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Technological "lock-in"

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1. Introduction

Technological "lock-in" has been the subject of growing academic enquiry by economists, historians and sociologists since the mid-1980s (David, 1985; Arthur, 1989; Cowan, 1990; Liebowitz & Margolis, 1995). More recently, it has caught the attention of scholars interested in the links between technological and ecological change, particularly in relation to the pollution externality from fossil fuel use (Kemp, 1994; Rip & Kemp, 1998; Unruh, 2000). Central to the idea of lock-in is that technologies and technological systems follow specific paths that are difficult and costly to escape. Consequently, they tend to persist for extended periods, even in the face of competition from potentially superior substitutes. Thus, lock-in is said to account for the continued use of a range of supposedly inferior technologies, ranging from the QWERTY keyboard to the internal combustion engine.

2. The origins of lock-in

Why are technologies subject to lock-in effects? This is a question that has been addressed by economists working within an evolutionary tradition for several decades. Broadly speaking, two explanations have been put forward, although there is considerable overlap between them.

3. Technological paradigms

The first explanation for lock-in type outcomes centres on the idea that the nature and direction of technological advance is strongly shaped by the cognitive framework of actors. Nelson & Winter (1977) use the term technological regimes to describe these frames while Dosi (1982) refers to them as technological paradigms. Both, however, point to the existence of certain "rules", "heuristics" or "principles" that define the boundaries of thought and action by members of the technological community (engineers, firms, technology institutes, etc.). These include, for example, engineering ideas about the nature of the technological problem and the worthwhile set of possible solutions.

One consequence of these shared mental frames is that efforts to advance the performance of technology are often focused in specific directions that build on past achievements, ideas and knowledge. For this reason, it is suggested that they can have powerful exclusion effects (Dosi, 1982), in that technological possibilities and solutions that lie outside the dominant technological paradigm are rarely explored. Hence, the tendency of technological change to proceed "incrementally" along certain trajectories, structured according to the bounded logic of the technological community, rather than "radically" in discontinuous leaps.

4. Increasing returns to adoption

A second explanation for the existence of lock-in, and one that closely follows on from the first, draws from the idea of increasing returns to adoption. These are positive feedback mechanisms that function to increase the attractiveness of adopting a particular technology the more it is adopted. As highlighted by David (1985) and Arthur (1989), in a situation where two or more technologies are competing for market share, the presence of increasing returns implies that the option which secures an initial lead in adoption may eventually go on to dominate the market. This arises because early adoption can generate a snowballing effect whereby the preferred technology benefits from greater improvement than its competitors, stimulating further adoption, improvement and eventual leadership. In fact, under conditions of increasing returns, technologies that fail to win early adoption success might eventually find themselves locked-out from the market, unable to compete with the improved technology.

More controversial still, however, is the suggestion that this process can lock society into an inferior design, thereby causing markets to fail. According to proponents of increasing returns, this can arise because technological choice during the early stages of competition is characterised by uncertainty and ignorance about the respective qualities and properties of various options. Consequently, a technology that would have been superior given equivalent learning, might find itself being lock-out by a lesser one. Indeed, the literature provides many examples where this is alleged to have occurred. Thus, the QWERTY layout triumphed over the Dvorak Simplified Keyboard (David, 1985), light water nuclear reactors prevailed over heavy water ones (Cowan, 1990), and the VHS video cassette recorder standard won-out in the competitive race over Betamax (Arthur, 1990).

Four principal classes of increasing return are commonly implicated in lock-in type outcomes although it is possible to find additional variants of these. The first two are perhaps the most familiar and commonly grouped under the heading of economies of experience. They include scale economies, the reduction in unit costs of a particular product or service with rising output; and learning economies, widely understood as the cost and performance improvements that commonly occur as individuals and organisations "learn" from experience and repetition how to operate equipment more effectively and efficiently. Empirically, these dynamic scale and learning effects have been well-documented and are commonly portrayed as learning curves, showing a reduction in unit costs with rising cumulative output. Their effects are reinforced by a third type of increasing return, adaptive expectations, whereby increased adoption reduces uncertainty about the performance, reliability and durability of a technology.

