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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.

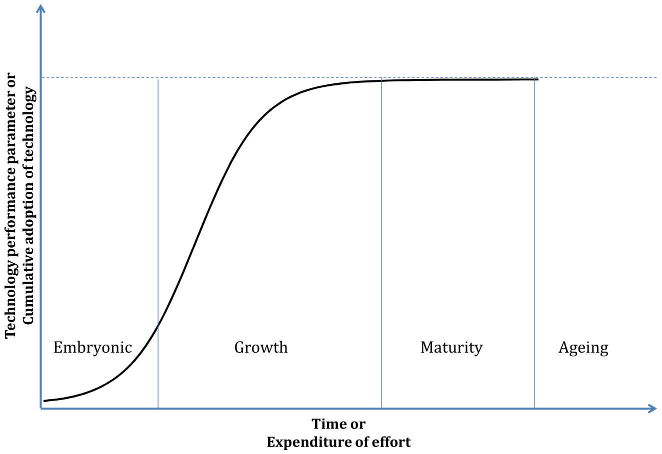

Fig. 1. Typical technology S-curve.
Source: Taylor and Taylor (2012)

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 period of time. A key element of transitions theory is the 'multi-level perspective' which stresses that transitions do not only involve changes in technologies, but also changes in user practices, regulation, industrial networks, infrastructure and symbolic meaning or culture (Geels, 2002).

The innovation frameworks and models of technology diffusion so far discussed highlight the importance of different activities to develop and deploy technologies, the institutions and actors involved in their penetration into the energy system, the role of consumer behaviour and information diffusion, as well as the different stages of technology maturity. However, the above concepts do not explicitly allow an *ex ante* quantification of the time taken for these processes to occur. To address this question, a more empirical literature has emerged, as discussed in the following sub-section.

2.2. Innovation and deployment in the energy sector

The foci of existing empirical analyses on innovation timescales are diverse, ranging from analysis of discrete technologies moving through a particular innovation stage (Bento and Wilson, 2016) to analysis of long term historical transitions of fuel sources, energy services and industries (Fouquet, 2010; Perez, 2002; Smil, 2010b; Pearson and Arapostathis, 2017). In addition, a very recent literature seeks to understand the feasibility of future low carbon scenarios by comparing low carbon energy technology deployment rates with historical deployment rates for 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).

It has been suggested that technological innovations typically take between five and seven decades to travel from invention to significant market shares (O'Neill et al., 2003, Grubler, 1998). Perez (2002) considers 'radical' innovations from the 1770s to 2000s, and observes that successive 'technological revolutions' took between 43 and 66 years to reach maturity. These include innovations associated with the industrial revolution, steam railways, steel and electricity and automobiles. Wilson and Grubler (2010) cite a variety of examples and conclude that on a global scale it has taken 80–130 years for new energy technology clusters to achieve market dominance, and about twice as long when considering the entire technology life cycle from first introduction to market maturity.

However, the timescales needed for new technologies to diffuse widely are contested. For example, Sovacool (2016) argues against the widespread view that energy transitions are inevitably slow, noting that it runs contrary to a number of important 'quick' empirical examples, from nuclear power in France to improved cooking stoves in rural China (Sovacool, 2016). Further rapid transitions include from petrol to biofuels in cars in Brazil (Grad, 2006), the switch from coal-based town gas to natural gas in the UK (Arapostathis et al., 2013) and the rapid expansion of wind energy in Denmark (Napp et al., 2017).

However there is no consensus definition of technological maturity in the sense of when or at what market share a particular technology can be considered as firmly established, widely available and commercially viable. Kramer and Haigh (2009) identify a distinct stage at which energy sources reach what they term "materiality", whereby they constitute about 1% of global primary energy supply, at which point their annual growth transitions from exponential to linear. Wilson et al. (2013) focus on the time taken for a range of energy technologies to grow from 10% to 90% of their long-term saturation level, termed the "duration" level by the authors, and in most cases taking several decades. One reason for the apparent disagreements over timescales would appear to be a lack of agreement over what constitutes widespread deployment.

Grubler et al. (2016) elaborate on differences between slow and rapid energy transitions, arguing that the examples of quick transitions provided by Sovacool (2016) are generally either new technologies which substitute for older ones or have been previously used in other markets, or which offer a high degree of tangible benefits for adopters. Conversely, slower energy transitions may require changes to take place in multiple technologies, infrastructures and institutions, extensive time to develop and test new concepts, and may entail investments in large-scale and costly technologies and infrastructures whose benefits may be longer term, social or environmental (i.e. non-market), and therefore less immediately tangible to consumers (Grubler et al., 2016).

Some of the most rapid energy technology growth rates have been used as benchmarks against which to test the feasibility of low carbon transitions. For example, Iyer et al. (2015) survey a range of national and international historically achieved energy technology deployment rates to inform a maximum 15% annual growth rate constraint on individual energy technologies in their low carbon pathway scenarios. This compares to Kramer and Haigh (2009) who observe an approximate 25% annual growth rate in primary energy sources achieved over the early decades of their deployment. Wilson et al. (2013) use a different combination of metrics to compare future low carbon technology deployment rates to historical rates, based on the time taken to grow from 10% to 90% of their eventual market saturation level. van Sluisveld et al. (2015) further develop this analysis to account for the growing size of the economy and energy system over time. Napp et al. (2017) combine a number of historical technology deployment metrics to impose constraints on modelled low-carbon pathways, concluding that if all available historical energy system transition metrics are taken into account, then the ability of their energy system model to meet a 2 °C climate target is severely compromised.

Overall it appears that there is conflicting evidence on the speed of energy technology penetration into energy systems, and considerable variability in the metrics used to measure the timescale to widespread deployment.

2.3. Gaps in the literature and contribution of this study

This paper sets out to improve understanding and clarity for policy makers on how long it can take for new technologies to significantly penetrate into the energy system from their point of invention. The paper addresses a number of gaps in the existing literature. In particular there are a wide range of metrics used to assess timescales in the existing innovation literature, and a lack of formal definitions of stages of technology development, particularly with respect to when a technology can be considered to be widely commercialised (Bento and Wilson, 2016; Grübler et al., 1999; Lund, 2006; Rogers, 1962; Smil, 2010a; Wonglimpiyarat, 2005). There are also a lack of analyses charting the whole innovation journey from invention to maturity. Bento and Wilson (2016) use a variety of metrics to measure the length of the 'formative phase', which represents the point at which a technology transitions from an emergent market into a more established market. Our paper goes beyond this analysis in applying a clear and comparable definition of widespread use that charts a more extended journey towards wider commercialisation.

We provide further weight to empirical evidence on historical deployment rates of energy supply and end use technologies which can be compared with deployment rates assumed in integrated assessment models used to construct low carbon scenarios. In general our findings contribute to existing empirical studies which contest whether diffusion timescales for energy technologies are longer and may take place over several decades (Wilson et al., 2013; Grubler et al., 2016) or more rapidly for particular technology substitutes (Sovacool, 2016). One surprising result from our analysis is the extended time taken for the car to reach widespread commercialisation, which is related to a number of contextual, income and economic growth-related factors (see Section 5.1).

