Research Policy 50 (2021) 104293

Contents lists available at ScienceDirect

Research Policy

journal homepage: www.elsevier.com/locate/respol

Innovation, growth and the transition to net-zero emissions

Nicholas Stern, Anna Valero [#,*]

London School of Economics and Grantham Research Institute, LSE

ABSTRACT

The climate crisis and the global economic impact of the Covid-19 crisis occur against a background of slowing growth and widening inequalities, which together imply an urgent need for a new environmentally sustainable and inclusive approach to growth. Investments in "clean" innovation and its diffusion are key to shaping this, accompanied by investments in complementary assets including sustainable infrastructure, and human, natural and social capital which will not only help achieve net-zero greenhouse gas emissions, but will also improve productivity, living standards and the prospects of individuals. In this article, we draw on the theoretical and empirical evidence on the opportunities, drivers and policies for innovation-led sustainable growth. We highlight the importance of a coordinated set of long-term policies and institutions that can enable and foster private sector investments in clean innovation and assets quickly and at scale. In doing so, we draw inspiration from Chris Freeman's work on the system-wide drivers of innovation, and his early vision of achieving environmental sustainability by reorienting growth.

Introduction

The climate crisis and the global economic impact of the Covid-19 crisis have occurred against a background of slowing growth and widening inequalities. The pandemic hit a precarious system exposing its fragilities; indeed, humanity's impacts on ecosystems made a pandemic more likely. A new environmentally sustainable and inclusive approach to growth is required in response to these twin crises and to the weaknesses that produced them. Investment in innovation and its diffusion will be key to shaping this, accompanied by investments in complementary assets across sustainable infrastructure, and human, natural and social capital which together will not only help achieve net-zero greenhouse gas emissions, but also transform prospects and living standards around the world.

Urgent action is required, at scale and across the whole economy. Any substantial delay in managing climate change will put a 2°C temperature target for global warming out of reach, let alone the 1.5°C we should be seeking, given that we now understand that the risks embodied in 2°C are so much greater than 1.5°C (IPCC, 2018). Delayed recovery from the Covid-19 health and economic crises will involve extended unemployment that risks endangering social cohesion and scarring education and work opportunities, particularly for young people. Technological change must be radical to enable the decarbonisation of economies in just three decades and drive sustainable increases in productivity and living standards.

This article examines ideas and evidence on how policies and institutions can enable and foster private sector investment in sustainable and productive assets at the scale and pace required to tackle climate change and simultaneously achieve a strong economic recovery and growth into the future.[1] While our focus is on policies in high-income economies operating on the global innovation frontier, interactions with and implications for sustainable development in poorer countries are highlighted. We also set out a research agenda on the key areas where further work is required.

The fundamental definition of sustainability is for this generation to offer the next generation opportunities in terms of well-being that are at

* Corresponding author.

E-mail addresses: N.Stern@lse.ac.uk (N. Stern), A.A.Sivropoulos-Valero@lse.ac.uk (A. Valero).

The authors are grateful for comments and perspectives from Amar Bhattacharya, Alan Freeman, Ralf Martin, James Rydge, Joseph Stiglitz, Charlotte Taylor, Sam Unsworth, Dennis Verhoeven and Dimitri Zenghelis and all the participants at the "GRI/CEP/STICERD Symposium on Technical Change, Innovation and Climate" held at the LSE in July 2019. We are grateful for support from the Grantham Research Institute on Climate Change and the Environment. Financial support from the ESRC Centre for Climate Change Economics and from the ESRC via the Centre for Economic Performance, the Programme on Innovation and Diffusion (POID) and in addition under grant ES/S001735/1 is gratefully acknowledged.

[1] There are important issues around public finances and the ability of the financial system to deliver on net-zero which are not the focus of this paper, for more discussion in the UK context, see Stern et al. (2020) and Robins (2020).

https://doi.org/10.1016/j.respol.2021.104293
Received 1 March 2021; Received in revised form 12 May 2021; Accepted 17 May 2021
Available online 21 June 2021

least as good as those which they had, assuming that the next generation behaves in a similar way to those that follow.[2] By "sustainable growth", we mean growth that is environmentally sustainable, driven by a zero-carbon transition that increases underlying strength and productivity across physical, knowledge, human, natural and social capital assets – and therefore can be sustained in the long run. The rise of populism and anti-globalisation sentiment in many countries has highlighted the importance of ensuring that the opportunities and benefits of economic growth are distributed across society. A zero-carbon transition can both boost productivity and growth and avoid severe climate change impacts that will hit the poorest and most vulnerable hardest. Lessons from history suggest that this transition, as it combines with technological change more broadly, will not automatically deliver inclusive growth (Rydge *et al.*, 2018). But with the appropriate forward-looking institutional frameworks and policy mechanisms in place, the zero-carbon transition can deliver not only sustainable and more inclusive growth, but also higher rates of growth compared with a high-carbon counterfactual. This article discusses sustainable and inclusive growth, and the zero-carbon transition, in this context. "Sustainable", "clean" or "green" growth, and the innovation required to get us there are used more or less interchangeably, although our emphasis would be on sustainability.

Throughout this article, we draw upon a number of strands of Chris Freeman's pioneering work, including that which has built an understanding of the drivers of innovation and its diffusion and how these relate to institutional or organisational factors in an innovation system, his analysis of major waves of technical progress and their evolution, his emphasis on inter-disciplinarity in the study of innovation, and on data to inform the development of theoretical approaches. Indeed, our main message is very much aligned with Freeman's vision of environmental sustainability which was to be achieved by reorienting growth, rather than stopping it (Cole *et al.*, 1973). In 1992, at the time of the Rio Earth Summit which, inter alia, established the UNFCCC, five years before the Kyoto protocol was agreed, Freeman argued that sustainability could be achieved through reorienting the R&D system and through major institutional change (Perez, 2014). More specifically, he asserted that "The ICT [information and communications technology] paradigm can be shaped and steered in an environmentally friendly direction. This was not true of the previous paradigm which was based on mass production and the exploitation of cheap oil" (Freeman, 1992).

Nearly three decades have passed, and digital technologies have created even more potential for resource efficiency and productivity gains (key examples in the UK context include the application of smart grids to energy networks and automated manufacturing techniques[3]). However, it is clear that the world is moving far too slowly for the achievement of the Paris 2015 UNFCCC target ("well below 2°C") and that climate action must be accelerated in order to avoid catastrophic and irreversible damage (IPCC, 2018). The next decade is critical. Choices made on investments in infrastructure, innovation and complementary assets now will either create lock-in to high emissions or enable reorientation towards a low-carbon growth path, which can be both sustainable and inclusive. And it can and must be resilient to the climate change which is now unavoidable. Global ambitions were raised in the twenty-first session of the Conference of the Parties (COP21) of the UNFCCC in Paris, and COP26 hosted this year (2021) in Glasgow will be critical in terms of driving action.

So far, the devastating impact of the Covid-19 crisis appears to have strengthened resolve to invest in sustainable innovation and infrastructure, with many countries setting out plans for a "green recovery". But this must be converted to robust and coordinated policies and investments at real scale and pace. There are lessons in the global response to the pandemic, which has highlighted the power of R&D in the development of Covid-19 vaccines and treatments, and also the importance of the diffusion of existing inventions in the adoption of digital technologies that have helped businesses (Riom and Valero, 2020) and individuals adapt to social distancing. In addition, Covid-19 has shown how rapidly we can change if we recognise clearly the need to do so and the incentives of key actors across policy, industry and society are aligned. The climate crisis, like the Covid-19 crisis, involves tackling market failures, fostering international cooperation, marshalling complex science, and asking questions of system resilience. And it requires political leadership, and whole sets of actions that hinge on public support (Hepburn *et al.*, 2020). The potential global impacts of the climate crisis are slower to materialise, but much graver than those from Covid-19. And the actions to be taken are no less urgent.

A sustainable recovery requires large-scale investment by the private and public sectors. And there are reasons to be hopeful that the required actions can be taken and sustained. Compared with the 2008 financial crisis, there appears to be more political support for a commitment both to grow out of the crisis and related debt and to "build back better" (Stern *et al.*, 2020). After the 2008 crisis there was a retreat into austerity before growth had been re-established, which was a key factor in the weak growth of the past decade.[4] And there was only a modest commitment to sustainability or a green response even though at the time of the 2008 financial crisis, analysis demonstrated the superior employment opportunities from clean energy infrastructure relative to fossil fuel investments, estimating that they would create twice as many jobs per dollar spent (Pollin *et al.*, 2008). Over time, the case for investment in clean energy infrastructure has been further strengthened, and there is evidence that such investments can generate job opportunities in the short and longer run (Unsworth *et al.*, 2020b). We are already seeing evidence of increasing returns to scale in the discovery and production of clean technologies (Ekins and Zenghelis, 2021), for example via the dramatic declines observed in the costs of renewable energy, battery storage and electric vehicles. Indeed, solar and wind are the cheapest forms of new power generation in countries representing over 70 per cent of global GDP.[5]

Sound, stable and credible public policy, sustained and long-term public investment, and a commitment to growth, play central roles in guiding and fostering private sector investment. The theoretical and empirical evidence we summarise here in relation to innovation and investment implies that a series of market failures will have to be tackled, requiring a suite of different policy instruments across carbon pricing, support for clean R&D, regulation and design, if the necessary investment and innovation for strong and sustainable growth is to be realised. The collection of instruments should be mutually reinforcing and supported by strong and long-term institutions, if the shift to sustainable innovation and economic systems is to occur at the pace and scale necessary to drive growth and stabilise climate. It is now necessary to examine a question which, all too often, economics fails to tackle. Beyond analysing whether or not a set of policies can yield improvements, we must ask whether they can deliver sufficiently rapidly. Time matters; delay is dangerous (Stern, 2018).

