UKERC Technology and Policy Assessment

Innovation timelines from invention to maturity

A rapid review of the evidence on the time taken for new technologies to reach widespread commercialisation

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The UK Energy Research Centre

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The Technology and Policy Assessment (TPA) Theme of UKERC

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The primary objective of the TPA is to provide a thorough review of the current state of knowledge. New research, such as modelling or primary data gathering may be carried out when essential. It also aims to explain its findings in a way that is accessible to non-technical readers and is useful to policymakers.

Rapid Evidence Review Draft Working Paper

This paper is published in draft form as a UKERC Working Paper.

Executive Summary

This report addresses the question: What is the evidence for the time new technological innovations take to reach commercial maturity?

Rationale

The role and importance of technological innovation in reducing greenhouse gas emissions is well established in national and international policies. If any new low carbon technologies are to play a substantial role in reducing carbon emissions then it will be necessary for them to be proven, available and deployed at a scale that is sufficient for them to make a material impact. There is a substantial literature on ‘innovation systems’, which emphasises the importance of government policies in promoting innovation directly, beyond support for research and development alone. In other words, the notion that it is possible to promote innovation in the absence of targeted measures to create market opportunities for early stage technologies is likely to be misguided. However a key consideration that has received considerably less attention is the amount of time required for a new technology to emerge from fundamental research, go through demonstration and early stage deployment and diffuse into the market place.

Scope of project and approach

The principal aim of this report is to characterise and quantify the timescales from invention to widespread commercialisation of 14 technological innovations, which comprise both energy sector technologies and consumer products. The aim is to understand how different technologies vary in the time they take to develop through the technological innovation system, and discuss some of the factors which affect these timescales. This study considers only successful innovations, and not failed innovations. The review of innovation timelines has been conducted using a Rapid Evidence Assessment (REA) approach, defined as “a short but systematic assessment on a constrained topic”. REAs have been designed to maintain much of the rigour of a full systematic review, but to deliver results rapidly within constraints imposed by cost and time.

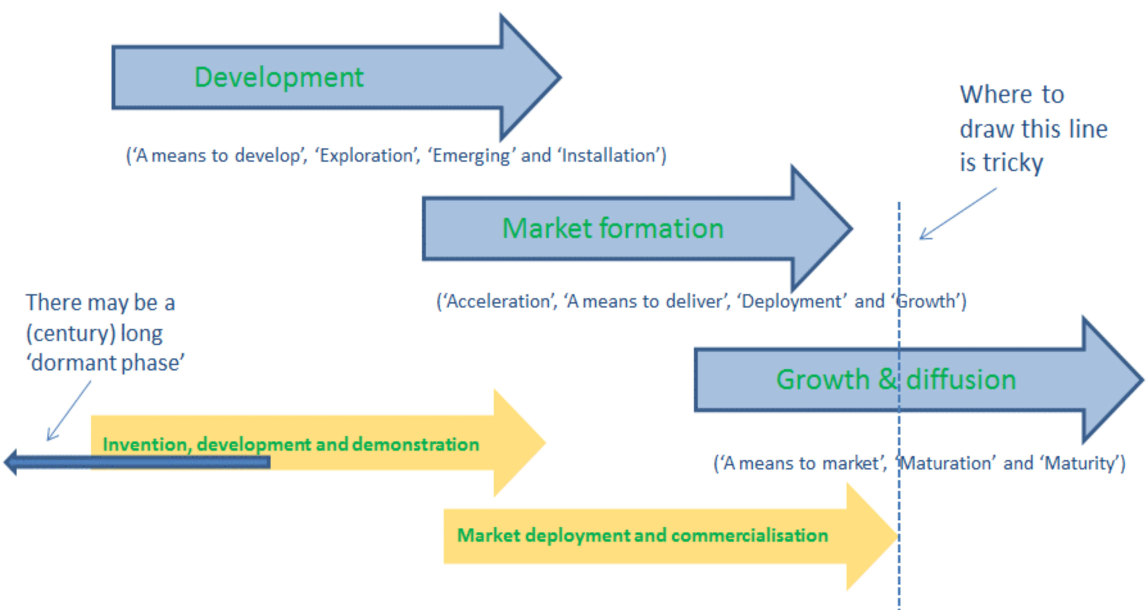
The review considers evidence on innovation timescales at global, regional or national scales, incorporating studies and data pertaining to the following geographies in particular: OECD, EU (including the UK), USA and Japan. Relevant literature was identified through keyword searches for innovation concepts, descriptors of time and technologies or products, within two databases: Elsevier Science Direct and World Cat.

Beyond the review of timescales, five of the energy-sector innovations have been considered further in order to understand detailed aspects of their historical development, market growth and wider commercialisation. These case study technologies are: combined cycle gas turbines (CCGT); nuclear power; solar PV; lithium ion batteries for consumer electronics; and energy efficient lighting.

Developing innovation timelines

Based on the rapid review of the literature, the timescales for each innovation were initially grouped according to three progressive phases in the innovation life cycle which could be applied to the technologies or products considered in this study: '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' (Figure ES1). The first of these begins with invention and encompasses research and development, prior to the market introduction of an innovation. The second phase starts with market introduction and ends when a technology or product reaches 'widespread commercialisation'.

Figure ES1: Phases of the innovation timeline



While pinpointing dates of invention or market introduction is relatively unproblematic, defining a point at which widespread commercialisation occurred is more difficult. The innovations have therefore been grouped into three classifications for the purposes of defining widespread commercialisation:

Novel products or technologies for new markets (the car; cathode ray tube (CRT) television; automatic teller machine (ATM)/cash card; and the videocassette recorder) are considered to have reached widespread commercialisation at 20% of the maximum cumulative units for a given product (where cumulative units can be expressed in terms of the ownership of cars or cathode ray tube TVs, for example).

Replacement products or technologies (the mobile phone; thin film transistor liquid crystal display (TFT-LCD) TV; catalytic converter; lithium ion rechargeable battery for consumer electronics; compact fluorescent light bulb (CFL); and LED light bulb) are defined as being in widespread commercialisation when their market share reaches and overtakes that of the incumbent products.

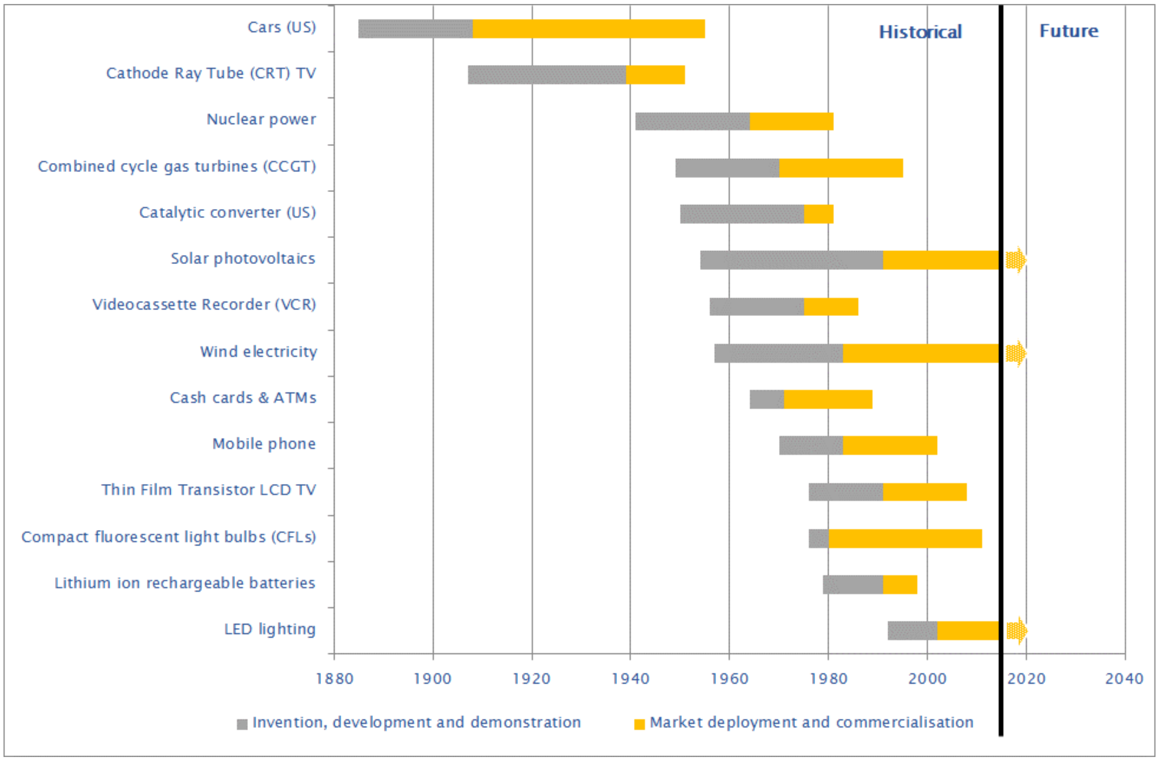
Electricity generation technologies (CCGT, nuclear power, wind and solar PV) are considered to be in widespread commercialisation when they contribute 10% of electricity production, to reflect a point at which low carbon technologies could have a substantial impact on carbon reduction.

Findings

Across the 14 innovations considered in this review, the average time from invention to widespread commercialisation was 39 years. Nevertheless, this timescale varies widely between innovations (Figure ES2). Lithium ion rechargeable batteries experienced the quickest rate of innovation, taking just 19 years. A large proportion of these batteries were sold in consumer electronic equipment such as mobile phones and other small electrical appliances. The car took the longest amount of time to reach our definition of widespread commercialisation in the US (70 years). This lengthy timescale is due principally to the extensive market growth which continued over most of the twentieth century, driven as much by growth in the economy and in private incomes, as by innovation in vehicle manufacturing and technology.

The successive phases of 'invention, development and demonstration' and 'market deployment and commercialisation' also showed a considerable range of variation between all 14 innovations (from 4 to 37 years and 6 to 47 years respectively), even if the average length of each phase was very similar at approximately two decades.

Figure ES2: Historical timeline and duration of innovation for all technologies reviewed



Overall, the innovations that replace existing products had shorter average timelines from invention to widespread commercialisation (29 years) than innovations aimed at entirely new markets (42 years). However, the longer average for novel innovations is due in particular to the extended time taken for the car to travel from market introduction to wide-scale deployment. Conversely, of all 14 innovations considered, two new products – cash cards / ATMs and the videocassette recorder – were the third and fourth quickest to become widely commercialised after invention.

Electricity generation technologies exhibit some of the longest commercialisation time periods within the technologies reviewed. The average time from invention to commercialisation was 48 years for electricity generation technologies and shortest for CFL / LED lighting and lithium ion rechargeable batteries for consumer products– 26 years. It is also important to note that LED lighting, wind electricity and solar PV are still yet to reach widespread commercialisation as defined above. In comparison, the seven non-energy sector innovations average 38 years to achieve widespread commercialisation.

Discussion and policy implications

In many cases the basic scientific or engineering principles underpinning an innovation are well known and predate even the laboratory stage by several decades. For example, the first silicon-based solar PV cell with an efficiency of greater than 5% efficiency was developed in 1954, but the photovoltaic effect itself was established using selenium in the late 1870s. Similarly, the cathode ray tube was invented in 1897; several decades before early TV sets were produced.

There is evidence that several of the innovations reviewed were developed as a spillover from earlier products, or from research and development aimed at military or space applications. For example, the first cash machine was created by assembling existing technologies into a new product, in essence a new idea using existing techniques. The precursor to nuclear power was the atomic bomb, while CCGT benefited from research conducted on jet engine design, also during the Second World War.

One general observation from the review is that technologies rarely move out of the R&D stage completely following market introduction, in that R&D continues to be part of the process of improving existing technologies. Ongoing R&D is crucial to improving performance and reducing costs even in the most mature of technologies.

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. However, unless it proves possible to radically accelerate innovation relative to historical norms then it is unlikely that inventions emerging from basic research this decade will make a material contribution to reducing carbon emissions before the mid to end of the 2030s at the earliest. Even 2050 is relatively soon in relation to the timescales typical in the development of the energy system.

As we look to the future therefore it is important that innovation policy (whether through R&D, subsidised markets or through regulation and targets) continues to recognise that sustained support for low carbon technologies is required over many decades. This means that policy efforts should focus as much upon improving existing technologies as developing new ones, and on creating markets and overcoming barriers to the deployment of established energy efficient and low carbon options. Support for R&D is a crucial component of low carbon policy development, but should not be predicated on the hope or expectation that it can deliver a ‘quick fix’ to the climate change problem.

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1. Introduction

The UKERC technology and policy assessment (TPA) research theme was set up to address key controversies in the energy field and to provide authoritative inputs for policy-making processes through accessible and credible reports that set very high standards for rigour and transparency. The TPA has been part of UKERC since the centre was established in 2004 and is now in its third phase, which started in 2014. The aim of the TPA is to conduct systematic reviews of literature, supplemented by primary research and wider stakeholder engagement where required.

In Phase III of UKERC the TPA team are developing a new methodology for rapid evidence reviews. This report uses a new approach to rapid evidence assessment, which is discussed in more detail below. The work has been undertaken in part to assist the Committee on Climate Change with analysis in advance of their recommendations for the Fifth Carbon Budget.

1.1. What we are trying to do and why

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). A substantial number of analyses emphasise the importance of government policies in promoting innovation directly – in part through support for research and development, but also through the creation of markets for emerging technologies (Anderson *et al.* 2001, Stern 2007, DECC 2012, Gross *et al.* 2012, CCC 2013, IPCC 2015). A central tenet of this analysis is that market creation facilitates cost reduction through allowing 'learning by doing' and by providing opportunities for market participants to realise economies of scale (Gross *et al.* 2013).

The creation of markets often relies upon targeted, technologically specific policies, for example feed in tariffs for renewable energy (IEA 2008, Gross *et al.* 2012). This gives rise to debate about the affordability of large scale deployment subsidies and the role of governments in deciding which technologies to support (Helm 2010, Gross *et al.* 2012, Less 2012). A related argument is associated with how governments should determine the balance between support for deployment and incremental improvement in existing technologies and support for 'blue skies' R&D which seeks to develop new technologies (Helm 2012, House of Lords 2015). Some protagonists argue that large scale support for deployment should be substantially reduced and support for R&D scaled up (Helm 2012). However if entirely new technologies are to emerge from R&D in time to contribute to the UK's decarbonisation goals in the coming decades then it is important to ask how long the 'journey' from the laboratory to large scale use is likely to take.

There is a substantial literature on 'innovation systems', much of which suggests that the notion that it is possible to promote innovation in the absence of targeted measures to create market opportunities for early stage technologies is likely to be misguided (IEA 2000, Anderson *et al.* 2001, Foxon *et al.* 2005, Gross *et al.* 2012). However a key consideration that has received considerably less attention in the literature is the amount of *time* required for a new technology to emerge from fundamental research, go through demonstration and early stage deployment and diffuse into the market place.

If any new low carbon technologies are to play a substantial role in reducing carbon emissions then it will be necessary for them to be proven, available and deployed at a scale that is sufficient for them to make a material impact. In the case of many end-use technologies that reduce demand for energy or move away from fossil fuels (such as energy-efficient products, insulation, or electric cars) then in order to make a material impact on carbon emissions they will need to be deployed in very large numbers, usually of the order of tens of millions of units in the UK alone. In the case of some new energy supply technologies such as new nuclear power stations, carbon capture plants, or offshore wind farms the number of units that need to be deployed may be quite small. However each individual unit usually represents a large, complex construction project that will take many years to build. In many cases supporting infrastructures also need to be built, adapted or upgraded – examples are new offshore power lines, CO_2 transport and storage systems, power distribution networks or district heating systems.

1.2. The Research question

In order to better understand the amount of time likely to be needed for a variety of low carbon technologies to go from invention to widespread commercialisation this project therefore asks:

“What is the evidence for the time new technological innovations take to reach commercial maturity?”

This report compares and contrasts technologies with different characteristics and scales of deployment, from light bulbs to large power stations. The work considers how rapidly a wide range of innovations took to diffuse into the market as well as assessing case studies associated with carbon abatement and energy.

The project will answer the research question by addressing the following objectives:

- Establish the concepts around technological innovation and the time to commercialisation.
- Examine the literature around the time technologies take to develop from invention to widespread commercialisation.
- Conduct selected case studies examining the time it takes for energy technologies to go from invention to widespread commercialisation.

- Conclude on the range of timescales different technologies take to develop through the technological innovation system and discuss the factors that affect those timescales.

1.3. Scope of the project

The report compares the innovation rates of a mixture of energy sector and non-energy sector innovations, which have been selected based on the systematic literature review conducted in this study. In total 14 innovations are considered, which are further classified according to whether they are entirely new innovations, replacement products, or electricity generation technologies (see Section 2 for more details).

The systematic review has identified relevant literature at global, regional or national scales, incorporating studies and data pertaining to the following geographies in particular: OECD, EU (including the UK), USA and Japan. In several cases, the rate of diffusion for some products or technologies has been considered for a specific national geography, taking into account that geographic differences may impact on the time certain technologies take to mature.

1.4. Approach: Rapid evidence assessment

The research has been conducted using a Rapid Evidence Assessment (REA) approach, defined as “a short but systematic assessment on a constrained topic” (GSR 2013). REAs have been designed to maintain the rigour of a full systematic review, but to deliver results rapidly within constraints imposed by cost and time (Hailey *et al.* 2000, Khangura *et al.* 2012). This report is the first formal REA undertaken by the TPA, which involved the following steps (a simplification of the steps followed in full systematic reviews undertaken by the TPA):

- Publication of a scoping note on the UKERC website
- Consultation with Experts
- A systematic search of a clearly defined evidence base using keywords
- Categorisation and analysis of the evidence
- Drafting of a working paper
- Peer review of the working paper
- Publication and dissemination through appropriate mechanisms.

1.5. Identifying Evidence

Given the short timescales available and the status of the study as a rapid evidence assessment, evidence was identified through keyword searches limited to two databases: Elsevier Science Direct (http://www.sciencedirect.com) and World Cat (http://imperialcollegelondon.worldcat.org/), using Boolean combinations of relevant terms. Initially, innovation and temporal keywords were used as the search terms which were then focused by combining them with specific technologies or products identified by the emerging literature search as being instructive to the research aims.

Returned results were filtered for relevance based on their title and abstract. If this was not sufficient to determine relevance, further inspection of the main text was necessary. The criteria for relevance were that, in relation to innovative technologies or products, the document considered some of all of the following: timescales from basic research to commercialisation; specific timescales of individual stages of the product or technology life cycle; or relevant historical information pertaining to the historical development of a given innovation.

Following the filtering of retained search results key descriptive information of each of the results were captured, namely: (i) the innovative product or technology considered; (ii) the timescales for specific innovation stages presented and; (iii) the geographic region (if not global). Given that the global scale is of primary interest, regional or national scale descriptors were used to constrain the number of studies, such that, in addition to those studies with a global scope, only studies focused on OECD or EU (including the UK) countries, the USA or Japan were retained.

Table 1.1: Keywords selected for use in the search terms

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"

1.6. Structure of this report

Section two provides an overview of key innovation concepts and describes the approach taken to defining different stages of innovation and commercialisation.

Section three provides the main results of the rapid evidence assessment and provides a brief discussion of some of the principal themes emerging from the review.

Section four presents five energy-sector case studies.

Section five concludes and considers requirements for further research.

2. Conceptual background: innovation theory and definitions of innovation timelines

2.1. Introduction

This section provides an overview of some key concepts and definitions in the literature on innovation and explains the approach taken in this report to categorising different innovation stages. 'Innovation' is a broad term. It can be applied to any area of human endeavour – including business practices, institutions, media, policy and social relationships – as well as the more traditional use of the term to refer to new products or technologies. Innovation in all its forms can help to reduce carbon emissions, as social, behavioural, economic or institutional innovations can all contribute to carbon abatement.

