Productivity opportunities and risks in a transformative, low-carbon and digital age

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Abstract

The low-carbon and digital transitions are likely to deeply transform economies and societies in the coming decades, with substantial implications for productivity. The scale of the digital, renewable and energy efficiency transition is so large, and replete with a mix of uncertainty and economies of scale in production and discovery, that it cannot be analysed using a static optimisation approach based on historic data.

Explicit account must be taken of the processes which drive and steer innovation and adoption of new networks, including strategic complementarities, expectation formation and the role of multiple actors. A study of systemic change must also acknowledge and confront barriers to change, which are as much political, behavioural and institutional, as they are technological and economic in nature. The evidence suggests these and other switching costs have the potential to delay long run productivity improvements and may even reduce productivity in the short run.

Analysing these implications requires an interdisciplinary conceptual approach that addresses the specificities of non-marginal transitions, including technological discontinuities, systemic transformation and uncertainty. The findings suggest policy must aim to clearly and credibly 'steer' the economy through an uncertain and changing environment by generating self-reinforcing feedbacks in the desired direction.

This requires replacing cost benefit analysis with analysis of risk and opportunity; a process which has already promoted financial markets to alter their asset pricing and investment decisions. Policy action to boost productivity in these conditions must focus on dynamic market shaping rather than static market failures. In line with the theory of endogenous technical change, governments seeking to sustainably boost productivity must strategically design, rather than passively forecast, the future.

This is part of a series of working papers outlining the key issues and questions of The Productivity Institute's key research themes. This paper covers the Social, environmental and technological transitions research theme. Other papers will provide an overview of Human capital, Organisational capital, Knowledge capital, Geography and place, Macroeconomic trends & policy, Institutions & governance and Measurements & methods.

1. Introduction

The transition to a low-carbon, resource efficient economy, together with the digital transition (the adoption of digital technologies like artificial intelligence-AI, machine learning, big data, the internet of things, to transform services or businesses, through replacing non-digital or manual processes) are two structural developments that are likely to define the economy of the next half century. They are likely to have substantial implications for national and firm level productivity and competitiveness.

There are two proximate drivers of improved productivity at the macroeconomic level: productivity growth within sectors and a compositional shift from low productivity (growth) sectors to new, higher value-added high productivity (growth) sectors. It is likely that the transition to low-carbon and the adoption of the digital economy will have a major impact on both productivity drivers for the UK. Innovation to drive resource efficiency, and get more out of resources, could form a key element of the first driver of productivity growth, freeing factors of production to generate value elsewhere in the economy.

Inducing innovation and developing comparative advantage through clean, connected knowledge and production clusters has the potential to drive the second route to new higher productivity for production for a medium sized, open economy like the UK. With a strong science base and leading universities, the UK is a global innovation leader. Yet, as a medium sized open economy, it will also be importing ideas and technologies developed elsewhere. This will require the physical, institutional and skills infrastructures to accommodate these ideas and processes, recognising the early mover advantage associated with developing integrated production clusters in growing sectors and providing a supportive environment to steer scaled-up finance.

A number of inter-related dynamic market failures apply to the digital and low-carbon transitions, including scale economies, learning spill overs and network externalities. They suggest that without public intervention to steer innovation and create new markets, the private sector is likely to underinvest in range of assets necessary to generate higher productivity growth. The transition will involve technological discontinuities, disruption, and systemic transformation. It involves not only the emergence and diffusion of radical innovations, but also the decline or reorientation of existing industries and technologies all along the supply chain from resource supplier through manufacturer and service provider through to consumer.

Furthermore, these transitions relate not only to innovation in technologies, but also to innovation in institutions and behaviours. Consequently, they relate to wider systems change concerning synchronous complementarities across a range of key assets. The assets might be produced, human, intangible or natural. They include infrastructures, complementary technologies, training and skills, institutions, markets and business models.

The sheer scale of the low-carbon and digital transition means network effects and economies of scale in production and discovery are so large that there is an underlying danger that we underpredict the scope for productivity-augmenting clean innovation and thereby inadvertently delay it. The low-carbon digital transition will involve multiple actors with different but inter-related interests, capabilities, and resources. These include incumbent firms, new entrants, workers, consumers, financial actors, national, regional and local (including city) policymakers.

A challenge for both transitions is the infrastructural and systemic lock-in and inertia of existing systems, which provides barriers for radical innovations and delays necessary reorientations. Lock-in can be due to sunk investments (in infrastructure, production factors, technologies, skills, institutions routines and operating procedures), but may also arise from active resistance by incumbent companies, workers and consumers trying to protect vested interests. It has the potential to delay productivity improvements and reduce productivity in the short run. Broadly speaking the less marginal the change, the more complex and intractable the politics.

Pervasive long-term transformations cannot be assessed using incremental optimisation models analysing marginal perturbations to a system with a unique, exogenously defined equilibrium. Consequently, there are deep uncertainties associated with the number of new equilibria that may emerge along a variety of innovation and investment paths. Because of these characteristics, it is not straightforward to analyse the productivity effects of low-carbon and digital transitions in different sectors.

The position paper is structured as followed. Section 2 outlines the key characteristics of low-carbon and digital transitions and their implications for productivity. It anchors these stylised facts in relevant economic literatures and received wisdom. Section 3 discusses the limitations of the neo-classical production function approach (which focuses on the optimal allocation of scarce resources to production factors) in its ability to assess dynamic, non-marginal transition characteristics with multiple path dependent equilibria. The section then articulates an inter-disciplinary approach to productivity and transitions that better accommodates the dynamics of non-marginal structural transitions. By analysing the drivers of innovation and the reinforcing feedbacks that enable systemic transformation, it offers better guidance to decision-makers. The section focusses on capabilities, strategy, and agency, as well as political economy impacts propagating resistance to change from incumbent interests. Section 4 then articulates fruitful research avenues assessing the drivers of behavioural change and propagation of systemic productivity boosting tipping dynamics.

2. Characteristics of low-carbon and digital transitions

2.1. The low-carbon transition

2.1.1 Multiple sectors and low-carbon technologies

The global low-carbon transition will directly or indirectly effect every sector. UK domestic greenhouse gas emissions, which were 440.8 million tons of CO_2-equivalent (MtCO2e) in 2018, were generated by the transport, industry, heating of buildings, electricity, agri-food, and waste sectors (Figure 1).[1] Most of the domestic transport emissions (124.4 MtCO2e) were generated by passenger cars, heavy goods vehicles, and light-duty vehicles (Figure 2). Industry emissions (104.8 MtCO2e) were mostly generated by chemicals, construction, oil refineries, iron and steel, cement and lime, and the food and drink industries (Figure 3). Heating emissions (88.9 MtCO2e) were mainly produced by residential homes (Figure 4). Emissions from the electricity sector were mainly generated by coal and gas-fired power.

[1] The focus on national GHG emissions means that emissions from international aviation, international shipping and food imports are not included. The former two were 35 MtCO2 for international aviation and 7.8 MtCO2 for international shipping in 2017. The figures also take no account of emissions generated abroad through the consumption and imports of goods and services to the UK.

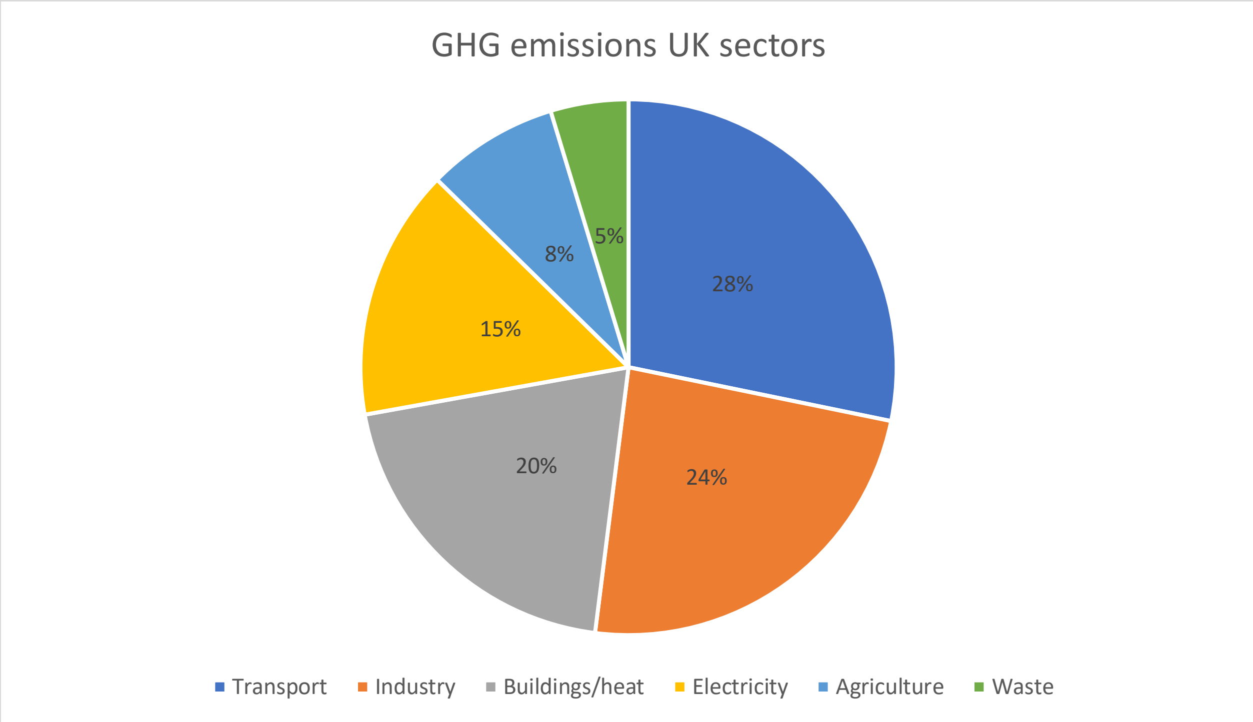

Figure 1: Sectoral contributions to UK domestic greenhouse gas emissions in 2018 (constructed using data from BEIS, 2020 Final UK greenhouse gas emissions national statistics 1990-2018)

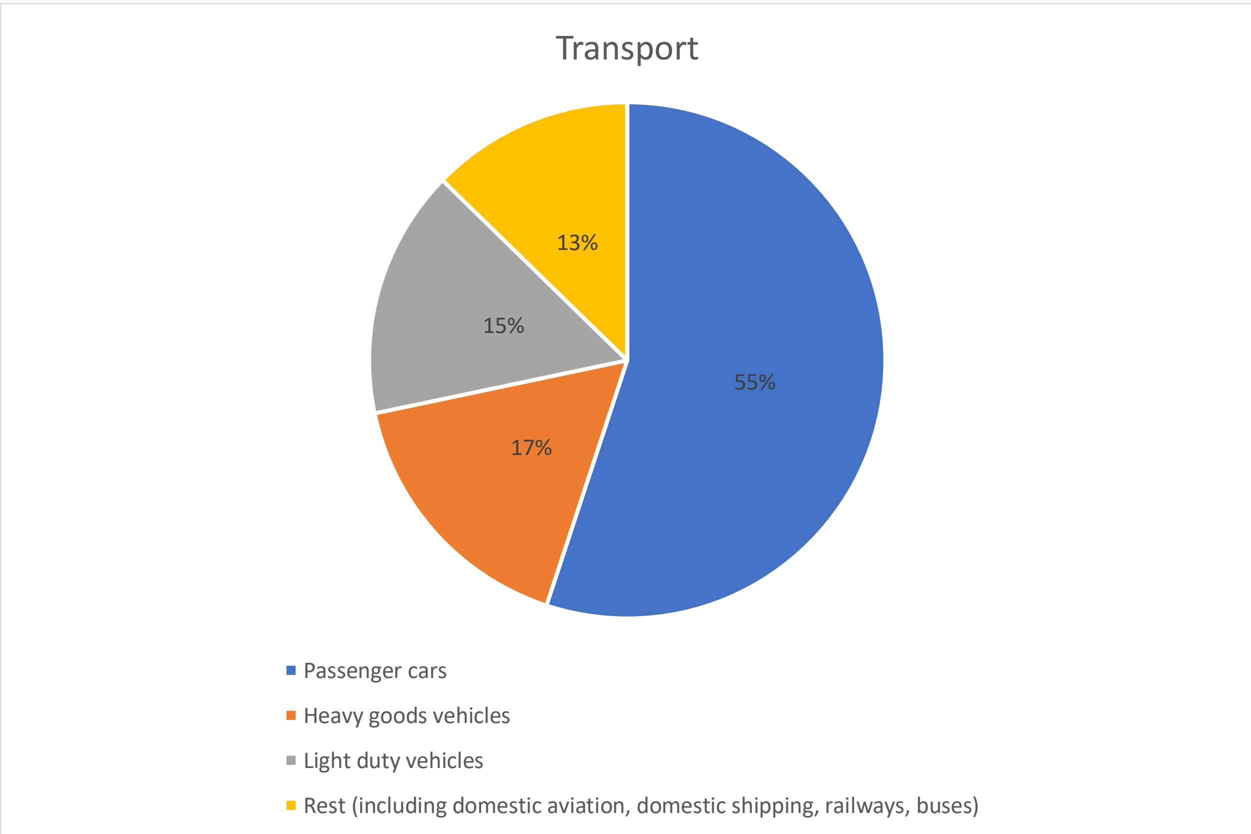

Figure 2: Contribution of different transport modes to UK domestic transport-related GHG emissions (constructed using data from BEIS, 2020 Final UK greenhouse gas emissions national statistics 1990-2018)