The paper is organised as follows. Section 1 sets out approaches for understanding and modelling innovation and growth in the presence of multiple market failures, with a focus on path dependencies in innovation systems, and draws out the implications for policy. Section 2 focuses on the empirics with respect to the drivers of sustainable innovation and investments, and the implications for growth and distribution. Section 3

[2] In 1987 the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising on the ability of future generations to meet their own needs".

[3] For example, Deloitte and TechUK (2020) estimate that digital technologies already being deployed can deliver 15% of the UK's required reduction in emissions by 2030.

[4] See, for example, Blanchard and Leigh (2013) who highlight how stronger fiscal consolidation was associated with lower growth, particularly in the early years post financial crisis.

[5] See, for example, SYSTEMIQ (2020).

considers political economy dimensions of the transition to a net-zero growth model. Section 4 provides some concluding comments.

Path dependence and clean innovation

Our starting point is the assertion that increasing "clean" innovation (defined broadly as that which directly or indirectly enables the net-zero transition) is necessary to enable the transformation required to tackle climate change, and we set out key findings from the theoretical literature[6] that can inform understanding of the conditions necessary for this to be the chosen strategy of profit maximising firms.

There is a strong rationale for policy that seeks to increase the *amount* of innovation in the economy. The market failures that are often targeted by government support for research and development (R&D) and innovation activities are well documented (see, for example, Bloom *et al.*, 2019). The central failure is associated with the existence of knowledge spillovers.[7] Even in the presence of an effective system of intellectual property rights, an innovator is unlikely to be able to capture all the financial returns from associated R&D investments, with the implication that investments in R&D tend to be lower than the level that would be "socially optimal". Further market failures arise due to imperfections in capital markets that may limit investment in "risky" projects, and from information or coordination frictions that can also hold back investment in innovation.

There are also robust economic arguments for policies, investments and incentives that influence the *direction* of innovation towards technologies that can tackle the climate challenge. First, the evidence suggests that knowledge spillovers appear to be particularly strong for clean technologies. Empirical analyses have found that the spillovers in clean technologies (as measured using forward citations in patents related to energy production and transport) tend to be higher than those generated by their dirty counterparts (Dechezleprêtre *et al.*, 2014). Such analyses imply that the general decline in clean energy patenting that was seen in the early 2010s (Popp *et al.*, 2020), which has started to reverse more recently (EPO and IEA, 2021), is of key concern from both a climate and growth perspective and that it is important for policymakers to look closely at the pace of innovation and R&D in these areas. Furthermore, over recent years and in the absence of strong policy signals and incentives, investments in early-stage clean technologies appear to have been viewed by many investors as more risky than the dirty alternatives that occupy established positions (see, for example, Nanda *et al.*, 2015; Gaddy *et al.*, 2017), implying heightened financing constraints.[8] Indeed, Popp *et al.* (2020) document a spike in clean energy start-ups and funding around 2008 in the United States, and a decline thereafter.[9]

Finally, further market failures apply in the context of greenhouse gas emissions. First, there is the negative externality that arises due to the damage that emissions inflict on others. In the absence of a robust carbon price, markets do not internalise the price of carbon emissions, and this reduces the incentives to invest in clean alternatives. Further, markets do not fully capture the societal co-benefits associated with decarbonisation via cleaner air, improved natural capital and related health benefits which in turn have positive economic impacts via, for example, a healthier and more productive workforce. Around the world air pollution contributes to many millions of deaths per year (World Health Organisation, 2020) with much of that pollution coming from the burning of fossil fuels. But even if the prices were right, strong inertia and path dependence in innovation systems make it difficult to shift from dirty to clean technologies quickly, without a strong and coordinated enabling package of policies.

Path dependence and directed technical change

"Path dependence" arises when initial conditions and history matter for eventual outcomes. There are a number of sources of path dependence in innovation processes (Aghion *et al.*, 2014) and these can be amplified and reinforced by increasing returns to scale. First there is path dependence in the production of research and knowledge – many scientists prefer to work in areas that are well-funded and where other good scientists are working, allowing them to generate, build upon and benefit from the knowledge spillovers we discussed previously. Second, there is path dependence in the deployment of innovation, as the incentives to deploy products or technologies that use existing infrastructure are higher than for those where the infrastructure is not yet rolled out at scale. Third, path dependence arises in the diffusion of new technologies, due to network effects and high switching costs. Network effects in technology adoption can create path dependence, where the benefits of using a particular technology rise with the number of others using the same technology, and infrastructure assets are often locked in due to the high costs of switching to alternative systems.

Concepts of path dependence are captured in the literature on directed technical change, as applied to climate change, which stems from Acemoglu *et al.* (2012). In this paper, the authors analyse endogenous and directed technical change in a growth model with environmental constraints and limited resources. In a model they develop, where the final good is produced from "dirty" and "clean" inputs, market forces naturally favour investments in dirty innovation (which might include technologies that improve fossil fuel efficiency). The network infrastructure and skills base are initially located in the dirty sector, and therefore, the immediate returns to innovating there are higher. A key implication is that clean technologies may never overtake dirty technologies without government intervention, which can shift the economy onto a clean equilibrium path. This is a problem beyond simply the greenhouse gas externality and, in order to avoid the excessive use of carbon taxes, optimal policy consists of both carbon taxes and research subsidies that support clean innovation. Another implication is that while there will be costs of adjustment during the transition, once the clean technology has gained sufficient productivity advantage and is able to benefit from its own patterns of path dependence, innovation policy incentives are no longer required. Innovation should be accelerated by policy, given the system inertia, because delay is costly; it would necessitate a longer transition phase with slower growth.

Aghion *et al.* (2016) take this type of model to the data in the case of the car industry, finding that firms tend to shift innovation from dirty (internal combustion engine) to clean (electric) when they face higher tax-inclusive fuel prices, and find that there is indeed path dependence in innovation type – based on both the aggregate spillovers to which firms are exposed, and firms' own innovation histories. These findings imply that a carbon tax not only helps mitigate climate change directly, through reducing carbon consumption, but also indirectly by re-orienting R&D investments towards clean technologies and away from dirty ones. Numerical simulations give policymakers quantitative

[6] Our focus is on the literature on directed technological change, as first applied to climate change by Acemoglu et al. (2012). Traditional Integrated Assessment Models (e.g. Nordhaus, 2018) are not focused on the processes of innovation and transformation (Aghion et al., 2014), or representing path dependence (Grubb et al., 2021b)

[7] Spillovers or externalities arise from the fact that technological knowledge is a public good (Arrow, 1962). Spillovers occur when recipient firms exploit knowledge that was originally developed by another firm (Griliches, 1992). The recipient firm either copies or learns from the original research, without incurring the full R&D costs.

[8] See also recent analysis by Beauhurst, a UK start-up and scale-up data platform, which suggests that the clean-tech sector is amongst one of the riskiest in the UK for venture capitalists and private equity firms (Beauhurst, 2019).

[9] The authors note that the decline in funding is less pronounced when considering clean energy firms that also claim to be "high-tech" firms. And they emphasise that studying firms or patents that are only identified as being in the energy sector is likely to underestimate the innovation and start-up activity that is relevant for decarbonisation. They highlight innovation in "high-tech" sectors that is also applicable in a number of areas relevant in the transition to net zero.

guidance on how quickly this can be achieved, finding that carbon taxes would have to increase very substantially given response elasticities. This analysis suggests that other policies such as R&D subsidies and regulation are also needed in order to meet the challenge at the pace and scale necessary.

Van der Meijden and Smulders (2017) emphasise the role of expectations about future energy use in a model of directed technical change. This analysis is complementary to the Acemoglu *et al.* (2012) model, but it emphasises lock-in that arises due to expectations rather than initial conditions. In this model, the anticipation of a transition to renewables reduces the incentives to invest in fossil technology, resulting in an equilibrium with renewables and low fossil efficiency. But an alternative equilibrium without renewables, but with high fossil use, albeit with greater efficiency, is also possible. Over and above the need for policy to address market failures and path dependencies, this paper highlights the important role of policy for guiding investor expectations towards the clean equilibrium (eventually without fossil fuels).

In summary, these key papers suggest that carbon pricing is necessary, but not sufficient to shift to a path of clean innovation that benefits from its own path dependencies. Further support for clean innovation, that accelerates diffusion via investments in the appropriate clean infrastructure assets, and effective regulation are required if a zero-carbon transition is to be achieved. And these must be brought together into a credible and coordinated package of policies and institutions that can guide expectations. This literature also highlights the importance of acting quickly and at scale. Delaying action means locking into dirty technologies and infrastructure thereby both prolonging emissions and making it more costly to change later.

The international dimension

The economic growth opportunities stemming from clean innovation must also be considered in an international context. Where countries have comparative advantage in particular areas of clean innovation that can be deployed in other markets, this can generate opportunities for growth domestically, while going further with respect to reducing emissions globally. Such issues have been considered with respect to the diffusion of clean innovations from more technologically advanced economies into emerging economies. While some emerging markets, such as China or Brazil, play a key role at the global innovation frontier, many are more likely to adopt or imitate clean technologies previously invented elsewhere.

Consideration of the international context implies that policies that promote clean innovation in high-income countries may not lead to socially optimal emission reduction unless there are additional interventions that support the transfer and deployment of clean technologies elsewhere. Hémous (2016) builds on the Acemoglu *et al.* (2012) framework to analyse a multi-country model: “North” with policy and “South” with laissez-faire. A unilateral carbon tax in the North leads to a dynamic pollution haven effect in the South. The model implies that policy interventions that price carbon and subsidise clean R&D in more innovation-intense economies (North), should be accompanied by policies that facilitate technology transfer and build absorptive capacity in the South. In the context of trade, over and above making clean technologies available and affordable in the South, carbon tariffs (or the threat of introducing them) may be required to prevent the South specialising in dirty goods (Aghion and Jaravel, 2015).

