and circular economy practices in production,
- 3) Demand-side measures, including energy and resource efficiency,
- 4) Reorienting innovation systems,
- 5) Enabling green finance,
- 6) Learning approaches embedded in governance.

We now discuss each of these in turn.

3.1. Mission-Oriented Approach

The case for the state as an active participant in economic processes that create markets and direct innovation has been clearly articulated by Mazzucato, Perez, Anadon and others (Mazzucato, 2013; Mazzucato and Perez, 2014; Perez, 2016; Anadon et al., 2016). This view of the state has crucial implications for industrial strategy. The function of an ‘entrepreneurial state’ (Mazzucato, 2013) requires the state to have the capabilities to carry out this role, and it must be enabled by supportive socio-technical institutions. That means both the resources of the state itself, and its relations to industry organisations, firms and other social and economics actors, must be strategically oriented to allow a mission-oriented industrial policy approach.

The importance of the capacity and capability of the state in implementing successful policy and legislation has been studied across multiple policy domains. The passage

of new climate legislation has been shown to be influenced most strongly by previous experience in passing legislation (and not significantly by political inclination) (Fankhauser et al., 2015). Mazzucato and Perez explicitly call for “sector and technology-specific expertise to be located in government” (Mazzucato and Perez, 2014, p.21) so that public actors can be effective. The current trend of austerity measures that is reducing the size of central and municipal governments in the UK runs counter to this, and the consequent destruction of political capability in UK energy policy has been discussed as an important limiting factor in the transition to a low carbon energy system (Kuzemko, 2016).

As important as the state’s capacity is its ‘embeddedness’ in the economic processes it is seeking to influence. The concept of embedded autonomy refers to a state that operates without undue influence from the private sector, but has high levels of interaction and communication through social ties and institutionalised communication channels (Evans, 1995). Rodrik describes this as government agencies that “need to be embedded in, but not in bed with, business” (Rodrik, 2014, p.485). Organisations that institutionalise such connections between the state and private enterprises exist in various forms across the innovation systems landscapes of different countries. Anadon (2012) compares and contrasts the energy technology innovation institutions in the United States, the United Kingdom and China, and the trade-offs involved in the design of these institutions. Rodrik (2014), similarly, reviews green industrial policies that have been applied in the United States, Germany, China and India (Rodrik, 2014). Both find that communication between the state and the business community is an important factor in the design of successful industrial policies. Anadon shows that there are significant differences in this embeddedness, and also in the degree of coordination in government activities and the missions assigned to implementation institutions, arising from the different political, cultural and geographic contexts of the United States, the United Kingdom and China.

Developing the government’s capacity and embeddedness required to implement a mission-oriented low carbon industrial strategy also requires a long-term perspective. Implementing institutions are most likely to be stable and resilient where they have a clear purpose that is reflected in the missions they pursue. Stability in the policy and institutional regime for innovation systems and low carbon finance is important; uncertainty and inconsistency in policy are often cited as major barriers to the diffusion of renewable energy technologies (Bergman, 2013; Reichardt and Rogge, 2014) and the availability of financing (Boissinot et al., 2015). Research on the European emissions trading scheme has suggested that a long-term perspective and stringency in policy could lead to better policy outcomes in terms of innovation in low emissions technologies (Schmidt et al., 2012). If the state is embedded in the low carbon industrial system, policy can be made in the context of institutions that foster long-term perspectives that are shared between the public and private sector.

The need for a long term perspective in low carbon industrial strategy is also suggested by the challenge of winding down undesirable industrial sectors. Sunset industrial policies, as suggested by Hallegatte et al. (2013), are important to address the influence of locked-in industries that block the transition to a low carbon economy. Where the rapid decline of such industries will result in politically infeasible social and

regional economic damage, policy is needed to effect a gradual descent where social and economic capital is preserved in the transition to alternative economic activities. A long-term perspective allows some foresight of the need for such policies, but their implementation is complicated by the political power of vested interests that can significantly hamper structural economic change (Moe, 2010). A clear and consistent strategy, and appropriate oversight to ensure discipline (Rodrik, 2014), must be in place to prevent vested interests from influencing public policy in the interests of their own profits (rent-seeking) and at the expense of environmental and social welfare.