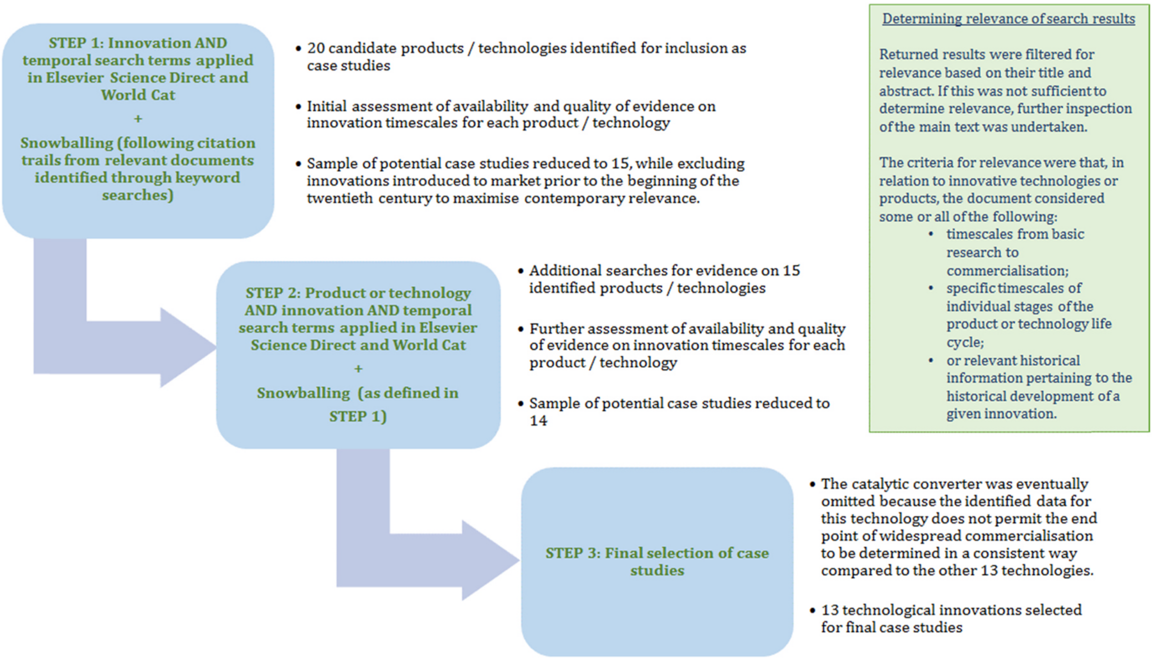

Fig. 2. Schematic illustrating approach to selecting case study technologies through the evidence review.

3. Methodology

This paper has two broad areas of investigation: an empirical review of the time taken from invention to widespread commercial use for a range of technologies and; a conceptual and definitional discussion of innovation stages, rooted in the literature on innovation. The empirical dimension of the paper, as discussed in Section 3.1, is based upon an evidence review undertaken using an approach developed by the authors for the UK Energy Research Centre (Speirs et al., 2015). The conceptual discussion of innovation stages, as presented in Section 3.2, is undertaken in order to develop our own definitions of innovation start and end points, which we apply to the empirical case studies.

3.1. *Evidence review on innovation*

The evidence review sought out a range of technologies and used a variety of innovation related search words. Relevant literature was identified through keyword searches for innovation concepts, descriptors of time and technologies or products (Appendix A) within two databases, Elsevier Science Direct (Elsevier, 2015) and World Cat (OCLC, 2015). Initially, innovation and temporal keywords were used as the search terms, and subsequently combined with product or technology keywords based on the initial searches (Fig. 2). A snowballing technique (Greenhalgh and Peacock, 2005) was also employed which involved following citation trails of documents identified through the keyword searches and including relevant cited documents in the evidence database, in order to widen the number of potential technology or product case studies. Ultimately, 13 successfully commercialised innovations were identified as being instructive to the research aims and for which sufficient information was available to quantify timescales from invention to widespread commercialisation (Fig. 2).

Following the filtering of retained search results key descriptive information on each of the results were captured: (i) the innovative product or technology considered; (ii) the timescales for specific innovation stages presented and; (iii) the geographic region (if not global).

It should be noted that there are several other technologies for which innovation journeys have been examined and discussed in the literature. These include: various innovations in the US steel industry (Gold et al., 1984); the dieselisation of railways (Mansfield, 1965); the diffusion of the basic oxygen furnace (Oster, 1982); and alternative fuelled vehicles (Yeh, 2007). However, as with Lund (2006), which compares market penetration rates for 11 energy technologies, we limit ourselves to those case studies for which data availability permitted a like-for-like comparison of innovation timescales.

We compare a wide diversity of technologies – energy supply and end use technologies, component parts (batteries), and various 'assembled products' (Utterback, 1994) including consumer electronics and the car. This technology diversity allows us to compare the time taken to widespread commercialisation for both technological innovations which can help to achieve energy systems decarbonisation, and wider consumer products or technologies such as the car, mobile phone, VCR and ATMs/cash cards.

Through this comparison we can observe differences in innovation timescales between technologies aimed at climate change mitigation and those which have experienced strong market demand from consumers or provide distinct novel or replacement services for consumers. The 13 innovations selected for the construction of innovation timelines were organised into three groups: novel energy end use and consumer products (new products with entirely new markets); replacement energy end use and consumer products (new technologies which replace but perform a similar function to an existing product with an incumbent market); and electricity generation technologies.

We deliberately chose technologies which have entered widespread use and have been commercially successful and widely adopted in at least some markets, and do not consider 'failed' technologies. This aspect of technology choice was largely pragmatic, reflecting a choice of technologies for which good data were available and which would be widely recognised by policymakers and a wider audience as being in widespread use, though not necessarily ubiquitous. We included electricity generation technologies that might be viewed as less than fully commercialised (for example wind power or solar PV) or for which market size might have been larger (nuclear power). The judgements

Table 1
Innovations and geographies.

Innovation category	Product or technology	Year of invention	Geography/ geographies applying to market introduction and widespread commercialisation
Novel products for new markets – energy end use and consumer products	**Cars**	1885	US
	Cathode Ray Tube (CRT) TV	1912	US
	ATM/Cash cards	1964	UK
	Video cassette recorder (VCR)	1956	UK
Replacement products – energy end use and consumer products	**Mobile phone**	1970	US
	Thin Film Transistor Liquid Crystal Display (TFT-LCD) TV	1988	Global
	Lithium ion rechargeable batteries for consumer products	1979	Global
	Compact fluorescent light bulbs (CFLs)	1976	UK
	LED lights	1992	UK
Electricity generation technologies	**Combined cycle gas turbines (CCGT)**	1949	UK
	Wind electricity	1957	Denmark
	Nuclear power	1941	France
	Solar photovoltaics (solar PV) – grid-connected	1954	Germany

we made around definitions of widespread commercialisation and overall market share are discussed in Section 3.2.

The categories are chosen to help provide insight into some of the key factors that affect how rapidly new products reach commercial maturity. As we discuss below, the innovation literature suggests that replacement products may reach widespread commercialisation more quickly than those which require the creation of new markets, infrastructures, regulatory environment and consumption patterns (Grübler et al., 1999). The distinctions are approximate in some instances and there may be debate at the margin, for example whether cars (‘horseless carriages’) are replacement horses, or whether VCRs could be considered a replacement for reel to reel cinematography. We argue that the capabilities of cars and VCRs represent such fundamental departures from any predecessors that it is better to consider them as entirely new products.

We note that Saviotti and Metcalfe (1984) discuss a categorisation of products in terms of whether they offer new technical characteristics and/or new services. In this regard, we consider that new forms of electricity generation are also replacement technologies – since they provide the same service or output as the power generation technologies which they replace. We give separate attention to electricity generation technologies because many analyses suggest that electricity sector decarbonisation is of particular importance in reducing overall emissions (IEA, 2015, IPCC, 2015, CCC, 2015, Bassi et al., 2013) and in addition the market for these technologies is not end users (as in the case of the other technologies), but rather utilities providing electricity supply.

The geography chosen to assess the time taken for innovation is also important, since in many instances particular countries or regions provided important early markets[1] for new technologies. In a manner similar to that used by Bento and Wilson (2014), we assess the time taken to reach widespread commercialisation in early or lead markets at a national scale. In two cases market diffusion occurred rapidly across multiple countries over a short period of time (LCD-TVs and lithium ion rechargeable batteries) and we therefore present data for global market growth for these technologies. Since the point of invention is not geographically restricted and may be distinct from the country that went on to provide the first market for an emerging technology we take the year of invention as the time it occurred in any location in the world.

Table 1 provides an overview of the main technologies and their year of invention, technology categories and geographies included in the analysis.