Intermediate technologies

While there is general agreement as to the need to accelerate the invention and diffusion of “clean” technologies, views differ with respect to the role of intermediate or bridge technologies that relate to reducing or removing carbon emissions from “dirty” processes. In the context of the directed technical change literature, Acemoglu *et al.* (2019) extends Acemoglu *et al.* (2012) to include intermediate (“bridge”) technologies. The model is calibrated to the US electricity sector to estimate the static and dynamic effects of a shale gas boom, and a key finding is that bridge technologies can “backfire” if they reduce clean innovation. Aghion *et al.* (2014) explain how the logic of path dependence due to reliance on intermediate technologies applies to gas - where there is also the risk of lock-in due to gas-based infrastructure (thus they do not turn out to be a bridge to clean technologies). Such intermediate technologies may warrant support as long as it is time-limited, and that it does not come at the expense of increased support for fully clean alternatives. In the case of carbon capture utilisation and storage, including air capture, while increased R&D in such areas could reduce, in principle, the incentive to urgently push for renewables, such strategies build in flexibility to meeting decarbonisation targets, and are likely to be important for certain sectors at certain times – such as steel or cement.

Customer values and product market competition

Other key forces shape the direction of firm innovation. Firms are more likely to invest in innovation in areas where demand is large and growing – and may therefore consider consumer preferences more carefully. Product market competition also shapes firm innovation, and while the impact is theoretically ambiguous (Bloom *et al.*, 2019), the empirical evidence generally suggests that competition increases innovation, particularly in markets with initially low levels of competition. Aghion et al. (2021) develop a theoretical model that allows customer environmental values and product market competition to shape firm R&D. The authors show (theoretically and empirically) that there is a complementarity between product market competition and pro-environmental attitudes of consumers. Thus, firms will invest in cleaner innovation when facing more environmentally-motivated customers. This effect is stronger the harder they must compete for their customers. These findings suggest that, from a policy perspective, public campaigns to promote citizens' environmental responsibility are likely to be an important policy lever for stimulating clean innovation, especially when combined with more competitive markets. Many firms, such as Unilever,[10] also point to their ability to attract more talented workers if they demonstrate commitment to environmentally (and socially) responsible policies. Further perspectives on the political economy dimension of directed technical change (Besley and Persson, 2020) are discussed in Section 3.

Alternative approaches for modelling complex economic systems

The literature on endogenous and directed technical change identifies and models key forces driving clean innovation in particular sectors, and highlights the importance of complementarities. However, achieving net zero will require rapid and radical structural change across the economy. Thus it is important to consider how the findings from such models can be integrated to provide insights and recommendations for economy-wide policy frameworks in the context of uncertainty. Moreover, there are limitations in the ability of traditional models to fully capture path-dependencies and reinforcing feedbacks that can lead to multiple equilibria, and therefore limitations in the ability of the traditional models to predict the costs and benefits of the transition over the next few decades.

One alternative approach suggests that dynamic models of the economy should be accompanied by models of opinion dynamics and behaviour via the use of agent-based models. Such models explicitly reflect interactions between heterogeneous, networked individuals in place of conventional utility-maximising “representative agents” (Farmer and Foley, 2009). They can therefore offer insights into the processes and associated probability with which economies shift from one equilibrium to another (Mealy and Hepburn 2019, Farmer, *et al.*,

[10] See Unilever (2020).

2015), in particular via "tipping points" which might be triggered by particular policies or a breakthrough technology, for example cheap and efficient energy storage.[11] While there are a number of drawbacks associated with such models, including the lack of commonly accepted standards and validation procedures (Mealy and Hepburn, 2017), they can help illuminate possible relevant outcomes and processes of change which might be excluded by the assumptions of standard equilibrium modelling.

Mercure et al. (2020) note that at times of long-run, non-marginal change, the primary concern is not how efficiently resources are allocated (in the context of static optimisation), but how effectively economic structures can be repurposed and steered. This implies a focus on expected processes that drive change over time, rather than attempting to model expected outcomes at particular moments in time. They set out a "risk-opportunity assessment" framework to inform policy where transformational change is required in the face of largescale uncertainty, path dependencies, non-linearities and heterogeneity of stakeholders, as is the case with respect to climate change mitigation and low-carbon innovation. The emphasis is on building understanding on the likely direction, rate, and magnitude of change under different policy scenarios, such that decisions can be based on a qualitative judgement of the scale of the opportunities and risks, compared to the cost of the intervention.

Broad lessons from theory

Conclusions for action: The theoretical evidence suggests that action at scale and across the economy, via a coordinated set of policies and institutions, is required in order to tackle the multiple market failures that coexist, and shift the trajectory of economies so that path dependence favours clean innovation and investment. Given the devastating environmental and substantial economic costs of locking-in to dirty assets and infrastructure, time scales and rates of change must be at the centre stage of policy assessments. Policy-orientated analytical work here should not be dominated by simple comparisons of equilibria.

Conclusions for research: The market failures and path-dependencies outlined raise questions concerning the right economy-wide frameworks for aligning incentives and expectations with the transition to net zero. Tractable and quantifiable models are needed, that can go beyond traditional growth models and capture the key ingredients of sustainability, inclusion and growth and the challenges associated with rapid change over the next two decades. A collection of models is likely to be required, each of which could capture different elements of the complex challenges, drawing upon insights from different disciplines. Within such models, and on how we combine insights from different models, more work is needed to understand complementarities between different features of the innovation system, and between different types of innovation too (e.g. improving batteries will lead to more innovation in solar/wind). Such models must be informed by careful empirical and forward-looking analyses, which is the topic of the next section.

Clean growth: Opportunities, drivers and policies

Achieving large-scale change quickly will require an understanding of the opportunities and displacements in the next wave of technological change, as the rise of automation (viewed by many to have accelerated due to the Covid-19 crisis[12]) intertwines with the zero-carbon transition. This must build upon lessons from previous waves of technological change and contemporary evidence on the impacts of policies for (clean) innovation and investment. This in turn requires timely metrics on the quantity of innovation, and its type; and robust evaluation to shed light on the relative effectiveness of different policy levers and their interactions at the international, national and local levels.

Measurement of clean innovation and future growth opportunities

The zero-carbon transition offers substantial economy-wide opportunities for growth (Rydge *et al.*, 2018; Stern *et al.*, 2020). Understanding these opportunities requires looking beyond supporting a narrowly defined "low-carbon sector".[13] Future growth must be sustainable growth and that means building a net-zero-carbon economy that is resilient to the changes and shocks that are likely to characterise the 21st century. Given that it is total world emissions that have to go to net zero, the transformation will involve all economic sectors and regions. These changes have the potential to empower local communities and improve living standards across society. They will both require and foster entrepreneurship.

The economic disruption caused by the pandemic, and the large-scale government interventions that have resulted from it, give rise to an opportunity for a green recovery. Net-zero-aligned investments can generate jobs quickly (see Unsworth *et al.*, 2020b, for discussion in the UK context). They can be both labour-intensive and fast in implementation (examples include retrofitting buildings, intensifying broadband, restoring degraded land). Further, technical advances are creating opportunities for improvements to labour and resource productivity, through complementary investments in innovation (invention and diffusion), infrastructure and human capital across the economy.

With global demand for cleaner and more environmentally friendly products and technologies set to increase rapidly in the coming decades, countries that take early action to develop clean technologies, products and processes may be able to go to scale quicker, establish markets and thus reap significant growth benefits. Government recovery packages and industrial policies in response to Covid-19 are likely to play a key role in shaping which economies are better positioned in this "green race" (Fankhauser *et al.*, 2013). Evidence from the 2008 financial crisis has shown how recovery packages can support future industries (Mundaca and Richter, 2015).

A key question for policymakers is how to best target investments and design policies to promote the development of a given country's current and potential future competitive strengths, and to avoid the pitfalls of attempting to "pick winners". The challenge is to set policies such as carbon pricing and effective regulation (e.g. dates to phase out the sale of vehicles with an internal combustion engine) which point firmly away from fossil fuels but do not prescribe particular ways of doing things. At the same time some paths are already clear in the sense that we must expand electricity supply very quickly and make it zero carbon.

Here we set out three examples of forward-looking and data-driven approaches that can help countries or regions to identify opportunities for sustainable innovation and growth.

[11] See also Farmer et al., (2019) for discussion on "sensitive intervention tipping points" (SIPs), which the authors argue can involve a kick to the status quo (e.g. subsidising renewable energy sources to lower their costs), or a "shift" in underlying system dynamics (e.g. a shift in the institutional regime). In practice SIPs are likely to consist of a mixture of the two. This paper sets out four SIPs that could contribute to decarbonisation: financial disclosure, targeted technology investments, political mobilisation and the UK Climate Change Act.

[12] See, for example, Autor and Reynolds (2020).

[13] In the UK, the ONS Low Carbon and Renewable Energy Economy (LCREE) Survey estimates that the LCREE accounted for around 1% of total UK non-financial turnover and employment in 2018.

Analyses of patents and spillovers

A body of empirical work has analysed clean innovation using patents data which provides an indication of the output of innovative activity.[14] While not all innovations are patented,[15] the advantages of this approach include the fact that patents data are available across countries, over time, and technologies can easily be classified as being "clean".[16] Patents contain detailed information about the invention in question[17] and citations to other patents, which allows the calculation of "spillover" measures (e.g. future patents that cite an original patent, or cite patents that cite an original patent). A key finding from analyses of clean versus dirty patents has been that knowledge spillovers (as measured via global patent citations) for clean innovations are over 40 per cent greater than their high-carbon counterparts in the energy production and transport sectors (Dechezleprêtre *et al.*, 2014). This finding suggests that there is an enhanced case for public support or incentives for innovation in clean technologies, even from a pure "market failure" perspective.