Addressing the risk of rent seeking must be balanced with an understanding that a mission-oriented approach that supports innovation in specific technologies and sectors has an intrinsic risk of supporting some failures. Such failures should not be seen as a failure of the strategy, but as an inherent part of a portfolio approach. An implication of this is that the missions sought must hold a high level of public support. Mission-oriented strategies must be democratically constructed and the public agencies that implement them must be accountable with high levels of public scrutiny (Lütkenhorst et al., 2014; Rodrik, 2014). Public sentiment and cultural context are a determinant in the balance of public-private activity that is deemed acceptable. As Mazzucato has argued, the roles of the public sector and private sector differ and should be seen as complementary. In particular, echoing Keynes, she has argued that the public sector should seek to support those activities that serve the public good but the private is unable or unwilling to do, because the risks are too high or the rewards too diffuse.

3.2. Renewables and a Circular Economy

The core mission for low carbon industrial strategy is to effect a transformation of the economy to operate within planetary boundaries. Crucial to this is the replacement of fossil fuel based energy systems with low carbon alternatives, and a more efficient use of material resources in the form of a circular economy. The economic implications of such a shift have long been the subject of debate. The Stern Review on the economics of climate change (Stern and HM Treasury, 2006) argued that the costs of inaction and suffering the impacts of climate change were higher than the costs associated with climate change mitigation. More recently, Stern and colleagues have emphasise the importance of large-scale investment in low carbon infrastructure, particularly in the design, building and retrofit of cities so as to encourage low carbon practices, e.g. through public transport systems that reduce car use. This could also have significant co-benefits, such as improvement in public health through reduction of local air pollution. Such green growth narratives also argue that greening the economy is not a cost at all but an opportunity for better growth (New Climate Economy, 2016; UNEP, 2011). Within this, renewable energy technologies for electricity generation, heat supply and transport provision, as well as energy efficiency options, would seem to carry the greatest potential for industrial policy benefits, in terms of job creation and export capacity (Kunapatarawong and Martínez-Ros, 2016; OECD, 2011; Perez, 2016). This is because they are reliant on large-scale manufacturing for renewables and small-scale installation for local renewables and energy efficiency measures.

More broadly, promoting structural change in economies could also bring significant industrial policy benefits. This could include the widespread adoption of so-called circular economy ideas, based on a set of new strategies, technologies and business models for delivering services whilst minimising resource use and waste production (Ellen MacArthur Foundation, 2015). These include: recycling; design for reuse and remanufacture; extending the lifetime of products; selling services (e.g. mobility) rather than products; and using ICT to optimise resource use and maximise value. Some of these strategies have been shown to have significant potential for carbon emissions reduction (Barrett and Scott, 2012).

The shift to renewable energy technologies and circular economy practices is seen by some as the basis for a radical economic transformation. Mirroring the perceived paradigm shift in climate policy (Hermwille, 2016), Mathews (Mathews, 2015) argues that renewable energy, circular economy and eco-finance instruments could form the basis for a new 'techno-economic-paradigm' and that China and other emerging economies are already beginning to reorient their economies in this way. In this new techno-economic paradigm, systemic changes enable a 'green transformation', through targeting of "new, innovative technologies and deliberative and determined market expansion through instruments such as public procurement" (Mathews, 2015, p.180). The economic rationale for this is that investment in manufacturing capacity for renewable energy and circular economy industries generates increasing returns to scale and scope, compared to decreasing returns that result from investment in fossil fuel sources that are increasingly difficult to extract (Arthur, 1994; Mathews, 2011).

Whether or not such a paradigm shift is seen, there is some evidence to suggest that green industries (so far as these can be identified) can offer better than average prospects for growth and employment (Perez, 2016). Parallels with state sponsorship of other industrial sectors and their supply chains indicate that there could be great potential for green industries to become important exporters of goods and services to a world economy that is increasingly committed to rapid decarbonisation (United Nations, 2015).

