Linking sustainability transitions to debates in evolutionary, institutional and ecological economics

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Abstract

A sustainability transition requires a transition to an economy and society that delivers enhanced human wellbeing and social equity whilst remaining within planetary boundaries. However, despite claiming to draw on evolutionary economics as one of its starting points, the sustainability transitions literature has largely failed to engage with a wide range of alternative economic thinking that challenges dominant strands of neo-classical economic thought. This paper argues that this represents a missed opportunity for productive synergies (as acknowledged at points in the new STRN research agenda).

In particular, this paper argues that unrealised synergies exist between sustainability transitions ideas and evolutionary, institutional and ecological economics. Engagement with evolutionary economics would link innovation systems perspectives with ideas on drivers and barriers to long-term techno-economic paradigm change. Engagement with institutional economics would link into current ideas on the role of finance and adoption of new business models. Engagement with ecological economics would address current debates on ecological limits, energy dependence and challenges to the dominant economic growth paradigm from the degrowth and steady state economy communities.

The author illustrates these points with ideas from his recent book on 'Energy and Economic Growth: why we need a new pathway to prosperity'.

1. Introduction

The sustainability transitions literature has made great progress in developing and applying concepts to understand how transitions can be promoted from current unsustainable systems of consumption and production to sustainable systems that address pressing environmental and social challenges (Markard et al., 2012; STRN, 2017). The core concept is that of socio-technical systems for meeting societal functions, such as provision of nutritious food, clean water and energy and mobility services. These systems are seen as multi-dimensional and multi-actor with change happening through coevolutionary processes involving a range of elements and dimensions. A particularly influential framework has been the multi-level perspective (MLP), which views change in dominant socio-technical regimes as being influenced by innovation in socio-technical niches and broader cultural changes at landscape level, as well as by internal dynamics within the regime (Rip and Kemp, 1998; Geels, 2002; Smith et al., 2010; Geels et al., 2017). This framework draws on ideas from evolutionary economics, sociology of innovation and institutional theory. However, in this paper, I argue that economic factors and arguments have been neglected within the sustainability transitions literature and that this is an important omission, given the dominance of economic framings in political and cultural debates around sustainability. I suggest that more attention to a range of alternative economic thinking, including ecological, evolutionary and institutional economics ideas, would therefore be beneficial in developing the richness of theoretical debates and policy relevance of sustainability transitions research.

2. Importance of economic framings for sustainability analysis

The most important global political framing for achieving a sustainability transition is the UN Sustainable Development Goals (UN, 2015). These are a set of 17 high-level goals (SDGs) and 169 detailed targets for global sustainability by 2030, agreed by all 193 countries within the United Nations. They combine social goals, including ending extreme poverty, hunger and malnutrition and reducing inequality within and among countries, with environmental goals, including ensuring universal access to clean water and sanitation, affordable and clean energy and taking urgent action to combat climate change and its impacts (in conjunction with the UN Framework Convention on Climate Change and the Paris Agreement for a maximum 2°C temperature rise). This also put in place an institutional framework for ensuring progress towards achieving these goals, including the UN High-level Political Forum on Sustainable Development, which reports to the General Assembly.

Importantly, SDG 8 is to promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all. This includes a target for economic growth of at least 7% per annum for least developed countries. Thus, explicit in the goals is a continued commitment to achieving high levels of economic growth in both industrialised and developing countries, broadly within the existing paradigm of high levels of consumption and trade of goods and services, but with greater emphasis on this being done in a way consistent with achieving social and environmental goals, sometimes referred to as 'green growth' (Global Commission on the Economy and Climate, 2014; OECD, 2017).