3.2. *Defining the different stages of the innovation journey*

As shown in Table 2, the innovation literature uses a wide range of terminology to describe progressive stages of technological innovation (Dismukes et al., 2009; Wonglimpiyarat, 2005; Perez, 2002; Taylor and Taylor, 2012; Gao et al., 2013; Yeo et al., 2015). However, it is possible to identify phases for which multiple terms are used but which appear to be, in broad terms, consistent. For the purposes of this study, the timescales for each innovation were initially grouped according to three progressive phases in the innovation life cycle, identified for every product in the evidence assessment: ‘development’, ‘market formation’, and ‘growth and diffusion’. These categories were further rationalised into two composite phases: ‘invention, development and demonstration’ and ‘market deployment and commercialisation’ (Fig. 3). The first of these begins with invention and encompasses research and development, and ends at the point of market introduction of an innovation. The second phase starts with market introduction and ends when a technology or product reaches a point which we have defined as ‘widespread commercialisation’.

Fig. 3 provides a schematic of the phases defined for this study, and the wider terminology used to define different phases in the literature. Defining the start and end points of these innovation stages is not uncomplicated and providing appropriate definitions and distinctions therefore comprised an important component of the research.

We have generally taken the point of invention for each innovation as the year in which a product or a technological application was conceived and tested at laboratory scale – the first laboratory test of a prototype such as a solar cell or cathode ray tube. This is similar to the narrow definition of innovation in Grübler et al. (1999) as the first ‘practical application of an invention’. However for many of the innovations studied, the basic scientific or engineering principles underpinning an innovation predate even the laboratory stage by several decades. For example, in 1954 Bell Laboratories developed a silicon-based, laboratory-scale solar PV cell which could be translated rapidly into practical application. In the following year, Bell Laboratories used this breakthrough cell design to construct a silicon solar PV module for outdoor use to power telephone lines in Georgia. Yet, the photovoltaic effect itself was established using selenium in the late 1870s (Perlin, 1999).

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[1] These are not necessarily the definitive lead markets for each technology included in this study, and they were also selected based on available data permitting timescales to be quantified according to the definitions for innovation stages applied in the analysis.

Table 2
Key terms used to describe processes and stages of energy technology innovation (adapted from Wilson and Grubler, 2014).

Key term	Definition
Invention	Origination of an idea as a technological solution to a perceived problem or need
Innovation	Putting ideas into practice through an iterative process of design, testing, application and improvement
Research and development (R&D)	Knowledge generation by directed activities (e.g. evaluation, screening, research) aimed at developing new or improving on existing technological knowledge
Demonstration	Construction of prototypes or pilots for testing and demonstrating technological feasibility and/or commercial viability
Research, development and demonstration (RD&D)	A commonly used grouping of the main pre-commercial stages of the innovation cycle
Niche markets	Application of a technology in a limited market setting (or niche) based on a specific relative performance advantage (or on public policy incentives) and typically protected in some way from full market competition
Market formation	Activities designed to create, enhance, or exploit niche markets and the early commercialisation of technologies in wider markets
Diffusion/deployment	Widespread uptake of an energy technology throughout the market of potential adopters
Innovation, technology or product (development) life cycle	The sequence of processes and stages of an innovation's journey from invention right through to senescence or obsolescence

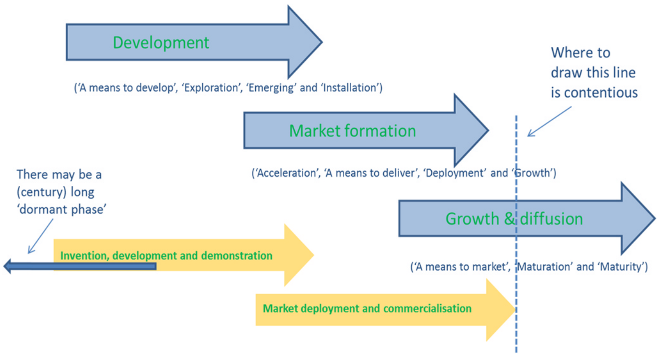

Fig. 3. Phases of the innovation timeline (authors' own).

For all end use and consumer products, we define market introduction as the point in time when products first became commercially available. For electricity generation technologies, market introduction refers to the commissioning of the first commercial units which generated electricity for supply to the grid, discounting early demonstration installations or grid-connected prototypes – similar to the approach taken by McDowall (2015) to pinpoint market entry for hydrogen fuel cell vehicles. Details of the judgements made for each technology are provided in Appendix C.

Defining 'widespread commercialisation' is more challenging. This is because a judgement is needed about when a technology is 'widespread' or 'mature' or 'established'. The term we use throughout this paper is 'widespread commercialisation'. This is not as hard and fast a concept as invention point or the entry of the first products into a market. We therefore utilised and extended definitions from the literature, which are summarised in Table 3. For example, Grübler et al. (1999) refer to the notion of the 'pervasive diffusion' of technologies in which a rapidly increasing commercial market share of 5–50% is achieved. Based on Rogers (1962), wider commercialisation might be represented by between 15% and 50% of potential adopters taking up a new product: if the early majority adopts an innovation, this would cover half the eventual number of adopters, as opposed to the first 15% being accounted for by initial innovators (2.5%) and early adopters (12.5%). Lund's comparison of market penetration rates for energy technologies uses a definition of 'market potential' taken at different market shares (1–50%) for different technologies, varying both by constraints to reaching higher market shares (e.g. renewable energy intermittency) and the geographical size of the market (Lund, 2006). Vaclav Smil provides a more consistent definition – referring to the time taken for the rise of a new "fuel or prime mover" from a 5% to a 25% share of global energy supply (Smil, 2010a). Wonglimpiyarat (2005) refers to a 'means to market' phase which begins after: '…the distribution capabilities (distribution channels) are sufficient to access 20% of the target population of users for the innovation'. Bento and Wilson propose that a 10% market share represents one indicator of the end of the 'formative phase' (Bento and Wilson, 2016). The precise meaning of the end of the formative phase is linked to innovation systems theory, representing a transition point between a technology that is in a nascent market and one that is in a more established market. In terms of the journey towards wider commercialisation, this falls some way short of the definition of widespread use sought for this paper.

There are thus no agreed quantitative definitions of invention, market introduction or widespread commercialisation in the literature. The size and specification of market share that is chosen to represent widespread commercialisation differs considerably within the literature and there is no more consistency (and indeed some ambiguity) over what reference point – ultimate market size, fully adopted, saturated, etc. – is used (Table 3). The definitions of start points and – even more challenging – the end point used herein were therefore chosen to permit technologies to be compared on a 'like for like' basis within each of the technology categories described in the main text. They were created to

Table 3
Definitions of widespread market diffusion of innovations: examples from the literature.

Author(s) (year)	Name / description of metric	Definition of widespread market diffusion
Bento and Wilson (2016)	Formative phase	10% of eventual market saturation (units produced and capacity installed); or 10% of maximum unit capacity
Grübler et al. (1999)	Pervasive diffusion	5–50% commercial market share
Lund (2006)	Market potential	1–50% market potential or adoption ceiling
Rogers (1962)	Early majority	15–50% of potential adopters taking up an innovation
Smil (2010a)	Time for a new 'fuel or prime mover' to achieve given shares of total global energy supply	25% share of global energy supply
Wonglimpiyarat (2005)	Means to market	Distribution channels can access 20% of target population of users for the innovation

Table 4
Defining the point of widespread commercialisation.