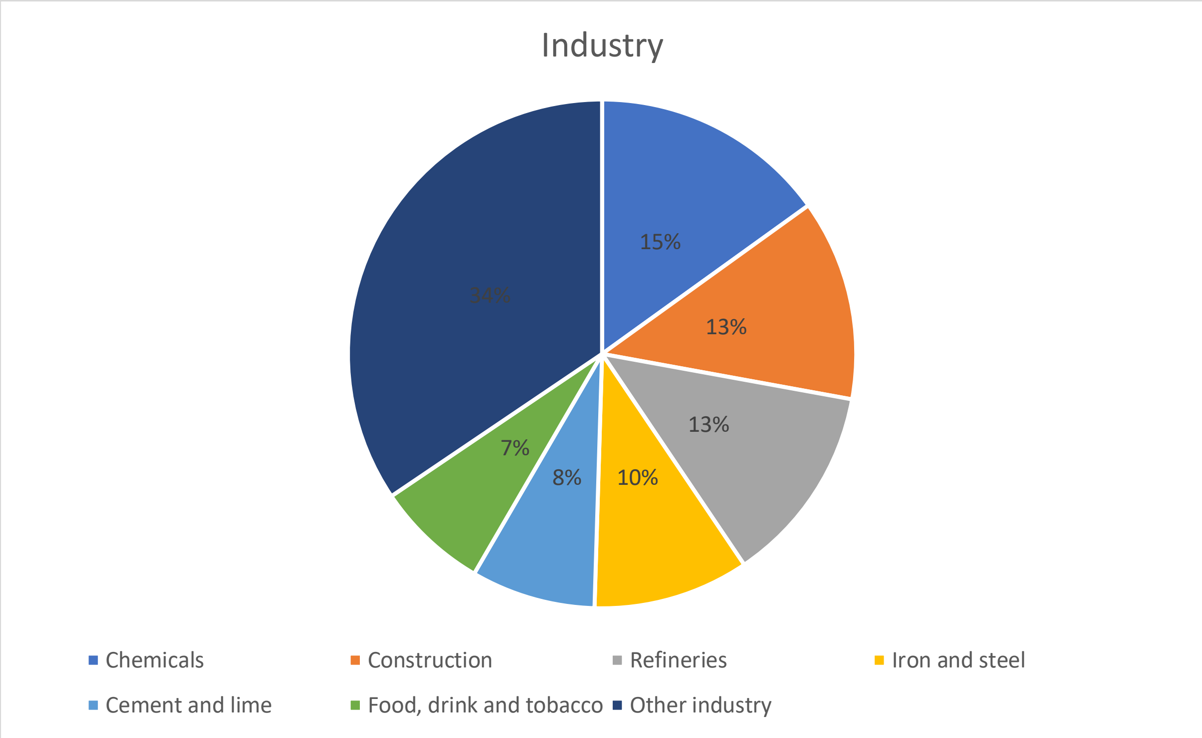

Figure 3: Contribution of different industries to UK industry-related GHG emissions in 2018 (constructed using data from BEIS, 2020 Final UK greenhouse gas emissions national statistics 1990-2018)

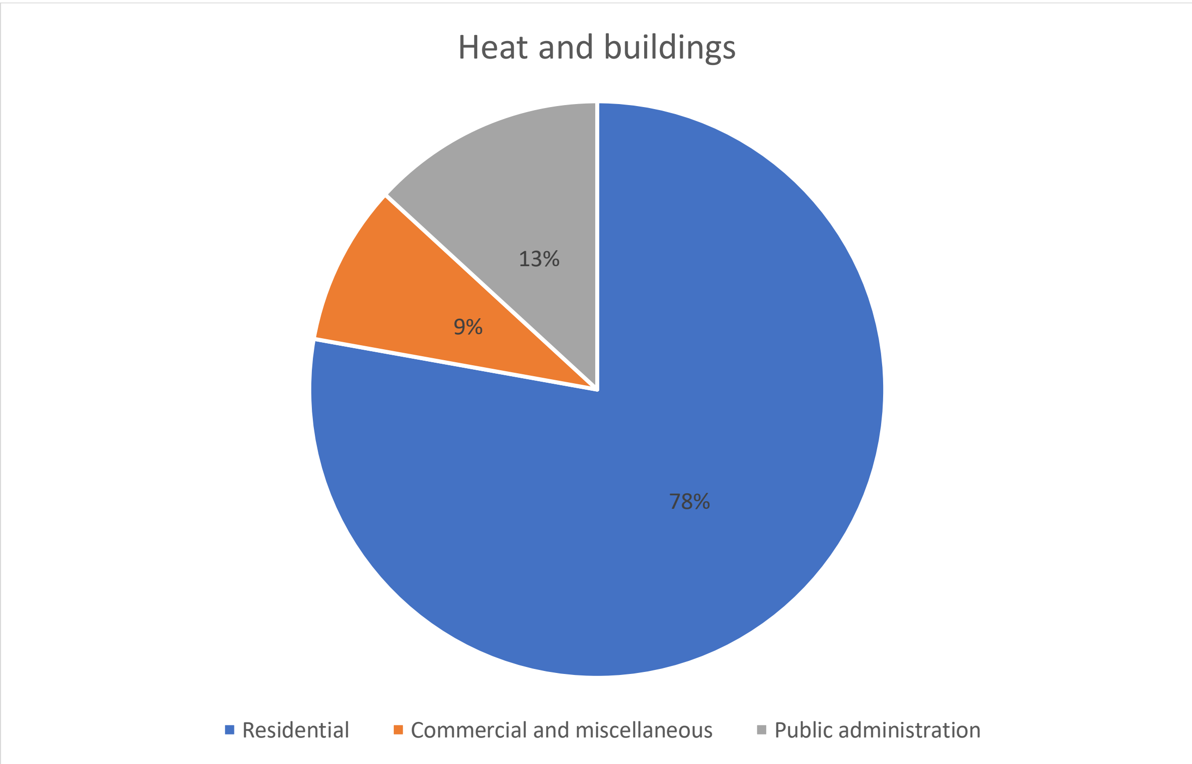

Figure 4: Contribution of different building types to UK heat-related GHG emissions in 2018 (constructed using data from BEIS, 2020 Final UK greenhouse gas emissions national statistics 1990-2018)

2.1.2. The scale of the low-carbon transition

In each (sub)sector there are multiple generic transition pathways and specific low-carbon innovations to reduce GHG emissions (Table 1). In transport, for example, transition pathways include: 1) the technological greening of vehicles starting with cars and moving to haulage, 2) a shift from cars to other transport modes, and 3) a reduction of mobility behaviour (Givoni and Banister, 2013; Holden et al., 2020). Examples of the first include battery electric vehicles, plug-in hybrid electric vehicles, biofuel vehicles, fuel cell vehicles (using hydrogen). Examples of the second include public transport (buses, trains), active transport such as cycling and walking and car sharing and mobility services. Examples of the third include tele-working, tele-shopping and compact connected cities. In all sectors, it will be the combinatorial impact of policies, behaviours and technologies that will radically re-purpose the system.

Generic low-carbon transition pathways	Specific low-carbon innovations
Transport	
Greening of cars	a) battery electric vehicles, b) (plug-in) hybrid electric vehicles, c) biofuel vehicles, d) fuel cell vehicles (using hydrogen)
Modal shift from cars	a) public transport (buses, trains), b) slow/active modes (cycling, walking), c) car sharing and mobility services
Reduced mobility (behaviour change)	a) tele-working, b) tele-shopping, c) compact cities
Electricity	
Low-carbon electricity generation	a) nuclear power, b) solar-PV, c) onshore and offshore wind turbines, d) biomass combustion (various forms), e) hydro-power.
Low-carbon fossil fuel	Carbon capture and storage (CCS) (as add-on)
Negative emissions	Biomass energy + CCS
Adjustments in electricity grids	a) smart grids, b) electricity storage (e.g. batteries, pumped hydro), c) grid extensions and new offshore grids
Demand reduction	a) LED-lighting, b) energy-efficient appliances (e.g. refrigerators, freezers, washing machines, televisions, computers), c) demand-side response
Heat and buildings	
Low-carbon substitutes (of individual gas boilers)	a) heat pumps, b) biomass heating, b) solar-thermal
Collective heat provisioning	district heating (with low-carbon sources)
Greening the grid	a) hydrogen, b) bio-methane (both may require adjustments in home-based heat-generating devices)
Deep insulation of buildings (e.g. lofts, walls, windows, doors, floors)	a) whole-house retrofit (for existing buildings), b) passive-house design (for new buildings)
Industry	
Iron and steel	a) CCS, b) fuel switching, c) energy efficiency
Oil refining	a) CCS, b) fuel switching, c) energy efficiency
Chemicals	a) electrification of heat, b) CCS, c) fuel switching (hydrogen, on-site renewables), d) energy efficiency, e) biomass fuel, f) biomass feedstock
Cement	a) biomass fuel, b) biomass feedstock, c) fuel switching (hydrogen, on-site renewables), d) energy efficiency
Food and drink	a) biomass fuel, b) material efficiency, c) CCS, d) fuel switching, e) energy efficiency

Table 1: Identification of the main low-carbon solutions in different sectors and sub-sectors (own compilation)

Estimates suggest that the UK needs an additional £33 billion/year (IPPR, 2020) or even 40 billion/year (PwC, 2020) to reach the new net-zero targets by 2050. Additional funding is especially necessary in transport, buildings, agriculture, industry, and for 'just transitions' (Figure 5). Globally, estimates suggest around $1tn dollars will be required in cumulative investment to decarbonise the economy consistent with meeting the Paris Agreement (Table 2).

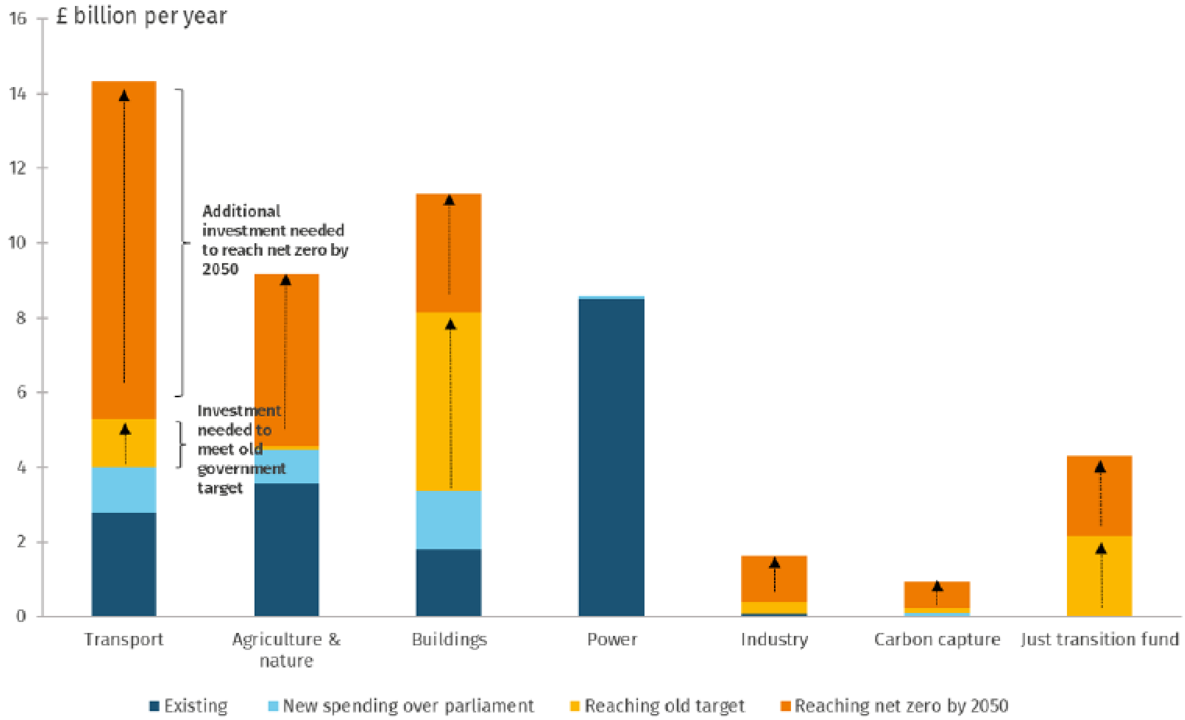

Figure 5: Estimated annual investments required in different sectors to meet the old (80% reduction) and new climate targets (100% reduction) by 2050 (IPPR, 2020: 5)

	Additional annual investments	**Reference**
Climate mitigation (**global**)	USD 550-860 billion	UNDP (2018)
	USD 800 billion (over 2010-2050 period)	**McCollum et al. (2013)**
	USD 650-900 billion	Campiglio (2016)
	USD 1.7 trillion	IEA and IRENA (2017)
	USD 1.38-3.25 trillion (over 2016-2035 period to accelerate transitions and limit climate change to 1.5 °C)	IPCC (2018)
Climate mitigation (**Europe**)	EUR 180 billion (to reach 2030 climate targets)	EC (2018)
	EUR 130 billion in 2011-2030 and EUR 330 billion in 2030-2050 (to reduce emissions 80 % by 2050)	De Bruyn et al. (2016)
	EUR 179 billion to reach 2030 climate change targets	Trinomics (2017)

Table 2: Estimates of additional annual investments to reach climate targets[2]

[2] These investments are additional to business-as-usual investments for upgrading ageing infrastructures, modernising cities etc.

The productivity effects of various low-carbon innovations are likely to vary substantially between sectors. Renewable electricity technologies like solar-PV and offshore wind have experienced large cost decreases in the last decade and are increasingly producing power that is cheaper than many coal- and gas-fired power plants (Figure 6).

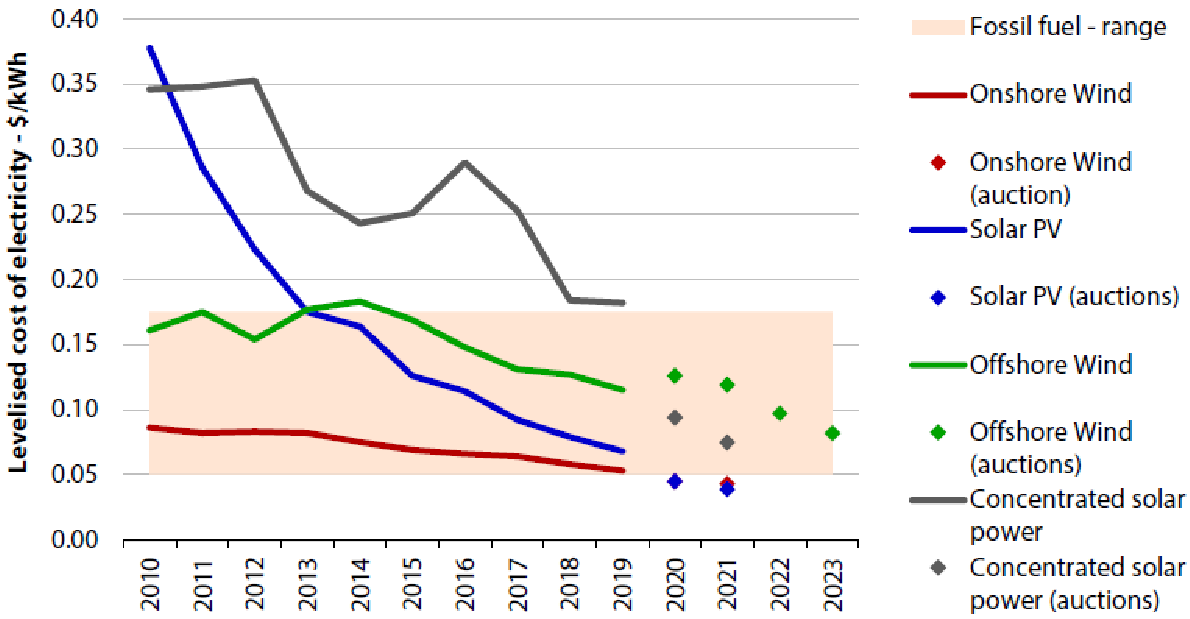

Figure 6: Levelised costs of electricity (in constant 2019 US dollars per kWh) for different technologies (from CCC, 2020: 70)

Between 2010 and 2018, the price of solar-PV modules and onshore wind turbines decreased respectively by 83% and 35% (Zenghelis, 2018). Offshore wind costs decreased by 46% between 2012 and 2018. Solar and wind are the cheapest forms of new energy generation in countries representing over 70% of GDP, with positive effects for productivity and economic growth (SYSTEMIQ, 2020). Battery costs decreased by 77% between 2007 and 2017 (Nykvist et al., 2019). By 2025, the purchase price of electric vehicles is expected to become lower than of petrol or diesel cars, while running costs will be much lower (because of low electricity prices and lower repair costs, due to fewer moving parts), leading to very large savings (Figure 7). A transition to electric vehicles will also have major welfare effects by contributing to reductions in air pollution, which are responsible for between 28,000 and 36,000 premature deaths in the UK each year (PHE, 2019).[3]

Despite these positive developments in some sectors, low-carbon innovations in other sectors may be more costly to implement, with potential negative productivity effects. In heat and buildings, for instance, a transition from natural gas to hydrogen or from gas boilers to heat pumps will be expensive. In industry, the application of CCS or hydrogen fuels will also be costly. The analysis and governance of productivity effects of low-carbon transitions thus has to accommodate technological and sectoral specificities.

