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Past, present and prospective energy transitions: an invitation to historians

Abstract
This paper argues that historians and their disciplinary practices can enhance the analysis of energy transitions by non-historians. It explains how energy economists and policy analysts have only recently taken account of historical experience and how energy studies have become more inter- and multi-disciplinary and more receptive to engagement with history and historians. The paper outlines the nature, variety and complexities of energy transitions, and then examines the growing policy focus on 'low-carbon transitions', which address the threat of climate change by seeking transitions away from greenhouse gas-emitting fossil fuels, towards low-carbon renewable and /or nuclear energy. It explores three areas in which further historical analysis is especially valuable: the duration and speed of past energy system transitions and the insights to be gained from their analysis; path dependence, lock-in and the strategies, responses and destabilisation of incumbent energy actors and institutions; and theoretical approaches to 'sustainability transitions' and innovation. The paper concludes with an invitation to historians to collaborate further with non-historians, to enhance their understanding of energy transitions and to share the findings, methods, subtleties and limitations of historical analysis.

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Plan of the article

INTRODUCTION AND AIMS

1 This paper, written by an economist, from a discipline focused mostly on the present and the future, has four aims: to argue that historical analyses offer insights into past energy transitions that are of value to non-historians who study past, current and prospective energy transitions and, where appropriate, to policy-makers who seek to grapple with them; to show how, in one social science discipline, economics, for some time historical aspects seemed of little relevance to energy economists and policy analysts; to indicate problem areas, issues and questions, especially those concerning 'low-carbon' energy transitions, that might be illuminated by insights from history; and to invite historians to collaborate more with non-historians and engage in further analyses.

2 Major ongoing or prospective energy transitions include those in the developing world towards greater provision of modern forms of energy,[1] as well as 'low-carbon' energy transitions that aim to address the perceived threat of climate change from rising concentrations of greenhouse gases such as carbon dioxide and methane, particularly those from hydrocarbon fossil fuels.[2] The paper illustrates some contributions that history and historians might make to our individual and collective understanding, thinking and decision-making about energy transitions. It also shows how the field of energy studies has become more inter- and multi-disciplinary and more receptive to engagement with history and historians.

3 The author believes both that access to modern energy in the developing world, and the growing, albeit not universal, scientific consensus about the potential threat of climate change and the role of human-made contributions to it, warrant actions by state, market and civil society actors to advance specific forms of energy transition. Some historians will not share these views and/or will think it inappropriate for the study of the past also to address the future or try to advance policy thinking.[3] In the author's view, even if there were no insights directly applicable to policy thinking, a knowledge of history would remain valuable to non-historians wishing to understand our changing energy systems and set them in perspective.

The view taken here accords with economic historian Sara Horrell's response to poet and critic Samuel Taylor Coleridge's declaration about learning from history, that 'the light which experience gives is a lantern on the stern, which shines only on the waves behind us!'.[4] She wrote: 'Rather than directives it offers a storehouse of guidance, pointers as to what might be relevant considerations in conditioning and shaping outcomes. It is invaluable in broadening the base of knowledge from which we operate and enables us to identify and read signals. ... A lantern on the stern can help with navigation ahead!'.[5] 4

Nevertheless, this paper does not follow a tendency to label such insights 'lessons from the past', because doing so risks implying that such knowledge is always transferable to or offers simple analogues for present and especially future contexts and their challenges. Furthermore, even when armed with such insights, we may not necessarily be able to apply them. Historians and their disciplinary practices are essential here in conveying to non-historians both the nuances and the limits of insights from the past, their transferability and applicability. 5

1 Global Energy Assessment (GEA), *Global Energy Assessment: Toward a Sustainable Future* (Cambridge: Cambridge University Press, Laxenburg: International Institute for Applied Systems Analysis, 2012); International Energy Agency, *Energy Access Outlook 2017. World Energy Outlook Special Report* (Paris: OECD/IEA, 2017).

2 Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva: IPCC, 2014).

3 For a contrary opinion, see Hirsh Richard F., Jones Christopher F., "History's contributions to energy research and policy", *Energy Research & Social Science*, vol. 1, 2014.

4 Coleridge Samuel T., "December 27, 1831", in Henry N. Coleridge (ed.), *Specimens of the Table Talk of S.T. Coleridge* (London: John Murray, 1835), Digitised by Project Gutenberg: https://www.gutenberg.org/cache/epub/8489/pg8489-images.htm [Accessed 20/09/17].

5 Horrell Sara, "The wonderful usefulness of history", *The Economic Journal*, vol. 113, 2003.

6 Although the author has neither space nor capacity to review them here, the point of this paper is not to underplay the extensive, valuable studies of past energy and infrastructure system developments and transitions carried out over recent decades by historians from several schools, including economic historians, business historians and historians of science, technology and society. Fine examples include: Landes,[6] Hughes,[7] Nye,[8] Chick,[9] Lagendijk,[10] Allen,[11] Wrigley,[12] Kander *et al.*,[13] Jones,[14] Beltran *et al.*[15] and Kaijser *et al.*,[16] to name but a few. Rather the aim is to invite historians to draw on and even extend their knowledge, to crystalize and share those insights from history that enhance our understanding of energy transitions. This could be in collaborative dialogue with a growing body of receptive social and physical scientists, engineers, and even those policy-makers who wish to appreciate the strengths and limitations of drawing on and interpreting historical experience.

7 Section 2 examines how and why, in this author's view and experience, until very recently historical studies of energy seemed to matter little to most energy economists and policy analysts. Section 3 discusses the nature, variety and significance of energy transitions. Section 4 examines the growing policy focus on low-carbon transitions, while Section 5 explores three areas in which further historical analysis is especially valuable: (1) the duration and speed of transitions; (2) path dependence, lock-in and the role of incumbent actors; and (3) theories and empirical analyses of sustainability transitions and innovation. Section 5 concludes the paper and ends with an invitation to historians to collaborate with and broaden non-historians' understanding of the methods, subtleties and findings of historical analysis and, for some, to engage in further dialogue with energy policy-makers.

HOW AND WHY HISTORICAL STUDIES OF ENERGY SEEMED IN THE RECENT PAST TO MATTER LITTLE TO ENERGY ECONOMISTS AND POLICY ANALYSTS AND HOW THIS HAS CHANGED

In writing this section, the author reflected on his experience of research into energy transitions and his growing awareness of the significance of history and how it can inform thinking about them. Consequently, some of what follows should be approached with caution, as it is clearly a partial view. In the 1980s, an economist colleague, Paul Stevens, and the author began researching transitions in developing countries between 'traditional' or 'non -commercial' energy sources and their supply and end-use technologies and 'commercial', mostly fossil-based fuels and their technologies.[17] These transitions had been proceeding rapidly in some countries and much more slowly in others; they raised and still raise important socio-economic, political and environmental issues.[18] 8

6 Landes David S., *The Unbound Prometheus* (Cambridge: Cambridge University Press, 1969).

7 Hughes Thomas P., *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins Press, 1983).

8 Nye David E., *Electrifying America* (Cambridge, Mass.: MIT Press, 1997).

9 Chick Martin, *Electricity and Energy Policy in Britain, France and the United States since 1945* (Cheltenham: Edward Elgar, 2007).

10 Chick Martin, *Electricity and Energy Policy in Britain, France and the United States since 1945* (Cheltenham: Edward Elgar, 2007).

11 Allen Robert, *The British Industrial Revolution in Global Perspective* (Cambridge: Cambridge University Press, 2009).

12 Wrigley E. Anthony, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010).

13 Kander Astrid, Malanima Paolo, Warde Paul, *Power to the People: Energy in Europe over the Last Five Centuries* (Princeton and Oxford: Princeton University Press, 2013).

14 Jones Christopher F., *Routes of Power: Energy and Modern America* (Cambridge, Mass.: Harvard University Press, 2014).

15 Beltran Alain *et al.*, *Electric Worlds/Mondes électriques* (Bruxelles: P.I.E. Peter Lang, 2016).

16 Kaijser Arne, van der Vleuten Erik, Högselius Per, *Europe's Infrastructure Transition* (London: Palgrave Macmillan, 2016).

17 Pearson Peter J. G., Stevens Paul J., "Integrated Policies for Traditional & Commercial Energy in Developing Countries", *Development Policy Review*, vol. 2, 1984; Pearson Peter J. G., "Energy transitions in less-developed countries: analytical frameworks for practical understanding", *Energy Discussion Paper*, vol. 40. (Cambridge: Cambridge University Energy Research Group, 1988).

18 GEA, *Global Energy Assessment* (cf. note 1); IEA, *Energy Access Outlook 2017*. op. cit. (cf. note 1).

9 During this research, not least for comparative purposes, it became important to know how energy transitions had unfolded in other places and times. There was useful information from a variety of sources about relatively recent transitions, for example ranging from America's late nineteenth century transition from wood-fuel to coal and petroleum,[19] to South Korea's more recent, remarkably rapid and heavily state-directed post-1960 transition from high dependence on wood-fuel to coal and other modern fuels.[20] While the author was also shamefully unaware of most of the work of economic historians on energy transitions, and probably thought that Britain's transition from biomass to coal was too long-drawn-out and distant to be relevant, the few sources he knew showed relatively little interest in how their insights into the past might enrich the thinking and approaches of economists and policy-makers concerned with the present. Moreover, searches of energy economics and energy policy journals at that time yielded only two papers that addressed Britain's extensive experience of energy transitions.[21]

10 Analyses of energy economics and policy issues in the 1970s and 1980s were strongly conditioned by the reverberating experiences of the two international 'oil price shocks' of 1973-74 and 1979-80. The 1973-74 shock was triggered by an oil export embargo by members of OAPEC (the Organization of Arab Petroleum Exporting Countries); it involved a fourfold increase in real, inflation adjusted prices per barrel relative to 1972, from $14 to $56, at US$2015 prices. The 1979-80 shock followed falling oil output after the Iranian Revolution; it saw a doubling of real prices relative to 1978, from $51 to $106 at US$2015 prices.[22] These shocks had major geopolitical and macroeconomic implications for both oil-exporting and oil-dependent importing countries.[23] They also spawned bodies like the International Energy Agency (IEA), set up by oil-importing industrialised countries partly in response to the perceived threat of cartelisation and embargo by OPEC (the Organisation of Petroleum Exporting Countries).