Yet, it is a fourth and final class, network externalities, that is most commonly associated with technological lock-in. Network externalities are the external benefits conferred on users of a technology by another's use of the same technology. Their significance stems from the fact that technologies are more than isolated physical devices. They are part of broader networks consisting of multiple, interdependent technologies and supporting infrastructures; the latter comprising, not only physical elements, but also the technical, economic and institutional relationships and structures that enable existing technologies to work together.

An important consequence of technological interdependencies is that as a particular network increases in size so does its attractiveness to potential users, giving rise to positive feedback effects. This stems from the benefits of compatibility, either in terms of physical products, services or related skills and experience. Thus, to take one popular example, the value of a telephone to an individual user increases with the number of people connected to the network with whom they can communicate.

According to the literature, network externalities account for the characteristic co-evolution of related technologies in clusters, consisting of interdependent technologies embedded within particular institutional and organisational settings (Freeman & Perez, 1988). At the macro-level, such clusters have long been recognised by scholars of technological change, going back to Nikolai Kondratieff (1892-1938) and Joseph Schumpeter (1883-1950). Thus, Grübler (1998) identifies four historical clusters, each associated with a complex of dominant technologies and infrastructures: (1) textiles, turnpikes and water mills between 1750-1820; (2) steam, canals and iron over the period 1800-1870; (3) coal, railways, steel and industrial electrification from 1850-1940; and (4) oil, roads, plastics and consumer electrification between 1920-2000.

The significance of network externalities for lock-in is based on the idea that they raise barriers to entry for radical technologies that are not part of the dominant technological cluster. This arises since, in the presence of technological interdependencies, any attempt to introduce a technology that is incompatible with existing technologies and infrastructures will require corresponding changes to the rest of the technological system in order to make it fit (Metcalfe, 1997). Such change can be the source of considerable inertia. This is because it implies large switching costs, both from the need to replace physical elements of the technological system and, equally important, associated work practices, skills and patterns of behaviour. It is precisely for this reason that vested interests, including firms, governments and consumers, may purposely resist the introduction of novel technologies that are not part of the existing technological cluster. Compounding this inertia are co-ordination failures. These are especially important in the presence of network externalities and mean that, even where switching to a new technology would be profitable, users may continue to opt for existing and inferior technological options.

To sum-up, the literature suggests that lock-in is co-produced by two dynamics: first, technological paradigms, embodying a shared set of skills, habits and outlooks about the nature and direction of technological progress; and second, increasing returns to adoption, whose impact is to create pervasive incentive structures that reinforce these paths. Together, they are said to account for the incremental and path-dependent nature of technological change in many manifestly system technologies, such as automobiles and telecommunications (Metcalfe, 1997).

5. Criticisms of lock-in

Although compelling, these narrative accounts of lock-in are by no means uncontroversial. Particular criticism has come from two economists, Liebowitz and Margolis (1994; 1995). They have questioned whether the existence of increasing returns during the early, and highly uncertain, stages of competition can actually provide an "inferior" technology with an unassailable market lead. According to the authors, little or no convincing evidence exists to support the presence of these inefficient market choices in practice. Even the QWERTY keyboard and VHS video recorder, two of the most commonly cited examples of sub-optimal lock-in, do not stand-up to scrutiny on closer inspection. Liebowitz and Margolis have also challenged the assumption that network externalities compel users to choose inferior technological options. To this end, they argue that the economic benefits of network effects are invariably overstated and, in any case, what matters are user expectations of the emerging product's network size rather than its current one.

Unfortunately, and as recognised by scholars in the field, substantiating claims for and/or against lock-in to inferior technologies by increasing returns is highly problematic (Foray, 1997). Therefore, in the absence of additional empirical and analytical work, the debate will no doubt continue. What is not in dispute, however, is the basic premise that technological choices can have long-term consequences. Moreover, these can be difficult and costly to escape, locking individuals, organisations and entire economies into specific technological configurations.

6. The environmental significance of lock-in

Much of the discussion of lock-in, at least in the economics and business literature, has focused on high-technology markets and their implications for the competitive strategies of firms (e.g., see Arthur, 1996). The past decade, however, has witnessed growing interest in the idea that lock-in might have far-reaching consequences for the understanding of environmental change (Kemp, 1994; Unruh, 2000). The starting point for this observation is that technologies differ with respect to their resource use and/or waste generation. Moreover, because technological choice takes place within the confines of specific technological paradigms and clusters, each characteristically associated with a particular energy source, it is suggested that technological and environmental change go hand-in-hand (Booth, 1998; Grübler et al., 1999).