Economic thinking is broadly divided into microeconomics and macroeconomics. Microeconomics examines the role of individual actors, such as households or firms, and their responses to incentives, whereas macroeconomics deals with whole economic systems at the national or international level, including issues such as productivity, employment, inflation and economic growth. Both of these theoretical frameworks have been very influential in framing policy responses to sustainability challenges, as they have been in many other policy areas. Microeconomics tends to emphasise the importance of price incentives on individual behaviours, leading to a focus on the implementation of carbon pricing through taxes or trading schemes as the predominant policy response to the climate change challenge, for example. The dominant macroeconomic framing has been to emphasise the need for high rates of economic growth, to stimulate job creation and generate tax revenues for public spending on health, education, etc., and so, as noted, the dominant policy framing for achieving sustainability incorporates this focus on economic growth. The combination of microeconomic and macroeconomic thinking that dominates leading academic departments and journals is usually referred to as the neo-classical synthesis. As we shall discuss in subsequent sections of this paper, other strands of alternative economic thinking seek to ameliorate or question the emphasis on price incentives and economic growth, leading to a wider range of policy tools and approaches that could be important for sustainability.

Sustainability transitions research is typically conceived as a meso-level theory. As such, research in this area tends to focus on how the interaction of social and technical elements gives rise to socio-technical systems in relation to particular industries or sectors that aim to deliver socio-technical functions, such as national electricity systems for meeting household and industrial energy service demands. Aspects at the micro and macro levels are typically framed in terms of the interaction of social and technical elements at these levels, such as

the deployment of new electricity generation technologies or business models at the niche level, or the increasing influence of climate change policies at the landscape level. However, little attention is typically paid to the role of economic arguments or framings at these levels. For example, a recent paper advocating a sociotechnical transitions perspective on reducing energy demand recognised the dominant neo-classical economic framing of policy responses, but argued that this framing "offers only limited insights into either the process of innovation or the most effective means of policy support" (Geels et al., 2017, p. 24). This leads to consideration of ideas such as emergence, diffusion and impacts of low carbon innovation on socio-technical systems. Whilst recognising the value of these framings in contributing to understanding of sustainability transitions, we argue that both the explanatory value and policy relevance of these types of framings is reduced because they fail to engage with alternative economics ideas that could provide complementary insights.

We highlight four limitations of the neo-classical economics framing that have led to the development of alternative bodies of economic thinking:

- Individual rationality and optimisation
- Aggregation of individual choices into macroeconomic outcomes
- Dynamics of meso- and macro-economic systems
- Consideration of non-market social and environmental impacts as 'externalities'.

Firstly, a consistent criticism of neo-classical economic thinking has been its focus on individual rationality, i.e. the idea that individuals and firms make rational decisions based on their preferences and the information available to them. This idea was already criticised in the 1950s by economist Herbert Simon, who argued instead that individuals have 'bounded rationality', i.e. they are limited in their ability to gather and process relevant information (Simon, 1956). This perspective has been accepted within the area of behavioural economics, which has demonstrated that this leads to systemic shortcomings in human decision-making processes, such as putting greater emphasis on avoiding losses than potential gains, and being influenced by how information is presented (Kahneman, 2011). However, this is still framed in the context of individual decision-making, and neglects the wider social factors that a socio-technical perspective emphasises.

A related concern is how individual choices are aggregated into macroeconomic outcomes. In integrated assessment modelling that is used to link economic changes to environmental impacts, it is usually assumed that macroeconomic outcomes are simply the sum of individual household and firm level decisions, combining rational choices into optimal outcomes. This neglects the way that interactions between individuals are mediated through institutions – the social rules that govern these interactions. Here, the field of institutional economics has developed to analyse how the development and realisation of institutions affects economic outcomes. Typically, institutions are seen as constraining and 'sticky', i.e. they make certain types of interactions easier than others and they become reinforced and hard to change through these processes. However, institutions also enable desirable outcomes by reducing 'transaction costs' that would otherwise occur, as discussed below.