[3] The cost of premature deaths from air pollution in the UK were estimated at $83 billion in 2010 by the World Health Organization (cited in HM Treasury, 2020: 29). HM Treasury, 2020, *Net Zero Review: Interim Report*,

2.1.3. Upfront investment generates lower future operating costs

The latest Committee on Climate Change 6th carbon budget report suggests an annual UK investment requirement of about £40-50 billion. But this is more than offset by reduced operating costs from mid-2030s as productivity gains kick in (Figure 7).

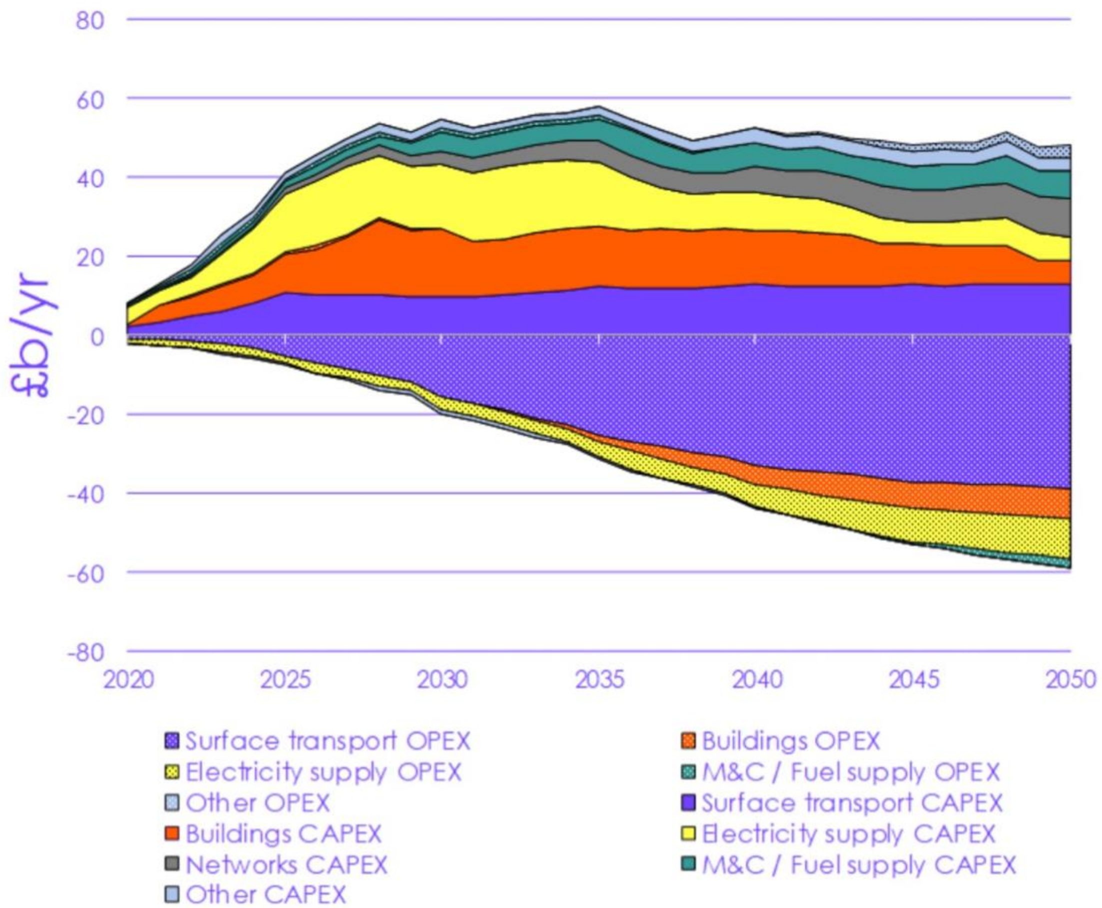

Figure 7: Annual CAPEX and OPEX in the 'Balanced Net Zero' Pathway: Up-front investment yields a more efficient economy: (UK Climate Change Committee (CCC), Sixth Carbon Budget 2021)

Cheaper (zero-carbon) electricity will raise the returns to electrifying all areas of the economy. But this will require large investment in the power grid. An additional US$800 billion per year is required to decarbonise the global economy (McCollum et al., 2013), the bulk of it associated with electrical power, but also including buildings, and clean transport infrastructure. By comparison, the world is expected to invest about US$60 trillion on infrastructure in the decade up to 2030.

This makes for an enhanced role for financial and capital markets (Figure 8). Indeed, from a macroeconomic perspective, it affords a great opportunity for private capital. Private sector investors in the advanced economies have, in recent decades, seen limited opportunities for productive investment. Facing few attractive options on where to put their money, they have been willing to buy government debt even though it paid an ever diminishing (in real terms negative) rates of interest (Lukasz and Summers, 2019). It is this enduring surplus of desired net saving over desired investment which has pushed global neutral real interest rates to below zero (Stern and Zenghelis, 2021).[4] The low-carbon economy provides a conduit to generate future returns to investors by boosting the productive capacity and resilience of the global economy.

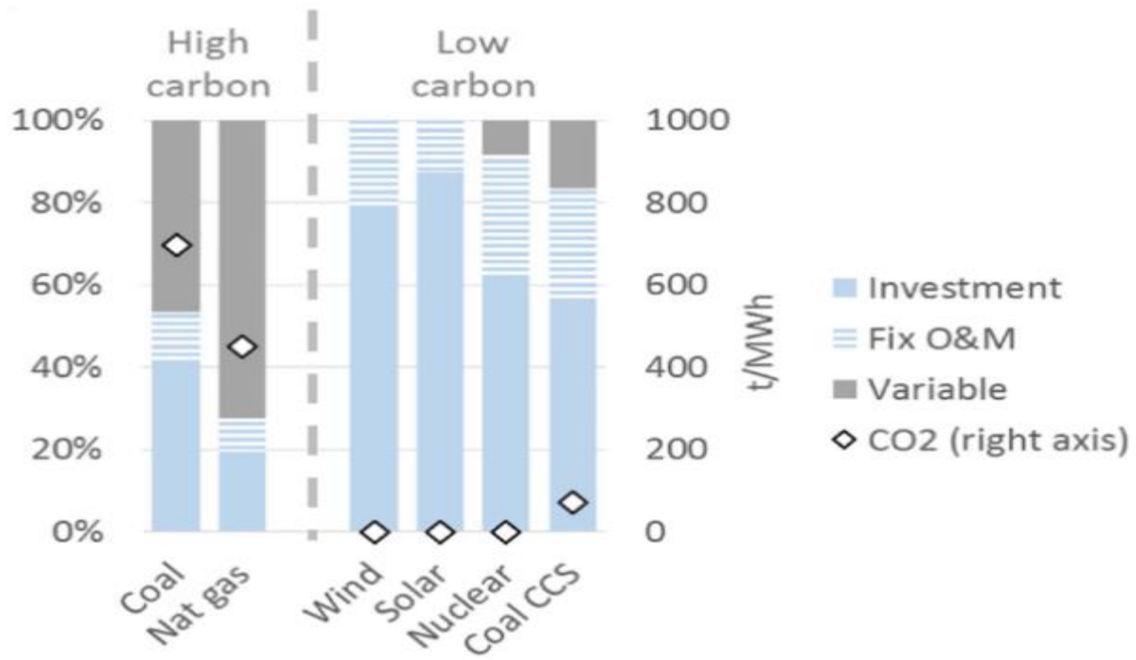

Figure 8: Cost composition of different power generation technologies, showing that clean energy is capital-intensive and that finance will thus be key (Hirth and Steckel, 2016: 2)

The OECD (2017: 7), suggests that: "Economic growth and the low-carbon transition both depend on the development and diffusion of new technologies and efficient reallocation of resources towards both low-carbon and high-productivity economic activity". And the special report for the LSE growth commission concludes that: "The pursuit of sustainable growth and the low-carbon transition provides opportunities for investment that are likely to improve labour and resource productivity across the UK's communities and regions. (…) (Rydge et al., 2018: 5). It is not about costs and burdens, but investments with attractive returns" The recent World Economic Outlook likewise suggests that "decarbonization policies focused on innovation policy (such as research subsidies) could trigger waves of technological change that would boost productivity and growth in the medium to long term" (IMF, 2020: 88).

2.2. Digital transitions: Technologies and sectors

There is much optimism about the potential for the digital economy to have a positive impact on productivity and economic growth (OECD, 2017). McKinsey (2017), for example, estimates that automation will contribute to global productivity growth with about 0.8 to 1.4 percent annually. Moreover, as general-purpose technologies, digital transitions are expected to have a transformative impact on *all* sectors of the economy.

[4] The term neutral refers here to the rate that would prevail when the economy is operating close to capacity, not requiring either a tight/loose monetary stance to contain/stimulate demand. It reflects underlying structural factors shaping preferences for desired savings and investment, rather than cyclical positions dictated by policy rates.

2.2.1. Multiple sectors and digital technologies

There are two key though related, aspects of the digital transition that deserve focus. The first is the transitions in process technologies that may transform production. Examples include robots, Artificial Intelligence (AI) and big data. The second includes transitions in end-use technologies leading to socio-economic transformations, for example, self-driving cars, smart meters, smart homes, tele-working, smart mobility.

As these technologies transform the production, distribution and consumption of goods and services, they will have far-reaching consequences for productivity, skills, income distribution, well-being and the environment (OECD, 2017b). Compared to earlier industrial revolutions, such as steam and electrification, the creation and international spread of inventions that can transform production is likely to occur quickly. Pervasive digitisation will be an inevitable feature of the future economy. Nevertheless, financial, institutional and behavioural barriers are already showing signs of delaying the diffusion of productivity enhancing new technologies throughout the economy (OECD 2017b).

2.2.2. The scale of the digital transition

The likely size and speed of transformational impact differs considerably across sectors. The entertainment and retail sector, for example, has already been transformed significantly over the past decade with digital content platforms like Netflix, YouTube, and Spotify now dominating markets for video and music streaming. And, while it perhaps took longer than anticipated, currently, the retail sector, too, sees a strong presence of digital platforms such as Amazon and Alibaba; a transformation that has sped up substantially during the COVID crisis.[5] Overall, though, "digitization has not yet reached scale, with a majority of the economy still not digitised. (…) While the ICT, media, financial services, and professional services sectors are rapidly digitizing, other sectors such as education, health care, and construction are not" (Remes et al., 2018: 40-41). That said, the Covid19 pandemic has perforce seen a marked acceleration in remote working, education and healthcare, not all of which will be reversed once the impact of the pandemic abates.

Digital transitions of traditional manufacturing are still in a nascent state. While the ICT revolution of the 1990s and robotization have had impact, it is only now with the advent of so-called 'Industry 4.0' (or advanced manufacturing) technologies that a more pervasive digital transformation of manufacturing is taking place (Horvath and Szabo, 2019; Remes at al., 2018). In a recent report for the G20, the OECD (2017: 4) foresees a "next production revolution (NPR) [which] entails a confluence of technologies ranging from a variety of digital technologies (e.g. 3D printing, the Internet of Things [IoT] and advanced robotics) to new materials (e.g. bio- or nano-based) to new processes (e.g. data-driven production, artificial intelligence [AI] and synthetic biology). […] As these technologies transform the production and the distribution of goods and services, they will have far-reaching consequences for productivity, skills, income distribution, well-being and the environment."

Industry 4.0 technologies have several attributes in common that explain their joint potential impact: improved options for interconnectedness and integration, increased use of big data and algorithms in decision-making, and improved automation and learning. That is, these technologies enable "the increasing digitization of the entire supply chain, which makes it

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[5] Alibaba's Online Orders Soar During Coronavirus, Fueling a Sales Recovery, Wall Street Journal, August 20, 2020.

possible to connect actors, objects and systems based on real-time data exchange" (Horvath and Szabo, 2019: 120). The integration with low-carbon technologies and real time monitoring and demand management response for energy affords significant potential for resource and energy use and GHG emissions.

The scope for digital technologies to reduce emissions and improve productivity is unbounded and spans almost every sector. Big data, cloud computing, geospatial tools (including remote sensing) can boost the efficiency of manufacturing supply chains and enable access to carbon markets. Smart digital networks interacting with smart grids and demand management response can improve the efficiency of electricity distribution, lighting management, HVAC monitoring. Transport networks can work better with real time integrated analysis of human mobility patterns. The efficiency of agricultural inputs and land use can be enhanced using machine-learning based tools, supporting more environmentally friendly practices on-farm and better managing logistics in the agro-food industry, reducing food waste in the movement and processing of food. Digital systems can provide better access to information on crop options, soil moistures and nutrients, market prices as well as weather and climate dynamics. Citizen engagement can be enhanced by use of democratised platforms to improve the transparency and accountability of institutions and so on. The list is long.

Automated manufacturing technologies such as robots, artificial intelligence (AI), and machine learning enable the integration of systems, thereby making production more predictable (Horvath and Szabo, 2019). For example, "[t]he combination of new sensors and actuators, data analytics, cloud computing and the IoT is enabling increasingly intelligent and autonomous machines and systems [which] can almost entirely eliminate errors in some production processes" (OECD, 2017: 9).