Innovation category	How widespread commercialisation is defined in this study	Geographies applicable
Novel products for new markets	When the yearly number of products in ownership, use or installed in the marketplace first reaches 20% of peak products in use (i.e. the maximum number of products in ownership, use or installed in the marketplace, based on annual time series data).	UK, US
Replacement products or technologies	As above	UK, US, Global
Electricity generation technologies	When installed capacity first reaches 20% of peak installed capacity (i.e. the maximum installed capacity of that technology based on annual time series data).	UK, Denmark, France, Germany

help inform policy by providing a reasonable approximation of the time taken for a successfully commercialising product to emerge from the research stage and commercialise – in particular, to represent when use of new products became widespread, though not necessarily ubiquitous or market saturated. This is important because a principal goal of the research is to assess the time needed to achieve usage on a scale where it might be material to carbon abatement goals. Whilst acknowledging that there is no 'right answer' (it could be 15% or even 50% of ultimate market) we propose 20% of ultimate market size as an approximate measure of widespread commercialisation, for all categories of technology. More precisely, our definitions are as follows (see also Table 4):

We consider both *novel products for new markets* and *replacement products* to have reached widespread commercialisation when the number of products in use (i.e. the yearly number of products in ownership, use or installed in the marketplace) first reaches 20% of peak products in use (i.e. the maximum number of products in ownership, use or installed in the marketplace, based on annual time series data). *Electricity generation technologies* are considered to be in widespread commercialisation when their installed capacity first reaches 20% of peak installed capacity of the technology in question (the maximum installed capacity of that technology – not all electricity capacity – based on annual time series data).

Only a few of the technologies included in this analysis are obsolete (e.g. CRT TVs have been replaced by LCD TVs; VCRs were replaced by DVD players), while the installed capacity of nuclear power in France peaked in 1999. Most of the innovations included in the study are contemporary, commercially established technologies, with sales that continue to add to the cumulative stock of products, and many have yet to reach their maximum market volume. In these cases, the current[2] number of products in use (or installed capacity for electricity generation technologies) is taken as a proxy for the peak market size. This is discussed further in Sections 4.2 and 5.1. In all cases a variety of alternative definitions were explored in the research, including when replacement products overtook sales of incumbent products, or when electricity production reached a fraction of total electricity sales (Hanna et al., 2015). The definitions above were chosen in order to maximise consistency across our categories of innovative product. In the case of electricity generation we chose fraction of total installed capacity of the *technology in question* (wind, gas, solar, etc.) rather than total installed capacity, electricity sales, or share of customers for the reason that in many (almost all) countries a mix of power generation sources are used and there is no reason to expect any one technology will come to provide all electricity. In line with the pragmatic approach taken generally we were seeking a measure that would permit a consistent and readily understood definition of widespread commercialisation.

We have characterised the innovation journey in terms of the cumulative adoption of each technology against time. Progress with innovation could alternatively be measured through patent applications or technological performance and there are alternatives to using time as a metric for the innovation journey, such as tracking innovation against investment in technological development (Taylor and Taylor, 2012). However the focus of the paper is on the temporal dimension of technology development.

In Appendices B and C we present in further detail the timelines for each technology reviewed and some of the assumptions and judgements that were used to determine these timescales. We also provide the historical context and reference sources used to construct timelines for each technology.

A final and crucially important point of note before discussing specific technologies is that innovation does not proceed in a linear fashion from one stage of the technological diffusion to the next (Wilson and Grubler, 2014). The 'innovation journey' should not be conflated with any suggestion that R&D is 'finished' for any particular technology. Technologies rarely move out of the R&D stage completely following market introduction. Ongoing R&D is crucial to improving performance and reducing costs even in the most mature of technologies (Sanden and Azar, 2005). This is a fundamentally important caveat to the historical analyses that follow and a point we reiterate in our discussion and conclusions.

4. Key findings on innovation timescales

4.1. Introduction

This section provides an empirical review of 13 products and technologies whose journeys from invention to widespread commercialisation span the late 19th Century through to the present time. A detailed review of sources of historical information is drawn together with the definitions of the start of each stage and reaching of widespread commercialisation, as explained in Section 3.2. Technologies are organised into three categories, described below in order to inform a discussion of factors which affect the time taken for products to enter into markets and reach widespread commercial use.

4.2. Chronology of innovations

The technologies here represent a diverse range of consumer goods, together with electricity generation options. Most were invented after 1940 – while the car and cathode ray tube TV (CRT TV) were invented in 1885 and 1912 respectively (Fig. 4). More recent products appear on the whole to have developed and commercialised more quickly, although additional research based on a larger sample of technologies more evenly distributed through time would be needed to confirm this trend. The nature of our definition of widespread commercialisation also creates a tendency towards comparatively longer timescales for older, obsolete products such as the CRT TV, whose market volume peaked and then declined. Conversely, our approach might create a tendency towards shorter timescales for those products which can be considered widely commercialised, but may have yet to reach their ultimate market volume. This latter effect applies both to the car and to more recent products in the sample (see Section 5.1).

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[2] Based on the latest available year of data collected as part of the evidence review.

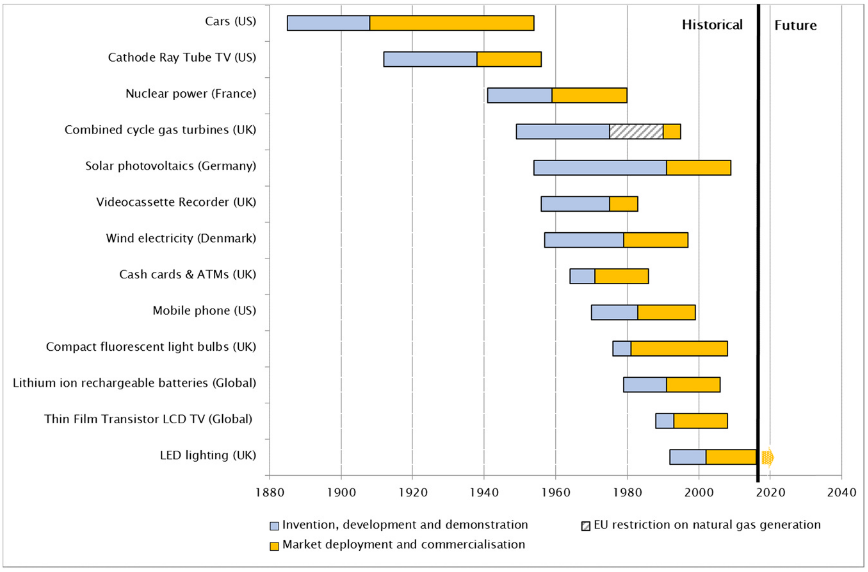

Fig. 4. Historical timelines of innovation for all technologies reviewed.

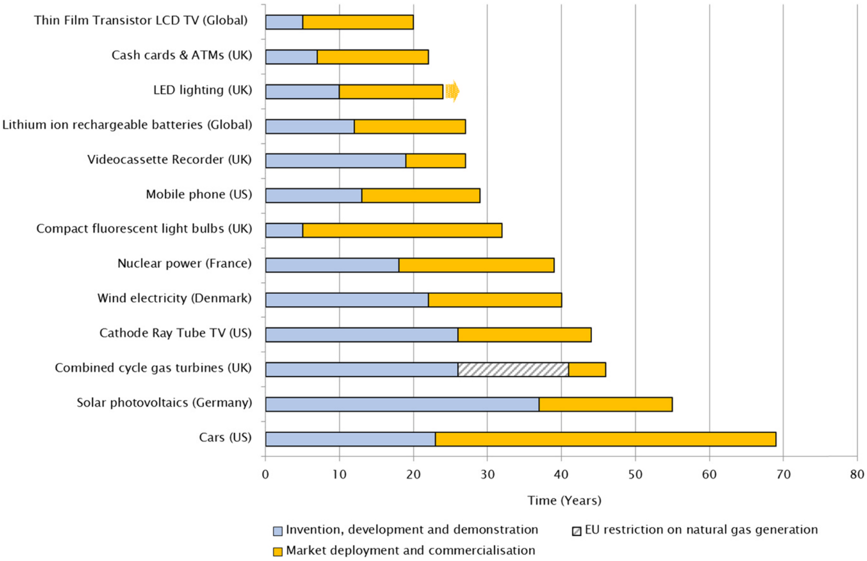

Fig. 5. Duration of innovation for all technologies reviewed.

