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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.

1. Introduction

The continuing challenging economic context in many countries and insufficiency of monetary policy, 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, 2017a). At the same time, the UK and other governments have committed to achieving substantial reductions in their projected national carbon emissions, in order to meet their commitments under the December 2015 Paris Agreement, which entered into force in November 2016 and has been ratified by 170 countries. 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). Under the 2008 Climate Change Act, the UK government committed to reducing national emissions by 80% by 2050 from 1990 levels, and published a ‘Clean Growth Strategy’ in October 2017, setting out broad plans to achieve an intermediate target of a 57% reduction by 2028–2032 (HM Government, 2017b).

Achieving these ambitious emissions reduction targets is increasingly recognised as requiring a transformation of the economies of both industrial and developing countries (Deep Decarbonization Pathways Project, 2015; Hermwille, 2016; International Social Science Council (ISSC)UNESCO, 2013; IPCC, 2012). Despite this, strategies for achieving emissions reductions have largely been formulated separately from economically-oriented industrial strategies. The UK’s Clean Growth Strategy marks a departure from this in that it aims “to put clean growth at the heart of our Modern Industrial Strategy” (HM Government, 2017a), a framing that builds on

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the argument that the investment needed for a low carbon transformation could provide an economic stimulus (New Climate Economy, 2016; UNEP, 2011).

The integration of industrial development and environmental goals has been advocated by a number of recent reports. Lütkenhorst et al. (2014a,b) elaborate a Green Industrial Policy that responds to four key challenges: (1) pervasive market failures, (2) uncertainty and long time horizons, (3) the creation of new pathways, and (4) the disruption of old pathways. In this, they pay particular attention to the normative nature of the social goals that such a policy would entail, and the need for this to be democratically negotiated. Aiginger (2015) outlines an industrial policy for a "Sustainable Growth Path" which emphasises the need for an alignment with other policy domains, and particularly with energy policy. This issue of policy alignment is also addressed by Ashford and Renda (2016) who describe a ten step programme for sustainable innovation in the EU policy programme, based on a double alignment of public policy that fosters innovation, and innovation for decarbonisation. Central to Ashford and Renda's proposal is the idea of mission-led innovation platforms, set up to tackle specific societal challenges and identify pathways towards deep decarbonisation.

Whilst each of these proposals contributes important ideas for the practical implementation of low carbon industrial strategies, further work is needed to explore the understanding on which the integration between industrial and environmental goals is based. In this paper, we draw on and combine insights from neo-Schumpeterian (evolutionary) and ecological economics perspectives to set out 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 overt 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 (Freeman, 1974; Perez, 1985), provide the basis for an alternative framing on the role of government action to create and shape markets, rather than just responding to market failures (Mazzucato, 2016, 2015a). 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. As the name suggests, the UK's new Clean Growth Strategy is very much formulated from a green growth perspective, arguing that, by changing priorities within the current economic system, it will be possible to simultaneously achieve economic and environmental goals.

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 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. This entails both a conceptualisation of the role of the state in the economy, and what goals industrial policies should pursue. 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 (P. A. Hall, 1993; Kern et al., 2014).

Drawing on Cowling and Tomlinson (2016), we define a low carbon industrial strategy as:

> the objectives and frameworks that determine how government seeks to guide the direction of industrial change 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.

A low carbon industrial strategy therefore consists of two parts. First, it should specify the *strategic objectives* both in relation to carbon emissions and the wider public interest, e.g. providing good employment opportunities or improving social 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. A recent report from the Deep Decarbonisation Pathways Project

(2015) illustrates the diversity of pathways that result from such downscaling for different countries. Economic structure and level of technological development, and national priorities and social preferences significantly shape the strategies developed for different countries in this project.

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. Drawing on the varieties of capitalism literature (P. A. Hall and Soskice, 2003), 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. As a consequence, Germany has developed a substantial green industry sector whilst GHG emissions have reduced by only 28% between 1990 and 2016. This dynamic is typified by the decision to phase out all nuclear power following the Fukushima disaster, which suggests that GHG emissions reductions are not the most important objective of the Energiewende. 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).