However this review is explicitly concerned with *technological* innovation; with the timelines that are associated with the development of new products that can reduce energy demand or produce energy more cleanly. Innovation in products has been defined by Utterback and Abernathy (1975) as: '…a new technology or combination of technologies introduced commercially to meet a user or a market need.' The success of a product or technological innovation can be measured in terms of its diffusion and whether it achieves widespread commercial uptake (Wilson 2014). Although the journey of an innovation most frequently ends in failure (Wilson 2014), this report is concerned with establishing the time it took for a range of *successful* innovations to reach a mass market.

In many cases technological innovation is associated with, or indeed driven by, a range of innovations in other domains, including societal and institutional changes. Innovation, and the complex interplay of actors and influences within an innovation system, has been widely studied within a range of academic traditions and from different theoretical perspectives. This report does not seek to provide a thoroughgoing discussion of the literature on innovation. Indeed the rapid assessment approach that has been adopted for this report militates against the possibility of providing a detailed review of this rich area. Nevertheless it is important to provide an overview of a few of the most significant dimensions of the literature as it pertains to innovation timelines in order to help orientate the empirical findings presented in Sections 3 and 4. The remainder of this section therefore discusses the way in which different dimensions of the wider literature on innovation consider the stages through which innovations pass and how such stages have been categorised.

Section 2.2 provides a review of a number of innovation concepts which have informed our thinking and categorisation of innovation stages. Section 2.3 considers the implications of innovation theory for this report. 2.4 explains the definitions of different stages of the innovation journey that we use in this study.

2.2. Key concepts in the innovation literature

2.2.1. A brief historical review of the innovation literature[1]

Early history

The literature on innovation is wide ranging and varied, drawing on a range of disciplines. Beginning in the 1930s, early perspectives viewed the innovation process as a relatively simple, one-directional journey from basic research to applied research to technology development and diffusion (Schumpeter 1934). This so-called 'linear model' suggested that advances in science determined the rate and direction of innovation and that the optimal way to increase the output of new technologies was to put more resources into R&D. This is the process of technology-or supply-push (Schumpeter 1934). An alternative perspective, demand-pull, gained traction in the 1950s, arguing that demand for products and services was more important in stimulating inventive activity than advances in the state of knowledge. Both perspectives have since been challenged as over-simplistic and recent theoretical approaches accept the importance of both (Nemet 2007) but also stress the importance of more complex, systemic feedbacks between the supply and demand sides (Foxon, 2003).

Perspectives on technological change

In the second half of the 20th century innovation theory was in particular furthered by three approaches to understanding technological change: induced innovation, the evolutionary approach, and the path-dependent model (Ruttan 2001). The induced innovation perspective emphasises market drivers and demand-pull mechanisms and highlights in particular the importance of changes in relative prices in driving the direction of technical change (Foxon 2003). The evolutionary and path dependency models stress the importance of past decisions which may constrain present innovation.

These approaches are associated with several concepts that are fundamental to contemporary innovation theory: The *evolutionary* model includes the concept of 'uncertainty' at various levels – technological, resource, competitive, supplier, consumer and political (Meijer *et al.* 2007) – and also the idea of 'bounded rationality' which emphasises that decision makers have a limited ability to gather and process information (Nelson & Winter 1982). One important suggestion is that both bounded

[1] A longer version of this summary first appeared in Imperial College working papers published by the authors as part of research for the International Renewable Energy Agency and available at http://www3.imperial.ac.uk/icept/publications/workingpapers

rationality and uncertainty result in mindsets that in general favour incremental innovations to current products or processes rather than radical and disruptive ones.

The *path dependent* model is underpinned by the idea of increasing returns to adoption whereby the more a technology is taken up by or the more a system becomes established, the more likely it is they will be further adopted. The process is supported by factors such as scale effects and learning by doing and will typically give rise to cost reductions and incremental improvements (David 1985, Arthur 1994). However, at both a technological and an institutional framework level, path dependency can result in technological dominant design, institutional inertia, and the 'lock-in' of incumbent technologies and systems and the 'lock-out' of innovations that may be more optimal to the achievement of a particular objective, such as reducing emissions (Foxon 2003, Gross 2008).

1970s to 1990s: Emerging concepts in systems theory

Alongside induced innovation, evolutionary economics and path dependency, the 1970s to 1990s saw the emergence of several key perspectives that would lay the foundations for a more general systems theory of innovation The evolutionary approach was adapted by Nelson and Winter into a more general theory of innovation, underpinned by the concepts of uncertainty and institutional structure (which provides incentives or creates barriers to innovation) (Nelson S 1977, Nelson & Winter 1982). This sees R&D as being guided by both technology-push and demand-pull factors to generate a variety of possible solutions. These are tested in an environment containing both market and non-market (institutional) elements. The prevailing set of technologies and institutions form a 'technological regime', which steer the R&D process along particular 'trajectories', typically favouring incremental innovations to existing products or processes (Nelson S 1977).

In the late 1980s Freeman and Perez (1988) applied innovation systems thinking to countries. The National Innovation Systems (NIS) approach that emerged focuses on individual and comparative analyses of the innovation systems in different countries, across a range of technologies. The idea is that key institutional drivers are found at the national level. Freeman and Perez defined the NIS as 'the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies'.

Life cycle and dominant design

Nelson also proposed that new technologies exhibit a 'life cycle' of development. In the early stages of development there are a variety of competing designs, but as advantageous features favour a certain design, so that design will be increasingly taken up. If the market grows, institutional change may gradually occur as the institutional regime adapts to match the needs of the new technology. Assuming the combination of improved technological capability and the adapted institutional framework is compelling the new technology will spread until it achieves the status of a 'dominant design'. From this point on, only incremental improvements will be made to the technology design. Many firms will cease to invest in learning about alternative design architecture, instead investing to refine their competencies related to the dominant architecture (Schilling and Esmundo 2009).

Recent systems thinking

The last few decades have thus seen an increasing theoretical interest in the complexity and interdependency of the innovation process. Examples of specific, recently developed approaches include 'technological innovation systems', 'technological transitions', and the 'multi-level perspective'. Although these still acknowledge the existence of stages of technology development, they put these in a wider context, emphasising the role of multiple agency and distributed learning mechanisms in technological change (Winskel and Moran 2008). Attention is given to aspects such as knowledge flows between actors; expectations about future technology, market and policy developments; political and regulatory risk; and the institutional structures that affect incentives and barriers.

In what follows we discuss selected approaches in more detail, in order to consider how recent innovation theory deals with the timescales for innovation that are the focus of this report.

2.2.2. Technology Innovation Systems

Technological Innovation Systems (TIS) theory (Bergek *et al.* 2008, Bento and Fontes 2015) aims to understand how new technologies can evolve through interactions between actors, networks and institutions. These actors might take the form of companies, universities and other public sector organisations, which interact through formal or informal networks such as supplier groups, public-private partnerships, university-industry links or buyer-seller relationships. In order to diffuse successfully, novel technologies need to be supported by institutions, e.g. laws, regulations, norms and culture, in a process of 'institutional alignment' (Bergek *et al.* 2008). Much of the TIS literature is concerned with the interaction of agents and how the interplay between various stakeholder groups affects the success or otherwise of emerging technologies (see for example (Jacobsson and Johnson 2000)). However, the literature also discusses various stages through which innovations proceed. These stages are of interest to this review.

The early development of a TIS has been represented in terms of two sequential 'formative' and 'growth' stages (Jacobsson and Bergek 2004, Bergek and Jacobsson 2003). The 'formative phase' corresponds to an initial stage of structural and market formation, with market entry of some companies, first alignment of institutions and initial creation of networks. In response to large uncertainties, entrepreneurs experiment extensively with a wide variety of new designs and applications, each of which entail the development and accumulation of knowledge. Knowledge development requires interactions in networks, particularly through supplier-buyer relationships, which can be established through the formation of niche markets, or if existing markets accept new innovations (Bergek *et al.* 2008). Niche markets may typically be understood as limited markets which support the growth of new technologies by protecting them from full market competition, e.g. niche markets created through the provision of financial incentives funded by public policy (Wilson 2014).

Eventually, the TIS reaches a point where it can sustain itself and progress to a 'growth phase', during which technology diffusion enables 'nursing markets' to expand into 'bridging markets' with greater volumes and a higher number of actors. Provided the TIS is successful, these bridging markets may develop into mass markets. The time for a TIS to reach a mass market frequently takes several decades after the original market formation, although the timescales will vary between different TISs. The formative/growth phase model does not apply uniformly or universally to every TIS, and although some elements of the model may be shared between separate innovation systems, in some TISs the pattern of development will differ (Bergek *et al.* 2008).

<u>Historical diffusion of energy technologies</u>

Recent analysis of the energy sector has also focused specifically on the importance of product scale (physical unit size/installed capacity) in the innovation of energy supply technologies such as wind electricity and coal power (Grubler 2012, Wilson 2012). For example, (Wilson 2012) discusses an 'upscaling' phase that occurs between the formative and growth phases (Bento and Fontes 2015):

Formative phase - experimental stage involving the production of numerous small scale units and the creation of an initial manufacturing base;

Up-scaling phase - increasingly larger units are manufactured to achieve economies of scale at unit level;

Growth phase - large-scale units are mass-manufactured, so that economies of scale are attained at the production level.

Overall the TIS literature provides a rich conceptual lens through which innovation can be understood in terms of the interaction of agents within a complex system and the flows of funding, influence and knowledge within that system. Institutions, policy and the relationships between interest groups are central to the success or otherwise of innovative products or services. This review has not sought to document these phenomena in reporting on innovation timelines and doing so in detail would be a valuable additional area for future research. For the purposes of this review we note that the TIS literature also considers the stages through which innovations pass; formative and growth, and the roles of niche markets, bridging and mass markets.

2.2.3. Transition theory

Research into transition theory is also relevant to our study. This focuses on the detailed process of technological change, which is not simply incremental but represents a radical, possibly even disruptive, shift in products and processes (Gross 2008).

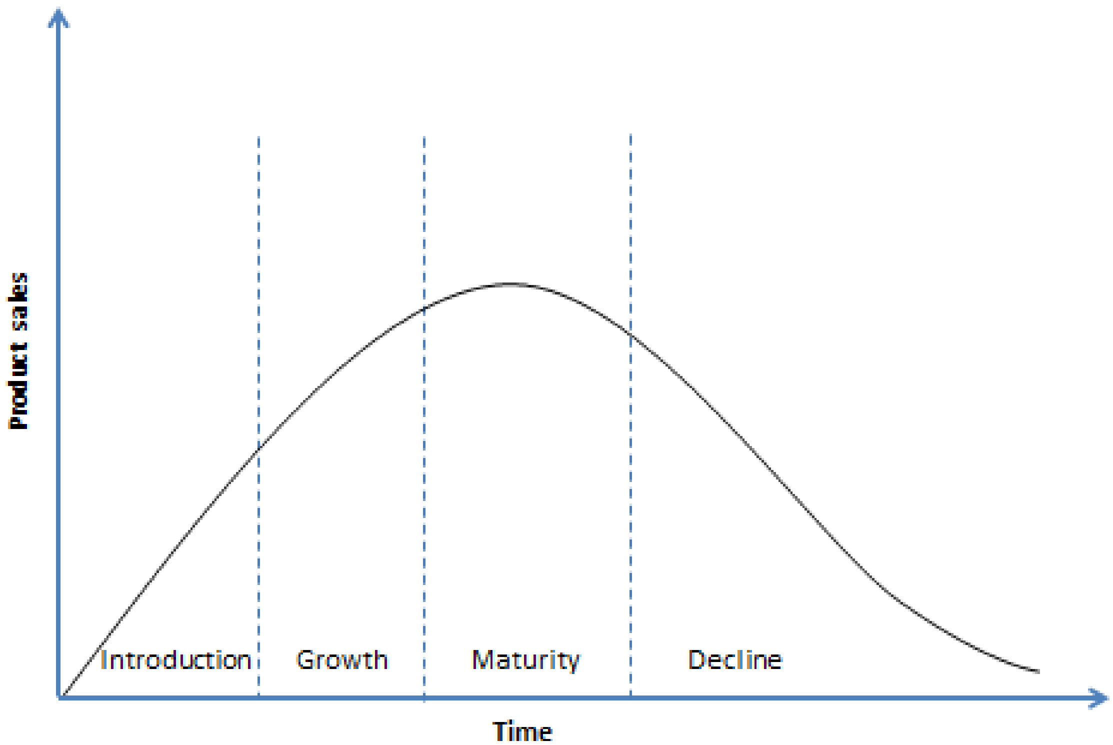
Transitions theory emphasises the importance of technological and market niches by which an innovation can be protected from normal market conditions and nurtured for a period of time. A key element of transitions theory is the ‘multi-level perspective’ which stresses that transitions do not only involve changes in technologies, but also changes in user practices, regulation, industrial networks, infrastructure and symbolic meaning or culture (Geels 2002). Geels explores these at three explanatory levels: ‘micro’ technological niches, ‘meso’ socio-technical regimes and ‘macro’ landscapes. Innovations break out of niches when they can link up with processes at the regime- and landscape-level. They may link to the established technology, to new regulations or newly emerging markets, or they may ride along with growth in particular markets.

2.2.4. Technology /product life cycles

As mentioned above, a further strand of literature of relevance to this review is concerned with ’technology life cycles’. With this approach, the focus is on the journey of an innovation from initial research and development, through market entry and growth, to market saturation and the eventual period of declining demand for a product. This journey has been referred to interchangeably in the literature as the ‘innovation’, ‘technology’ or ‘product’ life cycle (Taylor and Taylor 2012, Wilson 2014).

The product life cycle has been used for marketing and supply chain strategies, inventory control and demand forecasting. It is generally depicted in a plot of sales or revenue on the y-axis against time on the x-axis (Figure 2.1), with the progress of the product represented by a bell-shaped curve with four successive stages: introduction, growth, maturity and decline. The introduction phase begins when a product is brought to market, after which growth in sales volumes can occur as more consumers accept the product. The maturity stage is marked by a stabilisation in sales, prior to the final decline phase. Nevertheless, the product life cycle is by no means standardised, such that any given product might fail to make it beyond the introduction stage, may remain in maturity for a long period, or even revert from a maturity to a growth stage (Taylor and Taylor 2012).

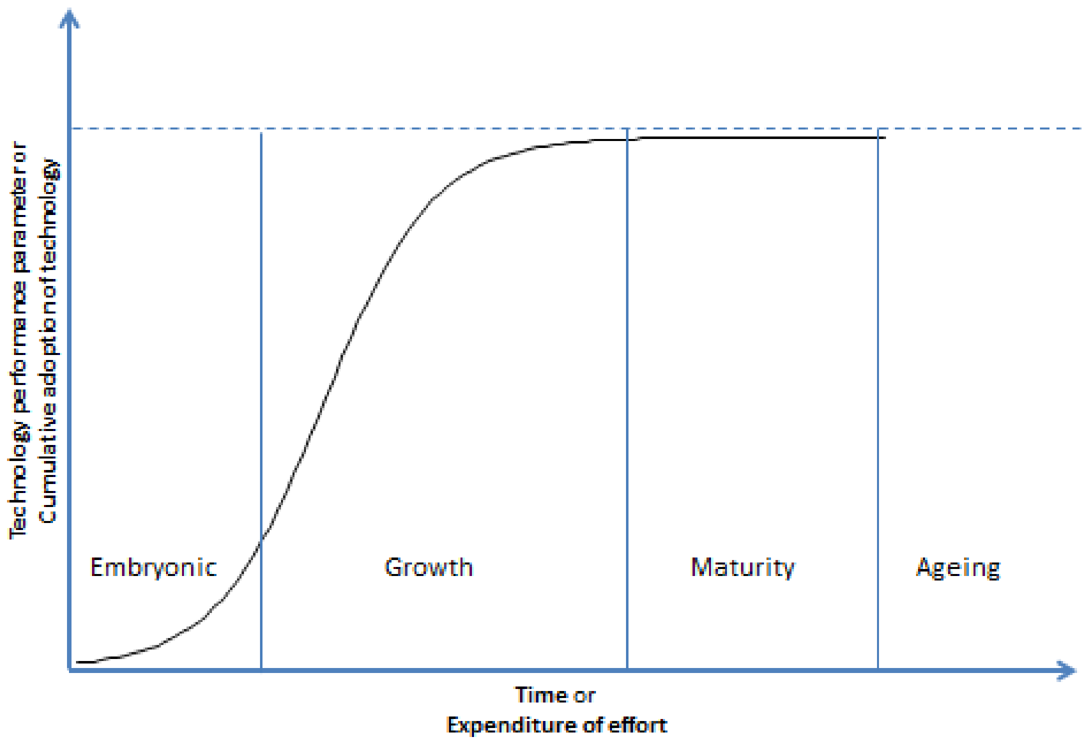
Figure 2.1: Typical product life cycle



Source: (Taylor and Taylor 2012)

Within the technology life cycle literature, another common representation of technological innovation charts how a technology is adopted cumulatively over time, capturing progressive phases such as 'embryonic', 'growth', 'maturity' and 'ageing' in the so-called S-curve (Figure 2.2). The names and numbers of stages used in different S-curve representations are multifarious. Furthermore, different S-curves may plot alternative metrics such as cumulative sales, patent applications or technological performance on the y-axis, and investment in technological development or expenditure of engineering effort on the x-axis. While investment may be a more empirically sound metric than time (since time does not reveal interruptions to investment), reliable data on total investment is difficult to access. Whichever metrics are used, the S-curve plateaus as market saturation is reached at the maturity stage and the incumbent technology may be replaced by a new, disruptive innovation, precipitating the beginnings of a new S-curve (Taylor and Taylor 2012).

Figure 2.2: Typical technology S-curve



Source: (Taylor and Taylor 2012)

2.3. Taking stock: the implications of innovation theory for this study

The brief discussion provided above clearly reveals the richness and diversity of the literature on innovation, and in particular the importance of institutions, market conditions and systemic interactions in driving or blocking innovation. These perspectives offer insights into the reasons that some innovations succeed and others fail that are far more sophisticated than approaches that focus solely on technology performance (though technology performance clearly also matters greatly).

Despite this focus on systems, the literature is also very clearly focused on delineating key stages through which innovations pass in the journey towards commercial maturity.

The rapid evidence assessment identified some limited examples of literature which has attempted to measure the time taken for different innovations to reach maturity. These frequently use more qualitative categories than those which we have applied, related to progressive, linear development through the innovation life cycle, to build innovation timelines. For example, in 'Technological Revolutions and Financial Capital', Perez (2002) considers historical 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. However, Perez's analysis is concerned with industry wide 'Kondratiev waves', and is not directly comparable to the review conducted in this report, which focuses on the level of individual products or technologies. Table 2.1 provides an overview of the wide range of terms used to discuss timelines for innovation and the drivers thereof.