Moreover, AI makes further automation of the production process possible. McKinsey (2017: 5) has estimated that "49 percent of the activities that people are paid to do in the global economy have the potential to be automated by adapting currently demonstrated technology. While less than 5 percent of occupations can be fully automated, about 60 percent have at least 30 percent of activities that can technically be automated." This automation is not always productivity enhancing (for example the automation of check-out kiosks), but policy can actively steer it in a direction that is (Acemoglu et al 2020)

By enabling horizontal integration, the organizational structure of vertical supply chains is also changing, as companies increasingly seek to be(come) orchestrators of digital platforms (or ecosystems). 'Platformization' is based on the logic of the multi-sided business model that connects different providers and users in multiple ways (Eisenmann et al., 2006). Platform competition depends on the strength of network effects and tends to create winner-take-all markets (Gawer and Cusumano, 2014; Teece, 2018). Consequently, while a few companies will be platform orchestrators, most will be pushed into the role of complementor instead and help orchestrators deliver a complex value proposition (Dattée et al., 2018). One of the predicted outcomes of digitization of manufacturing therefore is increased servitization and potential monopolistic network dominance.

Manufacturing companies are no longer suppliers of finished products only, but also start to offer services related to the end-use technologies (Coreynen et al., 2017; OECD, 2017). For example, one of the key interests of electricity companies to roll out smart grids is the opportunity to offer energy-efficiency services that make use of the advanced metering infrastructure (Shomali and Pinkse, 2016) and automotive companies have started to offer myriad new services in the roll-out of electric vehicles (Bohnsack et al., 2014). Recycling and better use of existing materials, as well as improved product design, longer product lifetime, and a move from ownership to rental using products as a service-based and sharing business models offers the potential to decarbonise plastics, steel, aluminium and building materials as well as transport (Energy Transitions Commission, 2018) introducing lifetime monitoring of components and products.

2.2.3. Upfront investment generates lower future operating costs

Like low-carbon technologies, digital technologies also require high initial investment costs with networks displaying high barriers to entry such that they profit from economies of scale. So, while entrepreneurial start-ups may be considered the main disruptors, scale economies actually create first-mover advantages for large (multinational) companies that can address large (home) markets (Horvath and Szabo, 2017). Coyle (2019: 64), for example, argues for example, that: “When initial costs are so high relative to ongoing costs of selling an extra unit (which are nearly zero for many digital products), the most efficient market structure is to have just a few very large firms. In digital markets, this advantage of large scale on the production side is reinforced by network effects on the user side: the more users there are, the more all of them gain from the service, as in telephone networks, but also booking platforms, online marketplaces or social media networks.”

System integration benefits will only materialise when a threshold of system components have been digitised and connected using standardised communication protocols for interoperability. Similarly, business model reconfiguration to create platforms that benefit from network effects is a lengthy process. Multiple sides of the platform need to be populated with a critical mass of users, suppliers, and complementors.

“The next production revolution (NPR) entails a confluence of technologies ranging from a variety of digital technologies (e.g. 3D printing, the Internet of Things [IoT] and advanced robotics) to new materials (e.g. bio- or nano-based) to new processes (e.g. data-driven production, artificial intelligence [AI] and synthetic biology). Some of these technologies are already used in production, while others will be available in the near future” (OECD, 2017b). Yet difficulty in securing agreed global standards for new generations of digital investment is a key barrier to investment in smart connectivity networks.

3. The dynamics of structural transitions and implications for productivity

3.1. Conceptual understandings of productivity and transitions

Productivity can be defined as the way productive factors (such as labour and capital, but increasingly broadened to include intangible factors such as idea, process and social capital as well as natural capital assets) transform inputs into outputs of goods and services that generate economic value.

Solow (1956) linked economic growth not only to investments in productive capital, but also to technical change (mathematically represented as A(t) in a production function) that improves the productivity of capital. Analysing US growth data between 1909 and 1947, to labour productivity Solow (1957: 320) concluded that “87.5 per cent of the increase was attributable to technical change and the remaining 12.5 per cent to increased use of capital”. But because technical change itself remained unexplained, Abramovitz (1956: 11) famously characterised this ‘Solow residual’ as a ‘measure of our ignorance’.

3.1.1 An endogenous capitals approach to generating productivity growth

Neo-classical understandings of productivity have subsequently developed along several lines, but an important innovation in the production function approach is to include a wider array of core assets (Zenghelis et al., 2020). These assets are mutually enhancing and complementary and include:

- **physical/produced capital**. This includes machinery, buildings, plant and low-carbon and digital infrastructure (e.g. electricity, internet, transport networks) which influence the production process and the efficient distribution of goods and inputs (Docherty, 2020).
- **human capital.** This includes the skills and jobs necessary to take advantage of new technologies and processes.
- **intangible capital**. This includes knowledge capital, the ideas and process with which other assets are put to productive use. It also includes social and institutional capital, required to deliver effective and functional government, with popular support, maintaining or rebuilding trust in the social contract. Social capital corresponds with collective trust in people and institutions enabling efficient social and economic interaction and institutional development. Other production factors have been identified such as organizational capital and entrepreneurship (Prescott and Visscher, 1980; Atkeson and Kehoe, 2005), which are not so much input factors as factors that coordinate, combine, and align other input factors in actual firm-level production processes (Bruhn et al., 2010; Eisfeldt and Papanikolaou, 2013). This literature strand has highlighted the role of intangible assets such as organizational structure, culture, and managerial and technical capabilities in production processes (e.g. Martín-de-Castro et al., 2006; Bruhn et al., 2010). The system of government and macro-institutions such as the rule of law, the legal system, and property rights influence economic transactions and productivity (North, 1990; 2005; Acemoglu et al., 2005; Acemoglu and Robinson, 2012); changing social norms, which shape consumer preference (Bowles, 1998) and consumer purchases through contagion and imitation (Young, 2009; 2015).
- **natural capital**. This includes non-renewable inputs like energy and natural resources. But it also includes renewable natural capital biodiversity and natural habitat, the loss of which increase the likelihood of diseases like COVID-19 that negatively impact productivity (Zenghelis et al., 2020).

Further influences have been identified that shape the input factors. Investments in productive capital, for instance, have been related to access to finance (Karlan and Morduch, 2009), the functioning of the financial system (King and Levine, 1993; Rajan and Zingalis, 1998), and monetary, fiscal, and macro-economic policies (Wray and Nersisyan, 2016).

The essence of a concave production function is that all the assets are to some degree complements, such that there are diminishing marginal returns to any one asset. This insight from the classical model, for the most part, carries through as a useful foundation to more complex characterisations which starts to include feedbacks and increasing returns. Investing in intangible assets like knowledge or social and institutional capital enables the economy to dematerialise and grow. But it also generates scale economies in innovation and production. Knowledge capital is not subject to diminishing returns: it grows as people learn and innovate.

The value of our critical assets is what economists refer to as 'endogenous' (Zenghelis 2019b). Their future values depend on choices made now. Investment in the right assets creates value and generates productivity growth. By starting early to induce the right technologies, behaviours and institutions, there could be huge benefits in the form of a cleaner, quieter, safer, more efficient, productive and ultimately wealthy world.

3.1.2 Dynamic feedbacks which drive innovation

The economy of the 21st century will be shaped by knowledge and innovation. Knowledge capital is the key driver of the growth in total factor productivity (TFP) and will determine our ability to get more out of the resources we have (resource efficiency) by directing the 'weightless' economy to foster dematerialisation and decarbonisation. In 1975 around 20% of the value of listed companies was intangible - the ideas, processes and networks that a company has nurtured. By 2015, that level had risen to around 80%.[6]

Yet innovation is highly *path dependent;* in other words, it is shaped by happenstance and events. Strong inertia and high switching costs make it initially difficult, for example, to shift the innovation system from dirty to clean technologies without direct policy intervention (Aghion et al., 2014). Firms and scientists tend to direct innovation toward what they are already good at (Aghion et al, 2016). But they can reach a tipping point, where expectations change rapidly and technologies switch from one network to another. Those late to the transition stand exposed to stranded or devalued assets.

Research and development externalities (Romer, 1990) and learning spill-overs in low-carbon and digital technologies have these features. As more scientists start thinking about smart, connected, clean energy and resource use, more ideas and innovations emerge that other scientists can use. Technology and finance costs fall and profitable new markets emerge. This increases the incentive to invest in the new innovations generating a positive feedback that can tip systems to entirely new networks.

Several key amplifying feedback mechanisms can be expected to drive productivity improvements from the large scale roll out of digital and low-carbon networks, including:

- **Learning effects**. A key reason for the sharp reduction in solar, wind and battery costs is learning-by-doing and experience curves because of rapidly expanding deployment. With deployment, lessons are learned on how to manufacture, distribute, instal, run and maintain equipment more efficiently.
- **Economies of scale in production and distribution**. Costs also come down because of the unit cost benefits accrued from larger production and distribution networks. This reflects large, fixed costs where, once the initial fixed costs have been incurred, low unit costs encourage increased output.
- **Network and coordination effects**. This is closely related to economies of scale but reflects the greater advantages of moving in tandem with others, such that the gains are higher the more economic agents are taking similar action. Sometimes the networks involve spill-overs across sectors. Give people more computers, and they come up with better things to do with them and more software which increases the value of getting more computers.
- **Sector spill-overs**. Not only have sustainable technologies been shown to have predictably higher cost-reducing learning rates, they also have been shown to have positive productivity spill-overs into other sectors of the economy. Using data on 1

[6] See Oceantomo: https://www.oceantomo.com/services/patent-indexes/ocean-tomo-300-patent-index/

million patents and 3 million citations, Dechezlepretre et al. (2014) suggest that productivity enhancing spill-overs from low-carbon innovation are over 40 percent greater than from conventional technologies (in the energy production and transportation sectors) (Aghion et al 2012).

- **Evolution of consumer behaviour.** Consumer tastes are key in the attribution of future value to goods and services and consumers routinely influence one another, leading to positive feedbacks and crowd effects and changing consumption patterns. Standard optimisation models assume a single representative consumer (the aim being to maximise her utility). Yet agent heterogeneity is important in the representation of real-world consumer behavioural diversity and behavioural biases. This is critical in the process of the diffusion of innovations, technologies and practices (Knobloch and Mercure, 2016). This is readily inferred from standard innovation diffusion theory where technology adoption typically follows s-shaped patterns from pioneers and early adopters, through the majority to laggards. Adoption is not homogenous.
- **Social and institutional feedbacks**. Social norms can be defined as the predominant behaviour within a society, supported by a shared understanding of acceptable actions and sustained through social interactions (Ostrom, 2000). Social feedbacks help make norms self-reinforcing and therefore stable. Formal institutions struggle to enforce collectively desirable outcomes without popular support. Acceptable standards of behaviour and social norms are the sources of law and ultimate drivers of legislative change (Posner, 1997). Business and trade union lobbies from expanding new industries can play a role in strengthening the policy support for emerging technologies (Meckling et al., 2015).

These effects, plus the cost savings as new networks and institutions are established, explain why Acemoglu et al. (2012) make a powerful theoretical case to suggest that policy to support clean innovation can be temporary, because once the "clean innovation machine" has been "switched on and is running," it can be more innovative and productive than the conventional alternative, with a positive impact on GDP levels and growth. Aghion et al. (2009) argue that clear, credible, and enduring policy signals are the most effective way to generate investor confidence to kick start the clean innovation machine. The policy intervention can be removed once the new networks outcompete established market participants.

What path dependent systems have in common is that history matters. The standard neoclassical idea of macroeconomics has an essentially timeless frame of reference: understood as a set of equilibrating markets, the economy is analysed with little reference to its own history or to the processes of systemic change. While this may have little impact on analysis of marginal changes, "it makes it difficult to comprehend why and how economies develop over time" (OECD, 2020: 21). Even in new growth theory, of dynamic (stochastic) general-equilibrium frameworks "encourage us to think in terms of the economy always moving along a dynamic equilibrium path" (Stiglitz, 2018: 91).

Hidalgo et al. (2007) and Mealy and Teytelboym (2021) used network analysis to demonstrate that it is easier for countries to become competitive in new green products that require similar production capabilities and know-how to existing sectors. As a result, green transitions are highly path dependent: countries which successfully invest early in green capabilities have greater success in diversifying into future green product markets. This also has potential implications for industrial policy seeking to develop comparative advantages in fast growing new sectors (Rydge et al. 2018).

In periods of rapid change, countries with flexible institutions that take early action to develop new technologies, institutions and processes may also be able to go to scale quicker, establish comparative advantage in new 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). Studies analysing "revealed technological advantage" indicate where opportunities for sustainable growth and recovery might reside. Martin et al. (2020) compare broad categories of technologies and find that the UK is relatively specialised in ocean and wind energy, as well as COVID-related technologies such as biotechnology and pharmaceuticals, and the returns to public investments in these technologies are also high (Stern and Valero, 2021).

In the early phases of transitions the problem is that actors are reluctant to invest, develop and deploy new technologies because of lock-in effects, inertia, high switching costs, and high technology costs (Aghion et al., 2014). But because they do not invest, the costs of these new technologies remain high which hinders and delays the transition. Radical innovations in digital and low-carbon technologies therefore first tend to emerge in small, peripheral niches or application domains (such as space applications for solar-PV), which offer protection from mainstream market selection and nurture the gradual development of new technologies (Schot and Geels, 2008; Smith and Raven, 2012).

Radical innovations can remain stuck in niches for prolonged periods, even decades, seemingly reinforcing the expectations that the new technologies will never be cost effective enough to provide an investment solution at scale.[7] Insights from social psychology suggest that solving coordination problems requires building expectations into models and generating 'common knowledge' as expectations anchor (Thomas et al., 2014).

3.1.3 Forward looking expectations can overcome inertia

There is a need to move beyond framing expectations as 'adaptive' or 'rational' to examine lessons from social psychology and game theory. Nobel Prize winning economist Robert Shiller (2019) refers to contagious narratives driving global events in what he famously labelled 'narratives economics'.

A key source of path dependence in socioeconomic systems is the presence of what game theorists call 'strategic complementarities' in expectation formation. These arise when agents make individual decisions that affect each other's welfare and one agent's action increases the welfare of all the other agents. The payoff to action by any agent thereby becomes a function of the actions of all the others. For example, a policymaker, business, or individual is more likely to invest in clean technologies if they feel everyone else will. This is because with everyone else investing, they would expect costs to fall, finance to go from niche to mainstream, and new markets to open up (Zenghelis 2019a). In other words, they will be driven by expectations (Krugman, 1991; Matsuyama, 1991). Van de Meijden and Smulders (2017) emphasise the role of expectations about future energy use in a model of directed technical change. This analysis echoes Acemoglu et al. (2012), but it emphasises lock-in due to expectations rather than physical investment and learning.