In this context, a recurrent theme of the literature is that developed economies are locked into a complex of hydrocarbon-intensive technologies and infrastructures (Rip & Kemp, 1998; Arentsen et al., 2002). These initially evolved within the context of abundant fossil fuels and limited knowledge and concern about the long-term consequences of greenhouse gas emissions. However, despite growing awareness of the negative impacts of fossil fuel use, attempts to shift towards low and/or zero-emitting substitutes are proving difficult. On the one hand, this is because hydrocarbon technologies have benefited from many decades of dynamic scale and learning effects, providing them with competitive advantages in terms of, for example, cost, performance and user-friendliness. While, on the other, fossil fuel-based technologies enjoy the support of a co-specialised network of technical assets which hinder the innovation and diffusion of technologies that lie outside the hydrocarbon technological paradigm. Going further, a number of accounts point to the role played by private and public institutions in resisting radical change in the direction of carbon-free technologies. Many of these, it is claimed, have interests in perpetuating the current technological paradigm and, consequently, are active in shaping market and non-market forces in ways that reinforce lock-in (Kemp, 1994; Unruh, 2000)

The literature generally remains sceptical about the prospects for escaping hydrocarbon lock-in in developed economies. Yet it does not rule-out the possibility that far-reaching shifts in energy use might take place in the future. Such changes, after all, have happened in the past. Thus, the historic dominance of fuel-wood and other traditional energy sources gave way to coal as the leading fuel over the period 1880-1960. Subsequently, most developed economies have come to rely on oil, and increasingly gas, as their primary energy source. In fact, because each of these fuel sources has a lower carbon content, the historic record of energy substitution is one of decarbonisation (Nakićenović, 1997). The real question is whether developed economies will be able to escape pervasive lock-in to the dominant petroleum-based technological system on the short time-scales required for climate stabilisation. History suggests that this is unlikely to be easy. Fundamental energy transitions characteristically take many decades to complete. Moreover, they depend on the support of a complex of private and public institutions involved in the development and diffusion of energy technologies, ranging from government regulators to consumer groups (Podobnik, 1999; Arentsen et al., 2002; Unruh, 2002).

Many analysts, however, are more optimistic about the prospects for developing countries who, it is often claimed, are well-placed to avoid becoming locked into the same hydrocarbon technological clusters that currently dominate in developed economies (e.g., see Wallace, 1996; Loucks, 2002). This is because they have yet to install much of their productive capacity. Consequently, in the absence of increasing returns favouring hydrocarbon-intensive technologies, they should be able to "leapfrog" straight to the next-generation of greenhouse gas neutral technologies (Goldemberg, 1998). Unfortunately, despite its rhetorical appeal, very little is known about whether developing countries are capable of exploiting their unique latecomer status. What research has been undertaken, however, suggests that many barriers exist for low-income economies seeking to advance straight to carbon-free technological systems as an integral part of capacity addition (Perkins, 2001).

Although much of the literature focuses on lock-in to hydrocarbon technologies a number of ecological economists have suggested that similar dynamics might also explain the persistence of other environmentally-damaging technological options and practices. Wilson & Tisdell (2001), for example, argue that farmers are locked into continued pesticide use. Thus, despite their adverse impacts on profitability, a combination of high up-front switching costs and co-ordination failures mean that, once pesticides have been adopted, reverting to more sustainable forms of agricultural pest control is difficult. Similarly, Messner (2002) finds evidence that increasing returns can lock users into the use of particular materials, thereby delaying or even preventing substitution towards less environmentally-damaging substitutes.

7. Conclusions

The idea that economy and environment are closely interlinked is well-known to scholars of ecological economics. The concept of lock-in expands on this in two important ways. First, it suggests that technologies and technological systems are inherently inert, giving rise to distinctive and, moreover, durable patterns of resource use and waste production over time. For this reason, insights from the field of lock-in (increasing returns, technological clusters, etc.) hold considerable promise in relation to attempts to model economy-environment relations. Second, it highlights how ecological change is deeply embedded in complex, interdependent technological and socio-economic systems. In doing so, research into the dynamics of lock-in points to the need for more sophisticated policy approaches that take a system-wide perspective to reducing the environmental burden of economic activity.

