Measuring the duration of formative phases for energy technologies

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Version of February 18, 2016

Abstract

Innovation processes during the early period of a technology's development establish the conditions for widespread commercialization. For comparative analysis of innovation processes across technologies, a common operational definition of the formative phase is needed. This paper develops a set of indicators to measure the start and end points of formative phases with reference to key innovation processes including experimentation and market formation. The indicators are then applied to measure the formative phase durations of sixteen energy technologies covering a range of historical periods and applications. Formative phases are found to last 22 years on average. Determinants of formative phase duration are explored. Duration does not appear to be explained by unit scale, up-scaling, nor initial cost. However, technologies that are ready substitutes for incumbents have shorter formative phases, ceteris paribus. Policy implications include the potentials and risks of accelerating formative phases to push low carbon technologies into the market.

Keywords: innovation systems; diffusion; formative phase; indicators; energy technologies.

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1. Introduction

Limiting climate change in line with the Paris agreement requires energy system transformation and the widespread diffusion of low-carbon technologies. Historical energy transitions show the importance of the early years of a technology's development on subsequent diffusion (Fouquet, 2014, 2008; Smil, 2010). This is often a period of many uncertainties surrounding the formation of a new technology. The formative phase designates the early stage of development that sets up the conditions for a technology to emerge and become established in the market (Wilson and Grubler, 2011).

Two streams of the literature address the challenges faced by a new technology during the formative phase. First, the formative phase has a parallel with the concept of 'era of ferment' in the literature on industry lifecycles (Abernathy and Clark 1985; Abernathy and Utterback, 1978; and for a recent review, Peltoniemi, 2011). An era of ferment is a time of intense technical variation and selection, initiated by a technological breakthrough and culminating with the emergence of a dominant design (Anderson and Tushman, 1990). During this period, the number of firms increases while sales remain relatively low as potential adopters wait for the emergence of a new standard before purchasing. This can be a lengthy process. As an example, 30 product innovations in the US were found to take on average 30 years to move from invention to commercialization, with 14 years more before sales take-off (Agarwal and Bayus, 2002, see also Tellis and Chandrasekaran, 2012; Tellis et al., 2003; Golder and Tellis, 1997). However this literature tends to overlook the systemic conditions (e.g., investment in the production chain, supportive institutions) that often accompany the emergence of new technologies.

Second, formative phases are articulated in the technological innovation systems (TIS) literature, which explains the emergence and growth of an innovation system around a particular technology (Markard et al., 2015; Bergek et al., 2015; Jacobsson and Bergek, 2012; Markard et al., 2012). During the formative phase, constitutive elements of a new innovation system are set up, and essential functions of the emerging innovation system begin influencing the technology's development (Bergek, 2008a; Hekkert et al., 2007). Experimentation and variety as an outcome of knowledge creation are decisive functions in the early years when a technology is surrounded by many uncertainties in terms of design, function and market demand (Kemp et al, 1998; Rosenberg, 1994). Interactions with established technologies and context can further influence the dynamics of growth (Bergek et al., 2015). Later on, resource mobilization and market formation become more influential functions as technology development shifts towards up-scaling and mass commercialization. Although innovation processes during the formative phase have been characterized in depth, the delineation of the formative phase through time remains unclear. It has been only loosely defined as a period lasting rarely less than a decade, and corresponding to a volume of diffusion that is a fraction of the estimated potential (Bergek et al., 2008a; Markard and Hekkert, 2013).

This research seeks to understand how long the formative phases of energy technologies last, and how this varies between energy technologies of different type. Specifically, the paper develops an operational definition of formative phase duration drawing on the TIS and industry lifecycle literatures. Indicators of specific innovation processes are proposed to estimate the start and end points of the formative phase consistently for any technology. Application of the indicators is demonstrated on a sample of 16 energy technologies, allowing generic determinants of formative phase duration to be tested empirically.