As more low-carbon or digital technologies are deployed, learning and experience can drive innovation and rapid cost reductions, which help to improve the political and commercial

[7] Solar-PV, wind turbines and electric vehicles, for example, trace their origins to the 1970s.

acceptability of investing. Investor perception of risks changes in favour of clean technologies and against carbon-intensive assets which risk devaluation and stranding. It also generates new institutions, such as new business lobbies, which can challenge incumbent vested interests (Meckling et al., 2015). Such self-reinforcing feedback loops and expectations dynamics, together with countervailing inertia from high switching costs, can generate potential systemic tipping points as investment, technological advancement and regulatory support collectively drive the transition (Zenghelis, 2019c). It also explains why economists and others are so readily caught out in making inaccurate predictions.

The OECD (2017: 136) points out that model-based analyses generate different results, depending on the choice of modelling approach (e.g. general equilibrium models, evolutionary models, agent-based models) and on "key parameter assumptions (e.g. the cost of low-carbon technologies, endogenous or exogenous technical change, the degree of crowding out of investment); and the choice of policy instruments (carbon pricing alone or in combination with low-carbon technology support, energy efficiency measures, etc.)."

Aghion et al. (2014) more generally identify challenges in analysing productivity effects of qualitative structural change: "compounded innovation shocks qualitatively alter the structure of the economy and its resource intensity and make it nearly impossible to forecast aggregate technological productivity in the long run" (Aghion et al., 2014: 5).

This more complete and dynamic understanding of the drivers of transitions is beginning to shift the economic discourse on climate mitigation from an emphasis on additional *cost burdens* towards acknowledgement of potential economic and productivity *risks and opportunities* associated with change. As markets grow and technologies improve, more companies are attracted, leading to 'swarming effects' (Schumpeter, 1927), which increase investments and industry size. Incumbent automakers, for example, have drastically changed their views and strategies regarding electric vehicles from reluctant engagement (before 2009), to cautious diversification (2010-2015) to strategic reorientation (post-2015) (Bohnsack et al., 2020). 'Animal spirits' (Keynes, 1936) may also capture financial actors and stimulate investments, potentially leading to inflated expectations and bubbles (Perez, 2002).

Huggins and Izushi (2020: 112) conclude that: "If we are to fully explore differences in innovation and productivity growth across economies, there is a need to understand how these differences stem from the behaviour of human agents". People change their expectations with shape the nature and pace of change (Van der Meijden and Smulders 2017). Social norms also change and new political institutions such as ministries, agencies and business and trade union lobbies are created. These are accompanied by supportive policies, which in the case of carbon may include carbon taxes, deployment support and new standards and regulations which are being deployed globally.

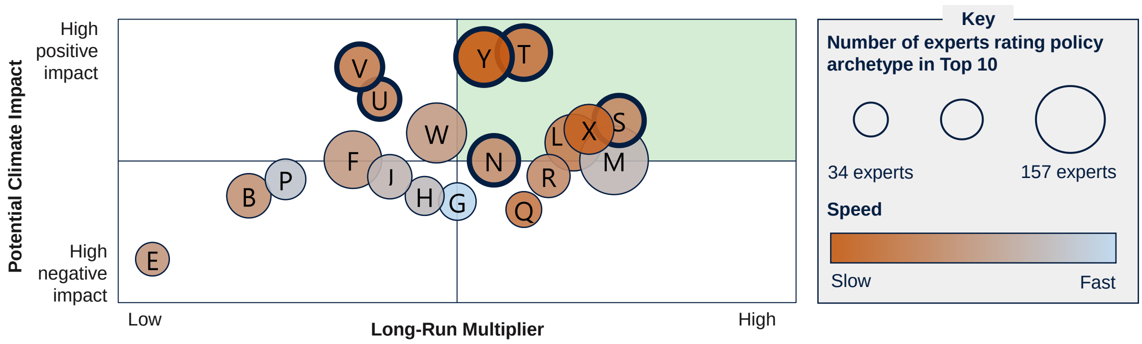
Recognising the role of multiple actors in economic transformations, Coyle (2019: 323) makes a plea for more interdisciplinary theorising with regard to agency: "When you add uncertainty about the future, and lessons about human decision making that are emerging from behavioural economics, the need for a subtler intellectual framework for economics is clear. The discipline is already shifting this way, with growing interest in psychology and social dynamics".

Economic models struggle to deal with unstable amplifying feedbacks, so these are usually ignored. The result is that forecast cost of transformative technologies are often overstated.

This has posed problems globally because the regular assertion by economists and others that environmental action is likely to be prohibitively expensive becomes self-fulfilling. By helping set expectations such assertions delay political action and investment that might lead to deployment and innovation which, in turn, would reduce future costs. In this way, economists "don't just get the future wrong, they make the future wrong" (Ekins and Zenghelis, 2021).

Sentiments are already shifting away from fossil fuels, placing moral pressure on large GHG emitters (Green, 2018). Companies and governments are facing litigation for deceiving shareholders and citizens by knowingly undertaking or supporting unsustainable and damaging activities (Nachmany and Setzer, 2018). This is driving global climate policies and legislation, and policy is likely to continue to respond to and accelerate these changes in social norms. The threat of litigation, in turn, impacts the behaviour and actions of business, aligning business action more closely with the low-carbon transition which can also influence behaviour in the wider sector.

The perception that 'green' conflicts with growth is not just being challenged, it is being turned on its head. A recent Oxford study (Hepburn et al., 2020a) of 231 global finance ministry and central bank officials and senior economists showed that investments with the highest economic growth potential are in many cases thought to be the cleanest and most sustainable (Figure 9).[8] Post COVID-19 recovery and stimulus packages could accelerate these trends as government funds are invested in resilient and sustainable infrastructure.



Policy archetypes

B	Assisted bankruptcy (super Chapter 11)	M	Healthcare investment	T	Clean energy infrastructure investment
E	Airline bailouts	N	Worker retraining	U	Buildings upgrades (energy efficiency)
F	NFP, education, research, health bailouts	P	Rural support policies	V	Green spaces, natural infra investment
G	Reduction in goods & services taxes	Q	Traditional transport infra investment	W	Disaster preparedness, capacity building
H	Income tax cuts	R	Project-based local infrastructure grants	X	General R&D spending
J	Business tax relief for strategic adj.	S	Connectivity infrastructure investment	Y	Clean R&D spending
L	Education investment				

*April 2020, survey of 231 finance ministry/central bank officials/senior economists (representing 53 countries incl. all G20):

Figure 9. Global survey – clean policies perform well on economic and climate metrics (Hepburn et al., 2020)

The implication of the above arguments is that the ultimate costs and productivity effects from systemic transitions are endogenous and dependent on actor choices and strategies:

[8] Highest scoring sectors include clean R&D spending, clean energy infrastructure, connectivity infrastructure, building upgrades and energy efficiency and investment in green spaces.

“The costs of the transition to net zero are uncertain and depend on policy choices. The amount of investment required to reach net zero and the consequential impacts on operating costs are difficult to estimate. They are affected by a range of factors, including the precise path of the transition, changes in behaviour and the rate at which technology costs fall and efficiency gains are made, all of which are subject to significant uncertainty” (HM Treasury, 2020: 4).

Building on these new understandings of dynamic change processes, research on low-carbon and digital transitions should thus further investigate the interacting techno-economic and actor-related processes and feedback loops that bring about tipping points and drive the deployment of low-carbon and digital technologies, lower costs, and increase productivity. Future research should thus aim to respond to Stern’s (2018: 4) recent call for new public economics research that investigates “how change happens and what happens during change. It asks directly about the processes and pace of change”.

3.2 Multiple actors and assets in systemic change

Technological transitions are multi-actor processes, in which firms play central roles besides other actors such as policymakers, consumers, financiers, workers, research organisations, and civil society organisations. The roles of actors and interaction processes vary between different transition phases. Both the low-carbon and digital transitions require strategic reorientations in existing companies towards new skills, products, production lines, supply chains and market positions. Low-carbon innovations can be developed by new companies (like Tesla) who may overthrow incumbents (Christensen, 1997; Kungl and Geels, 2018).

Many low-carbon technologies require wider system changes in infrastructures, business models, markets, consumer behaviour, and institutions. Solar-PV and wind turbines, for example, need to be accompanied by smart grids, storage technologies, back-up capacity, and grid extensions to overcome intermittency in power supplies (McMeekin et al., 2019). Likewise, electric vehicles require the creation of new recharging infrastructures (in neighbourhoods, along motorways and at work).

Complementary infrastructural innovations enhance the functionality of new technologies (Arthur, 1989; Markard and Hoffmann, 2016). Electric vehicles, for instance, require battery recharging facilities along motorways to enable long-distance journeys. Autonomous vehicle require real time sensors, GPS and super-fast processing speeds. Intermittent renewables like wind or solar-PV require storage or back-up capacity (e.g. batteries or gas turbines), adjustments in electricity grids (e.g. building new grids to remote wind parks, better monitoring of electricity flows), and possibly smart meters and demand-side response (to modulate demand to match fluctuating electricity production); This combinatorial effect, where new technologies feed off each other such that the whole is greater than the sum of its parts, affords the potential for multiplicative increases in productivity.

The OECD (2015) notes that: “There is a growing understanding that system-wide changes are necessary to make economies (…) sustainable. Achieving this goal will require wide-ranging changes in their underlying economic, technological and social systems, from transport, water and energy systems to modes of consumption and waste management” (OECD, 2015: 242). Achieving such systemic transformations involves major coordination problems, which may require new institutional governance.

A whole system approach is by nature inter-disciplinary. Mullan (2017: 46) argues "the dynamics of growth cannot be properly grasped when it is viewed as discrete components. Economic growth is not an arithmetical sum of various inputs, but is the measure of a process by which society develops its productive capabilities. The drivers of technological progress cannot be understood without seeing its tangible capital, as well as its intangible, constituents as part of the whole".

McCann (2020: 39) links the acknowledgement of systemic interactions to a call for interdisciplinary approaches: "When we adopt an interdisciplinary perspective on productivity, these various productivity channels are not entirely independent of each other and finding ways to articulate these linkages is essential. It will require a multi-disciplinary approach to achieve this".

Globally, low-carbon (and digital) transitions are still in early phases in most sectors (Figure 10), except for electricity and cars (where solar, wind, and electric vehicles have begun to diffuse). In each sector there are multiple low-carbon innovations (Table 1), which creates deep *uncertainties* about which transition pathway will unfold. It is in the nature of a path dependent system that shocks and surprises will cumulate rather than dissipate. Additionally, many of the low-carbon innovations are in early stages of development, so there are major uncertainties about future costs and markets. "These are always difficult to predict, but predictions become even more uncertain when systemic change is envisaged that stretches out over various decades" (Altenburg and Assmann, 2017: 14). Additionally, there are uncertainties about future policies (and their effects) and ecosystem dynamics.

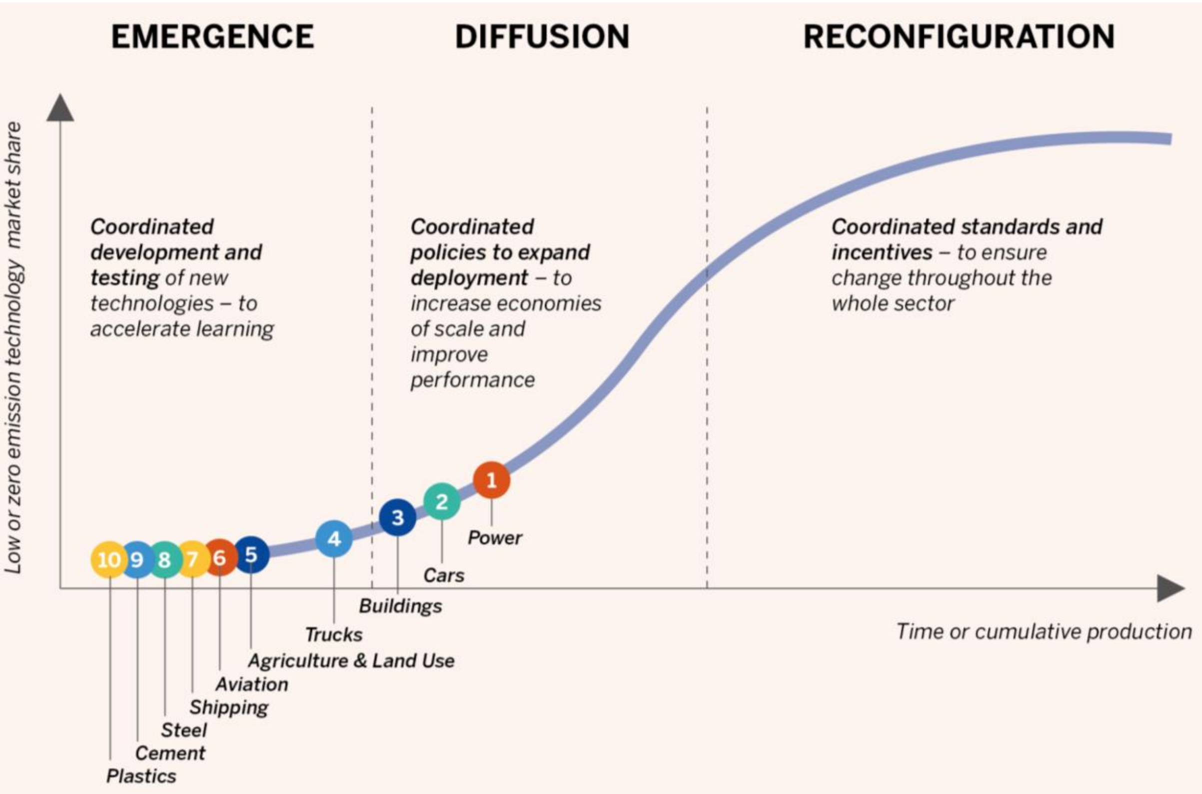


Figure 10: Global progress of low-carbon transitions in different sectors (Victor et al., 2019: 14)

3.2.1 Distinguishing incremental from systemic change

Based on extensive empirical research, the punctuated equilibrium framework (Tushman and Anderson, 1986; Anderson and Tushman, 1990; Tushman, and Murmann, 1998) distinguishes two kinds of change in sectors and industries (Figure 11): a) an *era of incremental change*, during firms elaborate and refine existing technologies and products through small improvements and modifications, b) an *era of ferment*, which is triggered by the emergence of technological discontinuities and competition between multiple design variations; these periods are characterised by uncertainties and turmoil, entry and exit of firms, strategic bets and repositioning. The selection of a dominant design ushers in another period of incremental change.