3.3. The Demand Side

Although renewable energy technologies and circular economy practices in production are required for the transition to a low carbon economy, they are not likely to be sufficient for the scale of low carbon transformation needed (Pye et al., 2014). It is not clear that the current growth of low carbon industries is significantly reducing carbon emissions (Gazheli et al., 2016; York, 2012). And little evidence exists that suggests an absolute decoupling of economic growth from indicators of environmental impacts (such as carbon emissions, material throughput, energy use) is possible (Peters et al., 2011; Steinberger et al., 2012a; Wiedmann et al., 2013). The important contribution that demand side interventions, including energy and material efficiency improvements, must make is thus widely recognised and reflected in the scenarios that are compiled by the IPCC (IPCC, 2014), and so should be a key feature of a low carbon industrial strategy.

Beyond direct interventions in end-use energy demand, driving change in the consumer demand for goods and services holds significant potential for carbon emissions reductions (Barrett and Scott, 2012). The implementation of Product Service Systems (business models based on selling services alongside products, e.g. maintenance contracts) to effect more resource efficient consumption has been the subject of research since the 1990s, and is increasingly embedded in business management literature (Tukker, 2015) reflecting the economic prospects of such alternative business models. Alongside measures such as product life extension and performance contracts, such strategies are part of a newly invigorated campaign for a circular economy transition that encompasses both production and demand side interventions (Ellen MacArthur Foundation, 2013).

A low carbon industrial strategy should more explicitly include demand side measures amongst its missions. For example, support for energy technology innovation, in particular, is biased towards supply technologies with a relative neglect of end-use technologies (Wilson et al., 2012). There is a strong case that energy efficiency improvements are the most cost effective way of reducing carbon emissions.

However, concerns have been raised that efficiency improvements may not always lead to absolute reductions in energy demand and carbon emissions, due to so-called 'rebound effects' (Sorrell, 2009). Direct rebound effects in household energy services, where more efficient service delivery is compensated by an increase in energy service demand, are generally less than 30% in OECD countries. This means that the reduction in overall energy demand, and hence carbon emissions, from energy efficiency improvements is still significant, but is a smaller reduction than expected (Sorrell et al., 2009). Indirect rebound effects, whereby the financial savings from energy efficiency improvements are used for other forms of consumption, may leave to even smaller overall energy demand reductions (Sorrell, 2009). Finally, macroeconomic rebound effects may be significant, though it has been argued that these are only significant if the energy efficiency improvements lead to a stimulus to economic growth (Barker et al., 2007). Whether this constitutes a contradiction for the internal consistency of green growth remains an open question that requires further empirical evidence to resolve; recent work suggests it is most significant in producer-sided economies such as China (Brockway et al., 2017). Combining efficiency improvements with the imposition of strict economy-wide carbon caps could enable both economic and environmental benefits to be realised.

Addressing the need for carbon reductions on a consumption basis is likely to be more challenging for policy makers, as international agreements are currently based on production emissions (Afionis et al., 2016), and under the present economic systems, absolute reductions in energy and material consumption would be likely to be seen as reducing social welfare. However, it has been argued that more transformative changes to present economic systems could deliver both absolute reductions in consumption and increases in social wellbeing, such as reductions in working hours meaning more 'quality time' spent with families (Jackson, 2016).

3.4. Innovation Systems

Innovation is a crucial element of any industrial strategy, including low carbon industrial strategy. An innovation systems approach is based on the conceptualisation of innovation as a process with a life-cycle that includes research, development, demonstration, niche markets, diffusion and phase-out (Wilson and Grubler, 2015). To function properly, this innovation system must be supported by appropriate institutions and actors, policies that target both technology-push and market-pull, and the provision of financial resources and knowledge through generation and learning. Institutions must bring together private firm actors with public regulators and policy makers and research scientists and engineers. Knowledge exchange networks that facilitate this are important in creating the embeddedness that a mission-oriented approach requires.