A third limitation of neo-classical economic thinking concerns the dynamics of meso- and macro-economic systems. As a consequence of the simple aggregation of micro decisions to macro outcomes, the evolution over time of macro-economic systems is usually assumed

to follow simple dynamic laws. However, if this aggregation is mediated through the formation of institutions and complex systems, then the dynamical processes of change require further detailed analysis. This is the realm of evolutionary economics. Evolutionary economic thinking was one of the theoretical inputs into socio-technical systems analysis, but it has subsequently been largely neglected in this field. The main exception to this is the analysis of innovation systems, which is a key meso-level concept in evolutionary economics. Innovation systems may be analysed at a technological, sectoral or national level, and have been argued to provide complementary insights to the multi-level perspective on sustainability transitions (Markard and Truffer, 2008). However, the macro-level dynamics of macro-economic systems studied by evolutionary economics has been almost totally neglected in sustainability transitions research. As we discuss further below, insights into long-term changes in economic and industrial systems highlighted by Carlota Perez and others could be particularly relevant.

Fourthly, sustainability transition research is concerned with transition to socio-technical systems that lower environmental impacts to within the 'planetary boundaries' of natural ecosystems. A persistent criticism of neo-classical economics is that it considers environmental and social impacts that are not contained within market transactions as 'externalities'. The dominant realm of environmental economics seeks to find ways to internalise these externalities, for example, by putting a price on carbon emissions through a carbon tax or trading scheme. However, this approach has been criticised as not fully incorporating the dependence of economic activity on natural energy and material flows. This is the realm of ecological economics. As we discuss below, an ecological economics perspective highlights the implications of these energy and material dependencies in ways that complement the more social constructionist perspective of much of sustainability transitions research. This is particularly relevant for debates around the feasibility of green growth strategies.

We argue that these alternative economic framings provide insights around the issues of investment, productivity, employment and economic growth that are concerns of policy makers in ways that overcome the limitations of the neo-classical economics framing. Only a few papers in the sustainability transitions field have so far sought to engage with these alternative economic framings (Jackson and Victor, 2011; Geels, 2013; Foxon, 2013; Perez, 2013; Antal and van den Bergh, 2013). In the following sections, we suggest how these insights could inform sustainability transitions research.

3. Institutional economics ideas for sustainability transitions

Institutional ideas are already incorporated into socio-technical systems analysis, usually in the form of rules shaping human social interactions. Drawing on Scott (1995), Geels (2004) identifies three key types of rules: *cognitive, normative* and *regulative*. Regulative rules refer to formal rules that constrain behaviour and regulate interactions, such as governance and regulatory frameworks. Normative rules refer to values, norms and expectations by which behaviours are formulated and assessed, and are often internalised through processes of socialisation. Cognitive rules refer to the frames and concepts that are used to make sense of reality. Behavioural economics uses this idea to highlight the limitations of human decision-making processes described above. Institutional economics focuses more on the regulative and normative rules governing social interactions. This provides tools for understanding the evolution of socio-technical systems. Geels (2004) describes socio-

technical regimes as semi-coherent social rule systems, in which the alignment between rules generates regime stability and a preferred direction of incremental innovation. Institutional economics can add to this by a focus on access to and distribution of resources as a factor influencing the development of regimes. One of the most well-known applications of institutional economic thinking is the work of Elinor Ostrom and colleagues, who showed that communities typically develop institutions to govern access to common land, such as for grazing animals, that avoid the 'tragedy of the commons' predicted by Hardin. Institutional economics also discusses the distribution of cognitive resources, such as skills. Institutional economists such as Douglass North (1990) and Paul Pierson (2000) examined the processes by which institutions become embedded, including increasing returns or positive feedbacks to adoption, such as adaptation and reinforcement processes, by analogy with the increasing returns to adoption of technologies, described by Brian Arthur (1989). Applying a coevolutionary framework, Unruh (2000) identified the sources of increasing returns to institutions supporting fossil fuel-based energy regimes, as well as to the technologies within those regimes, leading to the 'carbon lock-in' of these regimes.

In an important early work on sustainability transitions, Smith et al. (2005) developed a quasi-evolutionary theory of regime transformation, based on two processes – the selection pressures bearing on a regime, and the capacities and resources available within the regime to respond to these pressures. This and other work, such as that of Geels (2004), suggests that there could important synergies with institutional economics ideas. It is clear that achieving sustainability transitions will require significant institutional change at multiple levels. Though commitments have been made to new high-level targets and institutions, such as the Sustainable Development Goals and Intended Nationally Determined Contributions (INDCs) to carbon emissions reductions, these have often not yet been fully incorporated into national and industrial level institutions. Institutional economics and related political institutional theories, such as the multiple streams theory (Kingdon, 1986) and advocacy coalition theory (Sabatier and Weible, 2007) can provide tools and approaches for assessing these institution building processes that are central to sustainability transitions.