Such analyses have been extended in order to help inform clean industrial or innovation policy. While measures of spillovers, as reflected in chains of forward citations, are informative about the relevance of a particular patent for future patents, they do not provide information about the economic value generated by that patent. Accordingly, measures of spillovers have been refined to reflect the returns to public R&D investments in particular technologies[18] (Guillard *et al.*, 2020).

This methodology, combined with measures of comparative advantage in innovation ("revealed technological advantage"),[19] has been applied in the UK context in forward-looking analyses that seek to shed light on where opportunities for sustainable growth and recovery might lie.[20] Martin *et al.*, (2020) provide a recent analysis in the context of a sustainable recovery from the pandemic. This paper compares broad categories of technologies, but draws out results for clean technologies and the types of technology that are relevant for tackling and adapting to Covid-19 (e.g. vaccine development). The authors find that the UK is relatively specialised in ocean and wind energy, as well as Covid-related technologies, and biotechnology and pharmaceuticals more broadly, and that potential UK returns to public investments in these clean and Covid-related technologies are also high. Together, this evidence suggests that the UK innovation system is well-placed to tackle major societal challenges, and that it can also benefit economically from support to the areas identified. A further benefit accrues to clean innovation. Areas that specialise in clean innovations are relatively widely spread around the country, suggesting that support for such technologies could also play a key role in narrowing regional disparities and achieving growth that is more inclusive across the country (the "levelling-up" agenda).[21]

It is important to note that the economic returns calculated here do not include the value of other major, but hard to quantify, externalities associated with promoting some particular technological fields over others. For instance, the methodology does not capture the widespread benefits of reducing global warming. Nevertheless, this analysis can help to inform a clean industrial or innovation policy that could result in a "win-win" scenario of benefitting future growth as well as addressing societal challenges.

Analysis of product complexity and relatedness

Another approach for identifying growth opportunities uses data on traded goods. A standard way to measure areas of relative strength is to consider "revealed comparative advantage" in trade, for example, if a country exports a higher share of solar panels than the global average, we may conclude that this country has some degree of competitiveness in this product. However, products will differ in terms of their potential to generate future growth in a country. One way to capture such differences is via the Product Complexity Index (PCI) (Hidalgo and Hausmann, 2009). More "complex" products tend to be more technologically sophisticated and offer greater knowledge spillovers into other products. Mealy and Teytelboym (2020) apply these metrics to a data set of traded "green" products and show that these tend to have higher complexity than average.

Building on this work, Unsworth *et al.*, (2020b) consider a set of "net-zero-aligned" products, and combine product complexity and a measure of "difficulty transitioning" (this indicates how difficult it would be for a country to transition into a new product, given its relatedness to the products in which the country is currently competitive) to highlight where clean growth opportunities might lie in the UK and other core comparator countries. The analysis finds that there are a number of technologically sophisticated green products that are relatively close to the UK's existing capabilities and where the UK has comparative advantage internationally (mainly relating to power generation, carbon capture utilisation and storage, and hydrogen). The picture for France and US overall is similar to the UK, though in the categories where these countries do not yet have comparative advantage, the difficulty transitioning tends to be a bit lower than for the UK. In contrast, Germany is already competitive in the majority of net-zero-aligned products, and those in which it is not yet competitive tend to be closer to existing capabilities than in the UK.

Analysis of firm activities

Developing a better real-time understanding of clean innovation requires new, broader measures or indicators of innovation (to include products or processes that are not patented or identified in trade data), taking account of the evolution of technological systems and emphasising the interconnectedness of different types of technology and different parts of the innovation system.[22]

Advances in data and analytics have opened up new possibilities for understanding economic activity via the analysis of text in company websites, communications, hiring activities, fundraising announcements or other news. Such "web-intelligence" data can be particularly useful in understanding emerging sectors where the existing industrial classification system offers insufficient granularity (in the UK, the Standard

[14] Patents also provide a good indicator of R&D activity (Popp, 2019), as patent applications are usually filed early in the research process (Griliches, 1990).

[15] For example, broadly speaking, innovations in the service sector are less likely to be patented than in manufacturing; and innovations that relate to new processes within firms tend not to be patented.

[16] The European Patent Office "Y" scheme provides separate classifications for technologies relevant for climate change mitigation and adaption.

[17] Such text can be further analysed for more granular information analyses within technology classes using machine learning (see, for example Dugoua (2020) on CFC innovation).

[18] The calculations account for direct and indirect knowledge spillovers occurring within the UK, variations in private R&D returns, variation in R&D costs and differences in the responsiveness to subsidies between different technology areas.

[19] RTA compares an economy's patents in a particular technology field to the global share of patents in that field. A country with an RTA greater than one for a particular technology, is relatively specialised in that area. This is a similar concept to the more standard "Revealed Comparative Advantage" in trade.

[20] Rydge et al. (2018) provide an initial economy-wide analysis and Unsworth et al. (2020a) focuses on zero-carbon passenger vehicles.

[21] Examples include electric vehicle production in the West Midlands, wind turbines on the east coast and carbon capture in the North East of England and in Scotland.

[22] As suggested by Popp et al. (2020), traditional measures of energy patenting and innovation might not reflect the benefits that digital or other high-tech advances bring to the energy sector.

Industrial Classification System was last updated in 2007), and when seeking to capture the innovation activities of firms or agents that might not be patented or be straightforward to patent. Due to the rich information available, analyses of such data can also be used to reveal linkages between firms and other parts of the innovation system, including universities and investors that are engaged in net zero, and to analyse the drivers of their success. Importantly, text analyses can help to reveal patterns in the application of emerging "general purpose technologies" (for example, AI, robotics and the Internet of Things) to climate change.

The type of analysis that is needed, and is now in progress across the academic, policy and business community, involves creating new and evolving classifications of firms operating in technologies and sectors that are key to the transition. Recent years have seen such analyses of the digital economy (see, for example, Nathan and Rosso, 2015) and creative sectors (NESTA, 2018). Given the urgent nature of the climate crisis, and the need to have robust data to inform policy, it will be important to build definitions, mappings and measurement methods, including agreement on how these should be updated over time, that are sound, practical and widely shared.

Evidence-based policies for clean innovation and growth

Understanding the ultimate causes and paths of innovation trends and accelerations, and how policy can influence these, is challenging, and many inter-related factors have been suggested and analysed in the theoretical and empirical literature. A multitude of studies provide evidence that climate change regulations, either directly or through their impact on energy prices, encourage the diffusion of environmentally-friendly technologies and drive innovation activity further up the technology supply chain, favouring R&D in low-carbon technologies (Dechezleprêtre et al., 2019).[23] Moreover, where the mechanism is through prices, the evidence suggests that much of the innovative response occurs quickly. For example, Calel and Dechezleprêtre (2016) show that the European Union Emission Trading Scheme (EU ETS) has rapidly increased patenting in "clean" technologies amongst participating companies.

In terms of the types of environmental policies that are required to reduce emissions, the Carbon Pricing Leadership Coalition (2017) concludes that the evidence (drawn from theoretical, and empirical literatures and policy experience to date) implies that "Carbon pricing by itself may not be sufficient to induce change at the pace and on the scale required for the Paris target to be met" (p3). The types of policies that must accompany it will vary by context, across and within countries, but will include investment in infrastructure, R&D, natural capital, regulation and standards including for energy efficiency, urban planning and design and developing ways to lower the cost of capital in zero-carbon technologies and projects.

More broadly, in order to realise the investment that can both deliver the economic benefits from the transition to net zero and foster a strong and sustainable recovery from the Covid-19 crisis, environmental policies must fit and be embedded within coherent, coordinated and committed growth strategies that invest in people and productive assets (Stern *et al.*, 2020). Given the international nature of the climate crisis, the interconnectedness of economies, and the importance of expectations and scale, coherence, coordination, and commitment across nations is vital (Stern, 2021). More discussion of these areas, in the context of a sustainable recovery from Covid-19 follows.

Carbon pricing

As recovery turns into growth, finance ministries should consider where it is possible to both create positive incentives to decarbonise and raise revenues at a time of fiscal pressure. Periods of low oil prices present an opportunity to introduce a robust carbon price and build incentives to shift to cleaner sources of energy (Burke *et al.*, 2020). In the UK context, analysis suggests that a politically feasible carbon price could start at around £40 per tCO_2 and rise to £125 per tCO2, or more, in 2050 (Burke et al., 2019).[24] Both learning and the pace of change are central to the transformation to net-zero. In this context, and with other market failures, it may make sense to depart from a uniform price and give stronger signals in areas where innovation at the necessary pace is more difficult (or provide other sector-specific incentives).

The net-zero transition can and should be steered by a strong and rising carbon price. Protection of living standards of poorer groups will be a key issue; part of the carbon revenue should be used for this purpose. Care should also be taken with the liquidity of firms, taking into account possible fragility during the period of recovery from the Covid-19 crisis (Martin and Van Reenen, 2020).

Regulation, standards and design

Effectively designed regulations and standards (alongside economic incentives including taxes) can guide innovation successfully in clean directions. The phase-out of incandescent lightbulbs and the emergence of LED provides a case study, and there are a number of causal analyses of the impacts of more stringent standards (see, for example, Noailly (2012), which finds that changes in the stringency of European building codes induced innovations in energy efficiency). Ensuring that regulation in key decarbonisation areas is growing more ambitious through the current crisis – as opposed to becoming side-lined or loosened - could help to protect against possible downward movements in oil prices delaying the speed of the transition. For example, governments can accelerate the phase-out of petrol, diesel and hybrid vehicles by setting dates beyond which no vehicles with internal combustion engines can be sold; accompanying such regulatory change with supportive policies to enable the diffusion of zero-carbon vehicles, including demand-side incentives and accelerating the roll-out of charging infrastructure.