Mazzucato has illustrated the importance of state support at the stage of basic technology research using the example of the iPhone (Mazzucato, 2013). Many of the basic technologies that make the iPhone successful are the result of state sponsored innovation: GPS, touchscreen technology and the internet to name just some. Deployment and diffusion are as important a part of the innovation lifecycle that require the investment of resources and development of skills, knowledge and capacity. In the case of energy technologies, the diffusion phase of innovation can be extremely slow, taking many decades (Grubler et al., 2016). Low carbon industrial strategies must seek to create functioning innovation systems that support the entire innovation lifecycle. For example, ensuring sufficient skills training opportunities for low carbon industries could complement public support for early stage deployment of key 'green' technologies that meet the requirements of mission orientations. Support for entrepreneurial activities and knowledge development have also been identified as key functions of technological innovation systems (Hekkert et al., 2007).

An innovation systems approach to industrial strategy also entails creating regionally specific strategies. Regional specificity is recognised as an important determinant of successful policy intervention with diverse factors such as the availability of private finance for entrepreneurial activity (Brown et al., 2015) and differences in professional cultures (Wirth et al., 2013) playing important roles. This does not imply that all strategy should be devolved to regional governance – many important factors in industrial development can only be addressed at national level – but the appropriate scale should be sought. National strategy is needed to address the regional disparities created by industrial development, as some regions could be disproportionately affected by declining industries, whilst others will always be more economically active (Cox et al., 2016; Meadway, 2013; Molho et al., 2016).

3.5. Green Finance

An important, and still somewhat understudied, resource for a low carbon industrial system is the availability of green finance. Financing is identified as one of the key resources required for a functioning innovation system, including public funding of early stage R&D, tax subsidies and feed-in tariffs for niche market support, and private finance for market diffusion (Wilson et al., 2012). The IEA estimates that “\$48 trillion in

cumulative investment in energy supply and efficiency are required by 2035” for their main scenario (International Energy Agency, 2014, p.3). Realising this scale of investment, and its appropriate allocation in a low carbon economy, will be a significant challenge that a low carbon industrial strategy will also have to address. The UNEP Inquiry into the Design of a Sustainable Financial System has argued that a ‘quiet revolution’ is already underway, as the financial system adapts through innovation of financial technologies to deliver investment for a transition to a low-carbon, green economy (UNEP, 2016). National governments need to support and reinforce these changes, in order that financial systems become fit for this purpose.

The Paris Agreement reaffirmed developed countries commitment to mobilise \$100 billion a year for climate finance and increase funding channelled through the Green Climate Fund (United Nations, 2015). Whilst this funding is far from the total scale of finance required, the intention is to use it to leverage private sector investment and institutional finance. Public funding for low carbon development saw a significant boost as part of stimulus spending following the 2008 financial crisis. South Korea’s Green New Deal, for example, amounted to 0.5% of GDP (Barbier, 2010). Public expenditure on RD&D in renewables and energy efficiency increased globally between 2000 and 2011 (Rhodes et al., 2014). Private RD&D expenditure, in contrast, has remained heavily focused on fossil fuels with little growth in renewables (Rhodes et al., 2014).

Mathews suggests that once the potential of increasing returns from investment in renewables and circular economy technologies becomes clear, investment will rapidly flow in this direction and away from fossil fuel based technologies with diminishing returns (Mathews and Reinert, 2014). Such a trend would align financial resources with the need for renewable energy and circular economy technologies that should be an element of a low carbon industrial system. This thinking is in line with empirical evidence of the active role of the financial sector in promoting economic growth (King and Levine, 1993), and reflected in recent neo-Schumpeterian and Post-Keynesian modelling efforts that demonstrate the importance of the finance-innovation nexus (Aghion and Howitt, 2009; Caiani et al., 2014). Innovation systems research stresses the importance of patient, long term finance that is available for all activities along the innovation lifecycle (Mazzucato and Penna, 2015).

The financial institutions that provide green finance must also take appropriate organisational forms for an effective low carbon industrial strategy. Effective finance for industry firms is best provided by finance providers that understand the activities to which they are lending. The contrast between a highly centralised banking sector in the UK and a much more active local banking sector in Germany has been linked to the more successful deployment of distributed renewable generation in Germany (Hall et al., 2016). The failure of Scotland’s Intermediate Technology Initiative has also, in part, been attributed to its design not accounting for the specifics of the local financial system, notably the absence of venture capital of significant scale (Brown et al., 2015). This suggests that the strategic support of finance providers with the appropriate scale, organisational form and knowledge of the low carbon economy should be an important element of a low carbon industrial strategy.