Another area that can be informed by institutional economics is that of finance and investment. A key political challenge is that of diverting investment from unsustainable purposes, such as for further fossil fuel development, to sustainable purposes, such as renewable energy investment, whilst achieving macroeconomic goals, such as economic stability and employment. This is an area that has been neglected by sustainability transitions researchers, partly because of the complexity and opacity of financial systems. Institutional economics provides tools for opening up the black box of finance, such as understanding the role of pension funds in channelling individual savings into investment for financial returns. Research has highlighted the systemic constraints on the ability of pension funds to redirect investment towards achieving social and environmental goals, where these conflict with the primary aim of achieving financial returns (Hall et al., 2017). More broadly, understanding how financial systems can be reoriented to focus on long-term, productive and sustainable investment and away from short-term, speculative and unsustainable investment should be central to sustainability transitions research.

4. Evolutionary economics ideas for sustainability transitions

An important recent development in evolutionary economics thinking was the publication of Richard Nelson and Sidney Winter's book, *An Evolutionary Theory of Economic Change*, in

1982 (Nelson and Winter, 1982). They built on the ideas of Joseph Schumpeter, who analysed the roles of entrepreneurs and business cycles in driving macroeconomic change, and Herbert Simon, who, as we noted, emphasised the bounded rationality of individual decision-making processes. In their evolutionary theory, firms with bounded rationality follow 'satisficing' routines that deliver satisfactory, rather than optimal, levels of profit. When technological or institutional selection environments change and profits are no longer satisfactory, firms are stimulated to search for new routines that provide a better fit with these new selection environments. In this way, the set of routines evolve over time. Nelson and Winter showed that this provides a good explanation of changing industrial patterns without having to assume that firms make optimal decisions. At a macroeconomic level, they provided an evolutionary model of economic growth based on changing routines that reproduced the findings of the neo-classical Solow model without postulating unexplained technological change or an unrealistic production function linking outputs to inputs. Nelson (2005, 2008) further developed this into a theory of economic growth based on the coevolution of technologies and institutions.

These ideas were further developed and presented in a book by Eric Beinhocker (2006), who described economic growth as a process of coevolution of technologies, institutions and business strategies. He combined evolutionary ideas with ideas from complex systems theory, such as Arthur's (1989) identification of increasing returns to adoption of technologies, to describe economies as complex adaptive systems. This characterises economies in terms of five properties that challenge a neo-classical economic view:

- *Dynamics*: economies are open dynamic systems, far from equilibrium;
- *Agents*: economies are made up of heterogenous agents with bounded rationality;
- *Networks*: these agents interact through networks;
- *Emergence*: higher level emergent properties of economies arise out of these interactions;
- *Evolution*: evolutionary processes create novelty over time.

In this view, mutual positive feedbacks to the adoption of technologies, institutions and business strategies drive economic growth. This is important to sustainability transitions research, due to the predominant political focus on achieving high rates of economic growth for realising social and economic goals, including high levels of employment and government revenues to fund public services, such as health and education. If sustainability transitions are seen as challenging the achievement of high rates of economic growth without other direct social benefits, then they are likely to be resisted by governments, as well as by those industries and employees who would lose out from a transition.