Table 2.1 Key terms used to describe energy technology innovation

Relates to	Key term	Definition (Grubler and Wilson, 2014)
Innovation processes and stages	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
Types of innovation	Radical innovation (or breakthrough/disruptive)	A novel technology that strongly deviates from prevailing norms and so often entails a disruptive change over existing commercial technologies and associated institutions
	Incremental innovation (or continuous)	An improvement in performance, cost, reliability, design, etc. to an existing commercial technology

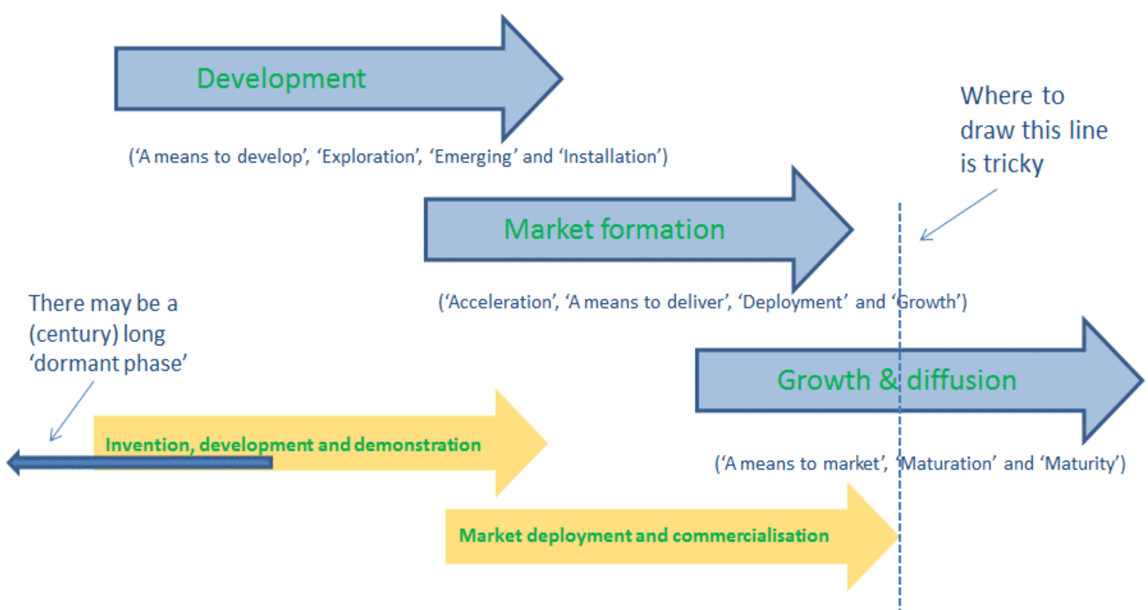
Source: adapted from (Wilson 2014)

2.4. Applying key concepts to develop innovation timelines

Although the innovation literature uses a wide range of terminology for different phases of innovation it is possible to identify three broad phases for which a wide range of terms are used but which appear to be in broad terms consistent. The first period (or phase) of development is referred to in the literature reviewed as 'A means to develop' (Wonglimpiyarat 2005), 'Exploration' (Dismukes *et al.* 2009), 'Emerging' (Gao *et al.* 2013) and 'Installation' (Perez 2002). The second stage of 'Market formation' in Fig. 2.3 includes timelines for periods referred to elsewhere as 'Acceleration' (Dismukes *et al.* 2009), 'A means to deliver' (Wonglimpiyarat 2005); 'Deployment' (Perez 2002) and 'Growth' (Gao *et al.* 2013) (Yeo *et al.* 2015). The third stage of 'growth and diffusion' has also been termed 'A means to market' (Wonglimpiyarat 2005), 'Maturation' (Dismukes *et al.* 2009) and 'Maturity' (Perez 2002, Gao *et al.* 2013, Yeo *et al.* 2015).

Based upon this, 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 rapid 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' (Figure 2.3).

Figure 2.3: Phases of the innovation timeline



2.5. Assigning start and end points

For each product, uncertainties remain over where precisely to assign a start point, end point and determine a specific duration for these phases – in other words determining when a technology moves from one phase of the innovation journey to the next. Moreover, as noted above, product or technological innovation does not necessarily proceed in a linear fashion from one stage of the life cycle to the next. Technology development may flow backwards as well as forwards (e.g. market research to optimise product design), while some successful innovations may not pass through every stage of the life cycle (Wilson 2014). In some cases, analysing innovation life cycles at the level of a complex product, such as an automobile, may obscure the fact that it consists of a variety of connected component technologies which are at different stages of their respective life cycles (Ayres and Martinas 1992).

Considering all of the above, we have generally taken the point of invention for each innovation as the first year in which a product or a technological application was conceived (e.g. the first silicon solar cell rather than the discovery of the photovoltaic effect; the first precursors to white LED lighting rather than the invention of LEDs per se). The market deployment and commercialisation phase is assumed to begin with market introduction, i.e. when a product first entered the market or became commercially available. For an energy supply technology this equates to the first commercial units which generated electricity for supply to the grid.

While pinpointing dates of invention or market introduction is relatively unproblematic, determining a minimum level at which significant commercialisation occurred is more difficult. To help define the point of widespread commercialisation, the innovations have been categorised into ‘novel products or technologies for new markets’, ‘replacement products or technologies’ and ‘energy generation technologies’ (Table 2.2).

For novel innovations aimed at new markets, such as the car or cathode ray tube television, we have defined a point of ‘widespread commercialisation’ at 20% of the maximum cumulative units for a given product (where cumulative units can be expressed in terms of the ownership of cars or TVs, for example). The purpose of this definition is to represent a degree of market diffusion at which a technology can be considered as mature and where a low carbon technology would be sufficiently well established as to be able to make a material impact on carbon emissions.

The second category of innovations shown in Table 2.2 is for replacement products, which we have defined as being in widespread commercialisation when their market share reaches and overtakes that of the incumbent products, in other words the point at which a new product becomes dominant in the marketplace.

For the electricity generation innovations, we have defined widespread commercialisation as being 10% of electricity production, to reflect a point at which low carbon technologies could have a substantial impact on carbon reduction. For these technologies we have chosen 10% to reflect the fact that a decarbonised power system might have a wide range of individual technologies/resources, each constrained by resource, economics or network constraints and none becoming dominant individually. We also chose 10% in recognition of the fact that although mature and clearly material to both global energy supply and to carbon emissions neither large hydro nor nuclear power ever achieved as much 20% of global supply (although both supply large fractions of total electricity supply in some regions or countries).

In all cases the definitions we have chosen represent a pragmatic judgement of what may be reasonably considered 'widespread commercialisation', in the light of the information available in the data sources revealed in the systematic review. Whilst these definitions provide a reasonable approximation of the point at which a technology is mature and widely deployed it is important to note that different definitions are possible and would lead to different conclusions about the duration of the commercialisation phase. Nevertheless we have applied the definitions as consistently as possible within the categories of technology discussed below and they therefore allow a reasonable comparison of the technology innovation timelines that this study sets out to report.

The timescales investigated in this report do not consider the period of maturity of a technology or product beyond its peak period of commercial success. While it is possible for new products to achieve market saturation in ten or twenty years from market introduction, the complete life cycle of an entire technology system can last for considerably longer than a century, from invention through to achievement of a dominant technological regime, and finally slow down and erosion arising from the challenge of new technologies (Freeman and Louca 2001). Table 2.2 provides a summary of the definitions of widespread commercialisation used in this report.

Table 2.2: Defining the point of widespread commercialisation

Innovation category	How widespread commercialisation is defined in this study	Geographies applicable
Novel products or technologies for new markets	When 20% of maximum cumulative units was reached[2]	UK, US, EU
Replacement products or technologies	When the market share of the replacement innovation overtook that of the incumbent / rival products and became the dominant market share (measured either by annual sales or cumulative units)	UK, US, Europe, OECD and global
Energy generation technologies	10% share of electricity production.	UK, global

2.6. Summary and main outcomes

This chapter has provided a brief review of the wide ranging and complex literature on innovations. We note that there has been a growing focus within this literature on the systemic interactions that can foster or hinder innovation and on the complex feedbacks within and between different stages of innovation activity. Nevertheless the literature does provide important concepts related to technological maturity and the timelines for innovation. We have adapted these to create two simplified categories in the innovation journey that many new products go through:

1. invention, development and demonstration

2. market deployment and commercialisation

Sections three and four use these concepts to describe the empirical evidence of innovation timescales.

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[2] For two innovations included in this review (ATM/Cash cards and the videocassette recorder (VCR)), the definition of widespread commercialisation is based on that applied to these products in a study by Wonglimpiyarat, who 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'. In the case of the VCR, for example, the 'means to market' stage began when 'the production capacity to supply 20% potential worldwide demand of VCRs was achieved within 2 years' (Wonglimpiyarat 2005).

3. Rapid evidence assessment of innovation timelines

3.1. Review findings: introduction and overview

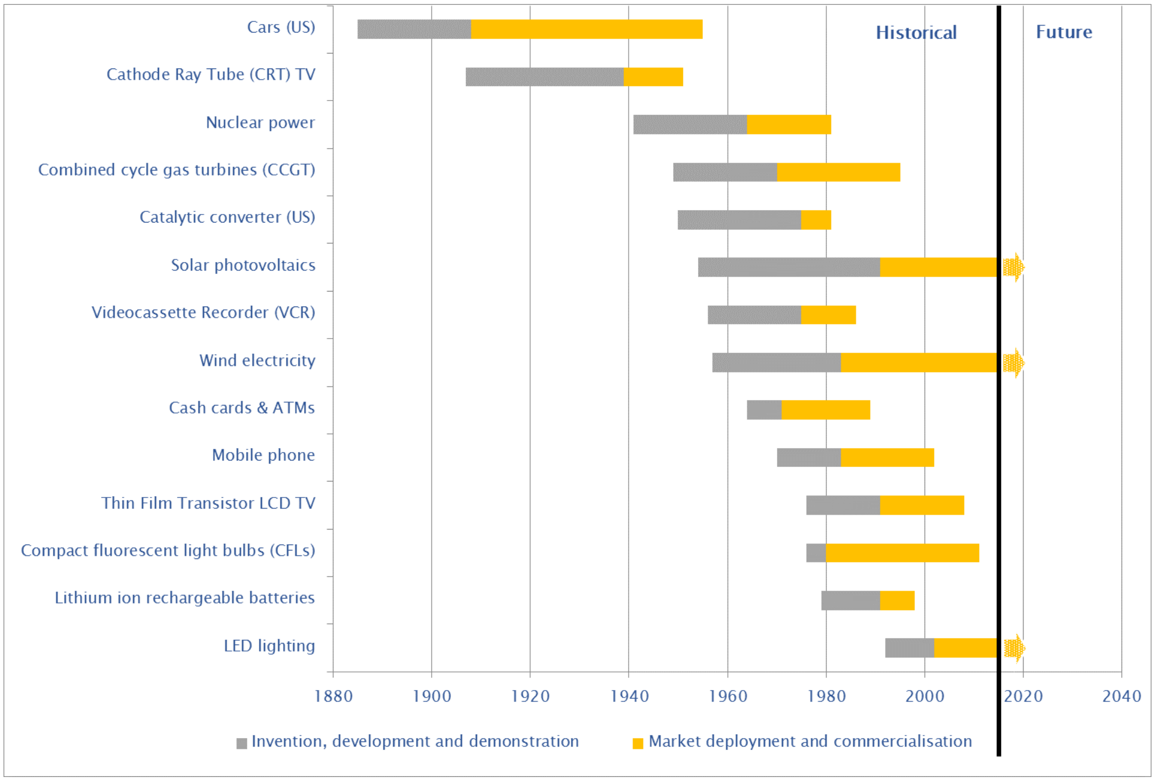
The rapid evidence assessment conducted in this study has collated timescales from basic research to widespread commercialisation for a wide variety of technologies and products. The review sought to encompass a wide range of innovations, which differ in terms of their economic sector and their scale, from bank cards and ATMs through to large scale electricity generation plants such as nuclear power and combined cycle gas turbines (CCGT). As described in Section 1, the review sought out a range of technologies and used a variety of innovation related search words. It was restricted in terms of databases and the amount of time available to return new data. It therefore cannot be considered to be exhaustive. Nevertheless a combination of cross checking between studies and discussion with experts was used to corroborate the principal findings.

In what follows, the main findings of the review are presented in a variety of ways, followed by a discussion of the qualitative material revealed by the review and of where caution is needed in interpreting findings. The principal objective of the report is to present empirical findings on timescales for innovation and it is not possible to provide a detailed commentary and analysis of the drivers of innovation. Nevertheless the discussion provides important context and caveats. The remainder of the section is organised as follows: 3.2 Presents findings organised chronologically, showing duration and summary statistics; 3.3 provides findings organised by technology type (new product, replacement product, energy); 3.4 provides a summary of the judgements made about innovation transition points (invention, beginning of commercialisation, widespread commercialisation); and 3.5 discusses the qualitative material revealed through the review.

3.2. The chronology and duration of innovation

Across the 14 innovations considered in this review, the total time from invention to widespread commercialisation ranges from 19 to 70 years. The mean time taken from invention to widespread commercialisation is 39 years. By this metric, the lithium ion rechargeable battery for small consumer electronics experienced the quickest rate of innovation, taking just 19 years. Using our definition of widespread commercialisation, the car took the longest amount of time (70 years – which needs to be treated with some caution, we discuss this finding in more detail below). Figure 3.1 provides an overview of the principal findings, organised chronologically.

Figure 3.1: Historical timeline and duration of innovation for all technologies reviewed



Across all the products and technologies considered, the successive phases of 'invention, development and demonstration' and 'market deployment and commercialisation' generally took a similar length of time on average (19–20 years), although the median was 20 years for the former period and 17.5 years for the latter. Figure 3.2 provides an overview of the range of findings ordered by duration. Table 3.1 provides summary statistics.

Figure 3.2: Duration of development and commercialisation for all technologies reviewed

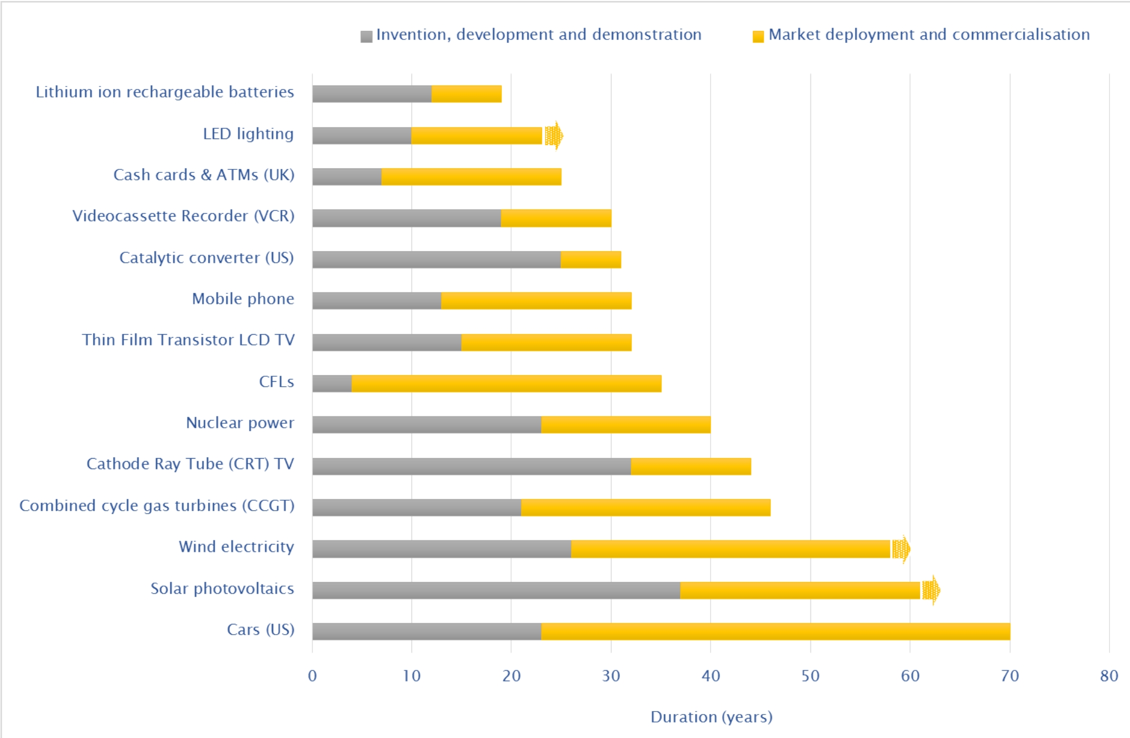


Table 3.1: Summary statistics: speed of innovation

Statistic	Invention, development and demonstration (years)	Market deployment and commercialisation (years)	Invention to commercialisation (years)
Mean	19.1	19.9	39.0
Median	20.0	17.5	33.5
Lower quartile	12.3	12.3	30.3
Upper quartile	24.5	24.8	45.5
Minimum	4.0	6.0	19.0
Maximum	37.0	47.0	70.0

3.3. Timescales for innovation by category of technology

In this section we provide a review of the differences between entirely new products, replacement products and energy sector technologies in terms of the timescales for innovation. Table 3.2 provides a summary of the average time taken, organised by these categories.

Table 3.2: Average speed of innovation differentiated by novel innovations, replacement products and electricity generation technologies

Sector / statistic	Invention, development and demonstration (years)	Market deployment and commercialisation (years)	Invention to commercialisation (years)
Novel products or technologies for new markets (Mean)	20.3	22.0	42.3
Replacement products or technologies (Mean)	13.2	15.5	28.7
Energy generation technologies (Mean)	25.5	22.8	48.3
Novel products or technologies for new markets (Median)	21.0	15.0	37.0
Replacement products or technologies (Median)	12.5	15.0	31.5
Energy generation technologies (Median)	22.0	24.5	46.0

Notes: Novel products or technologies for new markets include: cars (automobiles); Cathode Ray Tube (CRT) TV; ATM/Cash cards; and VCR. Replacement products or technologies include: mobile phone; Thin Film Transistor Liquid Crystal Display (TFT-LCD) TV; catalytic converter; lithium ion rechargeable batteries; compact fluorescent light bulbs (CFLs); and LED lights. Energy generation technologies include: CCGT, nuclear power, wind electricity and solar PV.

Table 3.3 provides a more detailed view of the timescales, chronology and geographical scope of the data revealed through the review. It might be expected that, compared to replacement products, new innovations aimed at new markets will take longer to prepare for market and to commercialise. Superficially, the data support this notion, indicating that, of the products and technologies considered in this report, novel innovations average 42 years to travel from invention to commercialisation, compared to 29 years for replacement products. However, this difference is due in particular to the long journey from invention to market introduction for the car and CRT TV, which might be problematic, as we discuss in more detail below. Additionally, two new products – cash cards / ATMs and the VCR – were the third and fourth quickest to become widely commercialised after invention. Overall, it is difficult to draw firm conclusions about the novelty or otherwise of the service/utility a particular product offers and how long it takes to commercialise. The Technological Innovation Systems (TIS) literature suggests that if new institutions or infrastructures are needed to commercialise a technology this will need to coevolve and that incumbent agents may affect resistance to change – both factors which might be expected to slow diffusion. However it was not possible within the constraints of the study to assess this empirically and doing so would be a valuable addition to the research.

Table 3.3: Comparison of timescales for passage through the innovation life cycle

(a) Novel products or technologies for new markets				
Innovation	**Geography***	**Invention, development and demonstration**	**Market deployment and commercialisation**	**Total time taken for widespread commercialisation (years)**
Cars	US	1885–1907	1908–1955	70
Cathode Ray Tube (CRT) TV	US	1907–1938	1939–1951	44
ATM/Cash cards	UK	1964–1970	1971–1989	25
Video cassette recorder	US, UK	1956–1974	1975–1986	30

(VCR)				
(b) Replacement products or technologies				
Innovation	**Geography**	**Invention, development and demonstration**	**Market deployment and commercialisation**	**Total time taken for widespread commercialisation (years)**
Mobile phone	US and Europe	1970–1982	1983–2002	32
Thin Film Transistor Liquid Crystal Display (TFT-LCD) TV	UK, US, EU, OECD	1976–1990	1991–2008	32
Catalytic converter	US, EU, global	1950–1974	1975–1981	31
Lithium ion rechargeable batteries for consumer products	US, Japan, global	1979–1990	1991–1998	19
Compact fluorescent light bulbs (CFLs)	UK, US, Holland	1976–1979	1980–2011	35
LED lights	UK, global	1992–2001	2002–2015**	23**
(c) Electricity generation technologies				

Innovation	Geography	Invention, development and demonstration	Market deployment and commercialisation	Total time taken for widespread commercialisation (years)
Combined cycle gas turbines (CCGT)	UK, US, Japan, Europe and global	1949-1969	1970-1995	46
Wind electricity	US, Denmark, global	1957-1982	1983-2015**	58**
Nuclear power	UK, US, OECD, global	1941-1963	1964-1981	40
Solar photovoltaics (solar PV) - grid-connected	US, Japan, Europe and global	1954-1990	1991-2015**	61**

*Geography refers to the geographical scope of the literature reviewed for each innovation.
**This product has yet to reach widespread commercialisation.