In oil-importing countries, the shocks led to rapid step-changes in the priorities assigned to energy policy, energy security and oil import substitution, and in the funds devoted to Research, Development and Demonstration (R, D & D) into alternatives to oil.[24] These changes led to surging, urgent demands from policy-makers for energy scenarios and forecasts. However, when estimating parameters like the responsiveness of energy demand or supply to changes in oil prices and /or incomes (income and price 'elasticities') or the responsiveness of the macro-economy and the balance of payments to such price changes, econometricians found little comfort in their data. This was not least because 'real' oil prices had been so much lower over several decades before the price shocks: between 1927 and 1972, they never exceeded $21 at US$2015 prices, a fraction of the peak prices of $56 and $106. Consequently, energy consumers' past reactions showed insufficient variations from which to extrapolate and estimate with confidence the responsiveness of energy demand or the economy to the much greater price changes of the oil price shocks. The ripples from this experience seemed to have influenced the dominant thinking and writing about energy economics and policy, which showed relatively little interest in the pre-oil shock energy experiences and data of many countries. 11

Thus, although developments had already occurred in economic history, especially in its application of 12

19 Schurr Sam *et al.*, *Energy in The American Economy, 1850-1975* (Baltimore: Johns Hopkins Press, 1960).

20 Kim Yoon Hyung, "Rational and effective use of energy in Korea's industrialisation", *Energy*, vol. 8/1, 1983.

21 Humphrey William S., Stanislaw Joe, "Economic growth and energy consumption in the UK, 1700–1975", *Energy Policy*, vol. 7/1, 1979; Ray George F., Morel Jenny, "Energy conservation in the UK", *Energy Economics*, vol. 4/2, 1982.

22 BP statistical review of world energy 2016 (2016), https://www.bp.com/content/dam/bp/pdf/energy-economics/statistical-revi... [Accessed 5/10/17].

23 Hamilton James D., "Historical Oil Shocks", *in* Randall E. Parker, Robert Whaples (eds.), *Routledge Handbook of Major Events in Economic History* (London - New York: Routledge, 2013).

24 IEA, "Energy technology RD&D budgets: Overview" (Paris: OECD/IEA, 2017), https://www.iea.org/publications/freepublications/publication/EnergyTec... [Accessed 8/12/17].

the quantitative methods of cliometrics,[25] and in the study of long run economic growth,[26] historically informed approaches were relatively rare in published work on energy economics and policy. Several aspects of (neo-classical) economics as a discipline at that time also tended either not to encourage or effectively to work against interest in past data or historical studies. They included: the growing emphasis on mathematical economics and somewhat abstract modelling, for example in areas like the theory of general equilibrium (exemplified in the work of Nobel Prize winners Kenneth Arrow, Gérard Debreu and Maurice Allais); a focus on rational economic behaviour; a tendency to assume ergodicity (effectively, that economic processes are inherently ahistorical);[27] and more sharply delineated boundaries between economics as a professional discipline and other related disciplines. For many economists, the neo-classical approach focused particularly on the 'comparative statics' of moves between modelled situations of presumed equilibrium, with relatively little concern for the temporal or spatial dynamics involved, the possibilities of persistent disequilibria and the messiness and complexity of other social sciences.

13 At that time also much of macroeconomic growth theory, despite its interest in technological change and the long run quantitative comparative studies of the growth of nations led by Simon Kuznets,[28] did not engage closely with the role and contribution of energy to long run economic growth and development. And environmental and resource economics played little part in the mainstream economics journals and undergraduate textbooks of the 1960s and early 1970s,[29] although during this period the growing economic and political concerns about environmental pollution, population growth, resource depletion and fears of possible limits to economic growth[30] were catalysing interest and rapid developments in these areas.

As a matter of perspective, Daunton,[31] in his insightful reflections on North's[32] approach to understanding economic change and his critique of neo-classical theory, reminds us that these largely 20th C. developments in professionalising and narrowing the focus of economics differed from the wider-ranging approaches of 19th C. political economy. Thus, by the 1920s the issue of historical specificity had mostly disappeared from British economics, and was detached into the new sub-field of economic history, while the influence of the German Historical school had faded by the Second World War.[33] 14

Much has changed in economics since the 1970s, including growing recognition of research that acknowledges the importance of institutional and societal change and other social and historical processes. This recognition has been signalled, for example, by several of the Nobel Prizes in Economics, such as: to Ronald Coase in 1991 ("for his discovery and clarification of the significance of transaction costs and property rights for the institutional structure and functioning of 15

25 Cliometrics, originally called "The New Economic History", was developed in North America in the 1950s. Economic historians (and other social scientists), building on earlier quantitative analytical approaches, increasingly applied formal economic theory and models and econometric (statistical) methods to examine historical questions.

26 Lyons John, Cain Lou, Williamson Sam, "Cliometrics", in Robert Whaples (ed.), *EH.Net Encyclopedia*, 2009, http://eh.net/encyclopedia/cliometrics/ [Accessed 27/09/17].

27 The behaviour of an economic system or sub-system, such as a market, is ergodic if it is independent of the initial conditions. If ergodicity does not hold, initial conditions influence later behaviour, which becomes path-dependent: "history matters". Then, in the face of new initial conditions, a system may branch – or "transition" – to a different path. Its processes are inherently historical.

28 Kuznets Simon, *Modern Economic Growth: Rate, Structure and Spread* (New Haven - London: Yale University Press, 1966).

29 e. g. Cairncross Alec, *Introduction to Economics* (London: Butterworths, 1966 [1944]); Lipsey Richard G., *An Introduction to Positive Economics* (London: Weidenfeld and Nicolson, 1971 [1963]); Nevin Edward T., *Textbook of Economic Analysis* (London: Macmillan, 1966 [1958]).

30 Meadows Donella H. *et al.*, *The Limits to Growth* (New York: Universe Books, 1972).

31 Daunton Martin, "Rationality and institutions: reflections on Douglass North", *Structural Change and Economic Dynamics*, vol. 21, 2010.

32 North Douglass C., *Understanding the Process of Economic Change* (Princeton: Princeton University Press, 2010).

33 Dorfman Joseph, "The Role of the German Historical School in American Economic Thought", *American Economic Review*, vol. 45/2, 1955.

the economy"); to Douglass North and Robert Fogel in 1993 ("for having renewed research in economic history by applying economic theory and quantitative methods in order to explain economic and institutional change"). North was a leading figure in the development of a 'new institutional economics', to "make more sense out of long run economic, social and political change".[34] Fogel and Engerman's 1974 *Time on the Cross*, on the economics of slavery in the US, while generating much controversy about its findings and its use of cliometrics, became a classic and stimulated further work in both areas.[35] In 2009, the Prize was shared by Elinor Ostrom ("for her analysis of economic governance, especially the commons") and Oliver E. Williamson ("for his analysis of economic governance, especially the boundaries of the firm"). Other prizes, including the 2017 prize awarded to Richard Thaler ("for his contributions to behavioural economics"), have acknowledged the value of work on economic psychology and behavioural economics.[36]

16 As noted, we have also seen rising interest in environmental and resource economics. Environmental economics has drawn heavily on the distinction between the private and social costs and benefits of economic activities and the gaps between them. These gaps provide an economic rationale for public intervention to correct this 'market failure' through non-economic regulation or economic incentives like pollution taxes or tradable permits (quotas). Much of this work, although not all (e.g. that of Coase) has been largely ahistorical, although growing concerns about sustainability and climate change have stimulated attention to longer-run processes of environmental change and degradation.

Resource economics addresses issues of the 17
allocation, exploitation, depletion, valuation and pricing of renewable and non-renewable natural and human-made resources on land, air and water.[37] It has addressed the nature of property rights over them and the roles of communities, the market and the state in their governance. For example, Ostrom explored how people and communities interact with and may manage ecosystems. She developed a new institutional approach to the governance of the commons or 'common-pool resources'.[38] Her approach, which will resonate with some historians, showed: a concern with how such institutions evolve and function; extensive use of empirical case studies; acknowledgement of the complex constellation of variables involved when people in field settings try to fashion rules to enhance individual and joint outcomes; a reluctance to "try to encompass this degree of complexity in a single model";[39] and a recommendation to draw on the intellectual efforts of Hobbes, Montesquieu, Hume, Smith and others.

The newer and more heterodox fields of eco- 18
logical economics[40] and evolutionary economics, while drawing on the ideas of neo-classical economics, have also challenged its key premises, including economic rationality, often replacing it with the notion of 'bounded rationality'.[41] The evolutionary approach borrows ideas from biology, a recourse to which Nelson and Winter modestly claimed economists are "entitled in perpetuity by virtue of the stimulus our

34 North Douglass C., "Addendum to Douglass C. North Biographical", 2015, https://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/199... [Accessed 27/09/17].

35 Weiss Thomas, "Review: Time on the Cross: The Economics of American Negro Slavery", *EH.net*, 2001, https://eh.net/book_reviews/time-on-the-cross-the-economics-of-american... [Accessed 27/09/17]; Lyons, Cain, Williamson, "Cliometrics" (cf. note 26).