4.3. Duration of innovation: general observations

The findings demonstrate that the journey to our definition of widespread commercialisation takes between two and four decades for most of the products and technologies reviewed. The median time taken from invention to widespread commercialisation was 32 years. Fig. 5 orders the innovations by the duration of their innovation journey. The shortest time to commercialisation was 20 years (for the LCD TV), while the longest was 69 years (the car). Although the median duration of the two innovation stages (invention, development and demonstration, and market deployment and commercialisation) is the same at 18 years, the length of each phase shows considerable variation across the innovations reviewed. For example, the shortest time taken for invention, development and demonstration was 5 years (the compact fluorescent light bulb and the LCD TV), while the longest was 37 years (solar PV). Similarly, the shortest time from market introduction to widespread commercialisation was 8 years for the VCR whereas the longest was 46 years (the car). In addition, CCGT in the UK took just 5 years to reach widespread commercialisation after a 15-year moratorium on gas generation and during the 'dash for gas.' The particular case of CCGT is discussed in Section 5.1.

4.4. Duration of innovation by technology category

Fig. 6 groups the innovation timescales by technology category: Novel energy end use and consumer products (new products with entirely new markets); Replacement energy end use and consumer products (new technologies which replace but perform a similar function to an existing product); and electricity generation technologies.

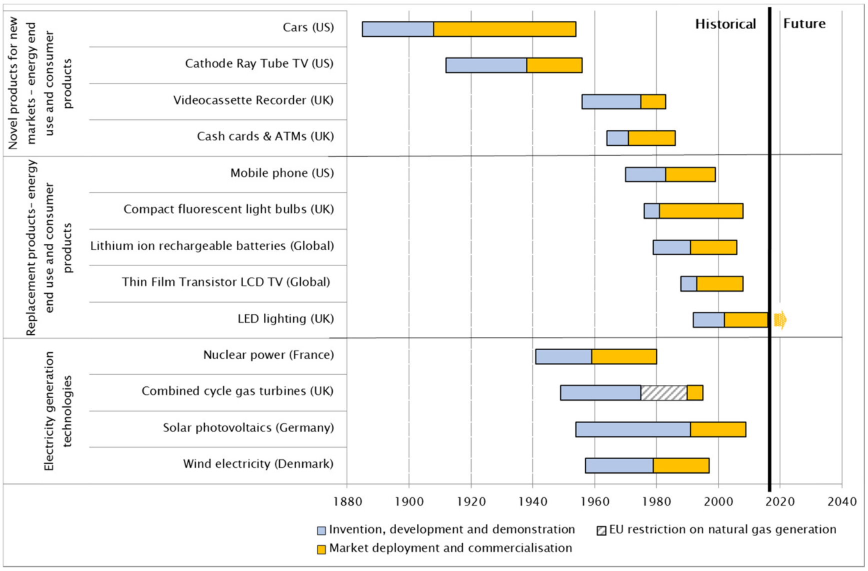

Fig. 6. Historical timelines by product / technology category.

Table 5
Range of innovation duration by technology category (median durations indicated in brackets).

Innovation group	Innovation sub-category	Invention, development and demonstration	Market deployment and commercialisation	Total duration (years)
Energy end use and consumer products	Novel products for new markets	7–26 *(21)*	8–46 *(16.5)*	22–69 *(35.5)*
	Replacement products	5–13 *(10.0)*	14–27 *(15.0)*	20–32 *(27.0)*
Energy end use or supply	Energy end use and consumer products	5–26 *(12.0)*	8–46 *(15.0)*	20–69 *(27.0)*
	Electricity generation technologies	18–37 *(24.0)*	18–21 *(19.0)*	39–55 *(43.0)*
All innovations	**Median**	**18.0**	**18.0**	**32.0**
	Minimum	**5**	**8**	**20**
	Maximum	**37**	**46**	**69**

Table notes.
Novel products for new markets: Cars; Cathode Ray Tube (CRT) TV; ATM/Cash cards; and VCR.
Replacement products: Mobile phone; Thin Film Transistor Liquid Crystal Display (TFT-LCD) TV; lithium ion rechargeable batteries; compact fluorescent light bulbs (CFLs); and LED lights.
Electricity generation technologies: CCGT, nuclear power, wind electricity and solar PV.
The market deployment and widespread commercialisation phase and the median total timescale for the electricity generation technologies include the EU regulatory restriction on gas generation (and therefore CCGT) from 1975 to 1990.

5. Discussion

In what follows we consider the implications and limitations of the findings of the review, and compare the findings to the observations made by other authors. Overall, electricity generation technologies exhibit some of the longest commercialisation time periods within the technologies reviewed. The median time from invention to widespread commercialisation was 43 years for the four electricity generation technologies included in our study. In comparison, the nine energy end use and consumer products have a median duration of 27 years from invention to widespread commercialisation (Table 5). Lund (2006) also finds a shorter time to market penetration for some energy end use products (which can be less than 25 years) compared to energy production technologies. Our research does not provide a clear reason for this difference; however it is consistent with a number of potential explanations. For one, electricity generation technologies typically have long asset lives – several decades in the case of power stations. They therefore take longer to replace than many consumer products (Grubler, 1998). A number of studies also indicate that electricity generation technologies require time to achieve up-scaling, thereby enabling the widespread deployment of large-scale units (Bento and Fontes, 2015; Grubler, 2012; Wilson, 2012).

The two renewable generation technologies, solar PV (55 years in Germany) and wind (40 years in Denmark), also have amongst the longest timescales of the 13 innovations included in our study. Slow diffusion timescales for renewable energy technologies were observed in the early 2000s in European countries by Negro et al. (2012), who point to a range of innovation system failures which constrain their deployment, such as a lack of long term and consistent institutional support. Such failures are compounded by lock-in to incumbent fossil fuel technologies which have become optimally aligned with supporting institutions and have benefited from economies of scale and technological learning over extensive periods of time (Negro et al., 2012). However it is important to note the significant growth in renewables capacity experienced in many countries in more recent years. It is possible that diffusion rates will increase as technology costs fall.

As noted in Section 3.1, it has been suggested that new products which replace the function provided by a pre-existing product diffuse more quickly than those products which provide a completely new service (Grübler et al., 1999). If new institutions or infrastructures are needed to commercialise a technology, it will tend to take a longer time to develop and its diffusion is likely to be slower. Conversely, the rate of technological diffusion may be faster for replacement products which have a greater perceived relative advantage over incumbent or rival products (Grubler, 1998). More rapid formative phases have been observed for innovations which are 'ready substitutes' for pre-existing technologies, compared to 'non-ready substitutes' which take longer to align with new institutions and stimulate market demand (Bento and Wilson, 2016). This is broadly consistent with our review findings, which show that replacement consumer products had a shorter median period from invention to widespread commercialisation (27 years) than products aimed at entirely new markets (35.5 years) (Table 5). Many factors are relevant here, not least the dramatic reduction in retail prices of 'aspirational' products such as flat screen TVs relative to prices for incumbent products and to incomes (Energy Saving Trust, 2007). The LCD TV travelled from invention to widespread commercialisation in less than half the time (20 years) it took the Cathode Ray Tube (CRT) TV (44 years).

It is important to exercise considerable caution in drawing overly firm conclusions from the relatively small sample the review considered. Moreover, two of the four new products - cash cards/ATMs and the videocassette recorder – achieved widespread commercialisation in less than three decades (Fig. 5). Nevertheless, it appears likely that replacement products which do not require new infrastructure or institutions will tend to reach widespread commercialisation more rapidly than entirely new concepts that require wider system change.

5.1. Limitations

In seeking a widely applicable definition of widespread commercialisation, based upon available data, our analysis gives rise to a number of difficulties and limitations. Some of these manifest with regards to particular technologies, others are more generic. We discuss each in turn.

The car: The long timescale for the car came as a considerable surprise given the rapid adoption of automobiles in the US in the early twentieth century. The principal reason it took so long for the car to reach our definition of widespread commercialisation in the US is that extensive growth in the market for automobiles continued over most of the twentieth century. This was driven as much by population and economic growth, and growth in private incomes, as innovation in vehicle manufacturing and technology. Incomes needed to reach a level sufficient for widespread uptake of the car to be possible (Grubler, 1998), since the purchase of a car required (and still does) a very large expenditure relative to income compared to all the other consumer products reviewed.