Energy sector findings

Electricity generation technologies (CCGT, nuclear power, wind electricity and solar PV) exhibit some of the longest commercialisation time periods within the technologies reviewed. The average time from invention to commercialisation is 48 years for electricity generation technologies and shortest for CFL / LED lighting and lithium ion rechargeable batteries for consumer products- 26 years. It is also important to note that LED lighting, wind electricity and solar PV are still to reach a stage of widespread commercialisation in line with the definitions provided in Section 2. In comparison, the seven non-energy sector innovations average 38 years. Summary data on timescales differentiated between energy/non-energy sector technologies is provided in Table 3.4.

Table 3.4: Speed of innovation by energy sector / non-energy sector

Sector / statistic	Invention, development and demonstration (years)	Market deployment and commercialisation (years)	Invention to commercialisation (years)
Electricity generation technologies (Mean)	25.5	22.8	48.3
Lighting or energy storage products (Mean)	8.7	17.0	25.7
Non-energy sector products (Mean)	19.1	18.6	37.7
Electricity generation technologies (Median)	22.0	24.5	46.0
Lighting or energy storage products (Median)	10.0	13.0	23.0
Non-energy sector products (Median)	19.0	17.0	32.0

Note: Electricity generation technologies include: CCGT, nuclear power, wind electricity and solar PV. Lighting or energy storage innovations include: CFLs, LED lights and lithium ion rechargeable batteries. Non-energy sector innovations include all other products considered in this review.

3.4. Detailed data on innovation timelines

For all the technologies reviewed judgements were made, based on the available literature about the point of invention, market introduction and widespread commercialisation. Table 3.5 provides a summary of the judgements made and the reference material used to inform these decisions.

Table 3.5: Definitions of invention, market introduction and commercialisation for each innovation

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 2015a).	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.'	20% of peak US vehicle ownership was reached by 1955, based on (Sivak 2013) and (Oak Ridge National Laboratory 2015).
Cathode Ray Tube (CRT) TV	While Braun's cathode ray tube was invented in 1897 (Feldmann *et al.* 2003), it was in 1907 that a CRT was first used to transmit	The first commercially practical CRT television was made by Allen Du Mont in 1931 (Bellis 2015c, Saperecom 2015),	The share of US households with a TV passed the 20% threshold in 1951 (TV History 2013)

	images through electronic scanning to create a television system. This was achieved through the independent efforts of Campbell Swinton and Boris Rosing. For example, Rosing transmitted basic geometrical patterns onto a television screen (Bellis 2015b).	however it was not until 1939 that the first electronic CRT television set (DuMont model 180) was introduced to the US market, available at a cost of approximately 125 dollars (Saperecom 2015).	
Automatic teller machine (ATM)/Cash cards	'Conception of the technical basis of the innovation' (Wonglimpiyarat 2005). 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). Nevertheless, the point of invention is taken as 1964, when	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). However, it was not until 1971 that cash machines were more widely introduced to markets worldwide	'..after the delivery channels to cater 20% of potential users using the innovation are established' (Wonglimpiyarat 2005).

	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) 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)	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)	
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 (h2g2 2004,	The VCR was 'launched into the market-place' in 1975 (Wonglimpiyarat 2005). This is the year when Sony released Betamax, with JVC's VHS	'..after the delivery channels to cater 20% of potential users using the innovation are established' (Wonglimpiyarat

	Castonguay 2006). This precedes the year attributed to the 'conception of the technical basis of the innovation', i.e. 1960 (Wonglimpiyarat 2005).	following in 1976, and Phillips releasing the V2000 in 1978 (Castonguay 2006).	2005)
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).	Analogue mobile phone launched commercially in 1983 by Motorola. (Giachetti and Marchi 2010)	In 2002 globally, the number of mobile phone users overtook the 1.1 billion people with fixed telephone lines (Bohlin *et al.* 2010). By the early 2000s, market saturation was reached in western Europe and the US, with market penetration per capita averaging close to 100% across developed countries (Giachetti and Marchi 2010).

Thin Film Transistor Liquid Crystal Display (TFT-LCD)	Based on an analysis of patent documents, 1976 is classified as the beginning of an 'Emerging' stage for the TFT-LCD TV (Gao et al., 2013).	Based on an analysis of patent documents, 1991 is classified as the beginning of a 'Growth' stage (Gao *et al.* 2013). In 1988, Sharp developed a 14-inch, colour TFT-LCD TV (Sharp 2015). The first LCD and plasma TVs introduced to the market in the 1990s (IEA 2009).	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).
Catalytic converter	First conception / application by Eugene Houdry's Oxy Catalyst company in 1950 (Chemical Heritage Foundation 2015).	California 1975 – 'The first two-way catalytic converters came into use as part of the ARB's Motor Vehicle Emission Control Program.' (California Environmental Protection Agency 2015b) The 1970 Clean Air Act in the US required new cars manufactured from 1975 to reduce their exhaust pipe emissions by 90%. Consequently, all US vehicles manufactured in the US were required to have a catalytic converter from 1975	The catalytic converter Is classified here as a replacement product, as it represents a modification of the incumbent car exhaust systems. In 1981, almost 70% of new US vehicles were fitted with three-way catalytic converters, representing the largest market share for a car emission control technology. Moreover, the three-way catalytic converter satisfied 90% of

		(Gerard and Lave 2003).	the 1970 Clean Air Act Amendments stipulations (Lee and Berente 2013).
Lithium ion rechargeable batteries for consumer products	Development of lithium cobalt oxide positive electrode (Mizushima *et al.* 1980).	First commercially available lithium ion rechargeable battery (Sony 1996).	(Pistoia 2014) and others. 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 lightbulb (CFL), the Phillips SL, was released to the US market in 1980 (Miller 2012). The first year of >0% market share of lighting products in UK households was in 1981 (DECC 2015a).	Market commercialisation based on the year when energy saving light bulbs attained the dominant market share in UK homes respectively (DECC 2015a).
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	Market introduction / based on the first year of >0% market share of lighting products in UK homes (DECC 2015a).	UK residential market share of LED lights in 2014 was 0.6% (DECC 2015a). Globally in 2011, residential lighting accounted for 40% of the

	Nichia in 1996 (Sanderson and Simons 2014).		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 3.5MW gas turbine operated in conjunction with a 35MW 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 1997a)	1970 – the first`large' CCGTs (greater than 100MW) 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	CCGT plants achieved a 10% share of UK electricity generation by 1994 according to DECC's 'Historical electricity data: 1920 to 2014' available from (DECC 2015b). CCGT assumed to have reached 10% share of global electricity production from mid-to-late 1990s based on (Watson 1997b) and (BP 2015).

		to exceed 40% (Watson 1997a).	
Wind electricity	In 1957, Johannes Juul completed the construction of a 200kW 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 (Danish Wind Industry Association 2003, Jones and Bouamane 2011). 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).	Feed-In Tariffs for wind power were first introduced in California in 1983, in the form of the Interim Standard Offer 4 (ISO 4). The ISO 4 provided contracts with a fixed-price for ten years, followed by 20 years of floating prices. Most new wind power generation capacity in California was added as a result of these tariffs from 1983 to the mid-1990s 1970s (Jones and Bouamane 2011).	Ongoing. (Wilson 2012) writes that 'In the Danish wind case, this was a period of experimentation and learning from the build out of many units of a relatively small and fairly constant unit size from the late 1970s to the early 1990s, a period extending well into the full commercial application of the technology.'
Nuclear power	The history of electricity generation from nuclear power	Nuclear power plants were 'first launched	The share of total global electricity production from

	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).	commercially' in the US in 1964 (Damian 1992).	nuclear power reached 10% at the start of the 1980s (Bradish 2008).
Solar photovoltaics (solar PV) - grid-connected	In 1954, three scientists at Bell Laboratories (Pearson, Chapin and Fuller) achieved a greater than 5% solar cell efficiency, 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	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	Ongoing. Using the 10% of global electricity production definition of technology maturity, demonstrates that solar PV has yet to reach this stage. The global share of electricity generation from PV passed the 1% mark in 2015 according to (CleanTechnica 2015).

	1999, Green 2005).	of 5.3 MWp on private homes from 1991-1995. 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).	

3.5. Discussion

Overall, there is a high degree of variation in the rate of innovation for the 14 products and technologies. Figure 3.2 shows that, for the 14 innovations reviewed in this report, the car (automobile) has the longest overall time for commercialisation at 70 years. Cars also experienced the slowest journey from market introduction to widespread commercialisation (47 years). Lithium ion batteries represent the shortest overall journey at 19 years, with this roughly evenly split at a decade or so each for the two stages. The longest time taken from invention to market introduction was for solar PV (37 years). Conversely, compact fluorescent light bulbs (CFLs) were introduced to the market four years after invention, while the catalytic converter demonstrates the most rapid deployment, taking six years to reach commercialisation (defined as a replacement for non-catalyst cars in the US market) after first being brought to market.

In what follows we discuss some of the non-energy cases in more detail. The discussion is not exhaustive and does not seek to be definitive or to apply any of the innovation theory frameworks in order to deconstruct the drivers of innovation in detail. Instead, the particular instances we discuss below provide an indication of some of the factors affecting the innovation journey. We focus in particular on instances where innovation was particularly fast or slow overall, or where one of the stages was passed through particularly quickly. It should be noted that in making these comparisons, the timelines for solar PV, wind electricity and LED lighting are incomplete, since these products have yet to attain widespread commercialisation as we have defined it. Electricity generation, batteries and energy efficient lighting products are discussed in Section 4.

Macroeconomic factors: The car

Cars are substantially more expensive than any of the other consumer products reviewed, representing a substantial fraction of consumer income, even in wealthy countries. The history of the car also correlates strongly with a period of huge economic expansion through the twentieth century. Increasing disposable incomes fed demand for mobility and for car ownership, in turn driving a growing vehicle fleet and production base. The result is an extended period of market growth, delaying the point at which 20% of cumulative sales is reached (the US is the geography reviewed here but this holds for other OECD countries slightly later in the twentieth century and for developing countries now).

In the case of automobiles in the US, production driven by emerging mass manufacturers, first Ford and then many competitors, both drove economic growth and was constrained by economic recessions, as well as interruptions caused by the World Wars. 65,000 cars were manufactured in the US in 1908 following a short recession in 1907, rising to 199,000 in 1911, a rate of production which roughly doubled every two years until 1917 (Mercer and Douglas Morgan 1971). Further expansion of automobile manufacturing continued in the early 1920s, reaching a point where market saturation was close to being achieved in the US prior to the Great Depression (Mercer and Douglas Morgan 1971), although this is contested by (George and Oksanen 1974).

Our focus is on mass produced, standardised vehicles that offer a basic functional form comparable to modern cars. Therefore we have taken the point of market introduction to be the start of mass production of the model T Ford in 1908. Although cars were available from 1885 we have treated these largely bespoke vehicles, made in very small volumes and available to early adopters, as an extension of the demonstration and experimentation phase. Unit costs of automobiles decreased rapidly from 1910 to 1920, with a plateau in costs following the early 1920s, although this was for a single product (the Model T) and is not indicative of the industry achieving a level of maturity at this point (Ayres and Martinas 1992). Since 1925, incremental product innovations have accompanied refinements to the manufacturing process to iteratively improve vehicle efficiency, comfort, reliability and performance. Vehicle ownership expanded continuously from the 1950s, and through the remainder of the twentieth century. Our data suggest the 20% point was reached in the mid-1950s (Sivak 2013, Oak Ridge National Laboratory 2015). Globally vehicle ownership continues to expand as income levels in developing regions reach levels where mass-ownership becomes possible.

A key concern for energy and climate policy is how rapidly internal combustion engine vehicles might be replaced by electric or hydrogen fuelled cars. This will be affected by many factors including technological progress, regulation and market drivers as well as infrastructural change. Hybridisation is also a facet of this transition, with increasing numbers of manufacturers offering hybrid electric cars as well as 100% non-fossil options. A review of the timelines associated with alternative drivetrains could not be undertaken within the constraints of the study, however assessing the prospective timelines associated with the roll out of alternatively fuelled vehicles would be a valuable addition to the research. Our review reveals that mass roll out of the car as a new product was a lengthy process, but this should not be taken as evidence that moving the vehicle fleet over to alternative drivetrains will take a similar period.

Regulation as a driver: the catalytic convertor

The catalytic converter is also an unusual case, with an unusually short diffusion stage. However the 6-year commercialisation period represents the transition between early two way catalysts (and other approaches to emission reduction) and the introduction of three way catalysts as manufacturers sought to meet mandatory requirements for new vehicles in order to meet clean air regulations in the US. Catalytic converters were first developed for gasoline car engines by Eugene Houdry's company Oxy-Catalyst in 1950. However, the initial application of this technology was not feasible, since catalysts were poisoned by the lead content in gasoline, and therefore lead needed to be eliminated in order for catalytic converters to be effective (Chemical Heritage Foundation 2015). It was not until 1975 that the catalytic converter was first introduced to market in California, following the Clean Air Act Amendments in 1970 (1970 CAAA), which mandated requirements for emissions reductions from car exhausts.

Car manufacturers also tried to meet regulatory requirements by using a range of alternative technologies to modify car engine architecture. Honda and Chrysler developed the compound vortex controlled combustion (CVCC) and lean burn engines, respectively, to meet reduction levels for hydrocarbon and carbon monoxide stipulated by the Environmental Protection Agency in 1975. However, both engines were not capable of meeting the 1970 CAAA's standards for nitrogen oxide reduction. The first two-way catalytic converters were used in 1975 for the California Air Resources Board's Motor Vehicle Emission Control Program (California Environmental Protection Agency 2015a, California Environmental Protection Agency 2015b). The three way catalytic converter, first introduced for Volvo's 1977 smog-free car (CEPA, 2015), presented a viable technology which could achieve the required emissions reductions for hydrocarbon, carbon monoxide and nitrogen oxide all at the same time (Lee and Berente 2013).

In 1981, the three-way catalyst converter became the dominant car emission control technology, reducing emissions by 90% and satisfying the 1970 CAAA stipulations. From this point forward the majority of cars in the US were fitted with catalysts, and as we are treating cars with catalysts as replacements for cars without this represents the point at which sales of the replacement overtook sales of incumbent technology. The presence of a regulatory driver together with the availability of a technology able to meet the regulation is important in this instance. Whilst the review has not sought to assess the interplay between technology and regulation in detail it is notable that the diffusion phase is quite truncated in this case, in part because the regulation drove US manufacturers quite rapidly towards the use of catalysts. This is also a facet of the fact that we have focused upon new car sales, treating catalytically equipped cars as a replacement product. A more extended period of vehicle turnover followed, as older cars without catalysts were gradually replaced by newer vehicles with catalysts.

In addition a focus on global diffusion would have revealed a different picture. The US uptake is reported here. Global developments proceeded more slowly. Uptake of catalytic converters did not begin in Europe until 1985, and it was only after car emissions standards were introduced by the EU in 1993, that the installation of catalytic convertors became compulsory on all new, gasoline-fuelled cars (Bosteels and Searles 2002) (Stoneman *et al.* 1995). Although Volkswagen and Audi fitted catalytic converters to their cars in the early 1980s, many car companies introduced this technology to coincide with the mandatory EU standards coming into effect in 1993 (Stoneman *et al.* 1995).

Notwithstanding these caveats, catalytic converters do appear to exemplify how regulation can accelerate the uptake of an innovation, where there is no clear market for a technology in the absence of regulation and standards. Other examples also suggest that with respect to environmental abatement technologies in particular, regulation can drive the uptake of a new innovation. Section 4 presents a case study on compact fluorescent and LED lighting, which describes the role of energy efficiency standards and progressive bans on incandescent light bulbs in promoting more efficient alternatives.

<u>Product differentiation and market pull: the mobile phone</u>

Our review of consumer products outside the energy sector highlights the important role that product development and market pull can play in driving innovation. As an example, the evolution of mobile phones exemplifies how rapidly new product technologies and features can be introduced in response to demand for a whole host of additional services, expanding the mobile phone well beyond its original core function as a portable telephone device (Giachetti and Marchi 2010). The history of innovation in mobile phone technology has been extensively researched, beginning with the first presentation of the mobile telephony concept by AT&T Bell Labs in the early 1970s (Yeo *et al.* 2015).

Advances in semiconductor and microwave technology in the 1970s paved the way for the development and commercialisation of the first cellular mobile networks in the early 1980s. Beginning in the US and Europe and then spreading to developing countries, innovation in mobile telecommunications has occurred iteratively over technological generations, in a similar way to semiconductor chips. The speed and extent of growth in mobile telecommunications can be expressed by the fact that, by 2002, the number of mobile phone users globally had overtaken the 1.1 billion people with fixed telephone lines worldwide. It took approximately 20 years for the mobile telephone industry to acquire the same number of users as fixed telephone lines did in at least 120 years (Bohlin *et al.* 2010).

The first analogue mobile phone systems were introduced to the US in the early 1980s, where the Federal Communication Commission established a common standard, the Advance Mobile Phone System (AMPS), to enable roaming and compatibility of handsets between states. The UK set up the Total Access Communication System (TACS), based on the US standard, while Germany, France, Italy and Japan also created their own local systems. The analogue mobile phone became available commercially in 1983 following its launch by Motorola, with Nokia and Ericsson launching similar portable products in 1984 and 1986 respectively. As mobile phones remained expensive they were restricted to business use, while also being fitted typically inside cars, until the end of the 1980s (Giachetti and Marchi 2010).

These first generation (1G), analogue systems based on separate national standards were not compatible, and therefore did not facilitate international roaming or cost reduction through economies of scale. They were succeeded by the introduction of digital (second generation or 2G) mobile telephone systems during the early 1990s (Bohlin *et al.* 2010). These new services provided better co-ordination through the establishment of the GSM (Groupe Spécial Mobile) standard in Europe in 1991, and the reduction of the number of different standards globally from seven to four (Bohlin *et al.* 2010, Giachetti and Marchi 2010). The number of users subscribing to 1G services peaked in 1997, and was quickly exceeded by the number of subscriptions to 2G technologies (Bohlin *et al.* 2010).

In terms of the product itself, portability was improved, reducing the size and weight of mobile phones, and enabling a transition from fixed carphones to handsets. Although demand for mobile phones continued to be predominantly from the business market, individual ownership began to increase quickly. The revolution in the personal ownership of mobile phones began from the mid-1990s, as handsets became rapidly smaller and lighter, prices fell and network coverage became widespread. The miniaturisation of the mobile phone into a pocket-sized product in the late 1990s, combined with a new innovative text message feature (SMS), were key transformational developments in reaching out to a mass market of individual consumers. Additional features were quickly added to mobile phones, such as video games from 1997, and the wireless application protocol (WAP) in 1999, allowing users to access the internet via a micro browser and configure personalised services (Giachetti and Marchi 2010).