36 https://www.nobelprize.org/nobel_prizes/economic-sciences/fields.html

37 Hartwick John M., Olewiler Nancy D., *The Economics of Natural Resource Use* (Reading, Mass.: Addison-Wesley, 1998 [1986]).

38 Ostrom Elinor, *Governing the Commons* (Cambridge: Cambridge University Press, 1990). See also: Dietz Thomas, Ostrom Elinor, Stern Paul C., "The Struggle to Govern the Commons", *Science*, vol. 302, 2003; Stavins Robert N., "The Problem of the Commons: Still Unsettled after 100 Years", *American Economic Review*, vol. 101, 2011.

39 Ostrom, *Governing* (cf. note 38).

40 Martínez-Alier Joan, Røpke Inge (eds.), *Recent Developments in Ecological Economics vol. I & II* (Cheltenham: Edward Elgar, 2008).

41 Simon Herbert A., "Rational decision making in business organizations" [Nobel Memorial Lecture], *American Economic Review*, vol. 69/4, 1979.

predecessor Malthus provided to Darwin's thinking".[42] The approach focuses on organisational 'routines' and includes the "substitution of the "search and selection" metaphor for the maximisation and equilibrium metaphor".[43] It is also argued that these ideas are consonant with approaches to theorising from Adam Smith's time to the Second World War, and that they have some compatibility with those of Marx.[44]

19 These four approaches have paid growing attention to issues of sustainability and intra- and inter-generational equity and justice,[45] including those relating to climate change, and whether and how economic progress might be reconciled with preserving the planet.[46] Stimulated by the long time-scales and complexity of climate change processes, these concerns have led to growing interest in historical processes, although not necessarily in the methods and findings of historical enquiry.

20 Despite these developments, it took time for economists and other non-historians concerned with energy transitions to recognise the value of history for their thinking. Again - to draw on experience viewed through the distorting lens of personal experience - in the late 1980s and early 1990s, the author began studying transitions away from greenhouse gas-emitting fossil fuels in developing and industrialised countries. By the mid-1990s, the author and his colleague Roger Fouquet became convinced of the value of studying historical transition processes, to see what insights might be gained into current and prospective energy transitions and the influence of the past on them. For some time, we found it hard to interest UK social science research funders in studies of this kind. Although, of course, this may simply have reflected the quality of our applications, few if any studies of this type seemed to be funded. Nevertheless, we published papers that drew on historical studies and Fouquet's newly-assembled centuries-long energy data sets,[47] and both of us have continued to work with researchers from several disciplines, including branches of history.[48] From the mid-2000s, however, energy economists and a broader range of research funders have increasingly acknowledged that the multi-faceted nature, causes and consequences of energy transitions, particularly low-carbon transitions, and the research and policy questions that they pose, can be enriched by knowledge of historical processes and historical thinking, as well as greater inter- and multi-disciplinarity.

This section has argued that energy economists have only relatively recently begun to take account of historical experience and approaches. It suggested that this neglect was partly because of the long stability of oil prices before the oil price shocks of the 1970s, and partly because 21

42 Nelson Richard R., Winter Sidney G., *An Evolutionary Theory of Economic Change* (Cambridge Mass.: Belknap Press, 1985).
43 *Ibid*., 227.
44 For a critical survey of theories and concepts that economics can offer for transition research, see Van den Bergh Jeroen C. J. M., Kemp René, "Transition lessons from Economics", Ch. 4 *in* Jeroen C. J. M. van den Bergh, Franck R. Bruinsma (eds.), *Managing the Transition to Renewable Energy* (Cheltenham: Edward Elgar, 2008).
45 Simpson R. David *et al*. (eds.), *Scarcity and Growth Reconsidered* (Washington, DC: Resources for the Future, 2005).
46 e.g. *Heal Geoffrey, Endangered Economies. How the Neglect of Nature Threatens Our Prosperity* (New York: Columbia University Press, 2017).
47 Fouquet Roger, Pearson Peter J. G., "A Thousand Years of Energy Use in the United Kingdom", *The Energy Journal*, vol. 19/4, 1998; Fouquet Roger, Pearson Peter J. G., "Five Centuries of Energy Prices", *World Economics*, vol. 4/3, 2003; Fouquet Roger, Pearson Peter J. G., "Seven Centuries of Energy Services: The Price & Use of Light in the United Kingdom (1300-2000)", *The Energy Journal*, vol. 27/1, 2006; Pearson Peter J. G., Fouquet Roger, "Long Run Carbon Dioxide Emissions & Environmental Kuznets Curves: different pathways to development?", Ch. 10 *in* Lester C. Hunt (ed.), *Energy in a Competitive Market (Essays in Honour of Colin Robinson)* (Cheltenham: Edward Elgar, 2003); See also: Fouquet Roger, *Heat, Power and Light: Revolutions in Energy Services* (Cheltenham: Edward Elgar, 2008).
48 Fouquet Roger, Pearson Peter J. G., "Editorial: Past & prospective energy transitions: Insights from history", *Energy Policy*, vol. 50, 2012; Fouquet Roger, Broadberry Stephen, "Seven Centuries of European Economic Growth and Decline", *Journal of Economic Perspectives*, vol.29/4, 2015; Arapostathis Stathis, Pearson Peter J. G. (Guest Eds.), "How History Matters: Governance, Public Policies and the Making of Sociotechnical Transitions", *Environmental Innovation and Societal Transitions*, Special Issue, 2019 [forthcoming].

of features of neoclassical economics at that time. However, recent developments in areas like resource and environmental economics and in ecological and evolutionary economics, reflecting concerns about environmental degradation, resource scarcity and sustainability, have encouraged greater interest in long run processes of change, including those involved in energy transitions, and in how historical approaches and methods may yield insights into them. The next section explores the nature and significance of energy transitions and points to why an understanding of history is so valuable in addressing them.

ENERGY TRANSITIONS: NATURE, VARIETY AND COMPLEXITIES

22 This section begins with an outline of energy transitions' contributions to human welfare and the involvement of energy transitions with much wider transition processes, such as industrial revolutions. It then looks at how energy transitions have been defined and the multifarious forms they can take.[49] It ends by indicating some areas where historical insights and methods might enrich the understanding of non-historians who seek to analyse and decode transitions.

23 Energy transitions have often enhanced human welfare by contributing to sustained increases in productivity and economic output and to the production and use of new commodities, services and lifestyles. They have often also influenced and been influenced by industrial revolutions[50] or 'long waves' of economic development,[51] and the non-energy transitions involved in them.[52] Indeed, as with some interpretations of the British Industrial revolution, energy transitions are sometimes thought to lie at their heart.[53] As Section 4 discusses, the 'dark side' of energy transitions includes their potential for ecological and environmental damage, resource depletion and impacts on health and welfare.

The many definitions of 'energy transitions' 24
reflect their variety, the epistemological challenges of identifying, classifying and understanding them, and the diverse preoccupations of those who address them. An energy transition is sometimes (over)simply defined as a changeover from one leading fuel or energy carrier to another. Another frequent definition is "the *change in composition (structure) of primary energy supply*, the gradual shift from a specific pattern of energy provision to a new state of an energy system".[54] Both definitions indicate a slowly changing tendency for 'headline' definitions - and many past and present energy policy strategies - to focus on transitions essentially as processes of (often large-scale, centralised) energy production, supply and delivery, with much less attention to changing patterns of energy access, energy use and energy-using practices.[55] Laird,[56] for example, stresses the need to broaden the concept of an energy transition and give more attention to the social and political features involved. This is an approach

49 Smil Vaclav, *Energy Transitions: History, Requirements, Prospects* (Santa Barbara, CA: Praeger, 2010); Pearson Peter J. G. "Energy Transitions", *in* Steven N. Durlauf, Lawrence E. Blume (eds.), *The New Palgrave Dictionary of Economics*, Online Edition, 2016, http://www.dictionaryofeconomics.com/dictionary.

50 Allen, *The British Industrial Revolution* (cf. note 11); Mokyr Joel, *The Enlightened Economy* (London: Penguin Books, 2009); Kander Astrid, Stern David I., "Economic growth and the transition from traditional to modern energy in Sweden", *Energy Economics*, vol. 46, 2014; Fouquet, *Heat* (cf. note 47); Wrigley, *Energy* (cf. note 12); Gordon Robert J., *The Rise and Fall of American Growth: The U.S. Standard of living since the Civil War* (Princeton, NJ: Princeton University Press, 2016).

51 Freeman Chris, Perez Carlotta, "Structural Crises of Adjustment: Business Cycles and Investment Behaviour", *in* Giovanni Dosi *et al.* (eds.), *Technical Change and Economic Theory* (London: Pinter, 1988), 38-66; Freeman Chris, Louçã Francisco, *As Time Goes By* (Oxford: Oxford University Press, 2001).

52 See also Nuvolari Alessandro, "Understanding successive industrial revolutions: A 'development block' approach", *Environmental Innovation and Societal Transitions*, Article in press, corrected proof, 2018. https://doi.org/10.1016/j.eist.2018.11.002 [Accessed 2/12/18].

53 Wrigley, *Energy* (cf. note 12).

54 Smil, *Energy Transitions* (cf. note 49).

55 Shove Elisabeth, Walker Gordon, "CAUTION! transitions ahead: politics, practice and sustainable transition management", *Environment and Planning A*, vol. 39, 2007.