3.6. Learning Approaches

A low carbon industrial strategy must be adaptable to changes in the socio-technical system by incorporating learning approaches in its institutional design and processes. The concept of adaptive policy-making represents the implementation of a learning approach in policy (Haasnoot et al., 2011; Hallegatte and Lempert, 2012), with the need for performance monitoring, mitigation and hedging actions and reassessments of initial plans included as integral parts of the policy making process. Haasnoot et al. (2013) describe an approach of “adaptive policy pathways” that combines adaptive policymaking with learning pathways, a method to sequence possible actions in the context of uncertain external developments. This approach is proposed for robust policy decisions in a deeply uncertain world, an apt description of low carbon transformations. The approach entails a learning loop including scenario analysis, planning and monitoring. A low carbon industrial strategy that enables robust policy decisions should ensure that such learning loops are institutionalised and provided with the resource they require.

In the context of low carbon industrial strategy, adaptive policymaking must account for a complicated policy mix (Rogge and Reichardt, 2016) involving a number of potentially complementary and contradictory strategies, ideas and instruments. These policy mixes must evolve over time to account for the evolution of the socio-technical systems they are intended to govern (Reichardt et al., 2016). This type of policy evolution in the German feed-in tariff for solar photovoltaic electricity generation has been described as ‘compulsive’ policy making (Hoppmann et al., 2014); policy instruments are applied to address a selection of issues, resulting in the emergence of new issues, which are then addressed by further policy. Embedding learning in the strategic framework of these policy domains would lead to instruments that facilitate their adaptation to new information, for example by designing feed-in tariffs with built-in digression that is dependent on market share.

Beyond learning in policy making, a low carbon industrial strategy also needs to create institutions that enable learning across the innovation system so that knowledge exchange networks, innovation agencies, and financial institutions can adapt to changes in the socio-technical system. The activities of these organisations will have to change according to changing technology costs and potentials, adjusting the tools and instruments they use and also adjusting the composition of networks and advisory bodies (such as the participation of industry representatives on the boards of innovation agencies). Hallegatte et al. (2013) and Rodrik (2014) both stress the importance of transparency and accountability to these processes to mitigate against the risks of capture by incumbent interests and a resulting lock-in that blocks the emergence of more productive innovators.

4. Implementing Low Carbon Industrial Strategy

The previous sections described an industrial strategy that is a general framework for low carbon industrial governance that should be created and the processes that enable this. But this is not yet the same as discussing industrial policy in terms of choosing appropriate instruments and applying them at appropriate scales. This would include the appropriate mix of horizontal policies, which are cross-cutting and designed to address market-wide issues, and vertical policies that target particular sectors or firms, or have a geographically regional focus (Skillings and Smailes, 2017). Although it is not our intention to propose particular industrial policies, in part because these are inherently dependent on particular social, economic and geographical contexts, in this section, we discuss three issues that are important to designing such policies. The first issue is the elaboration of design principles for low carbon industrial policy mixes, the second is the analysis of policy interventions in low carbon industrial development, and the third is the selection of appropriate measures and indicators to assess the success of policies.

4.1. Designing low carbon industrial policy mixes

Industrial strategy generally focuses on promoting innovation and the development of new industries. We have argued that support for innovation and deployment of renewables and circular economy approaches are likely to bring the largest economic benefits in a low carbon transition. A wide range of policy instruments have been applied to promote innovation in these technologies and approaches, including carbon taxes and trading schemes, feed-in tariffs, renewable portfolio standards, extended producer responsibility and take-back regulations to promote design for recycling and remanufacturing. However, low carbon industrial strategy also needs to include policies for the managed decline of high carbon industries. Drawing on analysis of innovation systems, Kivimaa and Kern (2016) have argued for the development of policy mixes to promote creative destruction, i.e. 'creation' of new industries and 'destabilisation' of old industries.