Clearly, lock-in and other insights from evolutionary economics have yet to make a significant impact on the mainstream ecological economics literature. Yet, there is increased recognition that they have much to contribute and, therefore, look set to play a greater role in describing and explaining the complexities of economy-environment relations.

Print references:

Arentsen, M., R. Kemp and E. Luiten (2002), ‘Technological change and innovation for climate protection: the governance challenge’, in: Global warming and social innovation: the challenge of a carbon-neutral society (M. Kok, W. Vermeulen, A. Faaij and D. de Jager, eds.), Earthscan: London, 59-82

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

Arthur, W. B. (1990), 'Positive feedbacks in the economy', Scientific American, 262 (February), 92-99

Arthur, W. B. (1996), 'Increasing returns and the new world of business', Harvard Business Review, (July-August), 100-109

Booth, D. E. (1998), The environmental consequences of growth: steady-state economics as an alternative to ecological decline, Routledge: London

Cowan, R. (1990), 'Nuclear power reactors: a study in technological lock-in', The Journal of Economic History, 50 (3), 541-567

David, P. A. (1985), 'Clio and the economics of QWERTY', Amercian Economic Review, Papers and Proceedings, 75, 332-337

Dosi, G. (1982), 'Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change', Research Policy, 11, 147-162

Foray, D. (1997), 'The dynamic implications of increasing returns: technological change and path dependent inefficiency', International Journal of Industrial Organization, 15, 733-752

Freeman, C. and C. Perez (1988), ‘Structural crisis of adjustment, business cycles and investment behaviour’, in: Technological change and economic theory (G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. Soete, eds.), Pinter: London, 39-66

Goldemberg, J. (1998), 'Leapfrog energy technologies', Energy Policy, 26 (10), 729-742

Grübler, A. (1998), Technology and global change, Cambridge University Press: Cambridge

Grübler, A., N. Nakićenović and D. G. Victor (1999), 'Dynamics of energy technologies and global change', Energy Policy, 27 (5), 247-280

Kemp, R. (1994), 'Technology and the transition to environmental sustainability', Futures, 26 (10), 1023-1046

Liebowitz, S. and S. E. Margolis (1994), 'Network externality: an uncommon tragedy', Journal of Economic Perspectives, 8, 133-150

Liebowitz, S. and S. E. Margolis (1995), 'Path dependence, lock-in and history', Journal of Law, Economics and Organization, 11 (1), 205-226

Loucks, O. L. (2002), 'Business capitalizing on energy transition opportunities', in: Climate change policy: a survey (S. H. Schneider, A. Rosencranz and J. O. Niles, eds.), Island Press: Washington, D.C., 495-507

Messner, F. (2002), 'Material substitution and path dependence: empirical evidence on the substitution of copper for aluminium', Ecological Economics, 42, 259-271

Metcalfe, J. S. (1997), 'On diffusion and the process of technological change', in: Economics of structural and technological change (G. Antonelli and N. De Liso, eds.), Routledge: London

Nakićenović, N. A. (1997), 'Freeing energy from carbon', in: Technological trajectories and the human environment (J. H. Ausubel and H. D. Langford, eds.), National Academy Press: Washington, D.C., 74-88

Nelson, R. R. and S. G. Winter (1977), 'In search of useful theory of innovation', Research Policy, 6, 35-76

Perkins, R. (2001), Technology and environmental leapfrogging: three case-studies from India, PhD Thesis, Department of Earth Sciences and Geography, University of Cambridge: Cambridge

Podobnik, B. (1999), 'Toward a sustainable energy regime: a long-wave interpretation of global energy shifts', Technological Forecasting & Social Change, 62, 155-172

Rip, A. and R. Kemp (1998), 'Technological change', in: Human choice and climate change: resources and technology (S. Rayner and E. L. Malone, eds.), Battelle Press: Columbus, 327-399

Unruh, G. C. (2000), 'Understanding carbon lock-in', Energy Policy, 28 (12), 817-830

Unruh, G. C. (2002), 'Escaping carbon lock-in', Energy Policy, 30 (4), 317-326

Wallace, D. (1996), Sustainable industrialization, Earthscan: London

Wilson, C. and C. Tisdell (2001), 'Why farmers continue to use pesticides despite environmental health and sustainability costs', Ecological Economics, 39, 449-462