Gas fired power stations: CCGT in the UK is also a special case, because it experienced a significantly later market introduction in the UK than globally (the first 'large' CCGTs over 100 MW were sold in Japan and France in 1970), due in part to an EU regulatory restriction on natural gas generation from 1975 to 1990 (Watson, 1997). The rapid deployment of CCGT that followed in the early 1990s has been associated with the liberalisation of the UK electricity market, and the so-called 'dash for gas' (Watson, 1997).

LED Lights: The replacement products selected in this study have gone on to replace the incumbent product(s) by achieving the largest share of annual sales or products in use, with one exception – the LED light bulb. LED lights have considerable potential to replace incumbent lighting products and in particular the CFL, but are still in an early stage of market growth and represent only a small fraction of light bulbs installed in UK households: 0.6% in 2016 (BEIS, 2017b). For these reasons, LEDs have not yet reached widespread commercialisation according to our definition, despite their widespread availability to consumers.

More broadly it is likely that as well as technology or market specific factors the length of any technology's gestation period could be affected by macroeconomic and societal factors, from wars and recessions to changing use of digital and social media. In compiling evidence for our case studies, we note for instance that the expansion of car manufacturing in the US in late 1920s was disrupted by the Great Depression (Mercer and Douglas Morgan, 1971). Bento and Wilson (2016) show a relatively quick formative phase for nuclear power associated with the unusually high demand pull from military users during World War Two.

The findings on innovation timescales are sensitive to the technology case studies selected. The approach taken to selecting technological innovations in our study sought to allow a comparison of innovation timescales across a diversity of energy-related and broader consumer products, so that insights might be drawn from observed differences between consumer products and energy supply or end use technologies. Our evidence review has not set out to categorise technological innovations or products in terms of whether they are consumer, investor or government-led, or to consider the impact of these aspects on innovation timescales. However, technology and market factors influencing commercialisation timescales may vary considerably between consumer-led products and those driven more by policy or investment by manufacturers or utilities. For example, compared to consumer-led products (e.g. the mobile phone or LCD TV), electricity generation technologies such as solar PV and wind may lack demand pull since their benefits are less immediately tangible to consumers and may be 'non-market' factors (such as lower emissions) which Grubler et al. (2016) associate with slow energy transitions.

It is conceivable that emerging developments such as the rollout of smart meters, household ICT and energy management, and peer-to-peer electricity trading could result in a blurring of traditional boundaries between electricity as a supply or end use activity. This could lead to increasing levels of consumer demand for smart and flexible energy services and potentially shorter timescales to widespread commercialisation for associated carbon abatement technologies.

A further caveat is with respect to the point of widespread commercialisation and peak product use. Widespread commercialisation has been taken as 20% of peak or current installed products in use (or installed capacity for electricity generation). Older technologies such as the CRT TV, which have already passed peak volume and declined into obsolescence, will tend to show a more extended timescale in comparison to products which have not yet reached their peak. For many of the more recent products in the sample as well as for the car, markets still appear to be growing. Hence the 20% level may be reached earlier, because the full extent of growth in the volume of products is not yet known.

6. Conclusions and policy implications

Our review suggests first and foremost that the process of innovation, as defined from the point of invention to the point of widespread commercialisation, can be a multi-decadal process – taking thirty or forty years for many of the technologies in this study. We also note that in many cases the scientific principles that were put to use in new technologies were established at an even earlier stage.

The first policy insight which follows is that any suggestion that the principal response to the challenge of climate change should be an intensive research effort to discover new, breakthrough low-carbon technologies needs to be treated with a considerable degree of caution. Such an approach risks taking too long to deliver the solutions needed to address climate change, even assuming entirely new, breakthrough technologies can be found.

Care needs to be taken in extrapolating innovation timescales from the past, and historical contexts from early in the twentieth century will obviously differ from the future of technological development. It is of course possible that entirely new, low carbon, technologies could be discovered in the coming years and that these could be pushed through the various phases of research, demonstration and market introduction exceptionally quickly. However the attainment of a low-carbon energy system in the coming decades is far more likely to be the result of the full commercialisation of energy technologies already available, or which are close to being deployed at scale. This implies that technology deployment policies, including regulation, subsidy schemes and targets continue to be at least as important as support for fundamental research and development.

Whilst not the principal focus of our research it is also important to reiterate that research and development continue throughout the period of commercialisation. Ongoing research is often undertaken in concert with the learning, innovation and cost reduction which results from the manufacture, market penetration and use of technologies. As such, the choice for policy makers is not one of *either* supporting R&D *or* supporting deployment, but of how to strike the right *balance* between these policies as technologies are first developed and then enter markets.

Another insight from this analysis concerns the potential for more rapid commercialisation of end-use products when compared to electricity generation technologies. The review does not provide a definitive view, since the sample size is small. However, the products reviewed here suggest that consumer products such as phones and flat screen TVs have tended to commercialise relatively rapidly. There is also evidence to suggest that replacement products which can benefit from established infrastructures and institutions commercialise more rapidly than those which are entirely new concepts.

A taxonomy of key low-carbon technologies that considers these factors could prove fruitful in identifying those which could penetrate into markets rapidly, versus those that are likely to do so more gradually. It may also be possible to begin to assess where various barriers to commercialisation exist and to address these directly.

Understanding the realistic timescales for the commercialisation of different energy technologies in this way could provide a critically important ‘reality-check’ for future low-carbon scenario-analysis, in terms of which technologies are required to be deployed at given points in time. Further research could investigate the consistency between historically-observed and modelled diffusion rates for different low carbon technologies, across a range of energy systems models and scenarios. This could help identify and avoid significant bottlenecks or errors, as well as identify where different policy efforts should be targeted to achieve the desired transition pathway.

As we look to the future it is important that innovation policy continues to recognise that sustained support for low carbon technologies is likely to be required over many decades. Policy efforts to promote ‘breakthrough’ technologies are important, particularly in areas where low carbon substitutes for existing products or processes are yet to be found. However it would be unwise if climate policy were to focus excessively on RD&D, neglecting the time and effort needed to ensure that low carbon technologies find a route to market. Climate policies will need to continue to ensure that lower carbon options are given the support that they may need to compete with incumbent technologies until they become established and secure widespread use.

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Author contributions

RG proposed the research design. RH led the review and analysis of empirical evidence, with contributions from RG, PH, JS and AG. RG wrote the first draft of the paper. All authors contributed to the final version.

Competing financial interests

The authors declare no competing financial interests.

Appendix A. Keyword searches used to identify relevant literature in Science Direct and World Cat

Initial search term categories		Subsequent search term filters
Innovation	**Temporal**	**Innovative technology or product**
Innovation	Time	Cars / automobiles
Research	Life	“Catalytic converter”
Mass market	Cycle	“Lithium ion” AND “car batteries”
"Market saturation"	Rate	“Lithium ion” AND “rechargeable batteries”
Commercialisation	Speed	Television / “Cathode Ray Tube TV” / “CRT TV”/ “Liquid Crystal Display TV” / “LCD TV”
Deployment	History	“Automatic Teller Machine” / ATM / “cash cards”
Diffusion		“Videocassette recorder” / VCR
Uptake		Photocopier / “plain paper copier”
"Innovation life cycle"		“Mobile phone”
"Technology life cycle"		“Compact fluorescent light bulbs” / CFLs
Technology		“LED light bulbs” / “LED lamps”
"Product development"		“Combined cycle gas turbines” / CCGT
		“Wind electricity”
		“Nuclear power”
		“Solar photovoltaics” / “solar PV”

Appendix B. Comparison of the timescales, chronology and geographical scope of the data revealed through our review, upon which the discussion of findings in our paper draws

(a) Novel products for new markets – energy end use and consumer products

Innovation	**Geography for market introduction and widespread commercialisation***	**Invention, development and demonstration**	**Market deployment and commercialisation** *(Widespread commercialisation taken at 20% of peak products in use or ownership)*	**Total time taken for widespread commercialisation** (*Time taken in years to reach 20% of peak products in use or ownership)*
Cars	US	1885–1908	1908–1954	69
Cathode Ray Tube (CRT) TV	US	1912–1938	1938–1956	44
ATM/Cash cards	UK	1964–1971	1971–1986	22
Video cassette recorder (VCR)	UK	1956–1975	1975–1983	27