56 Laird Frank N., "Against transitions? Uncovering conflicts in changing energy systems", *Science as Culture*, vol. 22/2, 2013.

that resonates with that of the 'sustainability transitions' literature (see Section 5.3), which has for some time called them 'socio-technical transitions'. The term aims to acknowledge that many transitions have co-evolved or been entangled with other broader socio-economic, demographic, technological and environmental changes and processes.[57]

25 Energy transitions can involve shifts in how, where and by whom energy is extracted, produced, transformed, supplied, accessed and used. They can unfold at global, regional, national, local or sectoral scales. These shifts have led to new, often much higher, amounts and qualities of fuels produced, to novel technologies and to fresh uses and behaviours. Over the centuries, large-scale, sometimes called 'grand', energy transitions have involved slow shifts from early humans' reliance on fuel-wood and human labour, to increasing employment of animal labour and more complex processing and uses of biomass fuels, to wind and water power, and to coal, oil, town and natural gas and electricity.[58] They have developed over multiple decades and sometimes centuries. And while the new energy sources may eventually dominate, overlapping, often extended, processes of change are involved. Thus, while the incumbent energy source(s) and their associated energy-using technologies tend to grow much more slowly than before, they may maintain a foothold for a considerable time after the new source(s) have gained ascendancy (e.g. the use of fuel-wood and candles persisted in Britain well after the dominance of coal and gas and electric light).[59]

57 Geels Franck W., Schot Johan W., "The dynamics of transitions: a socio-technical perspective", *in* John Grin, Jan Rotmans, Johan Schot (eds.), *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change* (London: Routledge, 2010); see also Kanger Laur, Schot Johan, "Deep transitions: Theorizing the long-term patterns of sociotechnical change", *Environmental Innovation and Societal transitions*, In press, Corrected Proof, 2018. https://doi.org/10.1016/j.eist.2018.07.006 [Accessed 2/12/18].

58 Smil, *Energy Transitions* (cf. note 49); Fouquet, *Heat* (cf. note 47); Kander, Malanima, Warde, *Power* (cf. note 13); Pearson, "Energy Transitions" (cf. note 49).

59 Fouquet, Pearson, "Seven Centuries of Energy Services" (cf. note 49).

Transitions occur in both primary and secondary energy sources. They occur in the use of primary energy sources, such as fossil and nuclear fuels, solar and wind energy. They also happen in secondary energy forms or energy-containing carriers, such as electricity, gasoline, and hydrogen, converted from primary sources and delivered for final use. When introduced, the secondary energy forms were often of higher quality, such that they could be employed in a broader and/or more valuable range of economically productive or satisfying activities.[60] They tend to be more expensive, especially when first introduced, partly because of the conversion processes and losses associated with producing and delivering them (e.g. electricity and gasoline cost more than the primary fuels transformed during their production). Nevertheless, users have been willing to pay these higher prices because of their broader range of valuable uses. For example, electrical power and electric motors proved more flexible and efficient in use than mechanical power from coal-fired steam engines, enhancing factory productivity; and liquid and gaseous fuels have powered the internal combustion and aero engines that have enhanced the speed, reliability and efficiency of transportation. These attractive attributes of modern fuels and energy-using technologies mean that they have been increasingly demanded as incomes and living standards grow,[61] as developing world experience vividly demonstrates. 26

The extent and pace of transitions are significantly affected not only by the spread of more advanced technologies of energy exploration, extraction, capture, processing, conversion, and end-use but also, as noted, by the development of energy transport, delivery and distribution 27

60 Cleveland Cutler J., Kaufmann Robert K., Stern, David I., "Aggregation and the role of energy in the economy", *Ecological Economics*, vol. 32, 2000; Stern David I., "Energy quality", *Ecological Economics*, vol. 69/7, 2010; Gentilvaite Ruta, Kander Astrid, Warde Paul, "The role of energy quality in shaping long-term energy intensity in Europe", *Energies*, vol. 8, 2015.

61 Fouquet, *Heat* (cf. note 47); Fouquet Roger, "Long run demand for energy services: income and price elasticities over 200 years", *Review of Environmental Economics and Policy*, vol. 8/2, 2014.

infrastructures (the historian Christopher Jones argues, for example, that developments in energy transmission in mid-Atlantic USA from 1830-1920 were as important as changes in the source of energy).[62] These infrastructures include land, water and air transport systems, as well as pipeline or wire networks at local, national and international scales, and - increasingly – communication and information technology networks. Behind these changes in 'hard' energy technologies and infrastructures, as indicated, lie changes in 'softer' social, cultural and political institutions, structures and behaviours, including those of industries, markets, prices and consumers and their governance and regulatory systems and interest-groups, and the social capital of knowledges and skills.

28 Transitions have involved much larger flows of energy services, such as thermal comfort, mobility and illumination.[63] It has been argued that the thirst for such services can be a key stimulus of transitions.[64] Moreover, the implicit costs of these services have fallen strikingly over the past two centuries, especially the cost of light, which in Britain declined nearly three thousand-fold between 1800 and 2000, as fuels changed and mostly because the efficiency with which lighting devices converted fuel inputs into light rose.[65] The demand for fuels and end-use technologies can grow rapidly but at changing and eventually declining rates when incomes and living standards rise and energy service costs fall.[66] The rates at which such demand has grown or might grow under such stimuli and be contained, or not, by saturation effects, improved efficiencies, or behavioural changes are of concern to economists and energy policy-makers, as is the financing of transitions.

62 Jones Christopher F., *Routes of Power* (cf. note 14).
63 Fouquet, *Heat* (cf. note 47).
64 Grubler Arnulf, "Energy transitions research: Insights and cautionary tales", *Energy Policy*, vol. 50, 2012.
65 Fouquet, Pearson, "Seven Centuries of Energy Services" (cf. note 49).
66 Fouquet, "Long run demand for energy services" (cf. note 61); Grubler Arnulf, "Energy transitions", *The Encyclopedia of Earth*, 2008, http://www.eoearth.org/view/article/152561/. [Accessed 29/09/17].

As indicated, there are many kinds of transition, from the grand to the not-so-grand, and from those that might myopically be viewed 'purely' as energy transitions, to those intimately bound up with non-energy transitions and/or with much more comprehensive and usually longer-term transitions. And transitions have and might unfold, slowly or more rapidly, smoothly or discontinuously, in steady or more turbulent situations, facilitated or constrained by wider social, economic, demographic, environmental or (geo) political factors. The complexity of transitions and transition processes and their interactions in different or changing temporal and spatial contexts partly explains why energy transitions are challenging to define, identify, analyse and generalise from. Historians are well-placed to offer key insights into these challenges and how to approach them, not least because they are "experts at comprehending the establishment of trends and changes in them"[67] and because they "spend much of their energy grappling with the question of why responses to similar situations differ between time and place".[68] 29

This section has briefly explored the nature, variety and complexities of energy transitions, indicated some of the epistemological and practical issues involved in defining, identifying and analysing them; and it has suggested areas where historians could make valuable, much-needed contributions. The next section addresses the growing policy attention given to energy transitions and to whether and how they might be guided. 30

THE GROWING POLICY EMPHASIS ON ENERGY TRANSITIONS

This section briefly examines the growing policy emphasis on energy transitions, particularly low-carbon transitions. Why focus on this transition? Because, while many governments wrestle with the 'energy policy trilemma', as the centre of gravity moves between three policy objectives 31

67 Hirsh, Jones, "History's contributions to energy research and policy" (cf. note 3), 106.
68 Daunton, "Rationality and institutions: reflections on Douglass North" (cf. note 31), 148.

(energy security; affordability and international competitiveness; and environmental quality), climate change and the low-carbon transition involve one of the most significant policy challenges of this century, not least because of the potential implications of climate change for future generations.[69] The section begins by discussing the various harmful impacts associated with energy transitions. It then moves to a more detailed consideration of the recent development of policies that focus on the low-carbon transition.

32 In contrast with their beneficial effects, changing mixes of energy resources associated with energy transitions and growing energy use can result in harmful impacts, with consequences for environmental quality, health and welfare that can be especially damaging for poorer and less resilient people and nations. The varied chemical properties of fossil, renewable and nuclear fuels and their differing forms, scales and places of extraction, capture, conversion and use create new temporal and spatial patterns of short- or long-term impacts on air, land and water.[70] Current policy responses to these impacts include attempts to govern, guide and manage transitions and their pathways to a different and much greater extent than in most earlier energy transitions.[71]

33 From the late 1980s, along with continuing debate about petroleum resource depletion, the volatile geopolitics of oil and gas, and ideas of sustainable development, there has been a sharpening policy priority given to the widely perceived societal threat of damage from climate change exacerbated by the enhanced greenhouse effect from human-induced greenhouse gas emissions from fossil fuels.[72] Thus, government policy on transitions in many countries now embraces transitions towards low-carbon fuels and technologies, to cut greenhouse gas emissions. This agenda involves branching to pathways away from long-established, highly-valued and energy-dense fossil fuels, their technologies, institutions and practices, towards less energy- and power-dense and, in some cases variable, forms of renewable energy, and nuclear energy, which bring their own often different side-effects and policy trade-offs.[73]

34 In most previous transitions, however, individual energy producers and consumers could gain or capture significant private financial or non-financial rewards from choosing to develop or adopt new energy sources and carriers. In contrast, until very recently such private benefits have been less immediately evident for most low-carbon fuels, except in niche applications, although this is diminishing as the costs of photovoltaics and wind fall. This gap between the private and societal climate-related benefits and costs of a low-carbon transition poses a challenge for public policy significantly different from previous, largely endogenous transitions.[74] Moreover, in economists' language, the moderation of climate-related damage and the externalities that exacerbate it is a global 'public good', i.e. it is 'non-rival' (one nation's benefit from avoided emissions does not reduce the benefit available to other nations) and 'non-excludable' (because over time greenhouse gas emissions tend to spread evenly through the atmosphere, nations cannot be excluded from the benefits of avoided damage, even if they have not contributed to this avoidance – a chance to 'free ride'). These properties mean that, although all countries have some (though diverse), incentives to limit greenhouse gas emissions, the development of successful worldwide strategies has required new and much-contested forms of global governance and international agreement.