By the early 2000s, market saturation had been reached in Europe and the US, with market penetration per capita averaging close to 100% across developed countries. Consequently, the principal source of revenue in these countries was from replacement purchases of new devices which were becoming increasingly multi-functional, integrating a succession of new technologies, such as colour displays, cameras and the multimedia messaging service (MMS). Meanwhile, in 2005 the mature, replacement market across western Europe and the US was contrasted by emerging markets based on new sales of mobile phones in Africa, Eastern European countries and China (Giachetti and Marchi 2010).

Nevertheless, third generation (3G) technologies, which were introduced in 2002 with a focus on improving data services, initially experienced a much slower diffusion compared to 2G up to 2007 (Bohlin *et al.* 2010). Despite the maturity of the market in developed countries in the late 2000s, innovation has continued through the large scale production of the more expensive, higher margin smartphones with advanced features such as a graphic interface, advanced operating system, and the capability to install multiple additional applications (Giachetti and Marchi 2010).

3.6. Summary and emergent themes

This section has presented the overall findings of our rapid evidence assessment of innovation timescales, in which we have evaluated the time taken from invention to market introduction, and market entry to widespread commercialisation, for 15 products and technologies. These include innovations both within and outside the energy sector. The 14 innovations reviewed average more than three and half decades and range between 19 and 70 years for the time taken from invention to widespread commercialisation, according to the definitions which we have applied, as set out in Table 2.2 and Table 3.5.

There is considerable variation between the innovations in terms of how quickly they reach market and become commercialised, and it is notable that the energy generation technologies in particular take significantly longer for the second phase of market deployment and commercialisation than the non-energy sector products reviewed. While the novel innovations reviewed took longer to reach market and longer to deploy than the replacement products on average, this masks a particularly wide variation between the new products, ranging from 22 to 70 years in their overall timespan from invention to commercial maturity.

In this chapter, we have reviewed some of the reasons for these differences, which include: whether products are novel products aimed at new markets or a new technology entering an existing market; macroeconomic factors that affect the affordability of a product; the role of regulation; the importance of market pull and technological differentiation. Chapter Four presents case studies of the innovation journey of five of these technologies in the energy sector (CCGT, nuclear power, solar PV, lithium ion batteries and CFLs / LED lighting).

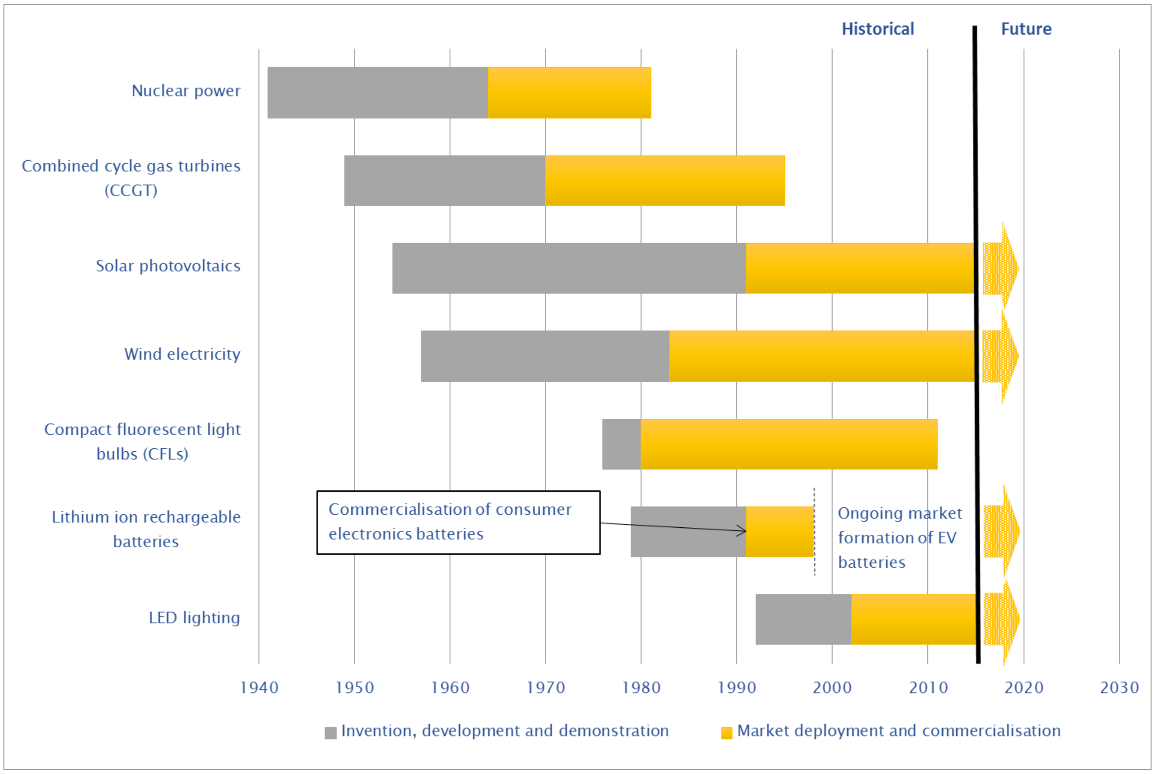
4. Innovation rates of energy technologies: case studies

4.1. Introduction and overview

In this section we present five case studies which examine the history of energy supply and end-use technologies. These case study technologies have been selected to represent a range of scales, including large-scale power generation technologies such as combined cycle gas turbines (section 4.2) and nuclear (section 4.3), a small scale renewable generation technology, solar PV (section 4.4), an energy storage innovation represented by lithium ion batteries for consumer products and for cars (section 4.5), and finally, two small scale, end use lighting products: compact fluorescent light bulbs (CFLs) and LED lighting (section 4.6). Each case study is structured to outline the historical periods equating to the successive phases of 'invention, development and demonstration' and 'market deployment and commercialisation', which were based on the systematic review of innovation timescales (see Section 2). Section 4.7 discusses how the case studies can inform an understanding of drivers and barriers to the rate of innovation with respect to energy sector technologies.

Figure 4.1 presents the timescales from invention to commercialisation for the energy sector technologies reviewed in this report (including wind electricity, which is not considered in detail in this section). The successive phases of invention, development and demonstration, and market deployment and commercialisation, are also shown. As noted in Section 3, the time taken for the first of these phases is longer for the electricity generation technologies (at least two decades for nuclear power, CCGT and wind electricity, and over three decades for solar PV), than for lighting products (a decade for LEDs and four years for CFLs) or lithium ion rechargeable batteries for consumer products (12 years). Of the seven energy sector technologies, lithium ion rechargeable batteries for consumer products reached widespread commercialisation most quickly after market introduction (7 years). The difference between the length of this second phase is less clear for the other technologies, particularly as solar PV, wind electricity and LED light bulbs have yet to be widely commercialised, according to the definition we have applied in this review. CFLs have actually taken longer (three decades) to complete the market deployment and commercialisation stage than CCGT or nuclear power. The following sections set out the key relevant historical developments in relation to each case study technology, in order to achieve an understanding of the particular contextual factors which have influenced the observed differences in progress timescales between the energy sector innovations.

Figure 4.1: Overview of energy sector technologies: innovation timelines



4.2. Case study 1: Combined cycle gas turbines

4.2.1. Invention, development and demonstration

Selecting a starting point for the innovation timeline of the Combined Cycle Gas Turbine (CCGT) is not straightforward. Although the first CCGT plant was built in 1949 (Watson 1997a), it was preceded by innovation in the gas turbine itself, dating back to the first patents by Frank Stolze in 1873 (Figure 4.2) for designs similar to modern gas turbine technology, consisting of a compressor, combustor and turbine. Testing of early gas turbines took place in the 1900s in Europe and the USA. For example, in 1905, a prototype gas turbine capable of delivering useful power was constructed by Armengaud and Lemale in France, but suffered from performance problems (Watson 1997b, Kern 2012). Meanwhile, the combined cycle concept was not a novel application for gas turbines, but had previously been developed with respect to mercury steam plants (Emmet 1925).

In 1939, the first commercial, industrial gas turbine was installed in Switzerland by Brown Boveri. However, the design of gas turbines by key manufacturers such as General Electric and Westinghouse was also influenced heavily by jet engine designs during the Second World War, with the first aircraft jet engine demonstrated in Germany in the same year – Von Ohain's flight by jet. Following the first jet aircraft flight in the UK by the Whittle engine in 1941, General Electric in the USA acquired a Whittle engine to clone, while Westinghouse was contracted by the US Navy to design a new type of jet engine (Watson 1997a, Watson 1997b).

The first example of the use of waste heat from an industrial gas turbine to provide a useful energy service for commercial buildings took place in 1949. In this year, General Electric installed a 'fully-fired combined cycle turbine' in the US, in which a 3.5MW gas turbine operated in conjunction with a 35MW steam plant (Watson 1997a). 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 1997a). Nevertheless, from the 1950s to the mid-1960s, steam turbines developed more rapidly than gas turbines, which were too small to compete effectively. Limited CCGTs were built, in which the gas turbines augmented power generated from steam turbines (Watson 1997b).

Figure 4.2: Key events leading to the commercialisation of CCGT

Source: compiled from (Watson 1997a, Watson 1997b, Kern 2012)

4.2.2. Market deployment and commercialisation

In the mid-1960s utilities in the US and UK installed gas turbines as an emergency resource due in particular to their fast start up speeds, and by 1970, gas turbines were being manufactured at a rate of 5GW per year globally. General Electric and Westinghouse used the resulting income from sales revenues to finance technology transfer from jet engines, and therefore increase unit power and efficiency. While the aforementioned two companies took their first orders for large CCGTs in the early 1970s, the first `large' CCGTs (greater than 100MW) were sold by Mitsubishi for location in Japan and by Brown Boveri for installation in France. These large CCGTs were also starting to achieve efficiencies which could compete with the incumbent steam turbine power plants (Watson 1997a).

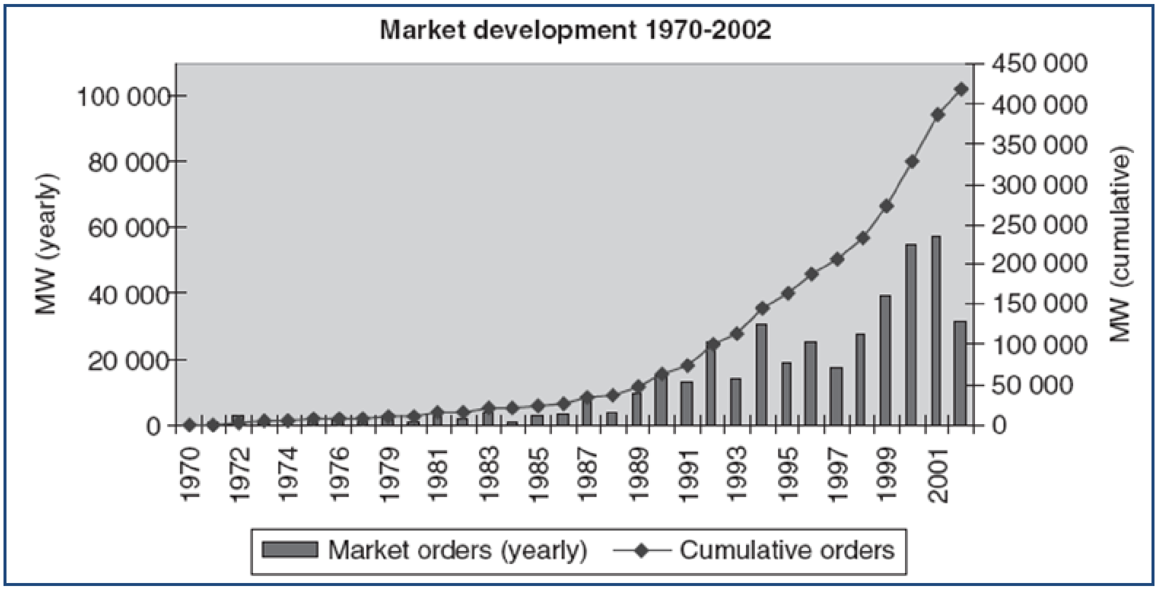
The progress of CCGT was disrupted in 1973/74 by the oil crisis. Following the quadrupling of the oil price by OPEC, oil and gas were not considered economically viable for power generation. Additionally, from the mid-1970s to the mid-1980s, the complexity of CCGTs was compounded by demand for larger units, leading to reliability problems. Nevertheless, the delay in deployment of CCGTs created an opportunity for manufacturers to improve CCGT technologies, through state funding from the Japanese Moonlight programme and the American High Temperature Turbine Technology programme. Elsewhere, the US Department of Defense spent $450 million per year on jet engines from 1976 to 1986 (Watson 1997b). Nevertheless, by 1985 the global market for gas turbines had decreased to 40% of the equivalent market in 1980 (Watson 1997a).

The late 1980s saw a rapid growth in global demand for CCGTs (Watson 1997b), precipitated by the collapse in the oil price from 1986, associated decreases in natural gas prices and a continuing decline in electric utility gas prices throughout the 1980s (Watson 1997a). Declining gas prices were also facilitated by an ongoing, upward trend in the availability of gas, with increased gas reserves and production outside the traditional markets of Western Europe and the USA. In Japan, lower costs of importing liquefied natural gas (LNG) allowed CCGT to become viable as an alternative to coal-fired generation technologies. By the late 1980s, orders were in place for the construction of three additional CCGT plants by Japanese utilities, to add to the three CCGT plants ordered in 1981/1982 (Watson 1997a).

In the USA, the transition to CCGT was facilitated by the delayed implementation of the Public Utilities Regulatory Policy Act (PURPA), following its enactment in 1978. This legislation encouraged independent generators to construct renewable energy and cogeneration power plants, particularly CCGT, and compete with the incumbent utilities. The capacity of CCGT added by these new market entrants grew steadily from the late

1980s (Figure 4.3), especially as the price of natural gas fell. In contrast, many American electric utilities were concerned about potential gas price rises, and did not invest significantly in new CCGT power plants until 1990 (Watson 1997a).

Figure 4.3: Worldwide CCGT market development 1970-2002



Source: Bergek *et al.* (2008)

In the UK, a 'dash for gas' was created by the restructuring of the electricity sector. This led private investors to favour the construction of CCGT power plants over coal-fired steam turbines and nuclear generation (Winskel 2002, Kern 2012). By 1994, CCGT plants had achieved a 10% share of UK electricity generation (DECC, 2015), with a 10% share of global electricity production being reached from the mid-to-late 1990s (Watson 1997b, BP 2015).

4.3. Case study 2: Nuclear Power

4.3.1. Invention, development and demonstration

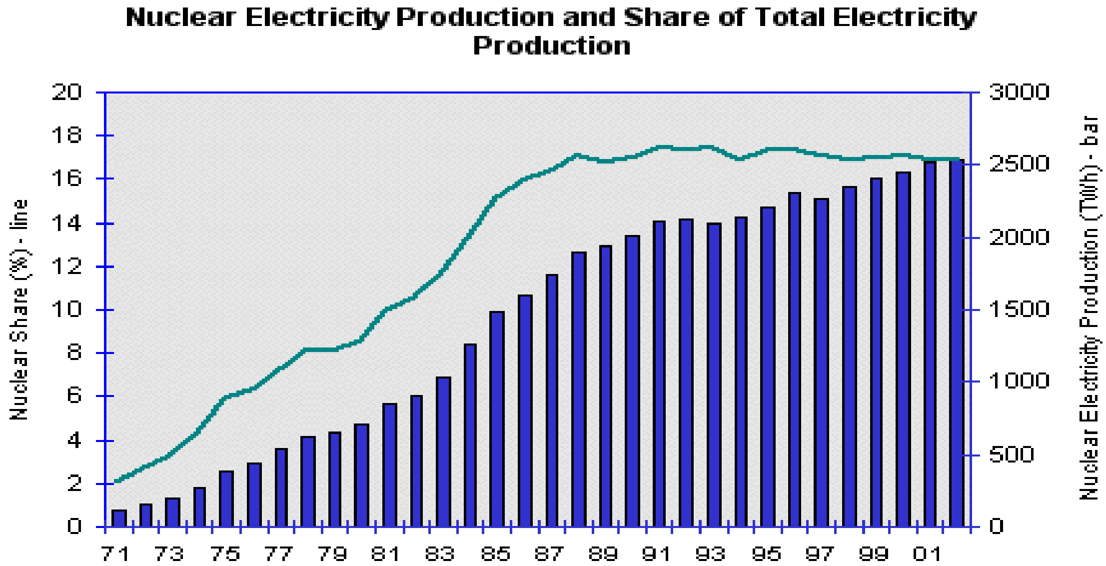
The history of electricity generation from nuclear power can be traced back to the 1950s, with the basic principles of an energy-releasing process using nuclear fission being established by 1939. During the 2nd World War, the intense focus of technology development in this field was on the production of a functioning atomic bomb, culminating in the use of such devices by the US in Hiroshima and Nagasaki during August 1945. Nevertheless, a report by the MAUD committee in the UK in 1941 first proposed the 'use of uranium as a source of power' but this was not pursued further until the end of the war. In the immediate post-war years, significant research resources were brought to bear by several countries (including US, USSR, Canada and UK) on the challenge of using the heat energy released by the fission process to raise steam to drive turbines and produce electricity (WNA 2014).

The first nuclear reactor to generate electricity was a 100kW plant built by the US in Idaho in 1952, and this was followed by a 5MW plant built by the USSR in Obninsk in 1954 (Taylor 2007). Nevertheless, it was the UK which claimed to have ‘the first power station in the world to generate electricity on an industrial scale from nuclear energy’ (The Engineer 1956). This plant, at Calder Hall in Cumberland was opened in 1956 although it was not until 1959 that all four reactors at the site were operational, bringing the total generation capacity to 200MW (WNA 2013). The plant, which operated until 2003, had the dual function of power generation and plutonium production (Thomas 2010), reflecting both the very close links that existed at the time between civil electricity generation and atomic weapon programmes, and the reality that the economic justification for building the plant was underpinned to a considerable extent by the value attached to the plutonium production for military use (Taylor 2007).

4.3.2. Market deployment and commercialisation

The global civil nuclear power industry did however develop rapidly from the late 1950s, with nuclear power plants ‘first launched commercially’ in the US in 1964 (Damian 1992), after which followed ‘an average of some 23 plants ordered annually between 1965 and 1973 in the US’ (Damian 1992). In the UK, a total of 26 reactors were built and in operation by 1971 with unit size increasing tenfold during this period (WNA 2013). This rapid increase in unit size was mirrored in other countries, albeit with differing reactor technologies, and went hand in hand with the further large-scale, global deployment of nuclear power generation capacity, to the extent that during the 1980s, a total of over 200 plants were commissioned worldwide, with an average size of over 900MW (WNA 2015). As Figure 4.4 below shows, by start of the 1980s the share of total global electricity production from nuclear power had reached 10%, and this share rose during that decade to reach approximately 17% by the late 1980s, a figure that is consistent with (Damian 1992) who attributed a similar share of global electricity generation for nuclear in 1991. OECD countries have consistently contributed the majority of total annual production during the entire period of nuclear deployment, accounting for over 90% (around 190TWh) of global output in 1973 and still over 85% (around 2,300TWh) by 2001 (IEA 2003).