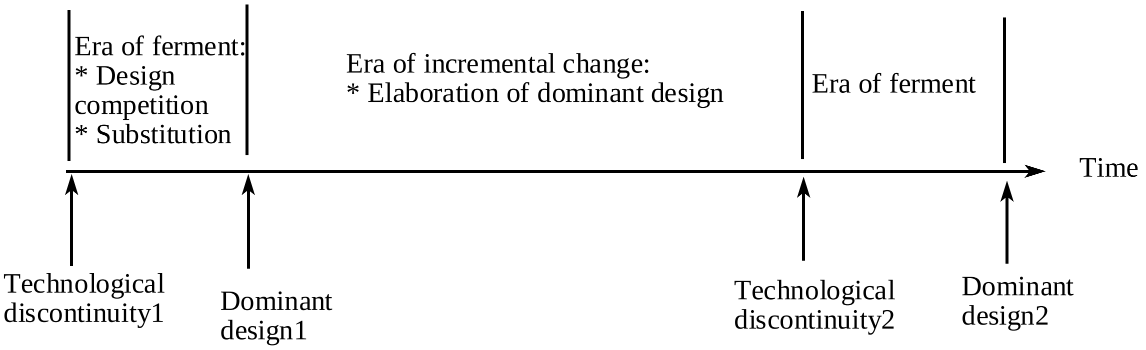


Figure 11: Punctuated equilibrium perspective (Anderson and Tushman, 1990: 606)

Firms need different strategic capabilities to manage the different nature of competition in both periods. During eras of incremental change, when competition on costs and efficiency are prevalent, firms should focus on the *exploitation* of existing capabilities and assets. During eras of ferment, however, when competition is about new technologies, firms should focus on *exploration*, the learning of new capabilities, and the opening up of markets for new products (Tushman and O’Reilly, 1996; Andriopoulos and Lewis, 2009).

The neo-classical framework is better suited for the analysis of incremental change than for ‘eras of ferment’ associated with the digital and low-carbon transition. Static optimisation approaches based on allocative efficiency of resources struggle to account for the potential for innovation to crowd-in new capacity and create new markets. Economic growth is therefore not a gradual accumulation process, but it is: “lopsided, discontinuous, disharmonious by nature (…) studded with violent outbursts and catastrophes (…) more like a series of explosions than a gentle, though incessant, transformation” (Schumpeter 1939: 102).

3.2.2. Lock-in, inertia, resistance, political economy

Economic lock-in mechanisms include sunk investments in the installed capital base, which companies will be reluctant to replace before their end-of-life (Mokyr, 1992; Bertram et al., 2015). Inertia in infrastructure based on incumbent technologies (e.g. petrol cars, gas boilers) is reinforced by network effects and high switching costs that alternatives (e.g. electric vehicles, heat pumps) would encounter (Aghion et al., 2014). Consequently, technological transitions and associated productivity improvements do not occur easily, because existing systems have been around for decades and are stabilised by multiple lock-in mechanisms (Klitkou et al., 2015; Seto et al., 2016).

At the same time “Socioeconomic systems have strong inertia (…). Unsurprisingly, therefore, it has been difficult to shift the innovation system from dirty to clean technologies” (Aghion et al. 2014: 6).

3.2.3 Short run transition costs and barriers

Historical studies suggest that technological transitions may temporarily lead to lower or stagnated productivity growth. David (1990) found that productivity growth was sluggish between 1880 and 1920 during the factory transition from steam engines to electric motors but accelerated afterwards.

The reason was that it took a long time to improve electric motors, diffuse them into diverse factories, and make systemic adjustments to optimally use the new technology. David and Wright (2006) also cite “increased rates of obsolescence in the older capital stock and in labour force skills; (…) and because major technological revolutions can be expected to have distributional consequences, very likely political adjustments will also be required if the full potential of the new technology is to be realised”. For the early 19th century British Industrial Revolution, Crafts (2004: 521) similarly found a “relatively small and long-delayed impact of steam on productivity growth”.

The high potential of automation to replace workers has also been long considered a key form of disruption (Frey, 2019) and, therefore, an important barrier to implementation due to under-qualified workers’ resistance to change (Raj et al., 2020). The impact of on net jobs will depend on differ through time. In the context of worker dislocation, Frey (2019: 13) explains that: “Replacing technologies render jobs and skills redundant”. In the longer run, however, “enabling technologies make people more productive in existing tasks or create entirely new jobs for them.”

Diffusion of new technologies must include not only the hardware, but also the complementary intangible investments and know-how needed to fully exploit the technologies, ranging from skills to new forms of business organisation. Here, among other things, the efficient deployment and reallocation of human and financial resources is essential. “Greater interaction between industry and education and training institutions is often required, and this need may grow as the knowledge content of production rises. Effective systems for life-long learning and workplace training are essential. (…) Public understanding and acceptance of new production technologies also matter. Policymakers and institutions should voice realistic expectations about technologies” (OECD, 2017b).

For low-carbon transitions, analysts have similarly suggested that productivity growth may slow or stagnate during the transitional period. Aghion et al. (2014: 6), for instance, argue that “shifting to a low-carbon economy may initially tie up factors of production and undermine the net returns from investment, potentially restricting the drivers of long-run endogenous growth.” It may therefore “take a certain period of time before there is higher and cleaner growth, powered by a clean innovation machine” (p. 8). The IMF (2020: 87) also diagnoses the potential for a temporary productivity growth slowdown in a low-carbon transition: “the economic transformation it requires may lower growth during the transition, especially in countries heavily reliant on fossil fuel exports and in those with rapid economic and population growth.”

The positive and negative productivity effects of low-carbon transitions are likely to vary between sectors and countries and across time. This point is reinforced by Bowen's (2016: 40) review on productivity growth and the environment, which concludes that: "Empirical research on the productivity effects of environmental policies is largely inconclusive. One problem is that results are usually very context-specific (…). Another is that past empirical work has focused on assessing short-term impacts, yet longer-term effects can be very different, as the discussion of learning and adaptation above indicates."

Similar up-front costs relate to the fourth industrial revolution in digital technologies. While the first wave of ICT investment starting in the mid-1990s was mostly from using technology to deliver supply-chain, back-office, and later front-office efficiencies, today we are experiencing a new way of digitization that comes with a more fundamental transformation of entire business models and end-to-end operations. Yet we appear to be experiencing a renewal of the Solow Paradox of the 1980s, with the digital age around us but not yet visible in the productivity statistics (Remes et al., 2018)

The first Solow Paradox of the mid-1970s and 1980s, for example, and the ICT boom in the 1990s. Productivity growth in the United States slowed in the former period, despite innovations at the time in the area of microelectronics and communications technology. Productivity gains were not automatic and did not occur in all industries that invested heavily in ICT. Instead, real productivity gains required significant changes in business process, as well as managerial and technical innovation (Remes et al., 2018).[9]

The servitization paradox (Gebauer et al., 2005) is one aspect of the more general productivity paradox (Brynjolfsson et al., 2017). Digital transitions involve a systemic change in consumer involvement in the production and distribution of products and services. "This form of digitization includes digitally-modified businesses combining physical and digital offerings" (Coreynen et al. (2017: 44). Nonetheless, this apparent opportunity is difficult to monetise due to a "servitization paradox" The "costs associated with servitization do not tend to lead to immediate financial return for manufacturers, and this interplay between service business model innovation and product innovation may even sometimes result in a short-term performance decline" (Coreynen et al., 2017: 43).

The challenge of adoption in the current digital wave may be even harder because of the broad range of uses of digital that not only help improve current processes but fundamentally transform business models and operations. For example, in retail, the first ICT revolution was focused on getting the right goods to the right place at the right time. With digitization, the transition to online requires building a new channel with a new supply chain structure to deliver goods directly to customers and determining what combination of stores and online presence is optimal. The current wave of digitization also requires customers to embrace developments such as mobile banking, online shopping, autonomous driving, and resolving questions with a bot.

Uncertainty over future risks also act as hurdles to investment. These are associated with: privacy and data security; standardization and compatibility of networks, interoperability, and integration issues; digital skills shortage; disruption to existing jobs; and resistance to change (Coyle, 2018; Horvath and Szabo, 2017; OECD, 2017; Raj et al., 2020).

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[9] A future that works: Automation, employment, and productivity, McKinsey Global Institute, January 2017. See also Comin and Hobijn (2010).

By the same token, the shift to low-carbon and digital technologies is about more than replacing existing technologies, it requires wider systems changes infrastructures, business models, markets, consumer behaviour, and institutions. A whole range of barriers to implementation has been identified, including, amongst others, high costs of initial investment, though in many cases these will be smaller and more incremental than investments in new transport and energy networks.

These may explain the latter-day Solow Paradox. While digital technologies, such as AI and machine learning, "hold great potential, there is little sign that they have yet affected aggregate productivity statistics" (Brynjolfsson et al., 2017: 4). Brynjolfsson et al. present several potential explanations of this 'modern productivity paradox'.

- Firstly, they argue that the optimism about the productivity might be misplaced. There tends to be much hype about technologies when they first enter the market. Yet many do not live up to their initial promise. This links to a broader literature arguing that many of the greatest productivity inducing innovations have already been cherry-pecked (Gordon, 2015) and that the returns to ideas have fallen (Bloom et al, 2020).
- Secondly, they argue that it could be an issue of mismeasurement. New technologies do provide benefits, but existing measurement methods are not yet capable of capturing these adequately, especially when this comes to intangible output or where new products enter the market without a continuous long run deflator series (Coyle et al. 2021).
- Thirdly, they argue that aggregate statistics might not pick up the benefits because they accrue to a small, concentrated group of 'superstar' companies. This explanation reflects the winner-take-all nature of platform markets.

As Remes et al. (2018: 43) argue: "While new digital entrants as well as fast-moving incumbents may increase profits and productivity, others can experience a transition that impedes productivity. As they lose revenue to disrupters and their growing digital arms cannibalise revenues further, some companies may end up with duplicate structures and processes, and underutilised capacity in their traditional operations."

However, Brynjolfsson et al. (2017) conclude by making the case that there might not be a paradox after all: "[I]t takes a considerable time—often more than is commonly appreciated—to be able to sufficiently harness new technologies." Ironically, this is especially true for those major new general-purpose technologies that ultimately have an important effect on aggregate welfare. "Indeed, the more profound and far-reaching the potential restructuring, the longer the time lag between the initial invention of the technology and its full impact on the economy and society."

Teece (2018), instead, labels digital technologies, such as AI and machine learning, as enabling technologies which he sees as technologies that can be used widely and undergo continuous technological improvement but do not yet have a broad transformational impact that is measurable. The underlying argument is the same, though; only when complementary technologies and concomitant skills develop, which build on the enabling technologies, will the full productivity benefits become attainable (OECD, 2017).

3.2.4. Overcoming barriers to transition

Nevertheless, barriers to scaling technologies and moving to a superior equilibrium remain real. A major uncertainty even after successful R&D trails, is whether or not the innovation will be able to make it across the 'valley of death' (Auerswald and Branscomb, 2003; Figure 12) or if it remains stuck in R&D projects and small market niches. This depends on (uncertain) improvements in price and technical performance, consumer interest, social acceptance and further policy support. In case of competing niche-innovations, there are further uncertainties about which technology will win the innovation race.

Companies may face difficult strategic choices with regard to which technology to back and what approach to adopt (e.g. first mover, rapid follower, wait-and-see). Because cost-benefit calculations offer limited traction in early transition phases (Christensen et al., 2008), managerial interpretations and strategic judgements play important roles in these strategic choices (Child, 1997).

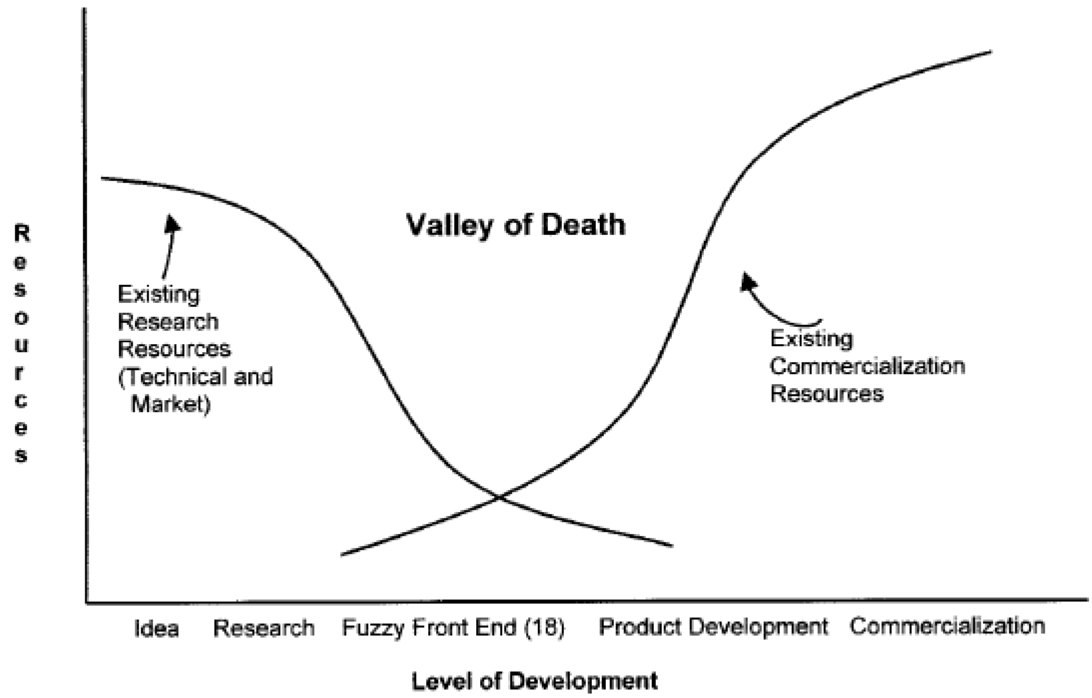

Figure 12: The valley of death is the decision space between R&D resources and commercialisation resources (Markham, 2002: 32)

Product development is also subject to great uncertainty. When new technologies enter mainstream markets, uncertainties relate to the outcome and vehemence of various struggles between the new and old system. Incumbent firms may resist change and lobby to overturn market-shaping policies (such as the 2006 zero-carbon homes policy that was scrapped in 2015). Disadvantaged workers or social groups can mount protests (such as taxi-drivers contesting Uber-licenses or the French 'yellow vest' protests against vehicle carbon taxes). Uncertainties may also relate to the speed at which complementary infrastructures are created (e.g. battery recharging infrastructure for electric vehicles).