69 IPCC, *Climate Change 2014: Synthesis Report* (cf. note 2).
70 National Research Council, *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use* (Washington, DC: The National Academies Press, 2010); Epstein, Paul R. *et al.*, "Full cost accounting for the life cycle of coal in 'Ecological Economics Reviews'", *Annals of the New York Academy of Sciences*, vol. 1219, 2011; IPCC, *Climate Change 2014: Synthesis Report* (cf. note 2).
71 Pearson Peter J. G., Foxon Timothy J., "A low carbon industrial revolution? Insights & challenges from past technological and economic transformations", *Energy Policy*, vol. 50, 2012.
72 IPCC, *Climate Change 2014: Synthesis Report* (cf. note 2).
73 Smil, *Energy Transitions* (cf. note 49).
74 Pearson, Foxon, "A low carbon industrial revolution?" (cf. note 71).

35 Despite the progress made in the 2015 Paris climate change agreement,[75] it continues to prove challenging to construct and implement (illustrated by President Trump's abrupt 2017 announcement of his intent to withdraw the USA from the agreement and his subsequent reversal of much of US domestic federal energy and climate policy). The historical dominance of greenhouse gas emissions from industrialised countries and the now rapidly growing emissions from China, India, Indonesia and several other large, highly-populated countries in the developing world, have raised issues of global and intergenerational equity, justice and compensation. They also pose dilemmas for the many countries that wish to provide modern energy and rising living standards to fast-growing populations, yet are troubled by the costs of restraining fossil fuel exploitation and use.

36 This section has outlined some of the harmful effects associated with growing energy use and the changing energy mixes associated with energy transitions. It has focused on the rising but diverse worldwide policy emphasis on one problem, climate change (although other environmental impacts, such as the health and ecological damage associated with other forms of local and regional air and water pollution, are also of grave concern). The long, complex dynamics of the greenhouse effect and climate change, the centuries-long, path-dependent, persistent use of fossil fuels, issues of equity and justice, and the difficulties of national and global governance and our capacity to govern, underlie many of the challenges involved. These attributes of climate change and governance indicate numerous aspects where historical knowledge might enhance our understanding of energy transitions, and of our capacities and potential to address them. The next section explores three such aspects.

75 UNFCCC (United Nations Framework Convention on Climate Change), *Adoption of the Paris Agreement*, FCCC/CP/2015/L.9/Rev.1. (Paris: UNFCCC, 2015), http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf [Accessed 8/10/17].

THREE AREAS IN WHICH HISTORICAL ANALYSIS IS PARTICULARLY VALUABLE

This section explores three aspects of the study of energy transitions that can be further enriched by historical analysis: the duration and speed of transitions; path dependence, lock-in and the roles of incumbents; and sustainability transitions and innovation theory approaches. 37

The duration and speed of past and prospective transitions

A significant element of recent energy transition debates concerns how long transitions have taken, might take and especially, given the perceived urgency of low-carbon transitions, whether and how the pace of change might be accelerated.[76] Historical evidence and analysis are directly relevant here, as are searching analyses of whether, how far and in what ways prior experience can help to think about and in practice influence energy and climate futures. 38

A recent set of exchanges initiated by Sovacool[77] in the journal *Energy Research and Social Science* is a good example of such a debate. Sovacool asked whether the 'mainstream' view of energy transitions as long drawn-out, taking decades or centuries to unfold[78] remained persuasive or whether evidence that some transitions had been accomplished more quickly might be more relevant for modern, purposive transitions.[79] The debate turned on several issues: on issues of scale and comparability, including 39

76 Grubler Arnulf, Wilson Charlie, Nemet Gregory, "Apples, oranges, and consistent comparisons of the temporal dynamics of energy transitions", *Energy Research and Social Science*, vol. 22, 2016.
77 Sovacool Benjamin K., Geels Franck W., "Further reflections on the temporality of energy transitions: A response to critics", *Energy Research & Social Science*, vol. 22, 2016.
78 Grubler, Wilson, Nemet, "Apples, oranges, and consistent comparisons" (cf. note 76); Smil Vaclav, "Examining Energy Transitions: A Dozen Insights based on Performance", *Energy Research and Social Science*, vol. 22, 2016.
79 Bromley Peter S, "Extraordinary interventions: Toward a framework for rapid transition and deep emission reductions in the energy space", *Energy Research and Social Science*, vol. 22, 2016; Kern Florian, Rogge Karoline, "The pace of governed energy transitions: agency, international dynamics and the global Paris agreement accelerating

differences between 'grand' global or country level transitions, such as transitions from biomass to coal, and transitions at end-use or sectoral scale, such as for lighting or transport; on measurement issues such as the delineation of the temporal or spatial phases and boundaries of a transition, including start- and end-points and formative phases;[80] on issues of temporal dynamics, such as whether the processes involved in transitions necessarily constrain attainable rates of change or have changed and become more open to influence in a more globalised world; on the changing agency of actors and policy instruments; on differences between analytical approaches and their foci; and on different ontological assumptions about the relationships between markets and the state.

40 Underlying much of this debate lie the problems of comparability, of knowing and agreeing what kinds of transitions are being compared and whether they are commensurate, of the choice of periods for comparison, and of what the differences between past and present contexts enable us to conclude. These are all areas in which historical understanding and methods can help to tighten the focus and quality of analysis.

41 Sovacool and Geels[81] suggest that Grubler and Smil see transitions as slow because of techno-economic rationales, including the time taken to construct large infrastructures, for innovative technologies to benefit from learning and scale economies, and because of reluctance to abandon sunk investments early. In contrast, they suggest that Kern and Rogge and Bromley see low-carbon transitions being potentially faster because political will and a sense of urgency, supported by wider publics and changed cultural discourses, may yield policies that change market and selection environments (such as financial incentives) and even phase out technologies early (as with Germany's nuclear power plants): "So, the core of their argument is that politics may trump economics...".[82] And Sovacool and Geels go on to advance the contestable view that, "We endow the fossil fuel regime with perhaps more agency than it actually has or need have",[83] an issue discussed further below.

A recent study illustrates how historical knowledge has been used to assess the plausibility of the duration and speed of technology adoption in future low-carbon scenarios. Thus McDowall[84] found that studies of future hydrogen fuel cell vehicle uptake have tended to be relatively optimistic about their possible rates of adoption compared with analogous historical situations in which alternative fuel motor vehicles have diffused. Moreover, although rapid transitions to alternative fuel vehicles have occurred historically, this was often in unusual conditions, such as Brazil's transition from 1975 to vehicles fuelled by ethanol produced from domestic sugarcane. 42

This transition was led by the Brazilian military government's development of a vigorous import substitution policy in response to four convergent stimuli: surging imported oil prices from the 1973-74 oil shock, restrictive European trade preferences on sugar imports, including those from Brazil; US substitution of corn syrup for imported Brazilian sugar, and the collapse in world sugar prices. While the specific circumstances of this transition might be thought to make it problematic to draw insights from it, Meyer *et al*.[85] claim that the key 'lesson' from the Brazilian experience is the importance of a consistent long-term policy framework, although they also suggest the decades-long continuity in policy made the innovation policy of Brazilian alcohol unique. 43

decarbonisation processes?", *Energy Research and Social Science*, vol. 22, 2016.

80 Bento Nuno, Wilson Charlie, "Measuring the duration of formative phases for energy technologies", *Environmental Innovation & Societal Transitions*, vol. 21, 2016.

81 Sovacool, Geels, "Further reflections on the temporality of energy transitions" (cf. note 77).

82 *Ibid*., 233.

83 *Ibid*., 236.

84 McDowall Will, "Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies", *Environmental Innovation & Societal Transitions*, vol. 20, 2016.

85 Meyer Dustin et al., "Brazilian ethanol: Unpacking a success story of energy technology innovation", Ch. 20 *in* Arnulf Grubler, Charlie Wilson (eds.), *Energy Technology Innovation* (Cambridge: Cambridge University Press, 2014).

44 Clearly there is a risk that those of us engaged in energy transition research select specific, sometimes inappropriate or perhaps unique, historical energy transition experiences from which to draw insights for current or future transitions, without being aware of the limitations of such inferences. Comparative studies by historians of unusually fast and unusually slow past transitions, and advice on the methods and pitfalls of selecting and interpreting such evidence, could be particularly helpful for transition researchers.

45 A study by Tim Foxon and the author,[86] which critically examined claims that a low-carbon transition might amount to another industrial revolution, suggested that caution is needed before assuming that past experiences of high-carbon transitions based on fossil fuels can provide simple analogues for today's new low-carbon transitions, or that insights drawn from them are necessarily and simply transferable to them. The study also suggested that climate change policy may have more in common with late 19th C. policy developments for the public good, than with more narrowly framed technological challenges viewed mainly in the context of private markets. For example, developments during that period in the UK in clean water supply, public sanitation and sewerage infrastructure (e.g. Bazalgette's London sewerage system)[87] and in other aspects of public health, produced big gains both for society and private actors, as in many other countries.[88] These developments were partly inspired by the work of Edwin Chadwick and others, who had exposed the inequalities and market failures of capitalist industrial and urban development, including pollution, congestion and disease, and/or campaigned for actions to address them.[89]

This sub-section has considered the speed and duration of transitions and illustrated some challenges of selecting and drawing from historical experience. Historians might engage with and share critical contributions that help non-historians in three areas: to appreciate how we might better understand the relationship between the pace and duration of past and prospective transitions; why a rapid low-carbon transition in today's world might present similar or different challenges and opportunities from those of past high-carbon transitions; and to assess whether and in what ways low-carbon transitions may be commensurate or incommensurate with historical experiences. 46

Path dependence, lock-in and the strategies, responses and destabilisation of incumbent actors

This section explores the influence of processes of path dependence and lock-in. It begins by outlining path dependence and lock-in and their influence on energy transitions. It then explores how incumbents can influence energy transitions, considers the roles incumbents can play in delaying and sometimes in advancing a transition, and the importance of destabilising them to reduce their capacity to impede desired transitions.[90] 47

As Foxon[91] and Fouquet[92] discuss, energy system evolution can be path dependent, in that a system's present and future trajectories are influenced by the sequence of events that led to its 48

86 Pearson, Foxon, "A low carbon industrial revolution?" (cf. note 71).

87 Bazalgette Joseph W., *On the Main Drainage of London: And the Interception of the Sewage from the River Thames* (London: William Clowes and Sons, 1865).