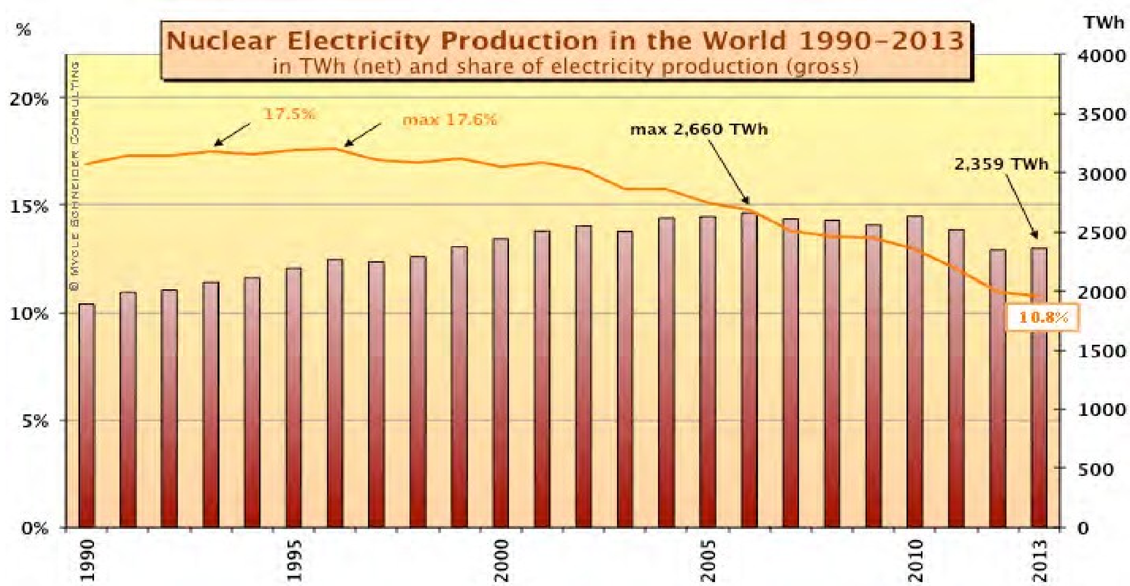
Figure 4.4: Nuclear electricity production 1971–2001



Source: (Bradish 2008), data from the World Nuclear Association

The figure of a 17% market penetration (on an annual production basis) that was achieved by the late 1980s has subsequently turned out be a peak (to date at least), and the proportion of annual total global electricity production supplied from nuclear power plants had declined to around 11% by 2013 (Figure 4.5).

Figure 4.5: Nuclear electricity production 1990–2013



Source: (Schneider and Froggatt 2014)

Some commentators have questioned whether nuclear power has genuinely progressed to a fully commercial status, with (Damian 1992) arguing that the large US orders from the mid-1960s through to the mid-1970s did not mean that nuclear power was a mature technology. The same author went on to say that 'initial US attempt to transform nuclear power into a marketable commodity like any other has been a historical failure' (ibid), and suggesting (correctly as it transpired) that nuclear power was unlikely to increase its market penetration. Questions have also been raised over whether nuclear power plants will be able to compete in liberalised markets, with a study by MIT in 2003 observing that all the then operating nuclear power plants 'were developed by state-owned or regulated investor-owned vertically integrated utility monopolies' (MIT 2003).

Notwithstanding these concerns, it would appear that approximately four decades elapsed between the establishment of the basic principles of nuclear power and the year by which the technology had achieved a market penetration level of 10% of global electricity production. This is based on the start year for the invention phase as being the report by the MAUD committee in the UK in 1941 which first proposed the 'use of uranium as a source of power', which followed from 'the classical analysis of the fission process' by Bohr and Wheeler in 1939 (WNA 2014). The start year for the market deployment phase is considered to be 1964 when nuclear plants were first launched commercially in the US (Damian 1992), and the end year for widespread commercialisation is 1981, the year that nuclear power reached a 10% market penetration on an annual electricity production basis.

4.4. Case study 3: Solar photovoltaics

4.4.1. Invention, development and demonstration

The photovoltaic effect, whereby light induces a voltage or current in a material, was established using selenium in the late 1870s, and the first solar modules based on selenium were produced a few years thereafter. For several decades the efficiency of these modules failed to exceed 1%, meaning that only 1% of the solar energy falling on them was converted into electrical energy. In 1954, however, three scientists at Bell Laboratories (Pearson, Chapin and Fuller) achieved greater-than-5% solar cell efficiency. This came about as a result of using silicon rather than selenium, and much trial and error to establish which chemicals to "dope" the silicon with so as to optimise its semiconducting properties. The first 5%+ solar cells used silicon doped with arsenic to create a negative charge in the silicon and a boron coating to create a positive charge in the silicon near its surface (Perlin 1999). The positive-negative (p-n) junction near the surface of the silicon resulted in an electrical field which propelled electrons and holes freed by incoming light to their respective electrodes, allowing current to flow from the cells around a connecting circuit (Sproul undated). A number of other PV technologies have been developed since the 1950s silicon breakthrough, but none has seriously affected the dominance of silicon solar PV modules, made of either single crystal (monocrystalline) or multi-crystal (polycrystalline) silicon wafers, which together accounted for over 90% of modules produced in 2014 (Fraunhofer Institute 2015).

In 1955, Bell Laboratories constructed a silicon solar PV module (based on the 1954 breakthrough cell design) for outdoor use to power telephone lines in Georgia, and a raft of commercial applications for similar modules were attempted, including for powering transistor radios and toys (Perlin 1999, Green 2005). High costs meant that these modules failed to make a dent in the market dominated by much cheaper batteries, but silicon solar PV modules rapidly gained dominance in powering a range of functions in satellites during the 1950s and 1960s, with technical advances in efficiency resulting from many millions of dollars of investment from the US Government (Perlin 1999). The US space programme was the first niche market for silicon PV modules, with demand from this programme and the Department for Defence accounting for over half of global PV demand in the 1960s and 1970s (Nemet 2014).

Silicon PV solar cell efficiencies achieved in laboratories continued to increase, from the 5% level of the mid-1950s to between 10 and 15% by the early 1970s. This resulted from improvements in silicon crystal quality, superior methods (solid state diffusion, compared to the earlier helium ion bombardment) to dope the silicon with boron and potassium, the use of a grid metallic contact on the top of the cell (as opposed to a back contact) to shorten the distance travelled by electrons to this contact, whilst allowing light through to the cell, and anti-reflection coatings to maximise the incident light absorbed into the cell (Wenham and Green 1996).

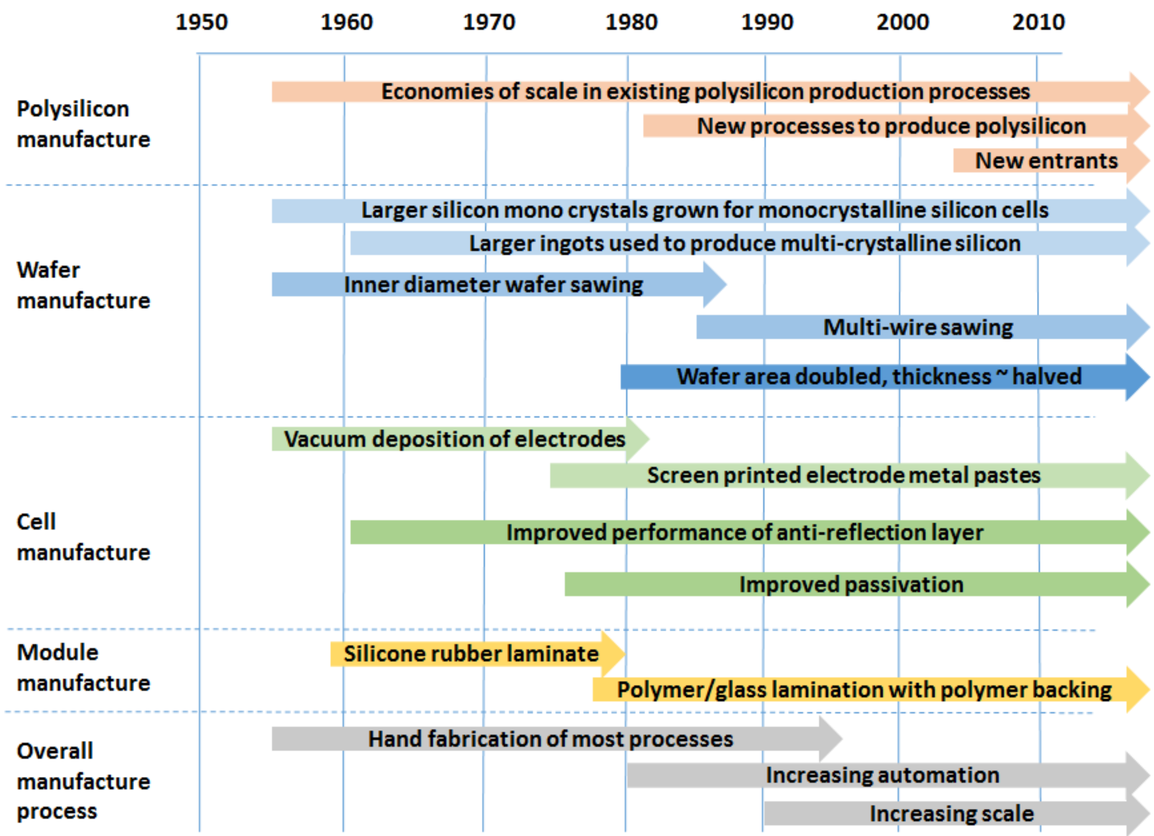
Although during the space programme era there was a continued effort to establish terrestrial applications such as telephone repeater stations, PV only gained a significant foothold in terrestrial markets in the 1970s, particularly in powering navigation aids in the offshore oil and gas industry (e.g. on rigs and platforms), where it could compete favourably on cost terms with batteries, whose servicing and replacement offshore was very expensive (Perlin 1999). By the early 1970s, silicon PV modules were selling at prices of around $50 per Watt (Green 2005), compared to costs of closer to $300 per Watt in the 1950s (Perlin 1999).

A major boost to module technology came from the US Department of Energy's Flat-Plate Solar Array programme, which ran over the period 1975-1985 and funded the purchasing of sequential blocks of modules from a number of early PV manufacturers, with a view to field-testing and improving module performance. The first block purchased cost $20-39/W (1980 dollars) and subsequent blocks saw efficiencies increase from around 5% in the first block to over 8% by 1979, as a result of improved techniques to dope silicon and apply electrode (silver and aluminium) contacts to the cells. In addition, durability improved with the use of glass – rather than silicone – as a protective layer on the cells, and Mylar and Tedlar (fluoropolymer) rear module coatings. By the end of the Flat-Plate Array programme in 1985, PV module designs had essentially reached their current form, with efficiencies of over 10% and costs around $10/W (Green 2005, O'Connor *et al.* 2010). Significant further improvements in laboratory cells occurred over the 1980s, leading to cell designs with efficiencies up to 25% which are only now being commercially produced (Goodrich *et al.* 2013a). Figure 4.6 summarises the major technical improvements which occurred over the period since the mid-1950s breakthrough in cell efficiencies at Bell Laboratories. These improvements spanned the entire process chain of silicon solar PV module production as follows:

- Polysilicon, the major material input into silicon cells, produced initially for the semiconductor industry through the dominant (Siemens) process, increased in scale and reduced in cost with the growth of this industry, with the introduction of new processes and with the significant entry of new producers resulting from the excess demand period in the mid-2000s;
- Silicon wafers, produced through purifying the polysilicon into either single crystals, or multi-crystal blocks, and then sawing these solid blocks into wafers, became cheaper as a result of making larger crystals and blocks, as well as through improved sawing techniques which simultaneously sawed multiple wafers;
- Cells, made from the silicon wafers, which became cheaper and more efficient through using better anti-reflection layers, "passivation" chemicals (referring to the process of preventing electrons and holes from recombining before they reach their respective electrodes), and cheaper and more effective electrode deposition techniques
- Modules, which became more durable and cheaper through using more durable and cheaper substances (glass/polymer laminates and polymer backings) to protect the cells.

In addition, plant sizes and the overall PV industry size grew, leading to automation, scale economies in manufacturing and reduced chemical input costs.

Figure 4.6: Major process improvements in manufacture of silicon solar PV modules



Source: (Gambhir et al. 2014)

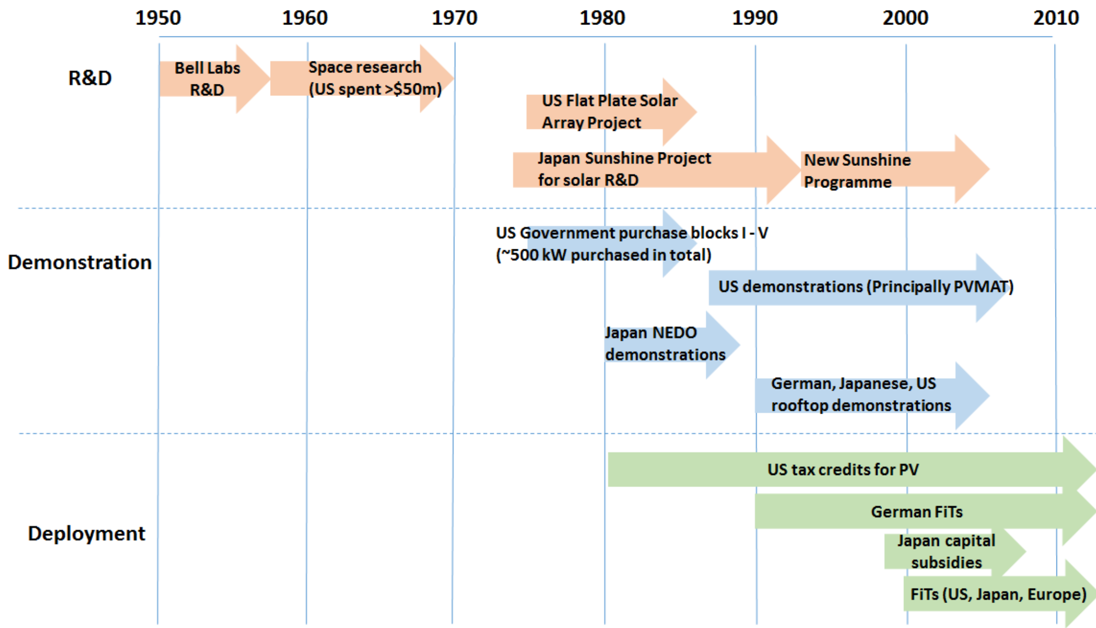
The 1980s saw two other critical drivers of solar PV growth and market formation. The first was the expansion into a range of niche markets including remote communications, and consumer electronics, particularly calculators, watches and toys (Nemet 2014). The second was an increased focus on demonstration projects which allowed the field-testing of a number of PV design aspects (Brown and Hendry 2009). In the USA, PVUSA was launched in 1986 as a joint programme between the Department of Energy and numerous utilities, to demonstrate utility-scale PV. PVMAT began in 1990, with the aim of reducing costs, PV Bonus in the 1990s with the aim of developing building applications, and TEAMUP in 1994, to provide energy service provider applications. In Japan a number of demonstration programmes aimed at testing grid connection and PV system monitoring were enacted in the 1980s and early 1990s, including PV for Public Facilities in 1992, as well as the PV systems (roof monitor) programme in 1994, which later became the Residential PV system demonstration programme. The first demonstration programme in Germany was the Rational Use of Energy and the Use of Renewable Energy Sources (REN) in 1988, to support R&D and demonstration across a range of technologies. During the 1980s and 1990s German municipalities and utilities installed several grid-connected systems, in which a large number of different types of module were evaluated (Brown and Hendry 2009).

4.4.2. Market deployment and commercialisation

The market deployment of grid-connected solar PV began in the early 1990s, with two diffusion support programmes in Germany and Japan respectively. In Germany, the 1,000 roofs programme, which led to the installation of 2,100 systems on private homes from 1991-1995, was initiated as a 'demonstration cum market formation programme' (Brown and Hendry 2009) to pre-empt parliamentary pressure for Feed-in-Tariffs. This programme 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). This is thought to be the first large-scale diffusion project for solar PV. In Japan, the emphasis of demonstration programmes changed in the 1990s from technical experiments to commercial programmes aimed at implementing substantial numbers of customer-owned installations. The first programme to follow this new approach was PV for Public Facilities in 1992, which aimed to lower costs, monitor system performance and improve public perception. The PV Systems Roof Monitor Programme in 1994 provided subsidies to expand the installed base of PV systems (Brown and Hendry 2009).

Deployment support policies in the mid-late 1990s were driven in large part by environmental and energy independence objectives. In 1997 in the USA the Million Solar Roofs programme was launched, whilst at the same time Federal programmes such as California's PV Pioneer programme were introduced, to trial 4kW rooftop systems in selected homes. In 1998 net metering laws were introduced in the USA, which stimulated significant market growth. In Germany, the initial FiTs offered (in the early 1990s) at 90% of retail electricity rates were not successful in stimulating the market, but the much more generous rates in 1999, combined with the 100,000 roofs programme, did stimulate rapid growth in the market (Brown and Hendry 2009). Japan's 1997 PV residential system dissemination programme began with a 50% subsidy for residential rooftop systems, with the subsidy rate declining as system prices fell (Jaeger-Waldau 2003). Several other deployment support policies have followed across the world, driving a very large expansion in solar PV installed capacity (currently at almost 200 GW worldwide (Pyper 2015) which has in turn increased industry scale and plant outputs, particularly in China, driving down costs to their current level of around $0.5-1/W (Goodrich *et al.* 2013b, PV Insights 2015). Figure 4.7 summarises key policies that have been instrumental in driving forward the development, cost reduction and commercialisation of PV since the 1950s, highlighting the early role of R&D, with demonstration programmes and then deployment subsidies bringing the technology to its current stage of widespread deployment.

Figure 4.7: Key policies driving solar PV innovation and cost reductions



Source: *(Gambhir et al. 2014)*

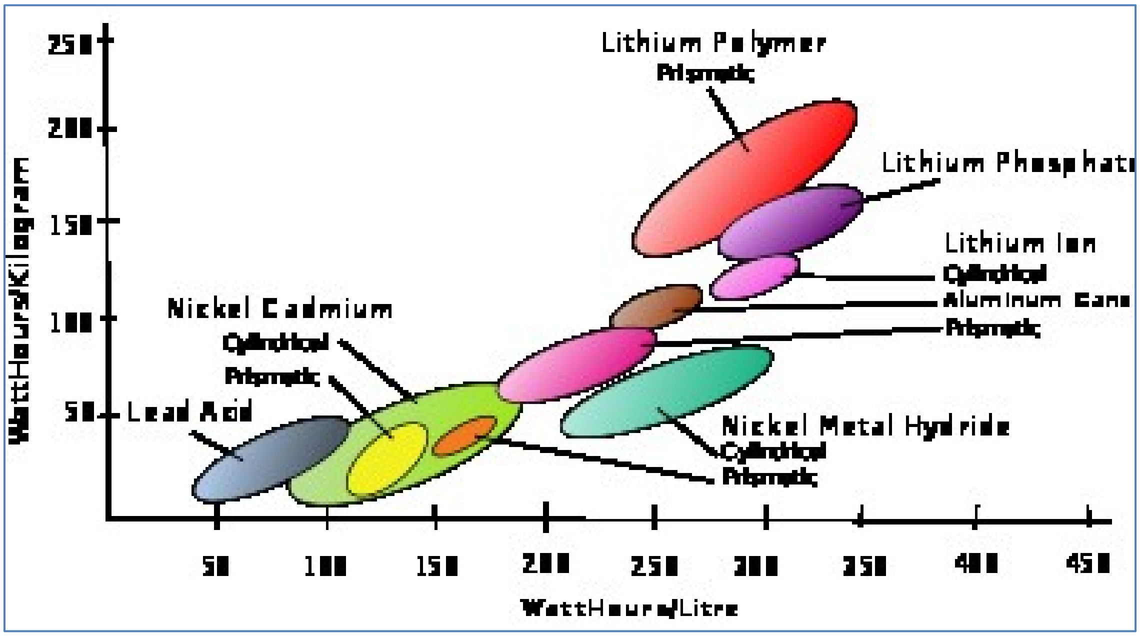
Using the 10% of global electricity production definition of technology maturity demonstrates that solar PV has yet to reach widespread commercialisation. The global share of electricity generation from PV passed the 1% mark in 2015 according to (CleanTechnica 2015). Nevertheless, the era of PV "grid-parity" (whereby PV rooftop generation costs can compete with retail electricity costs) has arrived in many regions (Shah and Booream-Phelps 2015). This is still not the case in many countries, however, with PV continuing to rely on subsidies in order to make it cost-competitive with fossil fuel technologies. Solar PV's evolution from invention (1954) to widespread subsidy-free commercialisation remains incomplete and will therefore have taken at least 60 years.