(b) Replacement products – energy end use and consumer products

Innovation	**Geography for market introduction and widespread commercialisation***	**Invention, development and demonstration**	**Market deployment and commercialisation** *(Widespread commercialisation taken at 20% of peak products in use or ownership)*	**Total time taken for widespread commercialisation** (*Time taken in years to reach 20% of peak products in use or ownership)*
Mobile phone	US	1970–1983	1983–1999	29
Thin Film Transistor Liquid Crystal Display (TFT-LCD) TV	Global	1988–1993	1993–2008	20
Lithium ion rechargeable batteries for consumer products	Global	1979–1991	1991–2006	27
Compact fluorescent light bulbs (CFLs)	UK	1976–1981	1981–2008	33
LED lights	UK	1992–2002	2002–2016**	24**

(c) Electricity generation technologies

Innovation	**Geography for market introduction and widespread commercialisation***	**Invention, development and demonstration**	**Market deployment and commercialisation** *(Widespread commercialisation taken at 20% of peak installed capacity)*	**Total time taken for widespread commercialisation** (*Time taken in years to reach 20% of peak installed capacity)*
Combined cycle gas turbines (CCGT)	UK	1949–1990	1990–1995	46
Wind electricity	Denmark	1957–1979	1979–1997	40
Nuclear power	France	1941–1959	1959–1980	39
Solar photovoltaics (solar PV) – grid-connected	Germany	1954–1991	1991–2009	55

*Geography is global for the invention of all innovations reviewed.

**This innovation has yet to reach the definition of widespread commercialisation to which the table column applies.

Appendix C. Summary of the judgements made and the reference material used in applying our definitions of invention, market introduction and widespread commercialisation to each innovation reviewed

Novel products or technologies for new markets

Innovation	How year of invention / conception is defined	How year of first market introduction is defined	How year of widespread commercialisation is defined
Cars	First vehicle powered by a combustion engine was built in 1885 (Bellis, 2015).	The first production of the Ford Model T in 1908 (Dismukes et al., 2009) has been taken as the point of market introduction. This is consistent with Mercer and Douglas Morgan (1971), who state: 'The American automobile industry really began its commercial existence only in 1900, while the rise of national corporations and the first real growth of the industry did not start until after the short business recession of 1907.'	In 2014 there were 258 million household vehicles in operation in the US, the highest number for any year from 1950 to 2014. 20% of this was achieved in 1954, when there were 53 million household vehicles in operation in the US (Oak Ridge National Laboratory, 2015).
Cathode Ray Tube (CRT) TV	Alan Archibald Campbell Swinton proposed an electronic television system in 1908. In 1912, Boris Rosing used a cathode-ray tube (CRT) for electronic television display (Magoun, 2009).	The first electronic CRT television set was introduced to the US market in 1938: 'the DuMont Corporation was the first manufacturer to sell all-electronic television receivers to the public when it made its model 180 sets available.....in the waning months of 1938' (Edgerton, 2007)	The peak number of CRT TVs in the US was 215–219 million in the mid-1990s. 20% of this is 43–44 million. The US had a total of 43 million TVs in use during 1956, with 47 million in 1957, so 20% of peak CRT TVs in use was reached in 1956, to the nearest year approximation (UNESCO, 1963; IEA, 2009, NationMaster, 2017a, NationMaster, 2017b).
Automatic teller machine (ATM)/Cash cards	The ATM / cash card represents a complex innovation which was developed based on the cumulative knowledge of a number of earlier innovations in the 1950s and 1960s, including self-service gas stations, automatic public transport ticketing and candy dispensers (Bátiz-Lazo, 2015).	The very first cash machine were installed by Barclays in London in 1967, while a Chubb ATM/ cash card system was also deployed in London a month later. Another cash dispensing machine was also installed independently in 1967, in the form of the Bankomat in Sweden (Batiz-Lazo and Reid, 2008; Bátiz-Lazo, 2015).	Based on data on the number of installed ATMs in the UK, from 1975 to 2003 (Batiz-Lazo, 2007). The highest number of installed ATMs for any year was in 2003, when there were 46,461 ATMs. 20% of this was attained in 1986, in which year there were 10,330 installed ATMs in the UK (Batiz-Lazo, 2007).
	Nevertheless, the point of invention is taken as 1964, when Smiths Industries collaborated with Chubb & Sons Lock and Safe Company (Chubb) to develop a system for dispensing oil to tanker drivers using a punched card (Batiz-Lazo and Reid, 2008).	However, it was not until 1971 that cash machines were more widely introduced to markets worldwide by manufacturers operating in Great Britain, the US and Japan, in their own countries as well as across Europe, Israel, Canada, and South America (Bátiz-Lazo, 2015).	
	This was the foundation upon which European banks conceived an automatic system to provide customers access to cash outside of bank opening hours. The first patent for a currency dispenser system was issued in 1966, integrating a private identification number (PIN) with a public number (PAN) (Batiz-Lazo and Reid, 2008; Bátiz-Lazo, 2015)		

Video cassette recorder (VCR)	The date of invention has been taken as 1956, when the first practical magnetic tape video recorder, the VRX-1000, was released by Ampex (Magoun, 2009; Castonguay, 2006). This precedes the year attributed to the 'conception of the technical basis of the innovation', i.e. 1960 (Wonglimpiyarat, 2005).	The VCR was 'launched into the market-place' in 1975 (Wonglimpiyarat, 2005). This is the year when Sony released Betamax, with JVC's VHS following in 1976, and Phillips releasing the V2000 in 1978 (Castonguay, 2006).	The dataset used is sourced from DECC (2015) and includes annual totals for VCRs and DVDs together but not separately. The year with the highest number of VCRs (19.3 million) owned by UK households has been taken as 1997, a year before DVDs were introduced in the UK (Andrews, 1998). The first year in which the number of VCRs in UK households first reached 20% of 19.3 million was 1983 (DECC, 2015).

Replacement products or technologies

Innovation	How year of invention / conception is defined	How year of first market introduction is defined	How year of widespread commercialisation is defined
Mobile phone	First presentation of the mobile telephony concept by AT&T Bell Labs in the early 1970s (Yeo et al., 2015).	In 1983, the analogue mobile phone was launched commercially in the US by Motorola (Giachetti and Marchi, 2010).	Over the period 1975–2015, the maximum number of mobile phone subscriptions in the US was 377 million in 2015. This subscription total was calculated by multiplying 1.2 subscriptions per 100 people from World Bank (2017) by the US population of 321 million in 2015 (US Census Bureau, 2016). 20% of 377 million subscriptions was reached in 1999, when there were 83 million subscriptions (0.25 subscriptions per person multiplied by 273 million population) (World Bank, 2017, US Census Bureau, 2000). Product replacement: In 2002 globally, the number of mobile phone users overtook the 1.1 billion people with fixed telephone lines (Bohlin et al., 2010).
Thin Film Transistor Liquid Crystal Display (TFT-LCD)	The invention point has been taken as 1988, when Sharp developed a 14-in., colour TFT-LCD TV (Sharp, 2015).	The first LCD and plasma TVs were introduced to the market in the 1990s (IEA, 2009). Market introduction has been taken as 1993 based on Figure 97 in IEA (2009), which estimates global market share of annual sales by television technology type from 1990 to 2008.	Using global LCD TV shipment data (Statista, 2017, TrendForce, 2017) and varying the assumed average in-use life span of an LCD TV from 3 years to 10 years to derive total numbers in-use year-on-year shows peak number of products in-use occurring in 2016 (the most recent year of data). The peak volume is 655 million to 1.8 billion products-in use depending on the assumed product lifespan. 20% of this peak was reached between 2007 and 2009, varying by the assumed product lifespan. We have used 2008 as the mid-point. Product replacement: Sales of LCD TVs first overtook sales of CRT TVs in 2006 in the UK (Energy Saving Trust, 2007) and in 2007 in the EU (Fraunhofer Institute, 2007). The global market share of LCD TVs and CRT TVs was approximately equal in 2008 (IEA, 2009) while in 2010 LCD TVs comprised 77% of global TV shipments, with CRT TVs making up just 16% (Park et al., 2011).