Once 'the valley' has been crossed uncertainties tend to diminish as new systems stabilise and become institutionalised. Widespread use of new technologies and systems may, however, have unintended consequences that were not foreseen (e.g. the effect of digital platforms on elections and socio-political debates).

3.3 Policy to overcome barriers, induce innovation and generate systemic tips

The interplay across agents as well as the path dynamics of innovation and market creation augur for an array of approaches to induce cost-effective deployment and transform the system. Innovation system and transformative innovation frameworks which both highlight the roles of actors, social networks, and various forms of agency and interactions are required (Table 3). Different policies and different forms of finance and support are important in different stages of the innovation chain (Figure 13).

Framing	Key features	Policy rationale	Policy approaches (examples)
1. Science and technology for growth (since 1950s)	Linear innovation model, driven by R&D (research & development)	Addressing market failures (firms insufficiently invest in R&D because of public good character of innovation)	State financing of R&D; subsidies or tax incentives for business R&D
2. National and sectoral systems of innovation for improved competitiveness (since 1980s)	Focus on knowledge flows between upstream actors (universities, firms, agencies)	Responding to system failures, e.g. improving linkages between actors, addressing institutional problems (in laws, property rights, regulations)	Promoting science hubs and science-industry collaboration; education and training; cluster policies
3. Transformative change to address grand challenges (since mid-2000s)	Nurture radical innovation and new pathways; shape directionality of innovation.	Promote system transformation, which incumbent actors are slow or reluctant to do	Missions and goals (SDGs, climate targets), assisting new entrants, creating transformative coalitions, learning, experimentation

Table 3: Three frames in innovation policy (based on Schot and Steinmueller, 2018)

Public policies should go well beyond carbon pricing and R&D subsidies, aimed at correcting market failures, important though they are. “Because tackling climate change will require such a major shift in economic systems, (…) it involves (…) a much wider range of economic instruments than the standard policy toolkit” (Zenghelis, 2015: 173). These wider instruments could include direct infrastructure investments, purchase subsidies, loans or capital grants as well as standards, regulations, targets and institutional reforms.

Support for radical innovations can include R&D subsidies, purchase subsidies (e.g. for electric vehicles), market shaping (e.g. feed-in-tariffs for solar-PV), legislation (e.g. tightening European CO_2 emission standards for cars), phase-out policies (e.g. of diesel and petrol cars by 2030), direct infrastructure investment (e.g. in vehicle recharging grids), or the creation of platforms or councils to enhance coordination between industry, policy and academia. State-led innovation can take the form of deployment support to create new markets, basic R&D support to stimulate innovation and ‘mission innovation’ to achieve targetted economic and social objectives, such as low-carbon innovation across all sectors. Since low-carbon transitions face many uncertainties and disagreements, there is also a need for “comprehensive policy coordination and consensus-building mechanisms (…) at the interface of industrial and environmental policies” (Altenburg and Rodrik, 2017: 17).

Pricing policy itself must be carefully designed. Nordhaus (2021) argues in favour of “equalizing the marginal costs of reducing emissions everywhere…in every sector and every country”. He also argues that “an effective policy is one that ramps up gradually.” (Nordhaus

2007). But this is premised on the static marginal abatement cost approach, whereby investors pick off the most cost-effective emissions reductions at the margin. Yet, as argued above, abatement costs are shaped by innovation (Aghion et al 2016). Once a globally scaled and integrated technology becomes sufficiently competitive, it undercuts incumbents and alters the entire environment in which it operates. Therefore, it may make more sense to have early and strong differential pricing to kickstart the innovation machine in the most expensive sectors, which have the greatest potential for induced cost reductions (Vogt-Schilb, 2018; Acemoglu et al, 2012.

Institutional reforms are also necessary to further the new growth model. This will vary across regions but might include increased localism and devolution of powers, the creation of public investment banks with strong sustainability mandates or enshrining long-term policy frameworks, such as the UK's Climate Change Act. Such reforms can help mobilise private sector finance by managing and reducing risk, especially policy risk which the private sector does not own. Strong, credible and supportive policies can help shift expectations through changing perception of risk, thereby stimulating clean innovation and influencing both the direction and pace of change.

Clear and credible policy designed to steer innovation can be immensely powerful in overcoming dynamic market failures. Whether one cares about climate risks or not, early policy action to support new technologies is already delivering cheaper electricity and more efficient cars than conventional fossil alternatives. The market would not have delivered these; economists with static models could not have predicted them (Ekins and Zenghelis, 2020).

Vorley and Nelles's (2020: 278) call for a dynamic approach to productivity and productivity policy which should be about "the *capacity to respond to dynamic economic challenges that change over time and in relation to the actions of other individuals, industries and economies* (italics in original). (…) The complexity of economies as economic and social systems, and the productivity puzzles therein, demands dynamic and reflexive government interventions".

Different kinds of financial actors are important in different stages of the innovation chain (Figure 13). The diffusion of low-carbon technologies (and the associated systemic transformation) will require large investments (Table 2) that go beyond public funding abilities. It is therefore thought that "banks, insurance companies and pension funds (…) could provide the critical mass of investments needed to close the gap for the transition to a more sustainable economy" (EC, 2018: 9). This, in turn, will require policies and institutional reforms that help reorient financial flows from 'grey' to 'green' sectors (UNEP, 2018).

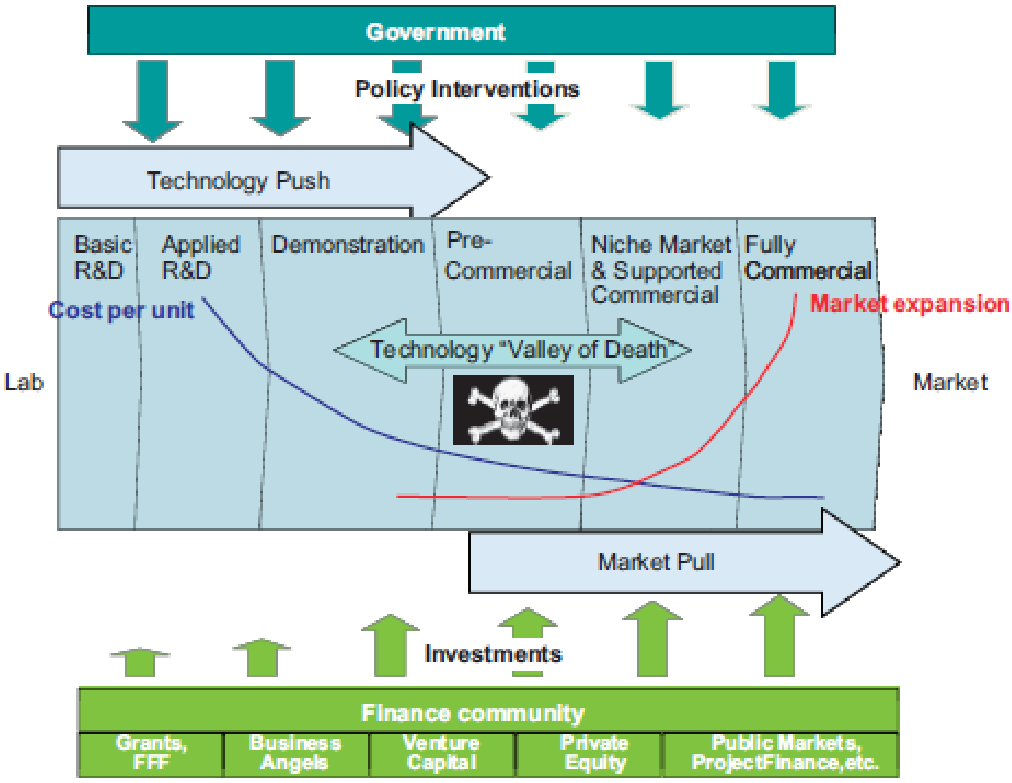

Figure 13: Segmentation of financial investors along the innovation chain (Würstenhagen and Menichetti 2012: 5)

Building capacity and resilience requires investing in vital assets necessary to boost factor productivity. These are mutually enhancing and include: physical capital, through direct public investment boosted by leveraging private finance through creating new markets. Human capital, enhanced by creating the skills and jobs necessary for the 21st century. Knowledge capital and innovation, fostered by accelerating R&D investment and providing long term deployment support. Natural capital, strengthened directly through carefully designed ecosystems creation, preservation and restoration projects. Social capital, enhanced by developing a vision and strategy for an inclusive and sustainable recovery that can gain support from businesses and communities and creates opportunities for all.

Ensuring a just transition will be crucial for maintaining social cohesion and economic justice and enabling the climate transition to unfold (European Commission, 2020). This requires enabling institutions that reskill, retool and compensate affected workers to secure the skills and jobs necessary to enable those affected by change to participate in the 21st century economy (Robins et al., 2019). Skills and education policies are important "during a process of creative destruction whereby the demand for some existing occupations or skills might disappear and demand for new low-carbon jobs will emerge" (Rydge et al., 2018: 9). Support might also be required to compensate consumers who, for example, face higher utility costs to fund investments in new networks.

Political economy considerations are especially salient for low-carbon transitions, which threaten the economic positions and business models of some of the world's largest and most powerful industries (e.g. oil, cars, electric utilities, agri-food).[10] Because of these lock-in mechanisms, innovation in existing systems is mostly incremental and path dependent, aimed at gradual improvements rather than transitions: "Most countries face political challenges in implementing ambitious policy reform. Vested interests and incumbent actors in today's high GHG-emissions societies can prevent governments from acting decisively and consistently. In a decisive transition, certain assets, especially in the fossil fuel and power sectors, will lose value and be economically stranded, with potential implications for employment opportunities" (OECD, 2017: 19). New coal fired power stations are hard to justify on commercial terms anywhere in the world, yet they are still being built for primarily political economy reasons.[11]

Additionally, there are wider governance challenges regarding flexibility, distributional issues, and "a willingness to take on entrenched interests" (Zenghelis, 2015: 184). Addressing these challenges may require new governance structures and more active policies aimed at steering and orchestrating change: "Ensuring that socio-technical systems move towards greater sustainability is a major challenge for governments, but also for civil society. At the core of such transitions is a shift in governance structures that not only allows change to occur but also directs and orchestrates some of the changes" (OECD, 2015: 242).

Technological adoption will also be swifter in institutional settings that more flexible and less susceptible to rent seeking and lobbying by vested interests of incumbent technologies (Comin and Hobjin, 2009). Most importantly, the presence of many actors and network complementarities augers for strategic planning with coordinated and coherent integration of policies, rather than the fragmentation of initiatives (Turnheim et al., 2018: 237) based on the creation of private or public internal markets to steer behaviour on the margin.

4. Future research avenues

This section discusses several substantive and methodological issues for future research.

4.1. Substantive research topics

4.1.1. Analysing productivity effects of low-carbon and digital transitions

An important future research topic is the further analysis of the productivity effects of low-carbon and digital transitions. This can build on insights from economic historians (Crafts, 2004; David, 1990) who suggest that productivity growth during historical transitions initially declined before subsequently increasing as new systems were established and new (often unforeseen) benefits were exploited. Similar propositions have been advanced for low-carbon transitions (Aghion et al., 2014; IMF, 2020). Future research avenue should further test and elaborate these ideas, and unravel the causal factors and mechanisms, and how these unfold over time.

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[10] The top-10 of the 2020 Fortune Global 500 list, for instance, includes five oil companies (Sinopec Group, China National Petroleum, Royal Dutch Shell, Saudi Aramco, BP), one electric utility (State Grid), and two automakers (Volkswagen, Toyota).

[11] Limiting climate change to 2^0C means that many proven fossil fuel reserves cannot be burned, which has led to debates about the size of potential stranded assets (Johnston et al., 2015; Mercure et al., 2018). Linquiti and Cogswell (2016) estimate that gas, coal, and oil companies may lose 63% of their value, dropping from $295 trillion to $110 trillion.

Such a focus on temporal patterns and causal mechanisms may be more productive than trying to quantify the size of the productivity effects of both transitions, which are still in early phases and surrounded my many uncertainties. Consequently, the long-term productivity effects of these transitions are “hard to model” (OECD, 2017: 9) and “nearly impossible to forecast” (Aghion et al., 2014: 5). Over-simplified models may even be “unhelpful” (Zenghelis, 2015: 182) if they leave out important factors and mechanisms because these are difficult to quantify. Moreover, to the extent that they help frame expectations, they may even become self-fulfilling (Zenghelis et al., 2020).

Other methods could potentially be used to assess the size of productivity effects such as soliciting expert judgment or systematic reviews of the literature (including clarification of underlying assumptions). But these methods are also unlikely to produce precise and reliable estimates. There is no way to circumvent the fact that with history only run once, providing a single time series observation, a definitive assessment of the cost and benefits of measures to enhance long term productivity is impossible as any counterfactual cannot be observed.

The issue of tipping points seems particularly fruitful to further explore. The findings reviewed in this paper suggest that transitions and productivity growth initially go through long periods of limited change, due to negative feedbacks, followed by rapid acceleration when tipping points are crossed and positive feedbacks kick in, so that: “A critical mass of attitudes, technologies, and actors can lead to system-wide transformation away from hydrocarbons. Network effects, economies of scale, and bandwagon dynamics can create self-reinforcing feedback loops such that a small push in the right direction can have outsized impacts” (Hepburn et al., 2020b: 8).

4.1.2. Feedbacks between digital and low-carbon transitions

There are many compelling promises regarding the positive contribution from digital networks to the low-carbon transition, as outlined in section 2.2.2. Critics, however, counter that information and communication technologies can have both substitutive and generative effects (i.e. they can produce new demand and user patterns); ICT data centres also use increasing amounts of energy, which generate greenhouse gas emissions (Sadowski and Bendor, 2019; Sadowski and Levenda, 2020; Van Oers et al., 2020). Potential research questions could include:

1. What are the positive and negative effects of digital transitions on greenhouse gas emissions, and productivity growth, in different sectors and how is investment best targeted?
2. How are the various innovations developing in terms of investments, demonstration projects and real-world deployment?
3. How do implementation speeds and drivers and barriers of transformative change compare across sectors?
4. How do on-the-ground implementation experiences compare to the grand visions and promises in different sectors?

4.1.3. Financing low-carbon transitions

Because new digital and low-carbon networks will require large capital outlays in the coming decades, an important research topic is the mobilisation of financial capital and investments. Finance plays a key role in accelerating the transition to a resource efficient digital economy. Public and private banks and institutional investors are increasingly aligning investments in climate resilience, biodiversity protection and sustainable development with the need to meet ever tighter regulatory and ESG criteria in their global investment strategies, markets and supply chains. Direct investment opportunities can also result from proactive engagement by multinational companies with suppliers in developing countries seeking to decarbonise and optimise production and supply lines.

