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How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology

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ABSTRACT

Recent climate change initiatives, such as 'Mission Innovation' launched alongside the Paris Agreement in 2015, urge redoubled research into innovative low carbon technologies. However, climate change is an urgent problem – emissions reductions must take place rapidly throughout the coming decades. This raises an important question: how long might it take for individual technologies to emerge from research, find market opportunities and make a tangible impact on emissions reductions? Here, we consider historical evidence for the time a range of energy supply and energy end-use technologies have taken to emerge from invention, diffuse into the market and reach widespread deployment. We find considerable variation, from 20 to almost 70 years. Our findings suggest that the time needed for new technologies to achieve widespread deployment should not be overlooked, and that innovation policy should focus on accelerating the deployment of existing technologies as well as research into new ones.

1. Introduction

The role and importance of technological innovation in reducing greenhouse gas emissions is well established in national and international policies (DECC, 2012; CCC, 2013, IPCC, 2015, IEA, 2015). Recent initiatives aimed at accelerating innovation in low carbon energy technologies focus in particular on enhancing government funding for research, development and demonstration (RD&D) (Mission Innovation, 2016; Breakthrough Energy Coalition, 2016; King et al., 2015; Dechezleprêtre et al., 2016). Yet if low carbon technologies are to play a substantial role in reducing carbon emissions in the coming decades, then it will be necessary to not just research, develop and demonstrate them, but to also make them commercially available and deploy them at scale, since emissions must fall rapidly during the period to 2050 to meet internationally agreed climate targets (IPCC, 2015, UNFCCC, 2015).

Much of the substantial literature on 'innovation systems' recognises that innovation policy needs to include *both* increased funding for RD&D *and* targeted measures to create market opportunities for low carbon technologies (IEA, 2000; Anderson et al., 2001; Foxon et al., 2005; Gross et al., 2012; Winskel et al., 2011), with ongoing debate on the optimal mix for specific technologies (Helm, 2010, 2017; Nemet and Baker, 2009; King et al., 2015; Policy Exchange, 2011).

However, the amount of *time* required for new technologies to emerge from fundamental research, go through demonstration and early stage deployment and diffuse into the market place also matters greatly, for the obvious reason that policy makers and innovators need a sense of how rapidly such technologies can make a material impact on reducing emissions. For this reason mitigation scenarios produced by integrated assessment models, which are central to low-carbon pathways analysis, are increasingly scrutinised with regard to their real-world feasibility, often by comparing their rates of low carbon energy technology deployment to historical rates of deployment of existing energy technologies (Wilson et al., 2013; Iyer et al., 2015; Napp et al., 2017; Van Der Zwaan et al., 2013, van Sluisveld et al., 2015), so as to determine whether or not they are simply "computerised fairy tales" (Smil, 2010b).

The issue of the time taken for technologies to commercialise has received relatively little attention in the innovation literature, in spite of its criticality to understanding the feasibility of future mitigation pathways and directing technology innovation and deployment policy. As discussed in Section 2.2, there have been a number of analyses on

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the timescale for the growth of different energy sources and energy technologies from initial prototype to various stages of development and maturity. But there has not yet been a detailed analysis of the timescale from invention to an agreed definition of widespread commercialisation of energy technologies. A key contribution of this paper is to provide new empirical evidence and insights on the topic of commercialisation timescales.

As we explain further in Section 2, there is a multitude of definitions and conceptualisations of various innovation stages. The paper therefore proposes new definitions of different stages in technology development and deployment that are designed to be simple and readily intelligible to non-specialists. In particular, the paper develops a new definition of 'widespread commercialisation' that represents a level of deployment of a technology that can be considered fully commercialised, but with potential to continue to increase market share. This allows innovation timescales to be presented in an accessible form that permits comparison between technologies and can be readily used by policy makers who need to understand how long it could take for new low-carbon technologies to become widely commercialised and able to make a material contribution to emission abatement.

To summarise, the paper's contribution is to enhance knowledge on innovation timescales, by providing empirical evidence and commentary on how long it has taken selected case study technologies to emerge from RD&D and achieve a readily understandable level of widespread commercialisation.

The rest of this paper is set out as follows: Section 2 presents a brief background on innovation processes and frameworks, before discussing the recent literature that specifically examines the timescales and rates of energy technology penetration; Section 3 describes the methodology used to calculate the innovation timescales for a range of energy supply and end use technologies, as well as justifying the selection of these technology case studies; Section 4 presents and discusses the results; Section 5 discusses the findings and limitations of the study. Section 6 concludes and discusses policy implications.