A second strand of evolutionary economic theory was developed by Chris Freeman and Carlota Perez, then at the Science Policy Research Unit (SPRU) at the University of Sussex (Freeman and Perez, 1988). They examined long waves of techno-economic change, dating back to the industrial revolution. Freeman and Louca (2001) explained this as a process of coevolution of technological, scientific, economic, political and cultural systems. Perez (2002) further developed this theory, identifying five surges of economic growth, each driven by a new technological/institutional innovation, which becomes cheap and creates spillovers to new uses and new technologies. In each long wave, initial speculative financial

investments lead to a bubble, then a turning point around a crash, after which productive investments leads to a surge of economic growth. Crucially, the full benefits are only realised when institutions coevolve to enable the benefits of new technologies to be realised. In 2014, Mariana Mazzucato and Carlota Perez argued that there are synergies between the implementation of green technologies, such as renewable energy and circular economy approaches, and deployment of the current wave of information and communication technologies (ICTs), that could deliver a fifth surge of smart, green growth (Mazzucato and Perez, 2014). The feasibility of the realisation of such a surge has significant implications for the political acceptability of a sustainability transition.

5. Ecological economics ideas for sustainability transitions

Finally, the area of thought known as ecological economics could also inform sustainability transitions research. Ecological economists typically distinguish themselves from environmental economists, who use the tools of neo-classical economics to study environmental challenges. Ecological economics, on the other hand, starts from the perspective of the global economy as a subsystem of the global ecosystem, on which it is dependent for flows of energy and material inputs and on the ability of the biosphere to assimilate the wastes produced by the economy (Common and Stagl, 2005). This was articulated in a 1966 essay, *The Economics of the Coming Spaceship Earth*, by mainstream economist Kenneth Boulding (1966), in which he described humanity as moving from a 'cowboy economy' of limitless frontiers to a 'spaceship economy' of increasing human wellbeing within the finite limits of the planet.

This was taken up by Donella Meadows and colleagues in the famous *Limits to Growth* report to the Club of Rome (Meadows et al., 1972). They used an early systems dynamics model to project the implications of continuing high rates of economic growth with high levels of resource use and environmental impact. Their core scenarios projected that resource constraints would place limits on future economic growth, leading to a crash in the early decades of the 20th Century, if action to reduce rates of resource-intensive consumption was not made. They were criticised by Chris Freeman and others as 'Malthus with a computer' for failing to take into account for potential for technological innovation to overcome resource constraints, though interestingly, pathways of resource use and environmental impacts have followed their core scenarios quite closely. These debates around the potential for innovation to overcome resource constraints continue to the present, with the proponents of green growth having faith in innovation to overcome these constraints, whilst some ecological economists see the impacts of climate change and other ecological system responses as constraining human wellbeing. Again, the outcome of these debates and the way that they play out in political and cultural debates are crucial for sustainability transitions.

More theoretical approaches to ecological economics were developed by Hermann Daly and Nicholas Georgescu-Roegen in the early 1970s. Daly (1977) argued for a steady-state economics, in which the throughput of energy and materials were constrained at a level within the sustainable limits of the Earth. Note that this is not necessarily the same as a zero growth economy, as growth is measured in terms of the economic value of goods and services exchanged, not physical flows. In his 1971 book, *The Entropy Law and the Economic Process,* Georgescu-Roegen (1971) developed a more detailed theoretical analysis of how economic systems rely on flows of ordered (low entropy) energy that is

converted in the process of production of goods and services, giving rise to disordered (high entropy) wastes. This thus provides a physical description of economic processes that could inform sustainability transitions research.

Building on this work, a theoretical model describing the role of exergy (the part of energy available to do physical work) as an input to production processes alongside labour and capital was provided by Ayres and Warr (2005, 2009); Warr and Ayres (2012). They identified the positive feedbacks to the substitution of exergy for labour and capital and the application of knowledge to improve the efficiency of energy conversion processes as two key drivers of economic growth.

Other recent work on ecological macroeconomics modelling has explored different ways of combining ecological dependence with representation of elements of macroeconomic systems, such as the role of banks in providing investment, through the use of input-output, stock-flow consistent and systems dynamics models (Rezai and Stagl 2016; Hardt and O'Neill, 2017).