4.5. Case study 4: Lithium ion batteries

The history of lithium ion batteries is preceded by a long history of rechargeable batteries dating back to the invention of the lead acid battery in 1859. A number of other rechargeable battery chemistries have been commercialised since the lead acid battery as battery chemists seek ever increasing energy densities (Figure 4.8). Lithium ion chemistry batteries represent the latest technology in that innovation journey.

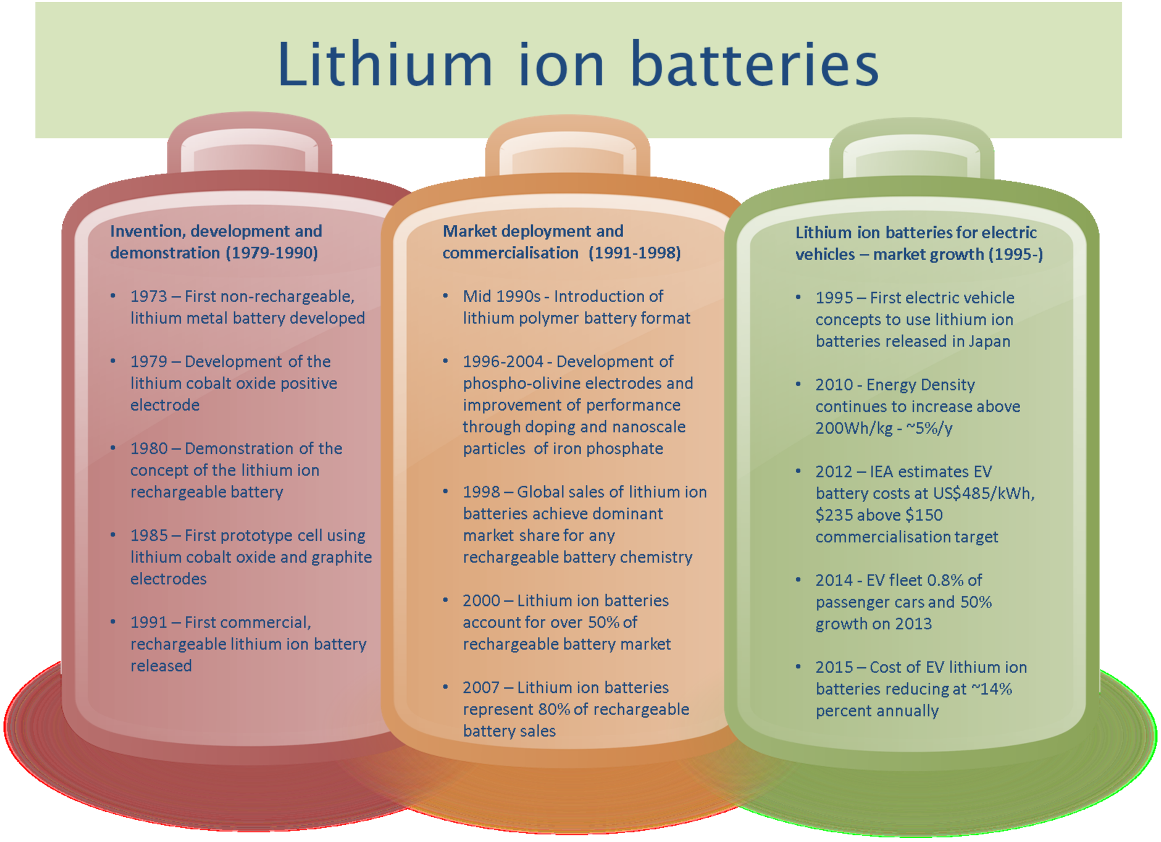
First proposed in the 1970s and released commercially in 1991, these batteries have continued to develop an attempt to meet the demanding requirements of energy technologies such as electric vehicles and electricity storage. This section briefly describes the development of lithium ion batteries, from first concept to current day commercial deployment (Figure 4.9).

Figure 4.8: Mass and volume densities of various rechargeable batteries



Source: (Wagner 2006)

Figure 4.9: Key events leading to the commercialisation of lithium ion batteries



4.5.1. Invention, development and demonstration

Lithium batteries were first proposed in the 1970s by M. Stanley Whittingham while working for Exxon (Whittingham 1976). In 1973 research by Adam Heller resulted in the development of the non-rechargeable lithium thionyl chloride battery (Heller 1975) However, these early designs involved lithium metal, which is highly reactive, creating safety concerns for wider commercial applications. To address these safety concerns the next phase of battery development focused on battery chemistries involving non-metallic lithium compounds capable of accepting and releasing ions.

The development of rechargeable lithium ion batteries required the development of positive and negative electrodes that could utilise more stable lithium ions and the reversible exchange of those ions, achieving recharging capability and safety. A number of further technological advancements followed:

- 1979 – John Goodenough and Koichi Mizushima developed the lithium cobalt oxide positive electrode, creating the possibility of replacing lithium metal (Mizushima *et al.* 1980).

- Late 1970s – Work at the University of Pennsylvania and Bell labs demonstrated the intercalation of lithium ions in a graphite electrode (Zanini *et al.* 1978).
- 1980 – Rachid Yazami demonstrated the reversibility of lithium ion intercalation in graphite electrodes (Yazami and Touzain 1983).
- 1985 – a prototype of modern lithium cobalt oxide battery assembled by Akira Yoshino, demonstrated the safety of lithium ion battery chemistries and opened up the possibility of large scale commercial manufacture (Akira *et al.* 1987).
- 1991 – Sony released the first commercial lithium ion battery (Sony 1996).

The commercial release of a rechargeable lithium ion battery can be considered the end of the early development of lithium ion batteries, a period lasting 15 years from the early concepts in 1976 to the first commercial manufacture in 1991.

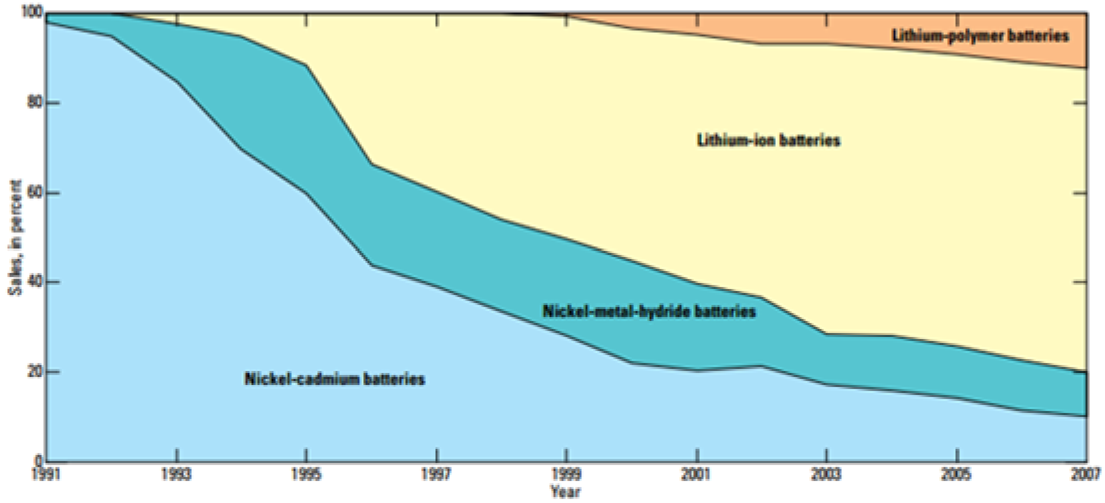
4.5.2 Market deployment and commercialisation

After the commercial introduction of lithium ion batteries in 1991 the market quickly grew to become a significant part of the rechargeable battery market (Figure 4.10). A number of technological improvements then arose as battery developers sought commercial advantage by improving aspects of lithium ion battery performance. This highlights the concurrent nature of development and market deployment. These improvements included:

- Developing the use of phospho-olivines such as Lithium Iron Phosphate as an inexpensive, non-toxic and environmentally benign alternative to the cobalt chemistry positive electrodes used in early commercial lithium cells (Padhi *et al.* 1997).
- Doping of phospho-olivines with aluminium, niobium and zirconium to improve conductivity (Chung *et al.* 2002).
- Improvement of the capacity and performance of phospho-olivine cells by utilising nano-scale iron(III) phosphate particles in the manufacturing process (Economist 2008).

Though technological improvements to lithium ion batteries continued throughout the early part of this century, their commercial success was already apparent, with sales of lithium ion batteries reaching 50% of total rechargeable battery sales in 2000, and 80% of rechargeable battery sales in 2007 and outselling all other types of rechargeable battery from around 1998 (Figure 4.10) (Goonan 2012). A large proportion of these batteries were sold in consumer electronic equipment such as telephones and other small electrical appliances.

Figure 4.10: Sales of rechargeable batteries between 1991 to 2007 as a percentage of global sales



Source: (Goonan 2012)

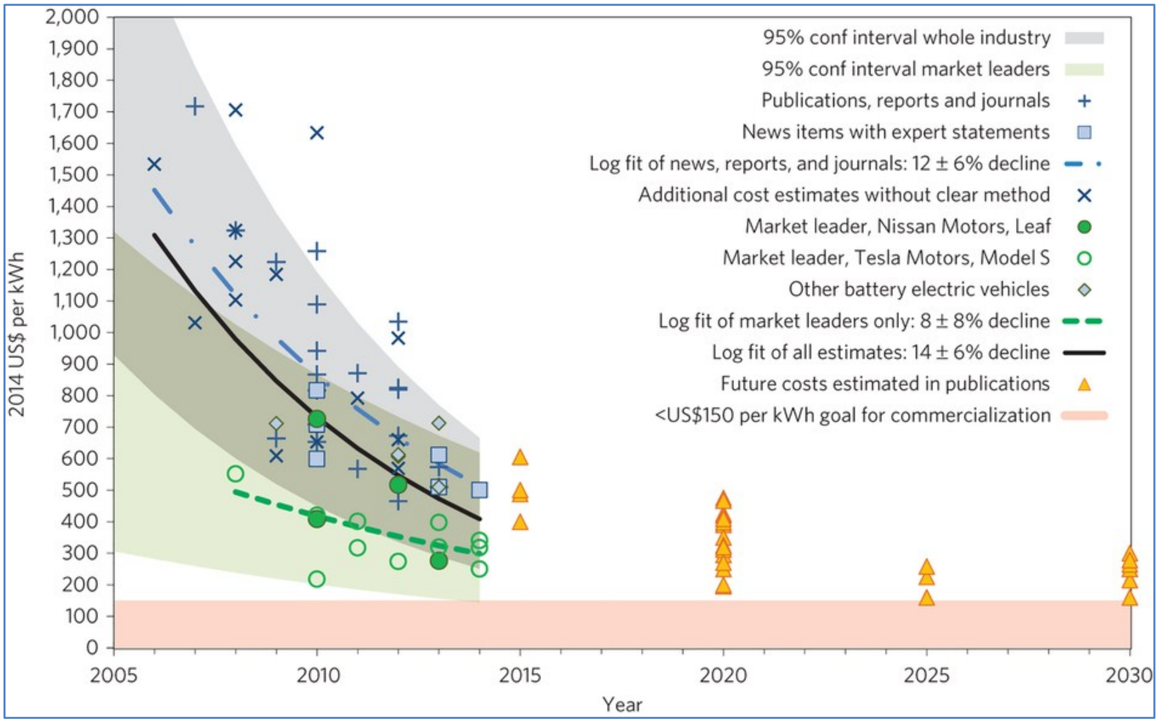
4.5.2. Lithium ion in electric vehicles

Though lithium ion batteries could be considered commercially mature in consumer electronics by 1998 the application of lithium ion batteries in electric vehicles has experienced a slower route to commercialisation. This is largely as a result of the more demanding requirements on electric vehicle batteries. Electric vehicle batteries are required to be more energy dense, cheaper per kWh, and faster to recharge than batteries used in consumer electronics applications (USABC 2014). While improvements on all these fronts have been made in recent years, improvements are still needed to achieve electric vehicles that provide similar utility and similar pricing in comparison to existing vehicle types.

The first electric vehicle concepts to use lithium ion batteries were released in Japan in 1995 (Xia 2011). Commercial lithium ion vehicles would not be widely available till the late 2000s. By 2014 the electric vehicle fleet had grown to 0.8% of the global fleet, a 50% rise year on year, with the vast majority of those vehicles using lithium ion batteries (IEA 2013). Since first introduction the price of lithium ion electric vehicle batteries has continuously improved (Figure 4.11). The energy density of lithium ion batteries has been improving at approximately 5% per year (Noorden 2014).

The cost of lithium ion electric vehicle batteries has also been improving. Figure 4.11 presents a systematic review of the costs of lithium ion battery technology over the past decade, and the forecasts of future lithium ion costs out to 2030 demonstrating cost reductions at ~14% year on year since 2006. Lithium ion cost data is presented in the context of the US Advanced Battery Consortium (USABC) medium term goals for electric vehicle battery commercialisation of <$150/kWh, a price that batteries may be able to achieve in the 2020s based on current trends (USABC 2015)[3].

Figure 4.11: Cost reduction in lithium ion battery technologies between 2005 and 2014 and cost reduction forecasts between 2015 and 2030.



Source: Nykvist and Nilsson (2015)

4.6. Case study 5: Energy efficient lighting

4.6.1. CFLs: invention, development and demonstration

Energy efficiency experienced a transformation as a policy concern following the first oil shock of 1973/4, leading to strong government action to promote the conservation of energy, for example through product standards and building codes (Howarth and Rosenow 2014). An intensification of research and development into the design of CFLs in the 1970s took place as a result of the oil shocks (Menanteau and Lefebvre 2000). Leading companies in the lighting sector took the opportunity to attempt to develop a new energy efficient light bulb capable of replacing the incandescent bulb (Menanteau and Lefebvre 2000). It can be said that according to (Miller 2012), the market diffusion of early CFL products in the US was aided from the 1970s by the recognition that

[3] Current system level battery cost goal is now lower at $125/kWh USABC (2014).

replacing incandescent light bulbs with CFLs could help avoid the costs of new power plants, fuel and air pollution.

Inventors proposed a variety of designs in the 1970s for energy efficient compact fluorescent lamps (CFLs), most of which worked in laboratory conditions but were too expensive for mass manufacture. For example, General Electric's 'Sequential Switching Lamp' in 1972 comprised multiple electrodes which each activated sequentially, but was not considered for mass production, given the complexity of its switching circuitry and glass-work. The 'Short Arc lamp' designed in 1974 by GTE-Sylvania was an attempt to achieve a ballast-free fluorescent lamp, but required high-current due to the shortness of the arc, causing energy losses, and was therefore not feasible (Smithsonian Institution 2015).

In 1976, Philips proposed the 'Recombinant Structure CFL', amongst one of a number of CFL designs being developed by the company. This CFL contained glass fibres which enhanced the light produced by modifying the electric current within the lamp, without lowering its energy efficiency. However, concerns over the manufacturing process for the recombinant structure dissuaded Philips from pursuing this design further. In the same year, General Electric developed the 'Spiral' CFL, in which a long thin fluorescent tube was contorted into a spiral form, creating a long electrical arc. While at this time General Electric dropped the design, considering the new machinery required to manufacture the spiral to be too expensive. However, spiral lamps were eventually introduced to the market in 1995 (Smithsonian Institution 2015).

Following this, Philips, Westinghouse and other manufacturers developed commercially successful CFL designs which retailed at initially high prices, reflecting the significant cost of new production machinery (Smithsonian Institution 2015). When the first commercial CFLs, the Phillips SL, was released to the market in 1980, it was more energy efficient and lasted longer than standard incandescent light bulbs. However, retailing at a minimum price of $12 at the time, the CFL was at least 16 times the price of a typical 100-watt incandescent light bulb (Miller 2012).

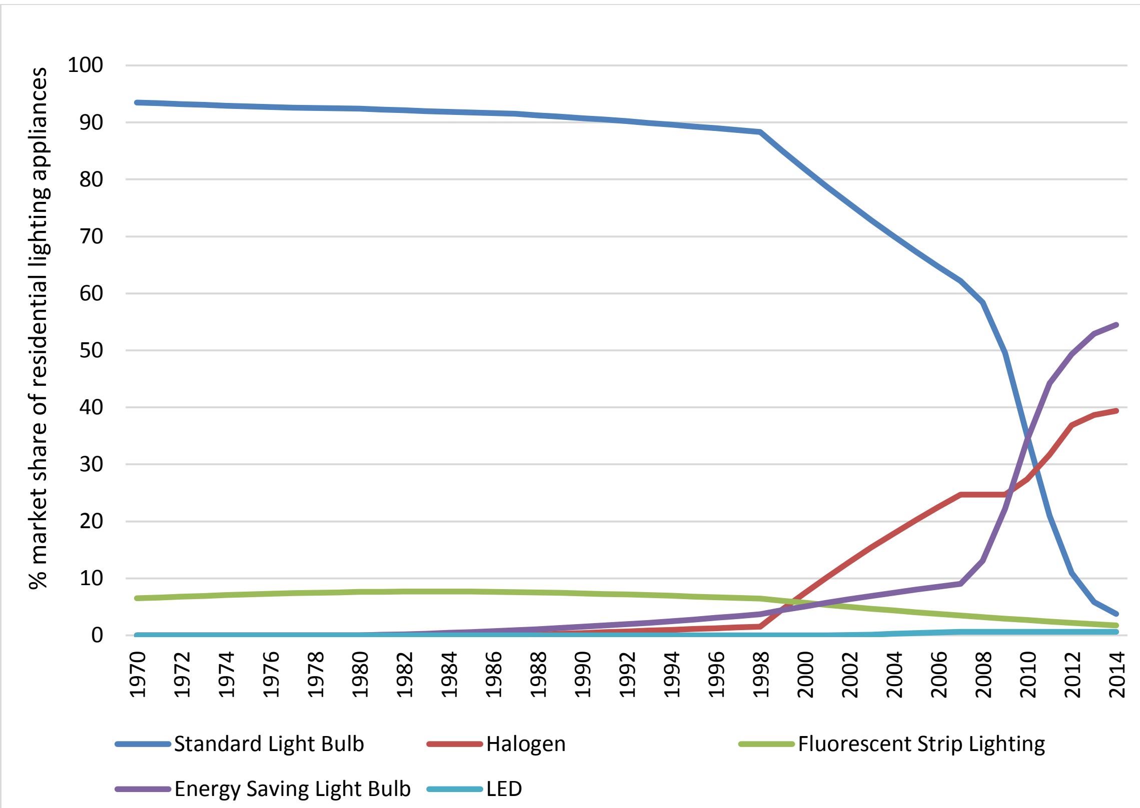
4.6.2. CFLs: market deployment and commercialisation

The CFL experienced slow market growth in countries such as the UK (DECC 2015a), Germany (Frondel and Lohmann 2011, Howarth and Rosenow 2014) and the US (Miller 2012), despite possessing a lighting efficiency four to five times greater than the incandescent light bulb (Fouquet and Pearson 2011, Frondel and Lohmann 2011, Parliament UK 2012), and offering significantly longer lifetimes (Howarth and Rosenow 2014). In 1997, 23% of households in the UK and 51% of households in Germany used a CFL (on average, households in these countries owned one and two CFLs respectively).