In the remainder of this paper, we take the position that government intervention in the economy is acceptable and required for low carbon transformations, but we are not prescriptive as to the precise role of government. Instead, we propose theoretically grounded elements for low carbon industrial strategy on whose basis specific interventions can be justified.

2.2. Integrating low carbon and economic objectives

Developing a low carbon industrial strategy requires the identification of a consistent set of policy goals. Climate change mitigation targets define the scale of the transformation needed; strategic goals must be consistent with achieving this scale 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, a low carbon transformation will require a massive expansion of low carbon energy sources that must almost completely replace unabated fossil fuels by 2050. 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 (Foxon, 2017).

The neo-Schumpeterian approach has two important insights for the economic and social benefits of a low carbon transformation. The first relates to the possibility of low carbon technology adoption driving further economic development. The neo-Schumpeterian approach identifies innovation as the principal driver of economic dynamics and development (Hanusch and Pyka, 2006). 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. This line of argument would support a green growth view of a low carbon transformation. It has also been argued that the more decentralised nature of many renewable energy technologies, including solar PV and advanced biomass technologies, mean that they are conducive to more bottom-up forms of social and economic development that would spread welfare benefits more widely (Ockwell and Byrne, 2016).

Even if such a surge does not materialise, a low carbon transformation remains a necessity. As the Stern Review (Stern, 2006) and subsequent studies have argued, unchecked climate change would lead to severe environmental, social and economic impacts, meaning that the economic costs of inaction 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 has a second insight that is important to the strategic objectives of a low carbon transformation. In recognising innovation competition rather than price competition as the principal coordinating mechanism of the economy, neo-Schumpeterian theory also suggests that the idea of a single optimal development pathway that is followed by a perfect market is false. There are many different possible trajectories that economic development can follow, driven by processes of lock-in and path dependence (Fouquet, 2016; Unruh, 2002), and each trajectory may lead to radically different economic and social outcomes. Economic development pathways are determined by the activities of networks of public and private sector actors and the institutional contexts that shape the markets in which they interact. Nowhere is this more relevant than in the highly regulated energy systems that are core to low carbon transformations. The 'optimal' choice of possible outcomes of economic development is therefore not determined by the efficient allocation of a perfect market; instead this choice is necessarily normative, can vary over time and space, and must be politically negotiated (Lütkenhorst et al.,2014a,b). A desired set of social and economic outcomes must be realised through the creation of appropriate institutions and governance arrangements that create and shape markets.

2.3. 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 restricting government action to only 'fix' market failures associated with the carbon externality is misguided. Reliance on an 'efficient market' with internalised 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[1] (Gallagher et al., 2011). Instead, there is an active role for governments in creating and shaping markets, not just fixing market failures (Mazzucato, 2016, 2015a), and helping to identify key industrial sectors that can drive the transition in similar ways to previous long-term techno-economic system changes (Perez, 2010).

The idea that industrial strategy should be about seeking to create and shape markets (Mazzucato, 2015a) breaks from the mainstream economics framing by rejecting the idea of a single optimal path of economic development that is followed by a perfect market. 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). 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, distributers and consumers (Perez, 2010). First described by Lundvall and Freeman as a 'national system of innovation' (Freeman, 1995, 1987; Lundvall et al., 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, 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, 2016).

Mazzucato builds on the techno-economic paradigm concept to argue for 'mission-oriented' innovation (Mazzucato, 2015a; 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, 2015b). 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).

In the next section, we set out strategic elements and framework for 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 for the two parts of a low carbon industrial strategy: the *strategic objectives* it should set and the *framework* within which policy interventions are justified.

As previously stated, the strategic objectives of industrial strategy combine the requirements of carbon emission mitigation targets and the economic and social goals of industrial strategies. Whilst the former should be principally informed by scientific analysis and are embedded in international and national agreements, the latter are necessarily normative and should be politically negotiated, primarily at national and sub-national levels. The strategic objectives we identify are:

[1] This is not to say that carbon taxes are not a useful instrument in effective industrial and climate policy mixes. As argued by Baranzini et al. (2017), carbon pricing is an effective tool to provide continuous incentives for innovation in carbon-efficient technologies, and it addresses rebound effects (which are discussed later) in a systematic way. As such, carbon pricing is complementary to the more active industrial strategies that we discuss in this paper.