There has been relatively little work, though, linking the ecological dependence perspective of ecological economics with the long-term dynamics of evolutionary economics. The present author developed a coevolutionary framework for analysing a transition to a sustainable low carbon economy, which aimed to provide a step towards this linking (Foxon, 2011). He combined this framework with Perez's evolutionary model of techno-economic change leading to five surges of economic growth in his recent book *Energy and Economic Growth: Why we need a new pathway to prosperity* (Foxon, 2017). This explored the role of the adoption and diffusion of energy technologies, such as the steam engine and electrification, in driving these surges of economic growth. He argued that this has important implications, challenging the long-term feasibility of a 'green growth' perspective. Other authors within ecological economics have explored the feasibility of an economy not based on continuing pursuit of economic growth (Dietz and O'Neill, 2013, Jackson, 2017).

6. Implications for sustainability transitions research

This paper has contended that the lack of engagement with substantial bodies of work on alternative economic approaches to understanding technological and institutional change is limiting the explanatory power and policy relevance of much sustainability transitions research. In this paper, I have focussed on this lack of engagement by researchers applying the multi-level perspective on transitions. However, a recent review of a wide range of conceptual frameworks for explaining sociotechnical change suggests that the majority of these frameworks are also dominated by sociological concepts with little attention being paid to economic concepts (Sovacool and Hess, 2017). Similarly, whilst recognising finance as an area for further research, the recent research agenda for the Sustainability Transitions Research Network (STRN, 2017) could point to little ongoing research addressing economic concepts, such as investment, productivity or economic growth.

Other authors have very recently argued for the need to integrate techno-economic, socio-technical and political perspectives for analysing energy transitions, and proposed a meta-theoretical framework for this (Cherp et al., 2018). They argue for the value provided by a range of approaches, including coevolutionary frameworks and Ostrom's institutional framework. We agree with their broad perspective, and argue that the range of alternative

economic ideas reviewed in this paper could provide useful theories and approaches contributing to this integration.

A complementary perspective coming from the economics perspective is provided by Michael Grubb and colleagues. They identify three domains for understanding a transition to a low carbon economy, and argue that policy mixes are needed that reflect the different perspectives in these domains (Grubb et al., 2014, 2015, 2017). Their first domain is that of individual and firm behaviours, which they argue can be addressed through behavioural economics. Their second domain is that of near-term economic change, which they argue can be addressed largely using the tools of neo-classical economics. Their third domain, crucial for a transition, is that of long-term systemic change, which they argue requires the approaches of evolutionary and institutional economics to address. Again, we would argue that sustainability transitions research can provide complementary ways of understanding long-term systemic change.

We expect that some researchers in the sustainability transitions research community will disagree with the argument for synergies with alternative economic research ideas that we have put forward in this paper. They may argue that socio-technical research frameworks, perhaps combined with political theory insights, are sufficient for understanding the potential for sustainability transitions and the policy actions that may be needed to achieve these. In response, we would say that it is not enough for these researchers to dismiss the relevance of economic arguments simply by pointing to the limitations of neo-classical economic thinking. They need to engage with these wider bodies of economic thought, in order to be able to argue whether or not a socio-technical perspective is sufficient for understanding transitions. Given the likely continuing prevalence of economic ideas in informing policy making for sustainability and the domains of macroeconomics, environmental and social policies, we think that exploring these synergies with alternative economics approaches is necessary for contributing to relevant policy debates, such as the feasibility or otherwise of green growth strategies for achieving a sustainability transition.

References

Antal, M. and van den Bergh (2013), 'Macroeconomics, financial crisis and the environment: Strategies for a sustainability transition', *Environmental Innovation and Societal Transitions* 6, 47-66.

Arthur, W.B. (1989) 'Competing technologies, increasing returns and lock-in by historical events'. *Economic Journal* 99, 116-131.

Ayres, R. U. and B. Warr (2005) 'Accounting for growth: the role of physical work'. *Structural Change and Economic Dynamics* 16(2), 181-209.

Ayres, R. U. and B. Warr (2009) *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Cheltenham and Northhampton MA: Edward Elgar.

Beinhocker, E (2006) *The Origin of Wealth: Evolution, Complexity and the Radical Remaking of Economics*. London: Random House.