88 Gordon Robert J., "Does the 'new economy' measure up to the great inventions of the past?" *National Bureau of Economic Research Working Paper 7833* (Cambridge, Mass.: 2000) http://www.nber.org/papers/w7833 [Accessed 19/6/18].

89 Mokyr, *Enlightened* (cf. note 50).

90 See also: Pearson "Energy Transitions" (cf. note 49); Pearson Peter J. G., "Path dependence & path creation: roles for incumbents in the low carbon transition?", *British Institute of Energy Economics Conference: Innovation and Disruption: the energy sector in transition* (St John's College, Oxford, 21 September, 2016).

91 Foxon Timothy J., "Technological lock-in and the role of innovation", *in* Gilles Atkinson, Simon Dietz, Eric Neumayer (eds.), *Handbook of Sustainable Development*, Ch. 9 (Cheltenham: Edward Elgar, 2007); Foxon Timothy J., "A co-evolutionary framework for analysing transition pathways to a sustainable low carbon economy", *Ecological Economics*, vol. 70, 2011.

92 Fouquet Roger, "Path dependence in energy systems and economic development", *Nature Energy*, vol. 1, 2016.

present state.[93] A system's state may become locked in because of past experiences, even though the conditions conducive to that lock-in are no longer relevant. Arthur[94] showed that four kinds of increasing returns may result in technological 'lock-in' (Klitkou *et al.*,[95] proposed five more lock-in mechanisms). Consequently, the incumbent technology or industry accumulates socio-technical advantages, including falling costs, impeding adoption of a potentially superior alternative. North[96] proposed that institutions (i.e. social rule systems) also experience forms of increasing returns. And Pierson[97] argued that such returns may prevail in institutions like market or regulatory frameworks, sometimes enabling incumbents to exercise undue influence.

49 Studies have shown both the negative and the positive aspects of path dependency. Arapostathis *et al.*[98] and Pearson and Arapostathis,[99] for example, show the advantages – how the late 1960s development of the UK's natural gas system benefited from the earlier construction of a 'backbone' distribution pipeline system for liquified natural gas - and the disadvantages - how previous developments reduced the UK gas industry to a state of uncompetitive 'incoherence' before the Second World War, inhibiting its development.

50 It has been shown how co-evolutionary processes and positive feedbacks led to the lock-in of current high-carbon energy systems, so-called 'carbon lock-in',[100] raising systemic barriers to investment in low-carbon technology systems. Some carbon actors have lobbied to dispute climate science and/or to resist institutional and policy changes that favour low-carbon technologies. They include some fossil fuel producers and the established large German electricity utilities that lobbied in the 1990s for the repeal of renewable energy feed-in regulations and tariffs.

51 While co-evolutionary thinking highlights the difficulty of leaving an energy system pathway widely supported by powerful actors, if increasing returns to the adoption of alternatives can be enabled, this might lead to virtuous cycles of change. Garud and Karnøe[101] argued for 'path-creation', whereby incumbent entrepreneurs may choose to branch away from structures and technologies they have developed. Historical studies have also suggested that lock-in can be avoided through forming diverse alternative technological options and ensuring promising options benefit from increasing returns and learning, to challenge dominant technologies.[102]

52 The 'sailing ship' effect (SSE) or the 'last gasp effect of obsolescent technologies' (LGE) arises where competition from new technologies and

93 David Paul A., "Path dependence, its critics and the quest for 'historical economics'", *in* Pierre Garrouste, Stavros Ioannides (eds.), *Evolution and Path Dependence in Economic Ideas: Past and Present* (Cheltenham: Edward Elgar, 2001).

94 Arthur W. Brian, *Increasing Returns and Path Dependence in the Economy* (Ann Arbor: University of Michigan Press, 1994).

95 Klitkou Antje *et al.*, "The role of lock-in mechanisms in transition processes: The case of energy for road transport", *Environmental Innovation & Societal Transitions*, vol.16, 2015.

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

97 Pierson Paul, "Increasing returns, path dependence, and the study of politics", *American Political Science Review*, vol.94/2, 2000.

98 Arapostathis Stathis, Pearson Peter J. G., Foxon Timothy J., "UK natural gas system integration in the making, 1960–2010: Complexity, transitional uncertainties & uncertain transitions", *Environmental Innovation and Societal Transitions*, vol. 11, 2014.

99 Pearson Peter J. G., Arapostathis Stathis, "Two centuries of innovation, transformation and transition in the UK gas industry: Where next?", *Proceedings of the Institution of Mechanical Engineers*, *Part A: Journal of Power and Energy*, vol. 231/6, 2017.

100 e.g. Unruh Gregory C., "Understanding carbon lock-in", *Energy Policy*, vol. 28, 2000; Unruh Gregory C., "Escaping carbon lock-in", *Energy Policy*, vol. 30, 2002; Unruh Gregory C., Carrillo-Hermosilla Javier, "Globalizing carbon lock-in", *Energy Policy*, vol. 34, 2006.

101 Garud Raghu, Karnøe Peter, "Path creation as a process of mindful deviation", *in* Raghu Garud, Peter Karnøe (eds.), *Path Dependence and Creation* (London: Lawrence Erlbaum, 2001).

102 Arapostathis, Pearson, Foxon, "UK natural gas system integration" (cf. note 98); Pearson, Arapostathis, "Two centuries of innovation, transformation and transition" (cf. note 98).

firms provokes innovation and improvements in incumbent firms and their associated technologies. There is now a substantial, diverse literature on the SSE/LGE, much of it with a management or innovation slant. There has been some debate about whether all cited instances of the SSE bear closer scrutiny,[103] including that of the sailing ship itself.[104] Nevertheless, recent evidence suggests that the idea that some firms react positively when the ascendancy of their technologies is threatened by competition from distinctive new technologies deserves further conceptual and historical investigation. Sick *et al*.[105] combined ideas about the SSE with the rationales of path dependence to show how such behaviour may be economically rational in the automotive industry. Similarly, Dijk *et al*.[106] argued that vehicle manufacturers have tended to avoid costly and risky radical technical innovation and disruption, partly by hybridisation, i.e. incorporating new technological developments into an existing technology: they describe this response as an SSE. And Furr and Snow[107] explored situations in which incumbent technologies might show a sudden performance leap.

53 The period after the Second World War merits further research into the many situations in which established technologies and their industries had to respond to the threat of significant technological and design innovations. Bergek *et al*.[108] contest two explanations of the 'creative destruction'[109] of existing industries from discontinuous technological change. According to Schumpeter, creative destruction involves, "competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms but at their foundations and their very lives".[110] Bergek *et al*. discuss how the two 'competence-based'[111] and 'market-based'[112] explanations of creative destruction suggest that incumbents are challenged only by 'competence-destroying' or 'disruptive' innovations, that render the firms' knowledge base or business models obsolete. Incumbents are burdened with 'core rigidities' of organization and strategy and outdated technologies: innovations will be pioneered by new entrants, who take market shares from incumbents.[113]

The cases analysed by Bergek et al. in the automotive and gas turbine industries suggest, however, that these analytical approaches tend to: overestimate new entrants' ability to disrupt established firms; and underestimate incumbents' capacities to grasp the potential of new technologies and integrate them with existing capabilities via processes of 'creative accumulation'. Creative accumulation requires firms to rapidly fine-tune and evolve existing 54

103 Howells John, "The Response of Old Technology Incumbents to Technological Competition - Does the Sailing Ship Effect Exist?", *Journal of Management Studies*, vol. 39/7, 2002; but see Arapostathis Stathis *et al*., "Governing transitions: Cases and insights from two periods in the history of the UK gas industry", *Energy Policy*, vol. 52, 2013.

104 Mendonça Sandro, "The 'sailing ship effect': reassessing history as a source of insight on technical change", *Research Policy*, vol. 42, 2013.

105 Sick Nathalie *et al*., "The legend about sailing ship effects - Is it true or false? The example of cleaner propulsion technologies diffusion in the automotive industry", *Journal of Cleaner Production*, vol. 137, 2016.

106 Dijk Marc, Wells Peter, Kemp René, "Will the momentum of the electric car last? Testing an hypothesis on disruptive innovation", *Technological Forecasting & Social Change*, vol. 105, 2016.

107 Furr Nathan R., Snow Daniel C., "Intergenerational hybrids: spillbacks, spillforwards, and adapting to technology discontinuities", *Organization Science*, vol. 26/2, 2014.

108 Bergek Anna *et al*., "Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation?", *Research Policy*, vol. 42/6–7, 2013.