Standards are also important for helping to move national and international systems (e.g. in the design of energy, transport or cities) onto structures and paths which can drive and support sustainable growth. Where standards are shared, then interactions across technologies and systems are enabled, creating larger markets and thus higher social and private returns for innovations.

Many regulatory authorities (for example, around telecoms, energy, water) were set in place following or accompanying privatisation in the 1980s and 1990s. They have largely been focused on prices facing consumers. Now the protection of society requires a first-order additional focus on sustainability and the transition to zero carbon. And regulators should take a "whole economy" view on how their own actions interrelate with those of other regulators and planning authorities. For example, regulation for new transmission and storage investments to provide for more renewable electricity will need to be coherent with those associated with local planning permissions.

Innovation policy

We have set out the strong rationale for government support and incentives for innovation, both in terms of invention and its diffusion, in

[23] For extensive reviews of research on environmental policy and innovation across a range of policy instruments and countries, see Popp (2019) and Popp et al. (2010). Grubb et al., (2021a) conduct a systematic review of the literature (across disciplines) that has analysed the impact of energy or carbon prices on innovation, and the impact on demand-pull policies (incentives and regulation). In general, the innovation outcome considered is patents. Grubb et al. (2021a) also analyse the engineering-based "experience curve" literature which links cost reduction to the cumulative deployment of clean technologies.

[24] Stern and Stiglitz (2021a, b) suggest a social cost of carbon/carbon price around $100 per tonne by 2030.

Section 1. Bloom *et al.* (2019) summarise the evidence on the relative effectiveness of different policy levers that have been used to increase innovation. The authors produce a toolkit for policymakers, assessing the strength of the evidence and key findings across nine categories of policy, some of which are explicitly invention-orientated (including R&D grants, tax credits and intellectual property rights) while others are broader (including the role of universities, skilled immigration, trade or missions). The authors conclude that, in the short-run, R&D tax credits and direct public funding appear to be the most effective tools for increasing innovation, while increasing the supply of human capital is more effective in the longer run.

Much of the evidence base relates to evaluating marginal changes in various policies or incentives. But given the urgency and scale of tackling climate change, the current economic crisis, and weak productivity that pre-dates it, there is a strong case for a step-change in the amount and direction of investment in innovation, and in a dynamic innovation policy that goes beyond fixing specific and static market failures to be "missions-driven" (Mazzucato, 2013), providing direction to the innovation efforts of firms (Mazzucato and Semieniuk, 2017). The importance of this type of approach was demonstrated during the Covid-19 crisis with resources being directed towards R&D and diffusion across a range of sectors to fight the virus and enable economies to function. Advance market commitments and coordinated action across relevant actors and stakeholders played an important role. Resources must be similarly mobilised towards the climate crisis.

It is clear that a broad view of innovation policy must be taken, considering the suite of policies and investments that are required to support innovation and its diffusion, and all aspects of national innovation systems (Freeman, 1987). Edler and Fagerberg (2017) set out a broad taxonomy of innovation policy instruments that captures this, including cluster policies, training programmes, the role of public procurement, standards and regulation. There are many areas where more research is needed to understand causal relationships, complementarities between different policy levers, and how collaboration between actors (e.g. universities and industry) can be encouraged (OECD, 2019).

But overall, the evidence suggests that effective support for clean innovation and its diffusion can take the form of grants and enhanced tax breaks for research, development, commercialisation and deployment, as well as subsidies, and can be coupled with effective regulation, obligations and other mechanisms (such as feed-in tariffs for clean energy generation). Positive innovation responses since the onset of the crisis – for example increased digital adoption (Riom and Valero, 2020), remote working, the associated fall in business travel – can be encouraged as the economy moves into recovery, where they increase labour and resource productivity, together with increased flexibility and job satisfaction. Given the economy-wide nature of the climate and economic challenges faced, innovation should be at the heart of the remit of policymakers and stakeholders across the board (Edler and Fagerberg, 2017).

Long-term sustainable and inclusive growth policies and institutions

In many nations, the extent of government support for industry due to Covid-19, and the scale of investment needed (in the public and private sectors) to meet net-zero commitments, together present an opportunity to develop a strong partnership between the public and private sectors with incentives aligned towards innovation-led sustainable and inclusive growth across the economy. Strong investment, and the associated innovation, requires confidence in the commitment of governments to sustained growth. Long-term and credible industrial policies for a sustainable recovery are necessary (at national and more local levels), to guide investor expectations and align incentives across the economy. And strong, long-term institutions will boost confidence and reduce the cost of capital, by sharing and reducing risk (Baker *et al.*, 2015). Development banks are particularly important, helping to reduce and manage crucial early stage and political risks, both through their presence and financing instruments – hence helping to mobilise private sector investment. The presence of a national development bank can help reduce risk and create confidence in both the sense of direction and the willingness to solve problems as they arrive. The European Investment Bank and the EBRD provide strong examples, as, is hoped, will the new UK national infrastructure bank.

Human capital is a key input for achieving sustainable and inclusive growth, driving innovation and its diffusion, and improving labour market outcomes and resilience for individuals.[25] Increased investment in human capital via the education system, and via training programmes will be required to help to realise new opportunities, manage dislocation and to avoid long-term labour market scarring for workers displaced by the pandemic. A number of net-zero-aligned investments are labour intensive and are expected to generate new jobs quickly (see Unsworth et al., 2020b for analysis based on the UK). But the transition will also have complex and multifaceted impacts upon labour markets, and these will interact with broader technological trends such as automation. It is therefore essential that skills and employment policies are at the heart of a clean recovery and just-transition for workers.

Internationalism

Climate change and the Covid-19 crisis are global emergencies requiring internationally coordinated responses. There is a vital necessity for an internationally coordinated response to recovery efforts to ensure that they are based on sustainable investments, and to reduce risks of disruptions to domestic production. Sustained unemployment not only damages the productivity of the workforce but the associated economic hardships can also play into an erosion of social cohesion and populist discourses.

There is clear need for stronger international institutions and multilateral action as the global economy seeks to recover from Covid-19. Institutions such as the IMF will be essential in servicing the financial needs of many countries in the rescue and recovery periods, and the IMF will need the resources and capabilities to meet this demand. International institutions and multilateral development banks such as the World Bank will need to step up lending to regions around the world which are vulnerable to the virus and its economic repercussions. This should also include new instruments for rapid disbursements.

The experience of Covid-19 can carry positive lessons. These include the recognition that we can change the way we live and work very rapidly if we see the imperative to do so. We have seen that strong response in severe crises require communities to pull together and, indeed, that global crises require nations to act together. Shocks and threats of the Covid-19 scale lead us to ask what kind of re-building we want to do and what sort of economies and societies we want to be. We have learned something about making the most efficient use of the resources we have and making "necessity the mother of invention". All these lessons can and must help us with the climate crisis. It is much bigger and longer lasting than Covid-19, but not yet quite as visible. Nevertheless, it is with us right now and delay in response is dangerous.

This is a moment where a strong and coordinated international response has a quadruple win. First, if countries act together to increase investment demand, the Keynesian expansion benefits all, as opposed to one country seeing its demand expansion increase employment elsewhere. Second, a strong commitment to sustained growth will improve expectations and lead to sustained investment. Third, a clear path to growth will lead to economies of scale which can drive down costs and foster innovation. Fourth, all of society stands to gain from emissions reductions, less pollution and strong biodiversity.

[25] For a summary of the literature that has linked education to economic growth at the country, region and firm level, see Valero (2021).

Broad lessons from the data and evidence

Conclusions for action: Given the scale of the climate and economic challenges faced, policies for a strong and sustainable recovery must include environmental and growth levers. A robust carbon price must be complemented by a suite of mutually reinforcing policies, regulations and investments in infrastructure, human capital and innovation, all of which are coordinated as part of a stable and long-term sustainable recovery plan.

Conclusions for research: While there is a body of research on the effectiveness of environmental and innovation policies on (clean) innovation, we need more causal evidence of the effectiveness of policies and how they interact with other policies or institutional features, domestically and internationally. In order to inform policy in real-time, detailed micro-analyses must be combined with top-down analyses; and new, complementary sources of data on innovation and clean growth opportunities (including using web-based data on firms' activities) are needed to inform policy.

Political economy and sustainable growth

So far, the discussion has been focused mainly on "production", or the supply-side drivers of technological change, and the role of policy in influencing both the amount and direction of innovation and investment. The "demand side" matters too. Changes in behaviours and preferences of consumers, workers, shareholders and voters are also key to driving change in business and policy decisions. And business decisions can have a powerful influence on consumer behaviours; there is clear endogeneity here. Conversely, resistance or a lack of support from consumers, voters and businesses (particularly larger firms with strong lobbying power[26]) can be key barriers to change. This section begins with a discussion of recent papers that have brought the considerations of values and politics into models of directed technical change, before considering recent trends in values and what all this implies for building support and consensus for a "green industrial revolution".

Values, politics and directed technical change

As summarised in Section 1, customer values have been built into models of directed technical change. Aghion *et al.* (2021) find theoretical and empirical evidence that such values matter, particularly in more competitive markets, and that the magnitudes of the effects appear large. In fact, their analysis suggests that a combination of realistic increases in pro-environmental attitudes and in product market competition can have the same effect on clean innovation as a 34% increase in fuel prices worldwide.