It is important therefore to better understand the potential ability and interest of different financial actors in providing large amounts of money for low-carbon investments. These actors include: national promotional banks (e.g. the new British Infrastructure Bank, Germany's KfW Group) and multi-lateral public finance institutions (e.g., the European Investment Bank), commercial banks, institutional investors (pension funds, insurance companies, and sovereign wealth funds), and private companies balance sheets.

Future research could fruitfully analyse the different goals, institutional remits, and investments strategies of these actors have and their ability and willingness to provide low-carbon funding. Because the low carbon digital transition will be predominantly privately financed, it will be especially important to understand the goals and strategies by which the public sector leverages scaled-up private finance.

Future research could focus on analysing the potential role of policymakers in reorientating private financial flows towards low-carbon transitions. High-level policy organisations like the United Nations (UNEP, 2015, 2018; UNDP, 2018), International Monetary Fund (IMF, 2019), Organisation for Economic Co-Operation and Development (OECD, 2017a, 2018), and the European Commission (EC, 2018) have started to explore how the financial system can be aligned with climate mitigation.

It will be important to further analyse if the required sums of money can be mobilised by adjustments in well-known policy tools that reorient investments (e.g., taxes, financial incentives, regulations, standards) or if deeper structural reforms will be needed that reduce the profitability of short-term, speculative investments (e.g. introducing a financial transactions tax, banning certain forms of non-transparent financial products) or change the mandate of central banks from the narrow focus on price stability to wider sustainability objectives (Campiglio, 2016; Campiglio et al., 2018).

4.1.4. Regional aspects of low-carbon transitions

Carbon-intensive industries are located in different parts of the UK. Important auto-motive clusters, for instance, are located in the Midlands and the North (Sunderland), while important industrial clusters (e.g., chemicals, iron and steel, oil refineries) are in the Teesside, Merseyside, Humberside, and Grangemouth). Low-carbon transitions pose both challenges and opportunities for these regions.

If industries in these regions do not seriously engage with the decarbonisation agenda, there is a risk that they will be outcompeted in the coming years by foreign companies that do develop and sell low-carbon technologies (e.g., electric vehicles or green steel). This could negatively affect job opportunities in these regions and further exacerbate regional inequalities. On the positive side, offshore wind, carbon-capture-and-storage, hydrogen and other low-carbon technologies may provide economic opportunities for these regions, provided that employees and companies are willing to develop new innovations and skills and able to attract sufficient investments.

Future research could fruitfully investigate the risks and opportunities across various sectors and regions, the innovation and investment strategies of different companies, and the support policies from national and local policymakers.

4.1.5 Institutional and governance barriers for transitions

The governance challenges associated with low-carbon and digital transitions are substantial because transitions require policymakers to deal with deep uncertainties and disagreements as well as inevitable conflicts and power struggles. Managing the social and political impact of declining or unsustainable industries is always politically challenging. Allowing everyone to partake in the opportunities associated with a more diverse and flexible economy requires careful consideration and is a key part of managing an economic transition. The Climate Change Act and the development of a British Infrastructure Bank provide examples of institutional success stories.

However, the UK governance style also has certain characteristics that may hinder its ability to effectively manage transitions.

- UK policymakers prefer working with incumbent actors rather than with new entrants, which may slow down transitions and/or lead to particular policy choices (Geels et al., 2016). This problem is not unique to the UK, but the pattern relates to the Westminster political system, which is characterised by close-knit policy networks that are relatively open to incumbent industry actors but remain closed for outsiders and new entrants (Bailey, 2007).
- The UK also has a top-down, centralised policy style that hinders broad stakeholder engagement and open-ended learning, which are important in early phases of transitions: "The government in the UK is still meant to govern – full stop. (…) The government of the day acts. Others react. (…) Reforms (…) are not negotiated painstakingly with stakeholders. They are handed down from above by governments" (King, 2015: 283).
- The UK's liberal market economy (Hall and Soskice, 2001) tends to default to explicit or internal markets to drive efficiency, because it is scarred by (negative) experience in 'picking winners' in the 1960s and 1970s. While market drivers tend to be transparent and non-discriminatory and work well for 'eras of incremental change', they are likely to be less well-suited for 'eras of ferment' and technological transitions, when intervention is required to overcome dynamic market failures and develop new markets and where governments can help firms navigate the many uncertainties and hurdles in the early phases (Sainsbury, 2020). In sectors where the UK has made progress (e.g. renewables, electric vehicles), policymakers have, in effect, adopted more interventionist policy approaches (Kern et al., 2014).
- The need for intervention heightens the importance of transparent regulatory institutions to ensure policy is non-discriminatory, limits rent-seeking in public procurement, and protects consumer interests by promoting competition. Policy must be sufficiently stringent to change behaviour, predictable in order to contain policy risk, yet flexible in evolving in response to changing circumstances while containing compliance costs (Helm, 2010).
- While there are many localised projects and demonstration projects with radical innovations, UK policymakers appear to struggle with the second phase of up-scaling and stabilization (Eadson, 2016). Project funding often follow stop-start patterns, which hampers accumulation and effective sequencing of projects. Consequently, innovation projects tend to fragmented and isolated with limited up-scaling and broader diffusion.

- Fragmentation of institutions and governance (even at the Whitehall level) including a lack of horizontal and vertical coordination and strategic visions which are particularly salient for system transformation. The development of a British Infrastructure Bank is a key innovation in this regard.

It is important to better understand how these and other governance-related issues affect low-carbon and digital transitions and their productivity effects by way of cross country and historical comparisons. The key barriers to a low-carbon transition are increasingly acknowledged to political, cultural and institutional rather than economic and technological.

4.2. Methodological issues for future research

4.2.1 Towards an inter-disciplinary approach

Studying the productivity impacts of systemic change requires an inter-disciplinary approach, as argued above. This is not easy, however, because economics "has historically been rather insular as a discipline" (Haldane and Turrell, 2018: 220) with less inward and outward flows of ideas than other disciplines, as represented by cross-citation data (Figure 14). But frontier economists highlight its importance to address future challenges, including low-carbon transitions. Coyle (2020: 9), for instance, suggests that: "Getting good at interdisciplinarity will pay dividends long-term. The specifics will vary, but the need for coordinated research and policy applies to building a post-pandemic social order and to crafting a net-zero economy that limits climate change as far as possible". Haldane and Turrell (2018: 224) identify 'technology and innovation', 'climate change', and 'how economic agents make decisions' as especially fertile areas for cross-disciplinary research.

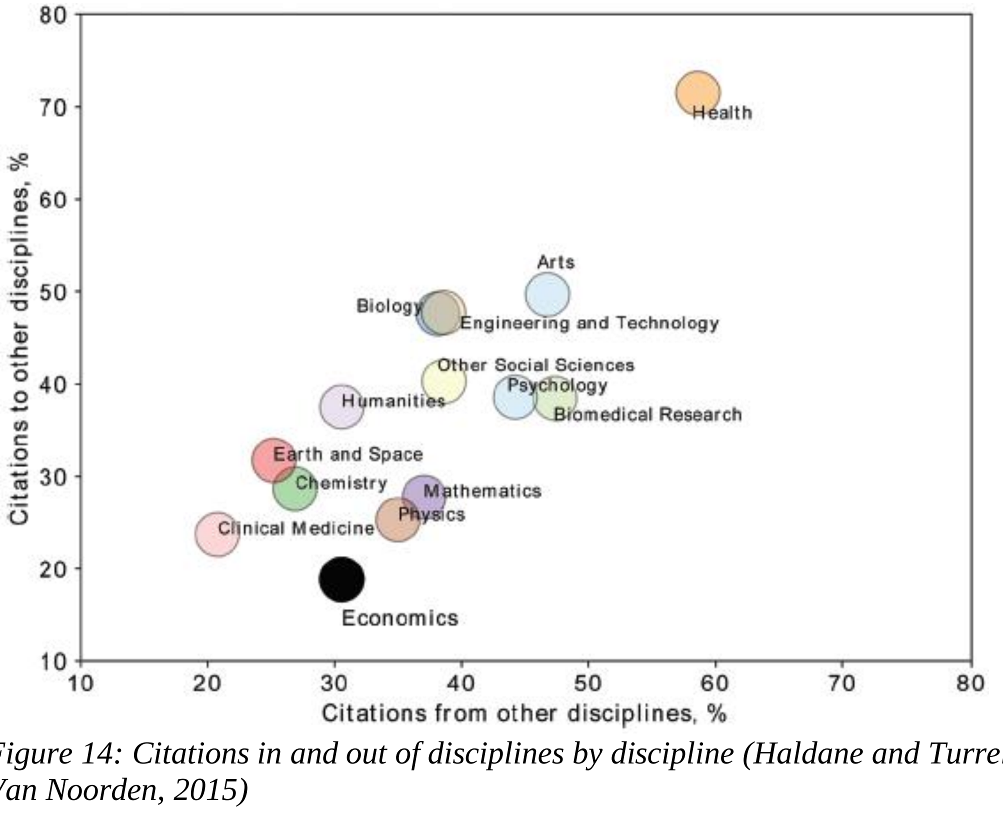

Figure 14: Citations in and out of disciplines by discipline (Haldane and Turrell, 2018: 221; Van Noorden, 2015)

One (general) future research avenue is therefore to build on these encouragements as well as on other recent calls for rethinking economics, including the OECD's 'New approaches to economic challenges' initiative, the 'Rebuilding macroeconomic theory' special issue in *Oxford Review of Economic Policy* (2018, Vol. 34, No. 1-2), and the World Economic Forum's 'COVID-19: The Great Reset' initiative (Schwab and Malleret, 2020). Although section 3 identified relevant insights and building blocks from mainstream and neo-classical economic, political science, business and management, and sociology, the synthetic task of conceptual integration remains to be done.

4.2.2. From cost-benefit to risk-opportunity analysis

This position paper has started to outline an interdisciplinary conceptual framework that better addresses specificities of technological transitions and productivity. While this framework mobilised some insights from evolutionary economics and strategic management, much more can be done to better conceptualise the *process* of technological transition as it unfolds over time and co-evolves with other productivity dimensions (rather than being a separate domain or production factor). These elaborations should further articulate the factors that drive the emergence and development of radical innovations in different phases and how these relate to productive capital, human capital, and financial investments as well as to markets, institutions, and political economy.

It is no coincidence that, to the authors' knowledge, not a single economic model predicted the sharp falls in the costs of renewables or battery technologies over the past decade. Models also miss the importance of early public intervention to tilt the economy onto a new, more productive, path. They understate the degree to which leadership matters (Ekins and Zenghelis, 2021).

Productivity pathways are subject to uncertainty and irreversibilities rendering quantitative forecasting futile. A recent study on the process of change (Sharpe et al., 2021) defined a risk-opportunity assessment (ROA) framework to guide policymakers and investors. They concluded:

- Models based on inappropriate assumptions will not provide helpful input to such an analysis.
- The expected value of (non-marginal dynamic) outcomes cannot be reliably calculated.
- Policy action in these conditions is about 'steering' in an uncertain, changing environment, rather than about 'optimising' an outcome in a world of certainty.
- It is therefore processes –the likely direction, rate, and magnitude of change –that should be the focus of analysis.
- The preferred option is determined by the decision-maker based on a qualitative judgment of the scale of the opportunities and risks, compared to the cost of the intervention.
- This will necessarily be a subjective judgment

Innovation to drive connected and integrated resource efficiency has the potential to free-up factors of production to generate value elsewhere in the economy. Such 'crowding in' and resource creation will form a key part of the route to higher productivity for a medium sized, open economy like the UK (Zenghelis 2021).

4.2.3. Comparative empirical research

Comparative research methodologies can accommodate complex causalities, because they aim to explain differences in outcomes as the result of multiple interacting variables and contexts (Van de Ven and Huber, 1990). Comparative research on transitions, including lessons from previous waves of technological change and productivity, could address many interesting and important issues, including:

- compare and explain productivity effects of different technologies and technological transitions within a particular industry or sector;
- compare speeds, pathways and productivity effects of low-carbon or digital transitions in different industries or sectors;
- compare how policymakers in different countries or city-regions manage low-carbon or digital transitions in particular sectors or industries.
- compare different up-scaling strategies in the second transition phase between countries, technologies or sectors;
- compare and explain how different companies in a sector adopt different transition strategies;
- compare how and why different financial investments flow at different speeds into different sectors and technologies

Rather than focus on predictions based on 'historical futures', information on innovation processes can be gleaned by looking at historical transitions, such as the change from kerosene use to electricity, horse and cart to combustion engines, and photographic film and records to digital photos and music (Zenghelis et al., 2018) or the development of more recent digital technologies like GPS or touchscreens. Most of these more specific research topics would enable crossovers to other Productivity Institute themes, including organisational capital, knowledge capital, geography, and human capital. While research questions need to focus on particular topics or questions, it is hoped that research in transitions theme will overcome the silo-problem (Vorley and Nelles, 2020) and investigate the focal topic in a systemic or co-evolutionary way.

4.2.4. Broaden the use of analytical tools

A number of viable approaches present opportunities for a richer and more valuable understanding with which to guide decision-makers (Haldane and Turrel, 2018, Ekins and Zenghelis 2021, Sharpe et. al, 2021). These include:

- dynamic policymaking frameworks including use of real options theory and robust decision making on new technology options (such as how and when to commit to one network over another);
- greater use of theoretical models, system dynamics models, and non-equilibrium macro-econometric models;
- expectations formation and social psychology dynamics including game theoretical analysis of strategic complementarities;
- spatial geographic approaches including analysis of spillovers, contagion, agglomeration and network science.

Another approach argues that dynamic models of the economy should be coupled with models of opinion dynamics and behaviour by use of agent-based models. These explicitly reflect interactions between heterogeneous, networked individuals in place of conventional 'representative agents' (Farmer and Foley, 2009). As a result, they offer insights into the probability and processes through which economies shift from one equilibrium to another (Mealy and Hepburn, 2019).

A number of authors now recognise that better understanding the processes and innovations which generate the cascades of tipping described above is more valuable to policymakers than speculative projections of costs. By taking advantage of the inherent domino effect of rapid, self-amplified and contagious change, policymakers can leverage highly sensitive "tipping interventions" that deliver outsized impact (Schellnhuber et al. 2016; Farmer et al., 2019) which could hasten global decarbonisation (Tàbara et al. 2018).[12]

Highlighting the importance of interdisciplinarity analysis, Stern and Valero (2021: 5) neatly capture the need to develop a better understanding of dynamic processes: "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. (…) 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."

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[12] See Oxford Martin School, "Programmes: Post-carbon Transition," www.oxfordmartin.ox.ac.uk/research/programmes/post-carbon

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