109 Schumpeter Joseph A., *Capitalism, Socialism and Democracy* (London: Routledge, 2010 [1942]), 72-75. See also: Reinert Hugo, Reinert Erik S., "Creative Destruction in Economics: Nietzsche, Sombart, Schumpeter", *in* Jürgen G. Backhaus, Wolfgang Drechsler (eds), *Friedrich Nietzsche (1844–1900), The European Heritage in Economics and the Social Sciences, vol. 3* (Boston, Mass.: Springer, 2006).

110 Schumpeter, *Capitalism*, 74 (cf. note 109).

111 Tushman Michael, Anderson Philip, "Technological discontinuities and organizational Environments", *Administrative Science Quarterly*, vol. 31, 1986.

112 Christensen Clayton M., *The Innovator's Dilemma. The Revolutionary Book That Will Change the Way You Do Business* (New York: HarperCollins Publishers, 1997/2003).

113 See also: Geels Frank, "Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective", *Energy Research & Social Science*, vol. 37, 2018.

technologies, acquire and develop new technologies and resources, and integrate novel and existing knowledge into superior products and solutions.[114] Bergek et al.'s findings help explain why some new energy technologies may find it harder to penetrate than might be anticipated. They also suggest, however, that some incumbents have or may develop the ability to embrace new technologies, particularly when hybridisation – as with hybrid powered motor vehicles - makes it possible to extend the life of established technologies.[115]

55 Thus, some incumbents may have the potential capacity to recognise both longer run opportunities and the writing on the wall of changing public attitudes and government policies towards climate change, and engage in processes of creative accumulation. Moreover, if policies seek to address climate change rapidly, this may require non-incremental, often time-consuming low-carbon developments and investments, at a pace and scale that new entrants may struggle with. In such circumstance, to rely solely on new entrants risks missing opportunities to build on and modify potentially responsive incumbents' accumulated technical and managerial capacities, infrastructures and learning.

56 Nevertheless, policy strategies aimed at stimulating innovation in and the penetration of low-carbon technologies also require policies that address path dependence and lock-in and reflect the importance in some circumstances of acting to 'destabilise' high-carbon incumbent firms, technologies and associated institutions. Thus, in their studies of the long, slow decline of the UK coal industry and the factors that destabilised it, Turnheim and Geels argue that, "...industries are committed to existing industry regimes, and are likely to resist major change in technical competencies, core beliefs and mission. (...) Weakening the cultural, political, economic and technological dimensions of fossil-fuel related industries is just as important as stimulating green options".[116] Turnheim and Geels' analyses are rare examples of studies of how and why energy path dependence and lock-in collapsed. Given the power and persistence of fossil fuel incumbents and institutions, further studies by historians and others of such historical precursors would be particularly valuable in identifying and interpreting further precedents.[117]

Sustainability Transitions and innovation

57 This section addresses an area of literature that reflects the widespread international interest in more sustainable energy futures,[118] and is one in which practitioners, mainly non-historians, have made extensive use of historical analyses (including Arapostathis *et al.*;[119] Geels;[120] Verbong and Geels;[121] Johnson *et al.*;[122] Martínez

114 Pavitt Keith, "'Chips' and 'trajectories': how does the semiconductor influence the sources and directions of technical change?", *in* Roy MacLeod (ed.), *Technology and the Human Prospect* (London: Frances Pinter, 1986).
115 See also: Furr, Snow, "Intergenerational hybrids" (cf. note 107).

116 Turnheim Bruno, Geels Franck W., "Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913-1997)", *Energy Policy*, vol. 50, 2012, 47, 49; see also Turnheim Bruno, Geels Franck W., "The destabilisation of existing regimes: Confronting a multi-dimensional framework with a case study of the British coal industry (1913–1967)", *Research Policy*, vol. 42, 2013; Geels Franck W., "Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective", *Theory, Culture & Society: explorations in critical social science*, vol. 31/5, 2014.
117 See also Kungl Gregor, Geels Frank W., "Sequence and alignment of external pressures in industry destabilisation: Understanding the downfall of incumbent utilities in the German energy transition (1998–2015)", *Environmental Innovation and Societal Transitions*, vol. 26, 2018; and for a recent critical review of approaches to incumbency, see Stirling Andy, "How Deep Is Incumbency? Introducing a 'Configuring Fields' Approach to the Distribution and Orientation of Power in Socio-Material Change", *SPRU Working Paper Series SWPS* 2018-23,http://www.sussex.ac.uk/spru/research/swps [Accessed 2/12/18].
118 GEA, Global Energy Assessment (cf. note 1).
119 Arapostathis, "Governing transitions" (cf. note 103).
120 Geels Franck W., "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study", *Research Policy*, vol. 31, 2002.
121 Verbong Geert P. J., Geels Franck W., "The ongoing energy transition: lessons from a socio-technical, multilevel analysis of the Dutch electricity system (1960-2004)", *Energy Policy*, vol. 35/2, 2007.
122 Johnson Victoria C. A., Sherry-Brennan, Fionnguala, Pearson Peter J. G., "Alternative liquid fuels in the UK in the interwar period (1918–1938): Insights from a failed

Arranz[123]). According to the research agenda of the influential Sustainability Transitions Research Network, research in this area recognises that many environmental problems require deep structural changes in key areas of human activity and society, including energy systems. It asserts, as discussed in Section 5.2, that a key "challenge for sustainable development is the fact that existing systems tend to be very difficult to 'dislodge' because they are stabilized by various lock-in processes that lead to path dependent developments and 'entrapment'".[124] These mutually reinforcing processes that tend to perpetuate existing systems are identified as a 'socio-technical regime', a notion that brings ideas from evolutionary economics together with insights from the history and sociology of technology. It emphasises how scientific knowledge, engineering practices and processes are socially embedded.

58 The overarching aim of sustainability transitions research is to study societal transformations involving governance and guidance,[125] through which systems shift towards more sustainable modes of production, consumption and lifestyles, while recognising that such transitions are complex, long drawn-out processes.[126] Thus, sectors like energy are seen as socio-technical systems with interacting networks of actors (people, firms, etc.), broadly-defined institutions, material artefacts and knowledge. An energy transition is thus likely to involve a shift to a new regime in which multiple actors engage with new commodities and energy services, with changes in social practices, business models and organisations, and altered technological and institutional structures, with repercussions beyond energy.

59 Studies of prospective and historical energy transitions and processes have often drawn on the multi-level perspective (MLP), an approach that grew out of works by Kemp, Rip and Schot.[127] The MLP combines concepts from evolutionary economics, science and technology studies, structuration theory and neo-institutional theory. It proposes that transitions can emerge out of dynamic non-linear interactions between three analytical levels, niches (the locus for radical innovations), socio-technical regimes (the locus of established practices and associated rules that stabilise existing systems) and an exogenous socio-technical landscape; transitions involve shifts from one regime to another.[128] Different interactions could then lead to various kinds of transition pathway, including pathways to future energy systems.[129] The MLP, although subject to a range of criticisms,[130] con-

energy transition", *Environmental Innovation and Societal Transitions*, vol. 20, 2016.

123 Martínez-Arranz Alfonso, "Lessons from the past for sustainability transitions? A meta-analysis of socio-technical studies", *Global Environmental Change*, vol. 44, 2017.

124 STRN, "A mission statement and research agenda for the Sustainability Transitions Research Network", 2010, http://transitionsnetwork.org/files/STRN_research_agenda_20_August_2010... [Accessed 8/6/17].

125 Smith Adrian, Stirling Andy, Berkhout Frans, "The governance of sustainable socio-technical transitions" *Research Policy*, vol. 34, 2005.

126 See also: Markard Jochen, Raven Rob, Truffer Bernhard, "Sustainability transitions: An emerging field of research and its prospects", *Research Policy*, vol. 41, 2012; Geels Franck W., Berkhout Frans, van Vuuren Detlef P., "Bridging analytical approaches for low-carbon transitions", *Nature Climate Change*, vol. 6/6, 2016.

127 Kemp René, Rip Aarie, Schot Johan, "Constructing transition paths through the management of niches", *in* Raghu Garud, Peter Karnøe (eds.), *Path Dependence and Creation* (London: Lawrence Erlbaum, 2001); Rip Arie, Kemp René, "Technological change", *in* Steve Rayner, Elizabeth L. Malone (eds.), *Human Choice and Climate Change – Volume 2: Resources and Technology* (Columbus: Battelle Press, 1998).

128 Geels, "Technological transitions as evolutionary reconfiguration processes" (cf. note 120).

129 Geels Franck W., Schot Johan W., "Typology of sociotechnical transition pathways", *Research Policy*, vol. 36, 2007; Geels Franck W. *et al.*, "The enactment of socio-technical transition pathways: A reformulated typology and a comparative multi-level analysis of the German and UK low-carbon electricity transitions (1990–2014)", *Research Policy*, vol. 45/4, 2016.

130 e.g. Smith, Stirling, Berkhout, "The governance of sustainable socio-technical transitions" (cf. note 125); responded to by Geels Franck W., "The multi-level perspective on sustainability transitions: Responses to seven criticisms", *Environmental Innovation and Societal Transitions*, vol. 1/1, 2011; see also Geels Franck W., "Regime Resistance against Low-Carbon Transitions: Introducing Politics and Power into the Multi-Level Perspective", *Theory, Culture & Society: explorations in critical social science*, vol. 31/5, 2014.

tinues to be widely and usefully - although not always discriminately – applied and developed.

60 Concerns with how transitions might be accelerated led to ideas about procedures to guide transitions.[131] The guiding principles for 'transition management', including 'strategic niche management' were informed by thinking about existing sectors as complex, adaptive systems and viewing management as a reflexive, evolutionary governance process.[132] Transition management has been explored in practice in the Netherlands with mixed outcomes,[133] while the political and practical feasibility of trying to 'manage' national level transitions through such processes has rightly been challenged. Shove and Walker, for example, questioned whether societies necessarily have the ability to transform themselves, and argue that transition management approaches "can…obscure their own politics, smoothing over conflict and inequality; working with tacit assumptions of consensus and expecting far more than participatory processes can ever hope to deliver".[134] Similarly, Meadowcroft[135] argued that transforming energy systems "will prove to be a messy, conflictual, and highly disjointed process."