Boulding, K.E. (1966) 'The Economics of the Coming Spaceship Earth'. In Jarrett, H. (ed.), *Environmental Quality in a Growing Economy: Essays from the Sixth RFF Forum*. Baltimore: Johns Hopkins University Press, pages 3-14.

Cherp, A., Vinichenko, V., Jewell, J., Brutschin, E. and Sovacool, B. (2018), 'Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework', *Energy Research & Social Science* 37, 175-190.

Common, M. and Stagl, S. (2005), *Ecological Economics: An Introduction*. Cambridge University Press, Cambridge and New York.

Daly, H.E. (1977/1991) *Steady State Economics* (2nd Edition). Washington, DC: Island Press.

Dietz, R. and O'Neill, D.W. (2013) *Enough is Enough: Building a Sustainable Economy in a World of Finite Resources*. San Francisco, CA: Berrett-Koehler Publishers and London: Routledge.

Foxon, T J (2011), 'A co-evolutionary framework for analysing a transition to a sustainable low carbon economy', *Ecological Economics* 70, 2258-2267.

Foxon, T.J. (2013), 'Responding to the financial crisis: Need for a new economics', *Environmental Innovation and Societal Transitions* 6, 126-128.

Foxon, T J (2017), *Energy and Economic Growth: Why we need a new pathway to prosperity*, Routledge.

Freeman, C and Louca, F (2001), *As Time Goes By: From the Industrial Revolutions to the Information Revolution*, Oxford University Press.

Freeman, C. and Perez, C. (1988) 'Structural crises of adjustment: Business cycles and investment behaviour', in Dosi, G. et al. (eds) *Technical Change and Economic Theory.* London and New York: Pinter and Columbia Press.

Geels, F.W. (2002), 'Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study'. *Research Policy* 31 (8-9), 1257-1274.

Geels, F.W. (2004), 'From sectoral systems of innovation to socio-technical systems', *Research Policy* 33 (6–7), 897–920.

Geels, F.W. (2013), 'The impact of the financial–economic crisis on sustainability transitions: Financial investment, governance and public discourse', *Environmental Innovation and Societal Transitions* 6, 101-108.

Geels, F.W., Sovacool, B.K., Schwanen, T. and Sorrell, S. (2017), 'The socio-technical dynamics of low-carbon transitions', *Joule* 1, 463-479.

Geels, F.W., Schwanen, T., Sorrell, S., Jenkins, K. and Sovacool, B.K. (2018), 'Reducing energy demand through low carbon innovation: A sociotechnical transitions perspective and thirteen research debates', *Energy Research and Social Science* 40, 23-35.

Georgescu-Roegen, N. (1971) *The Entropy Law and the Economic Process*. Cambridge, MA: Harvard University Press.

Global Commission on the Economy and Climate (2014) *Better Growth, Better Climate: The New Climate Economy Report*. Available at: http://2014.newclimateeconomy.report

Grubb, M. (2014), *Planetary Economics: Energy, Climate Change and the Three Domains of Sustainable Development*, Routledge, London and New York.

Grubb, M., Hourcade, J-C. and Neuhoff, K. (2015), The three domains structure of energy-climate transitions, Technol. Forecast. Soc. Change, 98, 290–302.

Grubb, M., McDowall, W. and Drummond (2017), 'On order and complexity in innovation systems: Conceptual frameworks for policy mixes in sustainability transitions'*, Energy Research & Social Science* 33, 21-34.

Hall, S., Foxon, T.J. and Bolton, R. (2017) 'Investing in low carbon transitions: Energy finance as an adaptive market'. *Climate Policy* 17(3), 280-298.

Hardt, L. and O'Neill, D.W. (2017), 'Ecological macroeconomic models: Assessing current developments', *Ecological Economics* 134, 198-211.

Hepburn, C. and Bowen, A. (2013) *Prosperity with Growth: Economic growth, climate change and environmental limits*. In: Fouquet, R. (2013) *Handbook of Energy and Climate Change*. Cheltenham, UK: Edward Elgar.