The main purpose of this work is to provide quantitative estimates of formative phase durations of energy technologies observed historically, and to assess the determining factors of those durations. This meta-analytic purpose, together with our use of some *ex post* measures applicable to full or completed technology lifecycles, means our work can not be used for prospective technology analysis. However, the insights from history that we can draw help inform current efforts to accelerate the commercialization of low carbon innovations (Winskel and Radcliffe, 2014; Henderson and Newell 2011; Weyant, 2011). This is a novel contribution to the current challenge of climate change mitigation.

The paper is structured as follows. Section 2 reviews the treatment of formative phases in the industry lifecycle and TIS literatures, and identifies relevant innovation processes. Section 3 develops a set of indicators to measure the start and end point of formative phases. Section 4 applies the indicators to a sample of energy technologies and tests potential explanations of the variability in formative phase durations. The paper concludes by discussing implications for energy technology policy in the context of climate change mitigation challenges.

2. Innovation processes during the formative phase

2.1. Industry lifecycles

Measures of progress through innovation stages have been clearly described in the literature on industry lifecycles (Abernathy and Utterback, 1978). A technological opportunity for new products is created from the pressure exerted by technological advances, changes in customer preferences, or regulation (Abernathy and Clark, 1985). This spurs the entry of many firms introducing different varieties of a product (Klepper, 1996). Increasing entry and rivalry in the early stages of the lifecycle improves the quality of the product, and may also reduce prices, contributing to sales take-off (Agarwal and Bayus, 2002).

The transition to technological maturity is typically characterised by a shift from product to process innovation, the emergence of a dominant design, and a decrease in product variety (Utterback and Abernathy, 1975; Gort and Klepper, 1982; Tushman and Anderson, 1986; Murmann and Frenken, 2006). Reducing uncertainties over technological attributes allows the expansion of production capacity and learning-by-doing economies. As the “era of ferment" ends, sales grow rapidly from the large number of potential adopters who wait to purchase the dominant design (Anderson and Tushman, 1990).

The decline in product variety and the shift in the nature of innovation activities help explain the exit of a large number of firms (Utterback and Suarez, 1993). Klepper (1997) proposes the notion of "shake-out" for the period of time during which the number of firms decreases as the market grows. This marks the end of the formative phase.

Other indicators of innovation activities during the formative phase focus on sales prior to market growth (Peres et al., 2010). Kohli et al. (1999) find that the "incubation time" of an innovation before market launch relates to subsequent diffusion. Golder and Tellis (1997) estimate the time from introduction to sales take-off of 31 innovations in the US and find significant variation as a function of price and market penetration.

In the specific case of energy technologies, the end of the formative phase is also marked by a transition from experimentation and production of many small scale units to an up-scaling phase which can see rapid increases in the maximum unit sizes of a technology (Wilson, 2012). Up-scaling to capture scale economies is a powerful and constant background condition of technology development, and a common heuristic in innovation systems (Winter, 2008).

2.2. Innovation systems

The role of the formative phase in the emergence of new technologies can also be analysed through the lens of the technological innovation system (TIS). A systemic perspective is well suited to analyse complex and interdependent energy technology innovation (Grubler and Wilson 2014). The TIS literature identifies and elaborates the key innovation processes that take place during the formative phase.

The TIS is a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz, 1991: 111). According to this definition, the three main elements of a TIS are actors, networks and institutions (Bergek et al., 2008a; Jacobsson and Bergek, 2004). Actors include firms and other organizations (e.g. universities, industry associations) along the value chain (Bergek et al., 2008a). Networks link disparate actors to perform a particular task (e.g. knowledge share, lobby). Institutions consist of formal rules (e.g., laws and property rights) and informal norms (e.g. tradition and culture) that structure political, economic and social interactions.