1) Promote innovation in low carbon technologies, business models and practices
2) Action to manage energy demand as well as supply
3) Enable flexibility for systemic change.

Following from the strategc objectives, we identify five elements for a low carbon industrial strategy that describe how policy interventions should be conceptualised and justified. These elements are derived from a synthesis of neo-Schumpeterian and ecological economics theories of industrial evolution. They represent the framework for a low carbon industrial strategy. The five elements are:

1) Defining and enabling a low carbon industrial mission
2) Creating markets with demand-pull
3) Shaping markets by identifying opportunities and rewarding success
4) Stimulating investment
5) Embedding learning approaches in governance

We now discuss each of these in turn.

3.1. Strategic objectives

3.1.1. Low carbon innovation

Achieving the Paris Agreement mandated 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, 2015). 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.

Clearly, international targets, such as the 2 °C target under the Paris Agreement, and national targets, such as the UK's 80% carbon reduction by 2050, can be seen as defining goals for transformations of energy and industrial systems needed to achieve these targets. However, it is not so clear how these translate into missions that can guide particular industrial transformations, given uncertainties about the social and technological pathways to achieving these targets. This suggests the need to define missions in terms of solving problems, rather than promoting particular solutions. Examples of problem-defined missions could include requiring all new electricity generation technologies to achieve a particular carbon intensity, e.g. 50 gCO_2/kWh, by a particular date, e.g. 2030, or limiting the amount of virgin materials allowed in new product or service provision.

Whilst the precise mix of technologies and sectors to be identified will vary from country to country, for a developed economy like that of the UK, these criteria suggest the importance of particular areas. Firstly, 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. Given the importance of infrastructure as an enabler of other economic activity, this leads to claims that low carbon infrastructure investment is not a cost 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).

Given that carbon emissions are closely linked to levels of resource use, a further key area could be the adoption of '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, 2013). 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 (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 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[2] 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).

3.1.2. Managing energy demand

In addition to the creation of markets for new technologies, demand side interventions, including energy and material efficiency improvements, have a key role to play in low carbon scenarios (IPCC, 2015), and so should be a key feature of a low carbon industrial strategy. We agree with the caution expounded by Mowery et al. (2010) that there are dangers in defining a climate change mission by analogy with the Apollo or Manhattan projects in that it may be too focussed on ‘supply side’ policies and the development of technological solutions, rather than on the “far more painful” demand side policies aimed at diffusion of these technologies, and promoting changes to energy-intensive human behaviours. New business models relating to selling services rather than products, as well as implementing circular economy ideas, may be as important to a transformation as low carbon electricity generation and heat supply technologies. Driving change in the consumer demand for goods and services holds significant potential for carbon emissions reductions (Barrett and Scott, 2012). The case for the implementation of Product Service Systems (business models based on selling services alongside products, e.g. maintenance contracts) to effect more resource efficient consumption (Tukker, 2015) reflects 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).

Reductions in energy demand, and shifts in demand to patterns more suited to renewable energy, may result from changes in consumer preferences and patterns of consumption, but state intervention through the imposition of regulations is also a powerful tool (Ashford and Hall, 2011a). Such regulations have been used very effectively in the past, as in the case of automobile fuel efficiency standards (Nemet, 2014).

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

3.1.3. Enabling more systemic changes

Though high levels of investment in innovation and diffusion of low carbon technologies could lead to a Keynesian stimulus to economic activity, as green growth advocates argue, it is not clear that a continuous decoupling of economic growth and environmental impacts is possible over the long term. Furthermore, unless ‘escape routes’ are blocked (van den Bergh, 2012), action to reduce carbon emissions in specific countries or sectors may lead to those emissions being transferred rather than contributing to overall global emissions reductions. So, low carbon industrial strategy needs to be developed in a way that promotes systemic changes contributing to global carbon emissions reductions.