Besley and Persson (2020) bring the political economy perspective to this type of analysis. They examine the interdependencies between environmental values, technological change and politics, combining a model of values and environmental taxation (Besley and Persson, 2019) with a model of directed technical change (consistent with Acemoglu *et al.*, 2012). A key starting point is the observation that the transformation required for a green industrial revolution entails a complementarity that drives a two-way dynamic between values and technologies. If clean technologies are more attractive, people are more likely to develop pro-environmental values and lifestyles. And if more people change their lifestyle, firms are more likely to develop clean technologies. Consideration of the role of policy in this context, they argue, must explicitly include politics and account for current political objectives; and the inability of incumbents to commit their successors to future policies.

A key finding is that changing values can support a shift towards an equilibrium of predominantly clean technologies. However, the complementarities between technology and values, mediated by politics, imply that society may or may not cross a tipping point which enables the shift to a clean trajectory. This framework also implies that politics can be influenced by forces or actions which empower those with pro-environmental attitudes, or increase the weight on their views in policy.

Citizens' views, behaviour change and voting

These analyses suggest that understanding the political and behavioural influences, constraints and opportunities shaping the net-zero transition, and how these may have changed in light of the Covid-19 crisis, will be key to policies and actions to achieve a strong and sustainable recovery.

The "finite pool of worry" hypothesis (Weber, 1997) states that environmental and climate concerns diminish as other worries gain in prominence. Under this hypothesis we would expect that the health and economic concerns associated with the Covid-19 pandemic would have reduced public perceptions of climate change severity or reality. In fact, surveys based on the UK (Evensen *et al.*, 2021) and US (Leiserowitz *et al.*, 2020) since the onset of the pandemic find little evidence of this, and suggest that this could be explained by climate change becoming more of a permanent concern in recent years.

But even where attitudes are pro-environmental, a number of barriers and frictions might prevent sustainable consumption patterns (Padilla, 2018). Clearly a key friction is price, where in many areas sustainable options are more expensive, perhaps seen as luxury items. For many, certain goods are unaffordable. And for others, just as is the case with countries,[27] there can be a problem of "free-riding", where there is a reluctance at the individual level to bear the higher costs of low-carbon goods and services, despite a desire to benefit from the public good of a clean economy.

As we have discussed, innovation and economies of scale are key determinants of prices, and investment, regulation and demand-side incentives can both accelerate these and change patterns of consumption quickly. These changes in costs and prices have become very powerful and on a recent estimate, clean solutions could be competitive (without a carbon price or a subsidy) by 2030 in sectors accounting for nearly three-quarters of emissions (see SYSTEMIQ, 2020). But there are other barriers to clean consumption. In many areas, the ability of an individual to choose the "clean" option depends on complementary infrastructure or systems being in place, e.g. charging infrastructure in relation to electric vehicles. Some of these barriers might be more severe for poorer people without government action. In other areas, inadequate information on production processes and supply chains can prevent consumers understanding differences between products. There is an important role for policy in addressing these types of friction, via environmental, social, and governance (ESG) reporting requirements to guide socially-conscious financial investments, and improved product labelling to enable robust comparison for consumers.

Ultimately decisions are made by elected politicians. Even in an environment of high and increasing concern for the environment, public buy-in is required for governments to pursue programmes of economic transformation at the scale and speed required and in the context of the unprecedented economic shock caused by Covid-19. This involves realising and better communicating the economic and wider benefits involved, clear strategies for managing the transition for those displaced or bearing costs, and public discussion of the issues. Indeed, the notion

[26] For example, Brulle (2018) conducts an analysis of US lobbying expenditures over the period 2000 to 2016 shows that climate lobbying expenditures of sectors engaged in the supply and use of fossil fuels greatly exceeded the expenditures of environmental organisations and the renewable energy sector. InfluenceMap (2019) highlights the expenditures of major oil and gas firms on lobbying and argues that such lobbying was in conflict with the goals of the Paris Agreement.

[27] See, for example, Nordhaus (2015).

of tipping points applies with respect to political mobilisation. Where a latent majority supports action to tackle climate change, and the size of a committed minority is close to a critical threshold, a small increase in political salience can have an outsized effect (Farmer *et al.*, 2019).

Emphasising and delivering short-run benefits for people and places

Investments in clean innovation and assets will create opportunities for growth in new or growing markets, and associated gains in productivity and resource efficiency. But in a context of unemployment due to the Covid-19 crisis, it will be important to deliver the rapid job-creation opportunities that can be generated by many low-carbon infrastructure investments and to realise and demonstrate the importance of the co-benefits of decarbonisation (including cleaner air, more liveable cities and associated health and wellbeing benefits). These will be key to the perception of climate action as an integral part of a strong and sustainable recovery where governments invest, and create the conditions for firms to invest in order to grow out of the crisis and the weak productivity performance that pre-dates it (Stern *et al.*, 2020).

Overall, research on the job implications of the transition to net-zero has generally concluded that it will be "a net generator of decent jobs" (UNEP, 2011), citing the spurring of "innovation, job creation and growth" (Fankhauser, *et al.*, 2008). More recent analysis by Montt *et al.* (2018) finds that most economies will experience net job creation in the low-carbon transition. Blyth *et al.* (2014) review the literature and express reasonable confidence that low-carbon projects are indeed more labour intensive under conditions of suppressed aggregate demand (as is in the Covid-19 crisis), while cautioning that "'job creation' ceases to be a meaningful concept if economies are assumed to migrate towards equilibrium conditions". However, even in a labour-market equilibrium the creation of employment opportunities that are more productive and cleaner, and hence "future-proofed" should be counted as a benefit. In the current context, investment in many areas of clean infrastructure is especially appealing because it is labour-intensive in the short run, and not susceptible to offshoring or imports.

In recent work focused on the UK, Unsworth *et al.* (2020b) review the available ex-post and ex-ante evidence of the job-creation potential across key net-zero-aligned investments. The authors find that investments in clean automotive, hydrogen and carbon capture utilisation and storage, renewable energy, and housing energy efficiency can each generate tens of thousands of jobs across the UK while building productive capacity for innovation-led growth in the medium to longer term. More broadly, these and other investments in the restoration of natural capital and active travel infrastructure will generate other attractive co-benefits including clean air, improved health and living standards.

The net benefits in the transition will coexist with significant challenges for workers that are displaced, and firms that have to change their business models. Moreover, such impacts will be complex and multi-faceted, going beyond narrow changes to jobs in the energy sector and impacting complex interrelated supply chains and secondary industries, while interacting with broader shocks and transitions related to Covid-19 and (potentially accelerated) automation (Autor and Reynolds, 2020). Programmes of adult skilling and lifelong learning will be central to build labour market resilience and ensure that changing skills needs are met. Where such dislocations are focused on particular places then it will be important to increase investment in skills and opportunities for people in those places.

Persistent and rising inequalities have been a feature in many advanced economies in recent years, and on some measures such inequalities are particularly pronounced in the UK. Evidence from successful transitions in particular regions (see, for example, Sheldon *et al.*, 2018) suggests that local decision-making and delivery mechanisms that utilise the latest innovations in public participation, such as Citizens' Assemblies, can help generate policies and projects for sustainable growth that are seen as fair and focused on local needs and perspectives.

As discussed in Section 2, a robust carbon price is critical for reaching net-zero emissions, and creating the incentives for sustainable innovation-led growth. To date, even moderate attempts to increase fuel prices have been met with fierce opposition. A key example is the "Gilets Jaunes" movement in France, where an often-cited quote from a protester ("the elites are talking about the end of the world, while we are talking about the end of the month"[28]) highlights that tackling climate change is simply not a priority for many, in the presence of inequalities and feelings of neglect. Carbon pricing policies could gain stronger popular support if revenues were distributed across society in ways that are equitable and perceived to be so. How the proceeds are used is a political choice. Proponents of carbon pricing often advocate the return of tax revenues to consumers in a "citizen dividend". There are strong arguments that targeting this at low-income households can build support. At the same time, the set of policies around carbon pricing should not be seen in isolation. A new and more inclusive form of growth, where the economic and broader co-benefits are understood and shared, can be a core element in overcoming the fraying of social cohesion seen in many countries in recent years.

A longer-term vision

While short-term gains are important, given the nature of political cycles, it will be crucial to build international and national support for a vision for a more sustainable, smarter and more inclusive future. Within nations, the management of change at the national and local levels will be critical to the necessary support. This will include organisational and financial action to enable change (such as retrofitting buildings) and facilitating alternative choices such as cycling, walking and public transport.

Internationally, we can now see the quadruple wins to acting together. First, if all nations invest to expand investment and demand, then as Keynes made clear, all can see the benefits in demand and employment. Second, strong expectations of world growth can drive and sustain investment. Third, commitment to sustainable technologies focuses innovation and gives the scale to reduce costs. Fourth, we all benefit from reductions in greenhouse gas emissions and the support of biodiversity. As in recovery and rebuilding from the Second World War, this is a crucial period for international collaboration.

Broad lessons on the political economy

Conclusions for action: Attitudes and awareness of individuals, who are consumers and voters, shape and are shaped by, business and policy decisions. In order to enter a virtuous cycle where pro-environmental attitudes can facilitate and feed off the transition to net zero, a coherent and coordinated package of policies and investments must be both effectively implemented and communicated. Effective implementation will maximise the chances that clean innovation can benefit from its own path dependencies that will not only accelerate decarbonisation, but also bring costs down rapidly and help to neutralise resistance to change. Effective communication and participatory decision-making processes at the national and sub-national levels will help ensure that the economic (and broader) benefits of decarbonisation can be realised and shared, costs distributed fairly, and transitions actively managed.