61 Indeed, key questions concern our capacity and ability to respond to the nature and scale of the threat of climate change, given the state of political institutions and economies, especially in the Western world - and after the economic fallout from the recent financial crisis. So, we need much better knowledge about: whether and in what respects climate change and low-carbon transitions form unprecedented challenges; how political, institutional and technical capacities to respond to apparently existential crises have or have not been developed in the past, and might be developed for the future; and whether history helps us to judge whether the responses to such challenges might be treated effectively in a piecemeal fashion, so that they become more manageable.

While much energy transition pathways research has been qualitative, increasing efforts are being devoted to forward-looking quantitative approaches[136] and to bringing them together with qualitative analyses[137] or to developing a hybrid approach.[138] McDowall and Geels,[139] however, question whether transitions can be represented within a single encompassing framework and suggest instead the pursuit of plural, diverse approaches. Further interdisciplinary work, especially that of historians, might play a valuable role in such endeavours. 62

131 Kemp René, Loorbach Derk, "Transition management: a reflexive governance approach", *in* Jan-Peter Voss, Dierk Bauknecht, René Kemp (eds.), *Reflexive Governance for Sustainable Development* (Cheltenham: Edward Elgar, 2006), Ch. 5.

132 Voss Jan-Peter, Smith Adrian, Grin John, "Designing long-term policy: rethinking transition management", *Policy Sciences*, vol. 42, 2009.

133 Smith Adrian, Kern Florian, "The transitions storyline in Dutch environmental policy", *Environmental Politics*, vol. 18/1, 2009; Kemp René, "The Dutch energy transition approach", *International Economics and Economic Policy*, vol. 7, 2010.

134 Shove, Walker, "CAUTION! transitions ahead"(cf. note 55), 768; Shove Elisabeth, Walker Gordon, "Transition Management™ and the Politics of Shape Shifting", *Environment and Planning A*, vol. 40/4, 2008; Rotmans Jan, Kemp René, "Detour Ahead: A Response to Shove and Walker about the Perilous Road of Transition Management", *Environment and Planning A*, vol. 40/4, 2008.

135 Meadowcroft James, "What about the politics? Sustainable development, transition management, and long term energy transitions", *Policy Sciences*, vol. 42, 2009, 323.

136 Li Francis G. N., Trutnevyte Evelina, Strachan Neil, "A review of socio-technical energy transition (STET) models", *Technological Forecasting & Social Change*, vol. 100, 2015; Holtz Georg *et al.*, *Prospects of modelling societal transitions: position paper of an emerging community, Environmental Innovation and Societal Transitions*, 17, 2015.

137 Trutnevyte Evelina *et al.*, "Linking a storyline with multiple models: a cross-scale study of the UK power system transition", *Technological Forecasting and Social Chang*, vol. 89, 2014; Turnheim Bruno *et al.*, "Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges", *Global Environmental Change*, vol. 35, 2015.

138 McDowall Will, "Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling", *Futures*, vol. 63, 2014; Geels, Berkhout, van Vuuren, "Bridging analytical approaches for low-carbon transitions" (cf. note 126).

139 McDowall Will, Geels Frank W., "Ten challenges for computer models in transitions research: Commentary on Holtz *et al.*", *Environmental Innovation & Societal Transitions*, vol. 22, 2017.

63 Innovation is a significant element of low-carbon transitions. Truffer *et al.*[140] critically examined the energy-related areas of the socio-technical 'innovation systems' literature. This literature spans four innovation system approaches: national (NIS), regional (RIS), sectoral (SIS) and technological (TIS) innovation systems. The NIS was created in the 1980s, stimulated by a desire to explain key ongoing economic challenges more effectively than approaches drawn from neo-classical economics. The RIS, SIS and TIS went outside national boundaries, encompassing broader influences like those of multi-national corporations. Truffer *et al.* argued that the TIS tradition has been the most productive of these areas in the energy field.[141] TIS studies have gone from examining energy innovations in specific countries, often focusing on those 'functions' of an innovation system required for it to operate well,[142] to inter-country comparisons and to some regional and global analyses of technological innovation systems. While Europe has been the main focus of existing studies, greater attention is now being paid to emerging economies. Truffer et al. suggested that the four approaches could be more effectively integrated, and would benefit from further conceptual and empirical development, as well as attention to the analysis of longer term energy transitions and their dynamics. Indeed, Weber and Rohracher[143] proposed combining insights from the innovation systems and MLP approaches.[144]

140 Truffer Bernhard *et al.*, "A literature review on Energy Innovation Systems. EIS Radar paper", 2012, http://www.eis-all.dk/~/media/Sites/EIS_Energy_Innovation_Systems/engli... (Accessed 19/6/18).
141 See also: Markard Jochen, Hekkert Marko, Jacobsson Staffan, "The technological innovation systems framework: response to six criticisms", *Environmental Innovation and Societal Transitions*, vol. 16, 2015.
142 Hekkert Marko *et al.*, "Functions of Innovation systems: a new approach for analysing technological change", *Technological Forecasting & Social Change*, vol. 74, 2007.
143 Weber K. Matthias, Rohracher Harald, "Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework", *Research Policy*, vol. 41, 2012.
144 See also: Fagerberg Jan, "Mission (im)possible? The role of innovation (and innovation policy) in supporting structural change & sustainability transitions", *TIK Working Papers on Innovation Studies*, n° 20180216. https://ideas.repec.org/p/tik/inowpp/20180216.html [Accessed 2/12/18]; And for a more ambitious synthesis, see: Cherp Aleh *et al.*, "Integrating techno-economic, socio-technical and political perspectives on national energy transitions: A meta-theoretical framework", *Energy Research & Social Science*, vol. 37, 2018.

Despite the need for and value of energy-related innovation, as a matter of perspective, Fagerberg[145] cautions against the tendency to view all innovations as comprehensively 'good'. In solving specific problems, innovation may also create new, unanticipated problems, of which the 'financial innovations' festering below the 2008 crisis are but a recent example. Energy is rich with instances, both particular (e.g. the development of tetra-ethyl lead additives for gasoline, now removed) and general (fossil fuels). Historically-informed insights from such episodes might help us to better anticipate such innovation pitfalls. 64

This sub-section has discussed recent approaches to sustainable transitions, their governance and guidance, and energy-related innovation. While research in these areas includes historical case studies and goes some way towards acknowledging the social, political, cultural, technological and path-dependent complexities and entanglements that historians embrace, this work would benefit from a deeper, broader and more rigorous acquaintance with historical methods and findings. Many practitioners would welcome more of this kind of collaboration. 65

CONCLUSION AND AN INVITATION TO HISTORIANS

This paper had four aims: to argue that historical analyses can offer insights into past energy transitions that are of value to non-historians who study energy transitions, including policy-makers; to show how, in one discipline, economics, for some time historical aspects seemed of little relevance to energy economists and policy analysts; to indicate problem areas, issues and 66

145 Fagerberg Jan, "Innovation – a New Guide", *TIK Working Papers on Innovation Studies*, n° 20131119, 2013, http://www.sv.uio.no/tik/InnoWP/tik_working_paper_20131119.pdf [Accessed 7/10/17].

questions, especially those concerning low-carbon transitions, especially suited to historical insights; and to invite historians to engage in further such analyses of energy transitions and to collaborate more with non-historians.

67 Section 1 explained the author's normative views about climate change and low-carbon transitions, and about the type of contribution that historical insights and knowledge can offer to non-historians' thinking. Section 2 drew on personal experience and critical literature review to address the second aim. Section 3 examined the nature, variety and complexities of energy transitions, including why they are challenging to define, identify, analyse and generalise from, and why historians are well-placed to embrace these challenges and share their expertise. Section 4 discussed the growing policy interest in transitions, especially low-carbon transitions. The long, complex dynamics of the greenhouse effect and climate change, the centuries-long, path-dependent, persistent use of fossil fuels, issues of equity and justice, and the difficulties of national and global governance, both underlie many of the policy challenges involved and suggest many aspects where historical expertise might enhance our understanding. Section 5 examined three areas in which further historical insights might be especially valuable: the duration and speed of past energy system transitions and whether they offer precedents for the future (Section. 5.1); path dependence, lock-in and the strategies, responses and destabilisation of incumbent energy actors and institutions (Section 5.2); and sustainability transitions and innovation theories (Section 5.3). Each of these sub-sections illustrated problem areas, issues and questions that might benefit from the further application of historical expertise.

Several of the problem areas identified, particularly but not only in Section 3, raise important, tricky epistemological issues concerning the development of knowledge about the nature, variety and complexities of energy transitions. They include the distinction between the many kinds of 'minor' and 'major' (or 'grand') transitions, with all that our ability to draw such distinctions with confidence implies for our capacity to comprehend the scale, pace, duration, smoothness and (dis)continuity or other 'special' properties of transitions, and for our ability to guide or manage them. Although the literature addresses most of these issues, because it also shows ambiguity, even contradiction, greater clarity would be valuable. A referee also suggested that, "these epistemological lines of inquiry are not only valuable intrinsically, but also are not necessarily predictive or prescriptive, and so are available to historians who baulk at either prediction or prescription." 68

Finally, this paper extends an invitation to interested historians to further share the methods, subtleties and findings of historical analysis with non-historians, to enhance our knowledge, understanding and thinking about energy transitions. 69

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