Lithium ion rechargeable batteries for consumer products	Development of the lithium cobalt oxide positive electrode (Mizushima et al., 1980).	First commercially available lithium ion rechargeable battery (Sony, 1996).	The total in-use capacity of lithium-ion rechargeable batteries has been estimated by using data on lithium-ion battery sales for consumer use in GWh from Deng (2015) and assuming battery lifetimes of 2 years and 3 years respectively based on (Muenzel et al., 2015) and (Tektronix, (n.d.)). Assuming an average battery lifetime of 2 years, the highest total capacity of lithium-ion batteries in use for any year from 1998 to 2016 was 83 GWh in 2016. 20% of this peak consumption was reached in 2006, when total in-use capacity was 19.5 GWh. Assuming an average battery lifetime of 3 years, the highest total capacity of lithium-ion batteries in use for any year from 1998 to 2016 is 119 GWh in 2016. 20% of this peak consumption was also reached in 2006, when total in-use capacity was 23.8 GWh. Product replacement: Global sales of lithium ion batteries reached 50% of all rechargeable battery sales in 1998 (Goonan, 2012).
Compact fluorescent light bulbs (CFLs)	In 1976 Jan Hasker (Philips) developed the 'Recombinant Structure CFL', while Edward Hammer (General Electric) developed the 'Spiral' CFL (Smithsonian Institution, 2015).	The first compact fluorescent light bulb (CFL), the Phillips SL, was released to the US market in 1980 (Miller, 2012). However, our geography for the deployment of the CFL is the UK, and therefore we have taken market introduction as the first year that CFLs had a > 0% share of all lighting appliances in UK households, i.e. 1981 (BEIS, 2017b).	The maximum number of products for any given year was in 2016, when there were 418 million 'energy saving light bulbs' in UK households. 20% of this maximum was reached and surpassed in 2008, when there were 88 million energy saving light bulbs in UK households (BEIS, 2017b). Product replacement: Energy saving light bulbs first achieved a dominant market share in UK homes in 2011, comprising 44% of all light bulb/lighting appliances in households (BEIS, 2017b).
LED lights	In 1992, a visible blue and green InGaN LED was developed by Nichia, attaining 10% efficiency. The InGaN LED was a key milestone leading to white LED lighting, with the first white LED introduced by Nichia in 1996 (Sanderson and Simons, 2014).	Market introduction based on the first year of that LED light bulbs had a > 0% share of all lighting appliances in UK homes (BEIS, 2017b).	LED light bulbs are still at a relatively early stage of commercialisation and have yet to replace incumbent lighting products to a significant extent, with only a small market share of installed lighting appliances currently. We therefore consider that LED light bulbs have not yet reached 'widespread commercialisation' as defined in this study. There were 4.9 million LED light bulbs in UK households in 2016, although LED lights comprised just 0.6% of all lighting appliances fitted in UK households (BEIS, 2017b). Globally in 2011, residential lighting accounted for 40% of the general lighting market, while LED lighting itself was estimated to have a 7% market share in residential lighting (McKinsey, 2012).

Electricity generation technologies

Innovation	How year of invention / conception is defined	How year of first market introduction is defined	How year of widespread commercialisation is defined
Combined cycle gas turbines (CCGT)	1949 – General Electric installed a 'fully-fired combined cycle turbine' in the US, in which a 3.5 MW gas turbine operated in conjunction with a 35 MW steam plant. Nevertheless, Brown Boveri had considered the possibility of CCGT since installing their first industrial gas turbine in Switzerland in 1939, leading to their installation of a CCGT in Luxembourg in 1956 (Watson, 1997).	1970 globally – the first `large' CCGTs (greater than 100 MW) were sold by Mitsubishi for location in Japan and by Brown Boveri for installation in France. These achieved contemporary standards for most CCGTs, in that two thirds of the power output was supplied by the gas turbine, with the steam turbine providing the remaining third. Additionally, plant efficiency for these CCGTs was starting to exceed 40% (Watson, 1997). In the UK, the first orders for CCGT occurred during the liberalisation of the electricity market and the 'dash for gas' from 1989/1990, with the first operational CCGT capacity in 1991 (Watson, 1997). CCGT in the UK experienced a significantly later market introduction in the UK than globally, due in part to an EU regulatory restriction on natural gas generation from 1975 to 1990 (Watson, 1997).	CCGT achieved a peak installed capacity of 33 GW in the UK in 2012 (BEIS, 2017a). 20% of this was reached in 1995, when there was approximately 8.5 GW of CCGT in the UK (Kern, 2012).
Wind electricity	In 1957, Johannes Juul completed the construction of a 200 kW wind turbine known as the 'Gedser-molle' and the father of modern wind turbines. This is because, as a three-blade, upwind turbine, it was effectively a prototype for wind turbines produced during the oil crises of the 1970s ((Jones and Bouamane, 2011, Danish Wind Industry Association, 2003). For example, in 1975 Nasa refurbished the Gedser wind turbine in order to extract measurement data for the US wind energy programme (Danish Wind Industry Association, 2003).	The first commercial wind turbine (a 30 kW turbine) was installed in Denmark in 1979 (Ministry of Foreign Affairs of Denmark, 2016). This is consistent with Danish Energy Agency (2009), which states that 'the first batch-produced Danish wind turbines from the late-1970s had an output of 22 kW' (Danish Energy Agency, 2009).	Peak installed capacity of wind power was 5.3 GW in 2017 (Danish Energy Agency, 2017). 20% of this was reached in 1997, when wind power in Denmark had a total installed capacity of 1.1 GW.
Nuclear power	The history of electricity generation from nuclear power can be traced back to the 1950s, with the basic principles of an energy-releasing process using nuclear fission being established by 1939. The point of invention has been taken as 1941, when a report by the MAUD committee in the UK first proposed the 'use of uranium as a source of power', although this proposal was shelved until the end of World War Two (WNA, 2014).	The first commercial nuclear reactors in France operated in 1959, while a pre-commercial reactor using a gas-graphite design was started up in France in 1956 (WNA, 2014).	Peak installed capacity of nuclear power was reached in France in 1999 when there was 63 GW (WNA, 2017). 20% of this is 12.6 GW. Installed nuclear capacity reached 8.6 GW in 1979 and 15 GW in 1980 (WNA, 2017), so the 20% threshold was crossed in 1980.
Solar photovoltaics (solar PV) – grid-connected	In 1954, three scientists at Bell Laboratories (Pearson, Chapin and Fuller) developed a laboratory-scale, silicon-based solar cell which could be translated rapidly to practical use, as a result of using silicon rather than selenium. In 1955, Bell Laboratories constructed a silicon solar PV module for outdoor use to power telephone lines in Georgia, with various commercial applications following (Perlin, 1999; Green, 2005).	The first large-scale diffusion project for grid-connected PV is considered to be the 1000 roofs programme in Germany (Brown and Hendry, 2009). This was initiated as a 'demonstration cum market formation programme' (Brown and Hendry, 2009) which forestalled parliamentary pressure for Feed-in-Tariffs, and led to 2100 installations with a total capacity of 5.3 MWp on private homes from 1991 to 1995. The scheme offered capital grants of 70% of the installation and capital costs, and by this time there was already a Feed-in-Tariff law in Germany (offering a rate of 90% of the electricity price) (Brown and Hendry, 2009).	Peak installed capacity of solar PV eligible under the German EEG (Erneuerbaren-Energien-Gesetz) was 39.3 GW in 2015 (Federal Network Agency, 2017). 20% of this peak capacity is 7.9 GW and this threshold was crossed in 2009, when there was 10.6 GW of installed capacity of PV in Germany (Federal Network Agency, 2017).

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