2. Background: the literature on innovation systems, stages and timelines

This section firstly provides a brief overview of the frameworks used to describe the stages and processes involved in technological innovation and deployment. Empirical analyses of energy transitions that have examined the timescales over which these stages and processes have occurred are then summarised. Finally, the section identifies gaps in the existing literature with regard to innovation and widespread commercialisation timescales, and discusses the contribution that this study makes.

2.1. Frameworks and models of energy technology innovation and deployment

There is a large literature on technology innovation in energy and other sectors. Early perspectives focused on a relatively simple, one-directional journey from basic research to applied research to technology development and diffusion, suggesting that the optimal way to increase the output of new technologies was to put more resources into R&D, a process called technology or supply-push (Schumpeter, 1934). An alternative perspective, demand-pull, gained traction in the 1950s (Carter and Williams, 1957), arguing that demand for products and services was more important in stimulating inventive activity than advances in the state of knowledge (Allen, 1967). Fri (2003) contends that the model of innovation called research, development, demonstration and deployment (RDD&D), which combines supply-push and demand-pull activities has set the form for virtually all discussions on energy innovation.

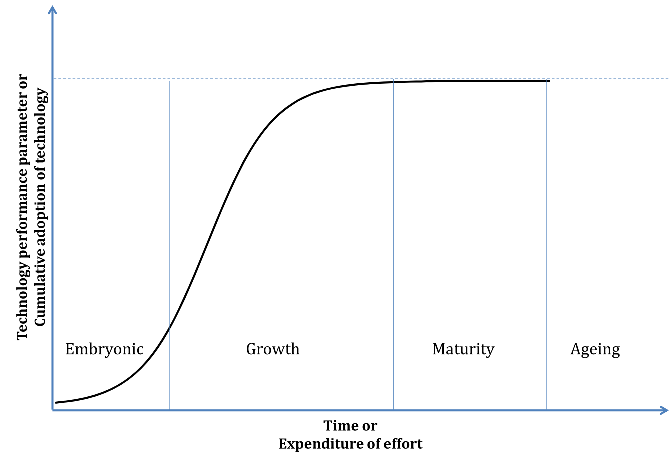

Fig. 1. Typical technology S-curve.
Source: Taylor and Taylor (2012)

There are a variety of models of technology diffusion in the literature which attempt to explain factors governing the speed of adoption of new technologies and giving rise to the typical shape of the technology S-curve (Geroski, 2000), illustrated in Fig. 1. Diffusion of innovations theory (Rogers, 1962) sets out the conditions under which innovative products may become accepted by consumers over time, so as to lead to their widespread acceptance and purchase. Whether consumers purchase an innovative product depends on how much they are aware of any relative advantage over alternative products, and whether they are motivated to find out more about the innovation (Faiers and Neame, 2006).

Five groups of adopters are identified by Rogers (1962): innovators, early adopters, the early majority, the late majority, and laggards. The Bass model of product growth (Bass, 1969) builds on Roger's adoption groups, so that early adopters through to laggards are considered to be 'imitators' of initial innovators. As more consumers adopt a product, imitators are influenced in the timing of their adoption by increasing social pressure to take up a product. According to the Bass model, the probability that the initial purchase of a new product will be made at a given point in time is 'a linear function of the number of previous buyers' (Bass, 1969).

The 'Epidemic' model (Bartholomew, 1973) is commonly used to account for the S-curve, and is based on the assumption that a lack of available information about a technology constrains its rate of uptake. Alternatively, the 'Probit' model (Davies, 1979), assumes that different firms have different objectives and skills, and therefore do not all adopt a technological innovation at the same time. In this model, diffusion takes place as different types of firms choose to adopt a new technology (Geroski, 2000).

The RDD&D, technology lifecycle and technology diffusion models present a somewhat linear, successive picture of technology development, which has been challenged by recent approaches which have noted the importance of more complex, systemic feedbacks between the supply and demand sides (Foxon, 2003), as well as the role of agents and actors in developing and deploying technologies within a broader socio-technical landscape. Examples of specific approaches include 'technological innovation systems', 'technological transitions', and the 'multi-level perspective' (Foxon, 2003). Technological Innovation Systems (TIS) theory aims to understand how new technologies can evolve through interactions between actors, networks and institutions (Bergek et al., 2008; Bento and Fontes, 2015). Transitions theory emphasises the importance of technological and market niches by which an innovation can be protected from normal market conditions and nurtured for a