Conclusions for research: More research is needed to understand the political economy and behavioural dimensions that will foster the transition to net zero, both in terms of generating the political will to create the long-term, robust policy frameworks required to stimulate sustainable innovation and investments at scale, and also in terms of understanding how to improve the diffusion of existing cleaner products and services amongst consumers across the economy. It will be

[28] Translated from quotation in Rérolle (2018).

important to understand in more depth how citizens' views on climate change and behaviour change have been shaped by the pandemic, and the most effective mechanisms for building consensus going forwards.

Conclusions

A sustainable and resilient recovery from the Covid-19 crisis will require boosted investments in clean innovation and its diffusion, together with complementary and inter-dependant investments in physical, human, natural and social capital. Such investments must be made quickly and at scale if the world is to meet the Paris 2015 UNFCCC target ("well below 2°C"), raise ambition to keeping warming below 1.5 °C and avoid catastrophic and irreversible damage (IPCC, 2018).

The achievement of these objectives requires a whole-economy approach with strong, coordinated and long-term policies and institutions, providing credibility and direction for private investment. Multiple market failures that hold back clean innovation must be tackled. But change on the pace and scale necessary also requires a broader "missions" approach, appreciating also the importance of aligning all actors in the national and international innovation system. While institutional stability is required, policies must also be dynamic and able to adapt as new evidence emerges. We require "predictable flexibility" in policies so that expectations are strong and stable enough to support investment and innovation whilst also building in the learning which will be a crucial part of the process of change.

While the body of theoretical and empirical work to date has provided important ideas, knowledge and recommendations for policy, it does not yet speak strongly enough to the urgency or mechanics of rapid action, or to the context of uncertainty. We hope that future work, across disciplines, can do so.

This is an agenda for action and for research which Chris Freeman would have both shaped and urged. He was a leader in a generation that sought to build a better world after the destructions of the Second World War. He was a thinker who analysed how basic structures of the economy would have to change. Chris Freeman saw not only the importance of fundamental concepts to guide analysis and thinking about fundamental change, but also the importance of detailed and careful empirical work. He was a pioneer in creating ideas about the importance of institutional structures in delivering change and that these would have to be understood and created at all levels, from local to national and to international. Chris Freeman was an internationalist to the core of his being, both in value and in understanding the processes of change. And he saw, as someone who, in large measure, lived for the natural world, as a long-distance walker and an avid bird watcher and naturalist, the centrality of our environment, biodiversity and climate. This would have been a moment for Chris to lead. But, as we mark the hundredth anniversary of his birth, we are very fortunate to have the ideas and inspiration of his work, of who he was, and of what he stood for, to guide us on our way.

Credit author statement

Nicholas Stern – Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing

Anna Valero – Conceptualization, Writing- Original draft preparation, Writing- Reviewing and Editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Acemoglu, D., Aghion, P., Bursztyn, L., Hémous, D., 2012. The environment and directed technical change. The American Economic Review 102 (1), 131–166.

Acemoglu, D., Aghion, P., Barrage, L., Hémous, D, 2019. Climate Change, Directed Innovation, and Energy Transition: The Long-Run Consequences of the Shale Gas Revolution.

Aghion, P., Bénabou, R., Martin, R., Roulet, A., 2021. Environmental Preferences and Technological choices: is Market Competition Clean. In: Or dirty? (No, 26921. National Bureau of Economic Research.

Aghion, P., Dechezleprêtre, A., Hémous, D., Martin, R., Van Reenen, J., 2016. Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. Journal of Political Economy 124, 1–51.

Aghion, P., Hepburn, C., Teytelboym, A., Zenghelis, D., 2014. Path dependence, Innovation and the Economics of Climate change, Centre for Climate Change Economics and Policy/Grantham Research Institute on Climate Change and the Environment Policy Paper & Contributing Paper to New Climate Economy.

Aghion, P., Jaravel, X., 2015. Knowledge spillovers, innovation and growth. The Economic Journal 125 (583), 533–573.

Arrow, K., 1962. The economic implications of learning by doing. Review of Economic Studies 29, 155–173.

Autor, D.H., Reynolds, E., 2020. The Nature of Work after the COVID Crisis: Too Few Low-Wage Jobs. The Hamilton Project. Essay, 2020-14.

Baker, S, Bloom, N, Davis, S, 2015. Measuring Economic Policy Uncertainty. NBER Working Paper, p. 21633. http://www.nber.org/papers/w21633.

Beauhurst, 2019. Growing Cleantech Funding, 14th Feb 2019. https://www.beauhurst.com/blog/uk-cleantech-funding/.

Besley, T., Persson, T., 2020. Escaping the Climate Trap? Values, Technologies, and Politics *Unpublished paper*.

Besley, T., Persson, T., 2019. Democratic Values and Institutions. American Economic Review: Insights 1 (1), 59–76.

Blanchard, O.J., Leigh, D, 2013. Growth Forecast Errors and Fiscal Multipliers. American Economic Review 103 (3), 117–120.

Bloom, N., Van Reenen, J., Williams, H., 2019. A Toolkit of Policies to Promote Innovation. Journal of Economic Perspectives 33 (3), 163–184.

Blyth, W., Speirs, J, Gross, R., 2014. Low carbon jobs: the evidence for net job creation from policy support for energy efficiency and renewable energy. In: BIEE 10th Academic Conference.

Brulle, R.J., 2018. The climate lobby: a sectoral analysis of lobbying spending on climate change in the USA, 2000 to 2016. Climatic change 149 (3), 289–303.

Burke, J., Byrnes, R., Fankhauser, S., 2019. How to Price Carbon to Reach Net-Zero Emissions in the UK. London: Grantham Research Institute on Climate Change and the Environment. Grantham Research Institute on Climate Change and the Environment, London.

Burke, J., Fankhauser, S., Bowen, A., 2020. Pricing Carbon During the Economic Recovery from the COVID-19 pandemic. London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change Economics and Policy. London School of Economics and Political Science.

Calel, R., Dechezleprêtre, A., 2016. Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. The Review of Economics and Statistics 98 (1), 173–191.

Carbon Pricing Leadership Coalition. In: Report of the High-Level Commission on Carbon Prices. International Bank for Reconstruction and Development and, 2017. International Development Association / The World Bank.

Cole, H.S.D., Freeman, C., Jahoda, M., Pavitt, KLR, 1973. Thinking About the Future: A Critique of "The Limits to Growth. Chatto & Windus for Sussex University Press, London.

Dechezleprêtre, A., Martin, R., Bassi, S., 2019. Climate change policy, innovation and growth, Chapter 10. Editor. In: Fouquet, Roger (Ed.), Handbook On Green Growth. Edward Elgar Publications. July 2019.

Dechezleprêtre, A., Martin, R., Mohnen, M., 2014. Knowledge Spillovers from Clean technologies: A patent Citation analysis. CEP Discussion Papers (CEPDP1300), Centre for Economic Performance. LSE.

Deloitte and TechUK, 2020. Tech For impact: The economic and Environmental Impact of Digital Technologies in the UK, Deloitte.

Dugoua E., 2020. Induced innovation and international environmental agreements: evidence from the ozone regime. Working Paper, London School of Economics.

Edler, J., Fagerberg, J., 2017. Innovation policy: what, why, and how. Oxford Review of Economic Policy 33 (1), 2–23.

Ekins, P, Zenghelis, D, 2021. Sustainability Science 16 (3), 949–965.

EPO and IEA, 2021. Patents and the Energy transition, Global trends in Clean Technology Innovation. April 2021 https://documents.epo.org/projects/babylon/eponet.nsf/0/3A283646135744B9C12586BF00489B38/$FILE/patents_and_the_energy_transition_study_en.pdf.

Evensen, D., Whitmarsh, L., Bartie, P., Devine-Wright, P., Dickie, J., Varley, A., Ryder, S., Mayer, A., 2021. Effect of "finite pool of worry" and COVID-19 on UK climate change perceptions. Proceedings of the National Academy of Sciences 118 (3).

Fankhauser, S., Bowen, A., Calel, R., Dechezleprêtre, A., Grover, D., Rydge, J., Sato, M., 2013. Who will win the green race? In search of environmental competitiveness and innovation. Global Environmental Change 23 (5), 902–913. https://doi.org/10.1016/j.gloenvcha.2013.05.007.

Fankhauser, S., Sehlleier, F., Stern, N., 2008. Climate change, innovation and jobs. CLIMATE POLICY Earthscan ISSN 80513, 421–429.

Farmer, J.D., Foley, D, 2009. The economy needs agent-based modelling. Nature 460, 685–686.

Farmer, J.D., Hepburn, C., Ives, M.C., Hale, T., Wetzer, T., Mealy, P., Rafaty, R., Srivastav, S, Way, R., 2019. Sensitive intervention points in the post-carbon transition. Science 364 (6436), 132–134.

Farmer, J.D., Hepburn, C., Mealy, P., Teytelboym, A., 2015. A Third Wave in the Economics of Climate Change. Environ Resource Econ 62, 329–357.

Freeman, C., 1987. Technology Policy and Economic Performance: Lesson from Japan. Pinter Publisher.

Freeman, C. (ed.). (1992) "A Green Techno-Economic Paradigm for the World Economy" in The Economics of Hope: Essays on Technical Change, Economic Growth and the Environment. London: Pinter Publishers. pp. 190–211.

Gaddy, B.E., Sivaram, V., Jones, T.B., Wayman, L., 2017. Venture Capital and Cleantech: The Wrong Model for Energy Innovation. Energy Policy 102, 385–395.

Griliches, Z., 1990. Patent Statistics as Economic Indicators: A Survey. Journal of Economic Literature 28 (4), 1661–1707.

Griliches, Z., 1992. The search for R&D spillovers. Scandinavian Journal of Economics 94 (1), 29–47.