Similarly, Hallegate et al. (2013) have argued for a broad combination of traditional 'sunrise' industrial policies and 'sunset' industrial policies as well as social and trade policies. Sunrise policies refer to those policies aimed at improving the ability of new and disruptive market entrants to gain market share, traditionally the domain of innovation policy. Sunset policies, in this context, are intended to effect a managed decline of industries where a rapid collapse is politically and socially undesirable (Peck et al., 1987). Trade policies can be used to similar effect (where this is not prohibited by WTO rules), and social policies could entail the expansion of social safety nets and re-skilling programmes to reduce the welfare impacts of lost employment.

A second challenge is the avoidance, as far as possible, to create incentives for 'rent seeking', i.e. for companies to capture the benefits of policy incentives without enabling spillover benefits to be realised. Rodrik has described an institutional system, and a set of design principles for industrial policy, that address the need to balance between market failure correction and avoidance of rent seeking (Rodrik, 2007). The institutional architecture he describes highlights three elements: political leadership at the top, coordination and deliberation councils, and mechanisms of transparency and

accountability. He further outlines ten design principles for industrial policy that complement this architecture:

- 1) incentives only for 'new' activities,
- 2) clear benchmarks for success and failure,
- 3) built-in sunset clauses,
- 4) public support that targets activities, not sectors,
- 5) subsidised activities must have potential for spill-over and demonstration effects,
- 6) authority for carrying out industrial policy must be vested in agencies with demonstrated competence,
- 7) implementing agencies must be monitored closely,
- 8) agencies carrying out promotion must communicate with the private sector,
- 9) mistakes with 'picking losers' will happen, and
- 10) activities must have the ability to renew themselves.

We argue that these design principles can be implemented in a way that is consistent with our proposed six elements of a low carbon industrial strategy.

4.2. Analysing low carbon industrial development

The design of energy policy has long been informed by sophisticated techno-economic models (Strachan et al., 2009) that project the likely response of markets to policy instruments, and the consequences for economic growth and carbon emissions (Ekins et al., 2011; Grubb et al., 2015; Scott et al., 2016). Low carbon industrial policies would benefit from a similar approach. The learning approaches and adaptive policy pathways methods we argue should be part of a low carbon industrial strategy could be informed by the elaboration of scenarios to analyse robust adaptive policies. Quantitative models that support this approach in the context of low carbon industrial development face particular challenges. Low carbon industrial policies aim to influence a system that has been described as a complex adaptive system (Beinhocker, 2006). The interactions between constantly evolving technologies, competing firms, and institutions subject to social change make the outcomes of interventions difficult to predict.

The models predominantly used to inform energy and climate policy have a techno-economic basis informed by mainstream economic theories of rational firm and market behaviour (Grubb et al., 2015; Koppelaar et al., 2016; Mercure et al., 2016). These models poorly represent many of the issues discussed here as being fundamental for a low carbon industrial strategy: systems of innovation that rely of knowledge creation and learning; the co-evolution of institutions, technologies and policy; the creation of markets and changing of behaviour on the demand side. New modelling approaches are seeking to integrate elements of socio-technical systems theories with formal energy system models to analyse energy system transitions (Holtz et al., 2015; Li et al., 2015); develop evolutionary economics based models of sustainability transitions and dynamics of industrial evolution (Safarzyńska and van den Bergh, 2011); and

produce agent based models of consumer behaviour in technology adoption (Rai and Henry, 2016; Robinson and Rai, 2015).

Alternatively, bridging approaches can combine insights from techno-economic models, socio-technical transitions theories and practice-based action research (Geels et al., 2016; Turnheim et al., 2015). Such an approach has been used to develop sustainability transition scenarios for the UK energy system (Barton et al., 2013). The strength of this type of approach, and what makes it suited to informing low carbon industrial policy, is that it can accommodate divergent perspectives of stakeholders in the development of a set of possible scenarios, whilst retaining checks on technological feasibility.

A challenge for formal modelling to support low carbon industrial policy making is that the relevant issues can be addressed by a variety of theories that describe different causal mechanisms. The spill-over effects that drive agglomeration economics, for example, can be attributed to the localisation of related industries or the proximity of diverse firms from different sectors. A strategy to address this is to develop 'history-friendly' models of industrial dynamics (Malerba et al., 2008). This approach ties computational modelling to appreciative theories that are constructed to explain the causal mechanisms behind empirically observed behaviours. Models are used to validate the internal consistency of theories and that the dynamics they describe result in the empirically observed behaviour (Malerba et al., 1999).