The current growth of low carbon energy industries is mainly expanding the range of energy supply options and not yet significantly reducing global carbon emissions by substituting for high carbon sources (Gazheli et al., 2016; York, 2012). An absolute decoupling of economic growth from indicators of environmental impacts (such as carbon emissions, material throughput, energy use) is not likely to be achieved on current trajectories (Jackson, 2016; Peters et al., 2011; Steinberger et al., 2012; Wiedmann et al., 2015). Hence, changes to current patterns of energy-intensive consumption may also be necessary, which could reduce economic growth as conventionally measured, even though proponents argue that this could deliver compensating benefits in terms of improvements in quality of life and reductions in inequality (Jackson, 2016). This would require changes to current economic systems and priorities that are largely beyond the scope of a low carbon industrial strategy, though such a strategy should be formulated and implemented in ways that allow for more systemic changes, should they be needed.

Ensuring that climate change policies do lead to significant carbon emissions reductions, especially those that seek to also promote economic activity, requires the blocking of ‘escape routes’, that would otherwise weaken the environmental effectiveness of these policies (van den Bergh, 2012). One of these escape routes is so-called ‘rebound effects’, in which energy efficiency improvements stimulate further economic activity that reduces or eradicates the energy and carbon savings (Sorrell, 2009). Direct rebound effects in household energy services, where more efficient service delivery leads to 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 lead to even smaller overall energy demand reductions (Sorrell, 2009). Finally, macroeconomic rebound effects[3] 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, 2008).

Whether rebound effects constitute 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

[2] Perez (2016) cites Silicon Valley, Industrial Districts in Northern Italy and the wind energy industry in Denmark as examples.

[3] Indirect rebound effects are those where efficiency improvements in the provision of one service results in the increased consumption of another, as in the famous example of savings from energy efficient lightbulbs paying for holiday flights. Macroeconomic rebound effects are tied to the issue of energy being an economic growth factor (Ayres and Voudouris, 2013), Sorrell (2009) discusses this issue at length.

(Brockway et al., 2017). To avoid this and other 'escape routes', efficiency improvements may need to be combined with imposition of strict economy-wide carbon caps to enable both economic and environmental benefits to be realised. On an international scale, the problem of carbon leakage where increasing costs of pollution in one economy lead to the shift of production and pollution to another will require international coordination. This type of rebound could be avoided through a comprehensive global carbon tax, or through border carbon adjustments (see, for example, Rocchi et al. (2018)). 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).

3.2. Framework for policy interventions

3.2.1. Defining and enabling a low carbon industrial mission

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 (Anadon et al., 2016; Mazzucato, 2013; Mazzucato and Perez, 2014; Perez, 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.

This still raises issues of the capacity and capability of the state to deliver and implement successful policy and legislation 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).

The role and form of interactions between government and industry are important, to avoid the dangers of poor targeting of interventions, for example, due to lobbying by particular industries or sectors (Rodrik, 2014). Rodrik describes this as government agencies that "need to be embedded in, but not in bed with, business" (Rodrik, 2014, p. 485). He argues that this requires institutions to support innovation to be put in place with clear mandates, for example, support for a portfolio of opportunities, allowing for some failures, together with a willingness to withdraw support when businesses fail to achieve stated goals. Mazzucato (2016) also argues that government agencies should benefit from successes, for example, by receiving equity shares in exchange for investments. Anadon (2012) shows that there are significant differences 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. She identifies three key trade-offs in the design of these institutions: (1) the need for a high degree of autonomy from direct government interference vs. the need for systems integration across the innovation chain; (2) the need for stable funding for institutions vs. the need for flexibility in redirecting efforts; (3) the need for private sector engagement vs. the danger of capture by private sector interests.

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, 2016) 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).

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., 2014a,b; Rodrik, 2014). 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.

3.2.2. Creating markets with demand-pull

Despite the recognition of the importance of thinking in terms of innovation systems, for example, in the work of the OECD, industrial policy is often framed in terms of a 'linear model' of innovation, driven mainly by research and development (R&D) in new technologies. An innovation systems perspective also shows the importance of support for demonstration and commercialisation of technologies, the need for 'demand-pull' driven by creating markets, and the importance of feedbacks between different stages in the innovation chain. This emphasises the importance of consideration of systemic factors in driving or creating barriers to innovation. This is particularly important in terms of designing industrial strategy to promote a low carbon transformation, as this involve changes to industrial systems that include new institutions, business strategies and user practices, as well as new technologies (Foxon, 2017, 2011).

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, with feedbacks between these stages (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.

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 disproportionally affected by declining industries, whilst others will always be more economically active (Cox et al., 2016; Meadway, 2013; Molho et al., 2016).