Grubb, M., Drummond, P., Poncia, A., McDowall, W., Popp, D., Samadi, S., Penasco, C., Gillingham, K., Smulders, S., Glachant, M., Hassall, G., Mizuno, E., Rubin, E., Dechezleprêtre, A, Pavan, G., 2021a. Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation. Environmental Research Letters.

Grubb, M., Wieners, C., and Yang, P., 2021b. Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation. Wiley Interdisciplinary Reviews: *Climate Change*, e698.

Guillard, C, Martin, R, Mohnen, P, Thomas, C, Verhoeven, D, 2020. Rational Industrial Policy: Standing on the Shoulders of Giant Gnomes? CEP Discussion Paper (forthcoming).

Hémous, D., 2016. The dynamic impact of unilateral environmental policies. Journal of International Economics 103, 80–95.

Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J., Zenghelis, D, 2020. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? Oxford Review of Economic Policy (S1), 36.

Hidalgo, C.A., Hausmann, R., 2009. The building blocks of economic complexity. Proceedings of the National Academy of Sciences 106 (26), 10570–10575.

InfluenceMap, 2019. Big Oil's Real Agenda on Climate Change. https://influencemap.org/report/How-Big-Oil-Continues-to-Oppose-the-Paris-Agreement-38212275958aa21196dae3b76220bddc.

IPCC, 2018. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Global Warming of 1.5°C. An IPCC Special Report On the Impacts of Global Warming of 1.5°C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission pathways, in the Context of Strengthening the Global Response to the Threat of Climate change, Sustainable development, and Efforts to Eradicate Poverty. World Meteorological Organization, Geneva, Switzerland, p. 32.

Leiserowitz, A., Maibach, E., Rosenthal, S., Kotcher, J., Ballew, M.T., Bergquist, P., Gustafson, A., Goldberg, M., WANG, X., 2020. Politics and Global Warming. April 2020.

Martin, R., Unsworth, S., Valero, A., Verhoeven, D, 2020. Innovation for a strong and sustainable recovery. CEP Covif-19 Analysis Series (14). No.

Martin, R., Van Reenen, J., 2020. The case for a Covid-19 carbon tax. LSE blog. https://blogs.lse.ac.uk/covid19/2020/06/02/the-case-for-a-covid-19-carbon-tax/.

Mazzucato, M., 2013. The Entrepreneurial State: Debunking Public vs. Private Sector Myths. Anthem Press, London.

Mazzucato, M., Semieniuk, G., 2017. Public financing of innovation: new questions. Oxford Review of Economic Policy 33 (1), 24–48.

Mealy, P., Hepburn, C., 2017. Transformational change: Parallels for Addressing Climate and Development goals, Forthcoming in the Handbook on the Economics of Climate Change. Edward Elgar Publishing.

Mealy, P., Hepburn, C., 2019. Transformational Change: Parallels for addressing climate and development goals. INET Oxford Working Paper. No. 2019-02.

Mealy, P., Teytelboym, A., 2020. Economic Complexity and the Green economy, Research Policy: 103948. https://doi.org/10.1016/j.respol.2020.103948.

Mercure, J.F., Sharpe, S., Vinuales, J., Ives, M., Grubb, M., Pollitt, H., Knobloch, F. and Nijsse, F., 2020. Risk-opportunity analysis for transformative policy design and appraisal. Economics of Energy Innovation and Systems Transition, Working paper 2020/01.

Montt, G., Wiebe, K.S., Harsdorff, M., Simas, M., Boneet, A., Wood, R., 2018. Does climate action destroy jobs? An assessment of the employment implications of the 2-degree goal. International Labour Review 157, 519–556.

Mundaca, L., Richter, J., 2015. Assessing 'green energy economy' stimulus packages: Evidence from the U.S. programs targeting renewable energy. Renewable and Sustainable Energy Reviews 42 (February).

Nanda, R., Younge, K., Fleming, L., 2015. Innovation and Entrepreneurship in Renewable Energy, chapter 7. In: Jaffe, A.B., Jones, B.F. (Eds.), The Changing Frontier: Rethinking Science and Innovation Policy. University of Chicago Press, Chicago, IL, pp. 199–232.

Nathan, M., Rosso, A., 2015. Mapping digital businesses with big data: Some early findings from the UK. Research Policy 44 (9), 1714–1733.

NESTA, 2018. Creative Nation, How the creative industries are powering the UK's nations and regions, https://media.nesta.org.uk/documents/creative_nation-2018.pdf.

Noailly, J., 2012. Improving the Energy Efficiency of Buildings: The Impact of Environmental Policy on Technological Innovation. Energy Economics 34, 795–806.

Nordhaus, W., 2015. Climate clubs: Overcoming free-riding in international climate policy. American Economic Review 105 (4), 1339–1370.

Nordhaus, W., 2018. Projections and Uncertainties about Climate Change in an Era of Minimal Climate Policies. American Economic Journal: Economic Policy 10 (3), 333–360.

OECD, 2019. UniversityIndustry Collaboration, New Evidence and Policy Options. https://www.oecd.org/fr/innovation/university-industry-collaboration-e9c1e648-en.htm.

Padilla, E., 2018. Factors leading to sustainable consumption (and barriers to it), UN Industrial Development Organization, Department of Policy. Research and Statistics Working Paper, 15/2018.

Perez, C., 2014. A Green and Socially Equitable Direction for the ICT Paradigm. Globelics Working Paper Series 2014-01, Globelics - Global Network for Economics of Learning, Innovation, and Competence Building Systems. Aalborg University, Department of Business and Management.

Pollin, R., Garrett-Peltier, H., Heintz, J., Scharber, H., 2008. Green Recovery: A Program to Create Good Jobs and Start Building a Low-Carbon Economy. Center for American Progress.

Popp, D., 2019. Environmental Policy and Innovation: A Decade of Research. NBER Working Paper, p. 25631.

Popp, D., Newell, R. and Jaffe, A.B., 2010. Energy, the Environment, and Technological Change. In Handbook of the Economics of Innovation: vol. 2, Bronwyn Hall and Nathan Rosenberg, eds., Academic Press/Elsevier, 873–937.

Popp, D., Pless, J., Haščič, I., & Johnstone, N., 2020. Innovation and Entrepreneurship in the Energy Sector (No. w27145). National Bureau of Economic Research.

Rérolle, R, 2018. Gilets Jaunes Les élites parlent De Fin Du monde, Quand Nous On Parle De Fin Du Mois. Le Monde. https://www.lemonde.fr/politique/article/2018/11/24/gilets-jaunes-les-elites-parlent-de-fin-du-monde-quand-nous-on-parle-de-fin-du-mois_5387968_823448.html.

Riom, C, Valero, A, 2020. The Business Response to Covid-19: the CEP-CBI Survey On Technology adoption. A CEP Covid-19 Analysis. Paper No. 009.

Robins, N., 2020. The Road to Net-Zero Finance, A report Prepared By the Advisory Group For the UK's Climate Change Committee, Chaired and Authored By Nick Robins. December 2020.

Rydge, J., Martin, R., Valero, A., 2018. Sustainable Growth in the UK: Seizing opportunities from Technology and the Transition to a Low-Carbon economy. CEP-GRI Special Report For the LSE Growth Commission.

Sheldon, P., Junankar, R., De Rosa Pontella, A., 2018. The Ruhr or Appalachia? Deciding the Future of Australia's coal Power Workers and Communities.

Stern, N., 2018. Public economics as if time matters: Climate change and the dynamics of policy. Journal of Public Economics 162, 4–17.

Stern, N., 2021. G7 Leadership For sustainable, Resilient and Inclusive Economic Recovery and growth: An independent Report Requested By the UK Prime Minister For the G7. London School of Economics and Political Science, London.

Stern, N., Stiglitz, J., 2021a. The Social Cost of Carbon, Risk, Distribution, Market Failures: An Alternative Approach. National Bureau of Economic Research, Working Paper 28472.

Stern, N., Stiglitz, J., 2021b. Getting the Social Cost of Carbon Right. Project Syndicate.

Stern, N., Unsworth, S., Valero, A., Zenghelis, D., Rydge, J., Robins, N., 2020. Strategy, Investment and Policy for a Strong and Sustainable Recovery: An Action Plan. Centre for Economic Performance: CEP COVID-19 Analysis.

SYSTEMIQ, 2020. The Paris Effect: How the Climate Agreement is Reshaping the Global Economy. December 2020.

UNEP, 2011. Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication. United Nations Environment Programme.

Unilever, 2020. Four Ways That Sustainability Has Made Us a Stronger Business. https://www.unilever.com/news/news-and-features/Feature-article/2020/four-ways-that-sustainability-has-made-us-a-stronger-business.html.

Unsworth, S., Valero, A., Martin, R., Verhoeven, D, 2020a. Seizing Sustainable Growth Opportunities from Zero Emission Passenger Vehicles in the UK. CEP-GRI Special Report For the LSE Growth Commission.

Unsworth, S., Andres, P., Cecchinato, G., Mealy, P., Taylor, C., Valero, A., 2020b. Jobs for a sustainable recovery. CEP Covid-19 Analysis paper 10.

Valero, A., 2021. Education and economic growth. CEP Discussion Paper No, 1764, April 2021.

Van der Meijden, G., Smulders, S., 2017. Carbon lock-in: the role of expectations. International Economic Review 58 (4), 1371–1415.

Weber, E.U., (1997) Perception and expectation of climate change: Precondition for economicand technological adaptation, in Psychological Perspectives to Environmental and Ethical Issues in Management, M. Bazerman, D. Messick, A. Tenbrunsel, K. Wade-Benzoni, Eds. (Jossey-Bass, San Francisco, 1997), pp. 314-341.

World Health Organisation, 2020. World Health Statistics, Monitoring Health For the SDGs. World Health Organization file:///C:/Users/Anna/Downloads/9789240005105-eng.pdf.