4.3. Assessing effectiveness of low carbon industrial policies

Low carbon industrial policy aims to effect a transformation of the economy with a reduction in carbon emissions that is consistent with limiting global temperature change to less than 2°C above pre-industrial levels. The single measure of carbon emission reductions is, however, not a sufficient measure of the success of specific policies implemented to achieve this transformation. To be politically and economically viable, low carbon industrial policies need to contribute to a wider range of high level goals. These could include: job creation, stimulating foreign direct investment, rebalancing of economies across sectors and regions, ensuring security of energy and resource supplies in the context of global crises, and reducing social inequalities.

Hallegatte et al. (2013) further differentiate three potential goals for industrial policies:

- 1) enhancing the overall innovation capacity of the economy,
- 2) economic development, job creation and rent capture, and
- 3) equity, acceptability and other social concerns.

This highlights the primacy of economic concerns as rationales for industrial strategies, but recognises the potential for also including wider social and environmental rationales. In the context of a low carbon transformation, these economic factors need to be related to the changes required to create a low carbon economy.

Approaches to developing objective measures of social wellbeing and relating these to industrial systems of provision are now being undertaken. In development economics, the adoption of a capabilities approach has become integrated in the policy process from the strategic level, for example in the adoption of sustainable development goals, down to the implementation of specific policies that address

education and the provision of financial resources to women. The relationship between economic development, prosperity and environmental impacts indicate that some dimensions of wellbeing, such as social inclusion and high levels of education, can be compatible with low carbon emissions (Steinberger et al., 2012b), whereas others, including some measures of individual wellbeing, are not (Fritz and Koch, 2016).

Improvements in energy efficiency of economic activity is an area where industrial strategy is traditionally applied. Both improvements in the energy efficiency of technologies, and structural changes in the economy towards more efficient activities contribute to this factor. Technology improvements are, in principle, easily measured according to technical performance. Assessing the effectiveness of policies that support the whole innovation system that creates technological progress requires a broader set of measures and methods and is much more difficult (Hu et al., 2016). These assessment measures apply also to the economic restructuring that results from innovation systems that direct development in desired directions.

5. Conclusions

Failure to divert from our current reliance on fossil fuels to underpin economic development will lead to catastrophic climate change and dire consequences for the prosperity of future generations. In this paper, we have argued that the re-emergence of interest by governments in formulating industrial strategy provides an opportunity to chart a course that integrates inclusive social and economic prosperity with low carbon development. Combining insights from neo-Schumpeterian analysis of industrial and economic system change with ecological economics ideas, the paper has set out six key elements for designing a low carbon industrial strategy:

- a mission-oriented approach from government;
- promoting renewable energy and circular economy practices that can deliver significant economic as well as environmental benefits;
- addressing demand-side measures including energy and resource efficiency to complement a supply-side focus;
- reorienting national and local innovation systems to promote entrepreneurial activities and skills and knowledge development;
- institutional changes to enable availability of green finance; and
- a learning approach that incorporates adaptive policy pathways and flexibility in the implementation of policy measures.

We argue that these elements should find support from a broad constellation of actors. Some of these elements, particularly investment in renewables and the provision of green finance, are already promoted by international development organisations such as the World Bank.

The implementation of low carbon industrial policies will always be politically controversial, as the losers in terms of declining industries are likely to be more visible and vocal than the potential winners in terms of newly created industries. Improved tools for assessment of the impacts of low carbon industrial policies and application of a wider set of measures and indicators of social and economic impacts, including job

creation and reducing social inequality, could help to enhance the political and economic feasibility of these policies.

Perhaps most importantly, political leadership and a clear sense of direction and ambition towards a low carbon future, steered in a way that enhances the social and economic benefits of a low carbon industrial transformation, can provide a supporting environment for a wide range of actors to adopt and implement a strategic approach to realising a low carbon future.

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