The public sector can also undertake more direct interventions to instigate the creation of markets that are aligned with low carbon industrial missions. Public procurement standards and feed-in tariffs are good examples of instruments that can be used to establish niche markets, or to facilitate the transition to mass market (Kivimaa and Kern, 2016). These can be used to support specific technologies, as in the use of feed-in tariffs for photovoltaics, or to support broader characteristics, as in energy efficiency guidelines for public procurement. Similar to public procurement, but with a greater range of impact across the economy, is the use of regulation to create 'lead markets' for products with improved environmental performance (Jänicke and Jacob, 2005). Scholars including Ashford have long argued for the use of regulation to drive innovation for sustainable development, and the need for integration of policies across the labour market, energy demand from consumers and industry, and industrial innovation (Ashford and Hall, 2011a). As such regulation is an important driver of technological change in businesses, it should be understood as a tool with the potential to drive disruptive innovation for low carbon industries (Ashford and Hall, 2011b).

3.2.3. Shaping markets by identifying opportunities and rewarding success

A key challenge in developing a low carbon industrial strategy is that pathways to a low carbon energy system are inherently uncertain. This uncertainty relates to the rate of performance improvement and cost reduction in key technologies, the level of changes in user practices and behaviours that can be achieved, the development of appropriate business models and the speed of institutional changes, relating to political will and incumbent resistance. This leads some economists to conclude that government intervention should largely be restricted to setting a carbon price to internalise the externalities and leaving it to markets to figure out the mix of changes needed to achieve carbon reduction targets (Helm, 2017). However, we argue that markets are created and shaped by actions of governments and other actors, and so incentives within the system need to be aligned with achieving a low carbon transformation. This should enhance expectations of the direction of travel, by institutionalising long-term targets and rewarding success for actors that contribute to meeting these targets.

Clearly, promoting technological innovation is a key part of a low carbon industrial strategy. Technological change is one driver of wider industrial change, though not the only one. This raises the question of the extent to which a low carbon industrial strategy should try to identify key technologies or key technological sectors to promote. The danger of this approach has been criticised by many economists as trying to 'pick winners'. However, in order to stimulate national economic benefits, some focussing of investment will be needed. Given that a low carbon transformation will be disruptive of existing industries and business models, it is not clear that incumbent businesses will necessarily have greater knowledge than governments of how this focussing should be achieved. Thus, criteria are needed to identify key technology areas or sectors in which investment should be focussed, such as the following:

(1) Potential scale of contribution of technology or sector to achieving carbon reductions:
This could include technologies that have been identified as playing a key role in low carbon energy scenarios, such as low carbon electricity generation technologies, or sectors where expected continuing growth in service demand means that technological change is needed, such as aviation;
(2) Potential scale of contribution of technology or sector to achieving national economic goals:
This relates to the mix of manufacturing and service industries in the national economy, and the extent to which investment in manufacturing is seen as a key source of positive economic spillovers by enabling technologies, synergies and supply chains across economies;
(3) Potential scale of contribution of technology or sector to achieving other 'co-benefits':

This relates to the potential of the technology or sector to contribute to achieving other social, economic or environmental benefits, such as reduction in local air pollution;

(4) Scale of existing skills base and industrial expertise in likely growth areas:
This relates to the extent to which investment in a particular technology or sector can draw on existing skills and expertise, with the expectation of being able to grow and develop.

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).

3.2.4. Stimulating investment

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 carbon emissions reduction 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.

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, 2009). 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; Godin 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 (S. 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.

3.2.5. Embedding learning approaches in governance

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., 2013; Hallegatte et al., 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. 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 three strategic objectives and five elements of a framework for policy interventions for a low carbon industrial strategy. The *strategic objectives* we suggest are:

1) Promote innovation in low carbon technologies, business models and practices
2) Action to manage energy demand as well as supply
3) Enable flexibility for systemic change;

And the elements of a framework for a low carbon industrial strategy are:

1) Defining and enabling a low carbon industrial mission
2) Creating markets with demand-pull
3) Shaping markets by identifying opportunities and rewarding success
4) Stimulating investment
5) Embedding learning approaches in governance

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.

Declaration of Interest

None.

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