Jackson, T. and Victor, P. (2011), 'Productivity and work in the 'green economy': Some theoretical reflections and empirical tests', *Environmental Innovation and Societal Transitions* 1(1), 101-108.

Jackson, T. (2017) *Prosperity without Growth: Foundations for the Economy of Tomorrow* (2nd Edition). Abingdon and New York: Routledge.

Kahneman, D. (2011), *Thinking, Fast and Slow*, Farrar, Strauss and Giroux, New York.

Kingdon, J. W. (1986), *Agendas, Alternatives, and Public Policies*, Pearsons Education Limited, New York.

Markard, J., Raven, R. and Truffer, B, (2012), 'Sustainability transitions: an emerging field of research and its prospects', *Research Policy* 41 (6), 955–967.

Markard, J. and Truffer, B. (2008), 'Technological innovation systems and the multi-level perspective: towards an integrated framework', *Research Policy* 37 (4), 596–615.

Mazzucato, M. and Perez, C. (2014) 'Innovation as Growth Policy: The challenge for Europe'. SPRU Working Paper Series SWPS 2014-13, July 2014, University of Sussex. Available at: https://www.sussex.ac.uk/webteam/gateway/file.php?name=2014-13-swps-mazzucato-perez.pdf&site=25

Meadows, D.H, Meadows, D.L., Randers, J. and Behrens III, W.W. (1972) *The Limits to Growth: a report for the Club of Rome's project on the predicament of mankind*. New York: Universe Books.

Nelson, R.R. and Winter, S.G. (1982) *An Evolutionary Theory of Economic Change*. Cambridge, MA: Harvard University Press.

Nelson, R.R. (2005) *Technology, Institutions and Economic Growth*. Cambridge MA: Harvard University Press.

Nelson, R.R. (2008) 'What enables rapid economic progress? What are the needed institutions'. *Research Policy* 37, 1-11.

North, D.C. (1990) *Institutions, Institutional Change and Economic Performance*. Cambridge: Cambridge University Press.

OECD (2017), *Investing in Climate, Investing in Growth.*

Pierson, P. (2000) 'Increasing returns, path dependence, and the study of politics'. *American Political Science Review* 94(2), 251- 267.

Perez, C. (2002), *Technological Revolutions and Financial Capital,* Edward Elgar.

Perez, C. (2013) 'Unleashing a golden age after the financial collapse: Drawing lessons from history', *Environmental Innovation and Societal Transitions* 6, 9-23.

Rezai, A. and Stagl, S. (2016), 'Ecological macroeconomics: Introduction and review', *Ecological Economics* 121, 181-185.

Rip, A. and R. Kemp (1998), 'Technological change', in: S. Rayner and E.L. Malone (eds), *Human Choice and Climate Change*, Columbus, Ohio: Battelle Press. Volume 2, pp. 327-399.

Sabatier, P.A. and Weible, C.M. (2007), *The Advocacy Coalition Framework: Innovations and Clarifications,* Westview Press, Boulder, CO.

Simon, H.A. (1955), 'A behavioral model of rational choice', Quarterly Journal of Economics 69(1), 99–118.

Smith, A., Stirling, A. and Berkhout, F. (2005), 'The governance of sustainable socio-technical transitions', *Research Policy* 34(10), 1491-1510.

Smith, A., Jan-Peter Voβ, J.-P., and Grin, J. (2010), Innovation studies and sustainability transitions: The allure of a multi-level perspective and its challenges, *Research Policy* 39(4), 435-448.

Sovacool, B.K. and Hess, D.J. (2017), 'Ordering theories: Typologies and conceptual frameworks for sociotechnical change', *Social Studies of Science* 47(5), 703-750.

Sustainability Transitions Research Network (2017), 'A research agenda for the Sustainability Transitions Research Network'.

United Nations (2013), Sustainable Development Goals, https://sustainabledevelopment.un.org/sdgs

Unruh, G.C .(2000) 'Understanding carbon lock in'. *Energy Policy* 28, 817-830.

Warr, B. and Ayres, R.U. (2012) 'Useful work and information as drivers of growth'. *Ecological Economics* 73, 93-107.