By 2007, 50% of households in the UK used at least one CFL, which was the same as the proportion for the EU, while Germany (70%), which could be regarded as an early adopter of the CFL, was significantly above the EU average. In this year, German households used seven CFLs on average, compared to two in the UK (Howarth and Rosenow 2014).

Our review of innovation timelines considers CFLs in the context of UK data on the market share of different household lighting appliances (DECC 2015a), indicating that CFLs took approximately three decades to reach widespread commercialisation after market introduction. This is based on 1981 being the first year in which energy saving light bulbs reached a greater than 0% market share of UK households, although it was not until 2011 that they attained the dominant market share in UK homes (Figure 4.12).

Figure 4.12: Market share of residential lighting appliances in the UK, 1970–2014



Source: (DECC 2015a)

One explanation for this initially slow market diffusion was that, from the perspective of many consumers, CFLs were merely another means of providing light, and did not offer any immediate and obvious advantages over incandescent light bulbs (Miller 2012). This has been compounded by high retail prices for CFLs during the initial stages of market penetration (Frondel and Lohmann 2011), and problems such as delayed initial heat-up times and low quality illumination. The European Commission sought to address these issues through the introduction of minimum performance standards for CFLs in 2009 through Regulation 244 / 2009 (Parliament UK 2012).

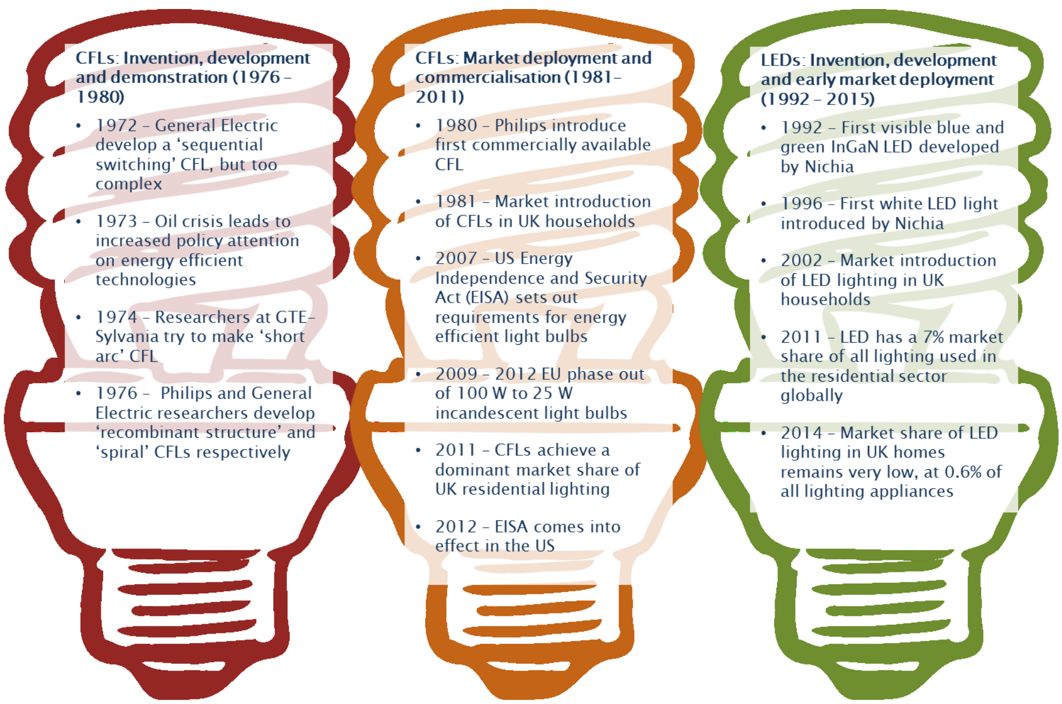
Within the last decade, the purchase of CFLs has accelerated, accompanied by a corresponding fall in the sale of incandescent light bulbs. The replacement of the incumbent incandescent bulbs by CFLs has been related to successive bans of 25 to 100 Watt incandescent bulbs in the EU which were implemented from 2009 to 2012 (Parliament UK 2012, Howarth and Rosenow 2014) (Figure 4.13).

In the US, a combination of public and private investment was focused on making CFLs smaller and lighter, and improving their performance, reliability and light quality. By the year 2000, research and development had improved considerably the reliability and light quality of CFLs, helping to address consumer concerns over these attributes. Importantly, the latest CFLs were also capable of being integrated with the existing lighting infrastructure, in that they could fit most light sockets and fixtures. This was facilitated by a partnership in 1999 between the US Department of Energy (DOE) and the Pacific Northwest National Laboratory to procure “sub-CFL” products targeted at homeowners and federal agencies. This produced smaller, high quality spiral-shaped CFLs which were more affordable, so that in August 2001 short, 15-watt CFLs retailed at $6.99. At the same time, the DOE also introduced an Energy Star scheme for CFL bulbs which set efficiency, performance and quality standards and mercury limits, offered a two-year warranty and required testing of CFLs through an accredited laboratory. Despite these developments, in 2001 CFL sales comprised just 1 per cent of the Californian market and less in the US as a whole (Miller 2012).

In order to achieve market transformation for energy efficiency products in California, the Upstream Lighting Program (ULP) was implemented from 2006 to 2008 (Cadmus 2010), offering reimbursements at a wholesale rather than at a retail level. The ULP allowed retailers to pass savings in wholesale costs onto purchasers of CFLs in their stores. In turn, the difference in price between CFLs and incandescent light bulbs was further reduced, helping to persuade previously reluctant customers to buy CFLs. Clear market signals that CFLs would be sold at much greater volumes persuaded manufacturers and retailers to offer discounted prices, while Walmart announced that they would sell 100 million CFLs in 2007. By 2008, Californian households had 10 CFLs installed on average, with close to 80% of households using at least one CFL. Requirements for product standards associated with the ULP and continuing innovation by manufacturers improved the consumer-friendliness of CFLs, raising overall satisfaction amongst users in California to 8.3 out of 10 in a 2009 survey, compared to 6.3 in 2004 (Miller 2012).

The Energy Independence and Security Act (U.S. Government Printing Office 2007) set out requirements for increasingly energy efficient light bulbs, regardless of type (incandescent, CFL, halogen or LED), with a target of avoiding investment in 30 new power plants by 2020. A federal standard came into effect in January 2012 in the US, requiring all light bulbs on the retail market to be 28% more energy efficient than a standard incandescent light bulb, with continuing improvements over time. Across the US in 2012, 27% of the bulbs fitted to approximately 3 billion, medium-sized, screw sockets were CFLs (Miller 2012).

Figure 4.13: Key events leading to the commercialisation of CFLs and LED lights



4.6.3. LED lighting: from invention to early market deployment

With advancements in electronics and materials, lighting technologies are improving rapidly. Notably, light-emitting diode (LED) lamps are more energy efficient than CFLs, and have substantially longer lifespans. They are available in white and a range of other colours, and sometimes integrate additional features such as daylight and movement sensors. Like CFLs, the currently higher prices of LEDs relative to conventional light bulbs are anticipated to fall rapidly with increased sales and manufacturing volumes (Miller 2012).

The LED light bulb has been developed through a series of incremental innovations over the last fifty years, initially relating to other LED applications in the 1960s and 1970s such as indicator lights, electronic displays, LED watches and black and white LED TV screens. Incremental innovation led to the successive development of red and orange

LEDs, followed by weak green and blue LEDs, and then brighter blue LEDs enabling the production of white light, while research is ongoing into the development of energy efficient green LEDs (Sanderson and Simons 2014).

The first white LED was introduced in 1996, by covering a blue LED with a yellow phosphor. As the colour distribution was fixed, there was no need for red, green and blue LED lights to be balanced through electronic controls. Through a modification of bright blue LEDs, the white LED represented a product which could compete with traditional lighting and alternative energy efficient lighting products, such as incandescent and compact fluorescent light bulbs (Sanderson and Simons 2014).

Based on data from (DECC 2015a), LED residential lighting first entered the UK market in 2002. While LED lighting technologies are technically ready to replace conventional incandescent or fluorescent lighting, market penetration varies according to sector and is limited with respect to lighting in homes (Sanderson and Simons 2014, DECC 2015a). In the US, most home supply stores sold LED light bulbs in 2012, while in January 2013, the internet retailer Amazon was selling close to 15,000 different LED bulb products (Sanderson and Simons 2014).

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. Nevertheless, the LED market share in the residential sector is expected to grow rapidly, to 70% in 2020 due to falling prices of LEDs, increasing cost-competitiveness with CFLs and therefore enhanced potential to accelerate the transition from CFLs to LEDs. The market penetration of LED light bulbs is also being facilitated by the phase out of inefficient light bulbs, e.g. in Europe and China (McKinsey 2012).

4.7. Summary and emergent themes

A common theme amongst the electricity generation technologies reviewed in this report is that the specific invention point for the conventional form of the technology is preceded by a frequently long history of earlier developments in related or predecessor technologies. For example, the installation of the first CCGT plant in 1949 was preceded by the historical development of the industrial gas turbine. The first silicon-based solar PV cell with an efficiency of greater than 5% efficiency may have been developed in 1954, but the photovoltaic effect itself was established using selenium in the late 1870s. While wind electricity is not presented as a case study in this chapter, the development of the ‘father of modern wind turbines’, the Gedser-Molle, in 1957, followed a long period during which small-scale wind turbines were used for mainly off-grid applications.

The early development of nuclear power and CCGT were also facilitated by military research during the Second World War. The UK’s initial proposal to use uranium for power generation in 1941 was delayed until the end of the war, while military objectives remained closely linked to the economic justification for building Calder Hall in 1956, which produced plutonium as well as generating electricity. Meanwhile, the first niche market for silicon-based solar PV was driven by the US space programme, in the form of satellite applications during the 1950s and 1960s.

Variability in oil and natural gas prices have played contrasting roles in disrupting or accelerating the progress of the case study technologies towards market deployment and commercialisation. For example, while the development of CCGT was delayed by the oil crises of 1973/4 and 1978/9, decreases in the price of oil and natural gas from 1986 eventually allowed CCGT to outcompete the incumbent technology, coal-fired generation. The first oil crisis in the 1970s also focused policy attention to the development of energy efficient technologies, which led to the invention of the CFL. The deployment of solar PV in the late 1990s was driven by policy objectives which included energy independence as well as environmental protection.

The electricity generation technologies have also been subject to an iterative process of research and development to scale up power generating units and improve their efficiency. These processes are not necessarily confined to the invention, development and demonstration phase, as with CCGT in particular, delayed deployment during the oil shocks provided an opportunity for research and development to overcome reliability problems associated with larger plants. Nuclear power experienced rapid deployment and increases in unit sizes in the late 1960s and early 1970s. Grid-connected solar PV differs from nuclear power and CCGT in that its scale of applications can vary widely, but nevertheless, progressive increases in solar cell efficiencies from the mid-1950s to the 1980s were critical in improving the commercial viability of solar PV and preparing for its market deployment. As the size of the solar PV industry grew economies of scale could be achieved in manufacturing. The market formation of solar PV through deployment support programmes was preceded by two key developments in the 1980s: the application of solar PV in different niche markets, such as consumer electronics and remote communications; and field testing and technological performance evaluation through demonstration programmes in the US, Germany and Japan.

It is possible that the slow market growth of CFL light bulbs in countries such as the UK and Germany, and their subsequent accelerated deployment linked to the phasing out of incandescent bulbs, may be instructive in interpreting the role of regulation as a means of influencing rates of innovation. The case of the CFL highlights the difficulties inherent in marketing the advantages of an initially more costly, energy efficient product which essentially provides the same energy service as a conventional, incumbent product.

A cautionary note should be applied when interpreting the total time taken from invention to date for those technologies which have yet to reach widespread commercialisation, i.e. grid-connected solar PV, wind electricity, LED lighting, and (although not considered in this report as a separate timeline) lithium ion batteries for electric vehicles.

Overall, whilst the case studies demonstrate a wide range of timescales, it is clear that the innovation timeline for electricity generation typically runs over several decades. There is evidence that consumer products, both for lighting and electronic batteries reached widespread commercialisation more rapidly. Chapter 5 considers the full range of findings and wider conclusions suggested by the research.

5. Conclusions

5.1. Introduction

If new low carbon technologies are to play a substantial role in achieving decarbonisation targets for 2050 and beyond, they will need to be proven, available and deployed at a scale that is sufficient for them to make a material impact. This report has therefore aimed to understand how long technologies take to emerge from fundamental research, go through demonstration and early stage deployment and diffuse into the market place. The Rapid Evidence Assessment has considered the timescales from invention to maturity of seven energy sector innovations and seven consumer products. The five energy-specific case studies presented in Section 4 provide further detail on the historical development, market growth and wider commercialisation of energy technologies.

5.2. Limitations of the approach

The review has included products or technological applications at the product/device level and not the multiple component technologies of which they may be comprised. Indeed, these component technologies may themselves be at different stages of their own respective innovation/commercialisation journeys. The review has also focused upon technologies rather than underpinning institutional structures, infrastructure, policy and societal issues. As we explain in Section 2 these factors are critical to the innovation process and fundamental to understanding innovation systems. The review is principally empirical in nature. More detailed analysis of the drivers of and barriers to innovation would be a valuable addition to this research.

We have also characterised the innovation journey in terms of the cumulative adoption of each technology against time. Some alternatives to these metrics were noted in Section 2. Progress with innovation can be measured through patent applications or technological performance and there are alternatives to measuring innovation against time, such as tracking innovation against investment in technological development. However the focus of this review is essentially empirical in nature, seeking simply to review the range of timescales that innovations have gone through in reaching widespread commercialisation. Again, further research into the relationship between innovation effort and innovation output would be a useful additional area of investigation.

The report has focused principally on quantifying and characterising innovation timelines rather than exploring in detail all of the drivers of innovation. The duration of these timelines are necessarily sensitive to the definitions that we have used to construct points of invention, market introduction and commercialisation.

Finally, this review does not consider failed innovations, even if most innovations fail rather than succeed (Wilson 2014). The Rapid Evidence Assessment has aimed to establish the time taken for the innovation journey of a range of successful products or technologies (including a number of innovations which have passed market introduction stage and are on a trajectory towards wider commercialisation).

5.3. Key findings

For each of the 14 innovations considered, this review has quantified the total time taken from invention to widespread commercialisation. These innovations vary considerably in the total time that they have taken to complete this innovation journey:

The average time taken from invention to widespread commercialisation was 39 years, but with a spread of 51 years between the minimum and maximum duration. The shortest time to commercialisation was 19 years (lithium ion rechargeable battery for consumer electronics) and the longest was 70 years (the car).

The innovation journey was broken down into two stages: a first phase of invention, development and demonstration, and a second phase of market deployment and widespread commercialisation. Although the average duration of these phases is similar (19 and 20 years respectively), the length of each phase shows considerable variation across the innovations reviewed. For example, the shortest time taken for invention, development and demonstration was 4 years (compact fluorescent light bulb), while the longest was 37 years (solar PV). Similarly, the shortest time from market introduction to widespread commercialisation was 6 years (catalytic converter), whereas the longest was 47 years (the car).

There are some exceptional contexts which explain some of the outliers. The six year period for deployment of the catalytic convertor represents the time period between the first use of catalysts in US vehicles and the mandatory adoption of catalysts on the majority of new vehicles sold in the US. Widespread diffusion of catalysts into the US vehicle fleet took place over a more extended period as the vehicle stock gradually turned over, and global adoption took place over subsequent decades.

The principal reason it took so long for the car to reach our definition of widespread commercialisation in the US is that extensive market growth continued over most of the twentieth century, driven as much by economic growth and growth in private incomes as innovation in vehicle manufacturing and technology. Income growth needed to reach a level sufficient for widespread uptake of the car to be possible, since the purchase of a car required (and still does) a large expenditure relative to income.

In several cases the specific invention point for the conventional form of the technology is preceded by a long history of earlier developments in related or predecessor technologies. Moreover many technologies use fundamental scientific concepts first developed many decades previously and often in the 19th century. For example, the installation of the first CCGT plant in 1949 was preceded by the historical development of the aero and industrial gas turbine. The first silicon-based solar PV cell with an efficiency of greater than 5% efficiency was developed in 1954, but the photovoltaic effect itself was established using selenium in the late 1870s. Similarly, the cathode ray tube was invented in 1897; several decades before early TV sets were produced and a wide range of wind turbine systems were used many decades before the invention of modern turbines for power generation.

There is evidence that several of the innovations reviewed were developed as a spillover from earlier products, or from research and development aimed at the deployment in military or space applications. The first cash machine was a created by assembling existing technologies into a new product, in essence a new idea using existing techniques. The precursor to nuclear power was the atomic bomb, while CCGT benefited from research conducted on jet engine design, also during the Second World War.

In Section 2, it was noted that innovation does not necessarily take place in one direction, according to the classic linear model of technology evolution. One general observation from the review is that technologies rarely move out of the R&D stage completely following market introduction, in that R&D continues to be part of the process of improving existing technologies. Ongoing R&D is crucial to improving performance and reducing costs even in the most mature of technologies.

Notwithstanding the effect of the outliers, the review finds that the average time taken from invention to widespread commercialisation is significantly longer for electricity generation technologies (48 years) than for lighting or energy storage products (26 years) or non-energy products (38 years). This is a factor both of the longer invention, development and demonstration, and market deployment and commercialisation phases for energy supply technologies (26 and 23 years respectively). Conversely, lighting and energy storage products were the quickest to become widely commercialised, again due to having the shortest timescales in both of the aforementioned phases (9 and 17 years, respectively).

The review also finds that in general innovations that replace existing products have shorter average timelines from invention to widespread commercialisation (29 years) than innovations aimed at entirely new markets (42 years), with a shorter invention, development and demonstration phases (13 and 20 years, respectively) and market deployment and commercialisation phases (16 years and 22 years respectively). However, the difference for the latter phase is skewed by the lengthy time taken for the car to reach wide-scale deployment after market introduction, and the median for market deployment and commercialisation is actually the same (15 years) for these two groups, while being significantly shorter for new innovations at the invention, development and demonstration phase.

5.4. Implications for policy

Overall the review suggests that it takes at least two decades for a new technology to reach widespread commercial deployment and a figure of three or four decades is more typical. Care needs to be taken in extrapolating from the past, and historical contexts from early in the twentieth century will obviously differ from the future of technological development. However, unless it proves possible to radically accelerate innovation relative to historical norms then it is unlikely that inventions emerging from basic research this decade will make a material contribution to reducing carbon emissions before the mid to end of the 2030s at the earliest. In addition, in many cases the basic scientific or engineering principles underpinning an innovation are well known and predate even the laboratory stage by several decades.

As we look to the future therefore it is important that in promoting innovation policy continues (whether through R&D, subsidised markets or through regulation and targets) to be mindful of the fact that innovative processes take time, and that innovation often proceeds incrementally. Innovation is crucial to containing carbon emissions and avoiding dangerous climate change. However supporting low carbon innovation requires sustained effort over many decades. Even 2050 is relatively soon in relation to the timescales typical in the development of the energy system. This means it is important that policy efforts focus as much upon improving existing technologies as developing new ones, and on creating markets and overcoming barriers to the deployment of established energy efficient and low carbon options. Support for R&D is a crucial component of low carbon policy development, but should not be predicated on the hope or expectation that it can deliver a 'quick fix' to the climate change problem.

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