The emergence of a new TIS has been typically analysed in terms of the development of its key structural elements including (Jacobsson, 2008): entry of firms and other organizations; formation of networks; and institutional alignment. A more recent approach also analyses key innovation processes or functions (Bergek et al, 2008b; Hekkert et al., 2007). Table 1 (first column) summarises seven important innovation system functions. The performance of these functions provides indications about the effective functioning of innovation systems.

Interactions between a subset of four functions have been associated with virtuous cycles of development in the emergence of new innovation systems (Suurs et al., 2010). These four functions are: knowledge creation, entrepreneurial experimentation, influence on the direction of search, and market formation (Suurs et al., 2009; Hekkert and Negro, 2009).

‘Knowledge creation’ refers to how knowledge is generated, combined, codified and shared to establish the necessary scientific and technological base for an innovation to progress (Jacobsson and Bergek, 2012). ‘Experimentation’ refers to the development of a more applied, tacit and explorative knowledge by risk-taking and hence ‘entrepreneurial’ actors in the innovation system. ‘Influence on the direction of search’ relates to the mechanisms that influence how new actors in the innovation system allocate their activities and investments between competing technologies and designs (Bergek et al., 2008b). ‘Market formation’ refers to the articulation of demand around increasingly organized markets, from demonstration projects to niches and bridging markets which enable increasing volumes of production before mass commercialization (Bergek et al., 2008a; Hekkert et al., 2009).

As the innovation approaches mass commercialisation, other innovation system functions become increasingly important. These include materialisation, resource mobilization, and legitimation as well as continued market formation (Bergek et al., 2008b). Clear evidence of these functions signals the end of the formative phase.

‘Materialisation’ describes the first major investments in capital stock or artefacts (e.g. factories, infrastructure). ‘Resource mobilisation’ refers to the need to draw in human capital, financial capital and complementary assets from outside the innovation system. Finally, ‘legitimation’ is a socio-political process by which actors’ expectations are formed and shared, creating a network of potentially diverse actors as a coalition of advocates for the technology’s development (Bergek et al., 2008a; Borup et al., 2006). ‘Legitimation’ can play a key role in the cumulative strengthening of innovation systems by aligning institutions with the needs of the emerging innovation (Hekkert and Negro, 2009).

Both the performance of each system function and the interactions between them are necessary during the formative phase, along with the structural processes described above. The performance of more system functions is likely to enhance development of the TIS in terms of the generation, diffusion, and utilization of the new technology. In contrast, underperformance of the system functions will hinder development of the TIS. Various indicators have been used to track performance of individual innovation system functions (Table 1). Applying indicators is not straightforward, and in many cases it is difficult to objectively quantify comparable indicators. Examples include measuring expectations and their implications for diffusion, or clearly defining legitimation. However, they provide helpful information to map the emergence of new innovation systems.

The functional and structural processes should co-evolve with the technology to prepare the innovation system for expansion. Table 2 summarizes the contributions of both the industry lifecycle literature and the technology innovation system (TIS) literature to the understanding of the formative phase.

Table 1. Indicators used to measure innovation system functions (Sources: Bergek et al., 2008a,b; Hekkert et al., 2007; Vasseur et al., 2013; Gosens and Lu, 2013)

System function *	Indicators	Application issues & challenges
Knowledge creation	R&D funding and activities. Scientific publication and patenting. Research networks (knowledge exchange). Workshops and conferences.	Distinguishing basic from applied R&D. Comparing data on networks, workshops and conferences.
Entrepreneurial experimentation	Studies, demonstration pilots, field trials activities. Number of firms (new entrants and diversification of activities of incumbents).	Distinguishing experimentation from deployment.
Materialisation	New factories opened. Investment in new production plants, physical infrastructure.	Separating materialisation from resource mobilization.
Influence on the direction of search	Targets set by government or industry (e.g. roadmaps). Expectations and opinions of experts. Articulation of demand by leading consumers.	Measuring expectations and their implications for diffusion.
Market formation	Policies that stimulate market formation and expansion (e.g. protected niches, regulatory or fiscal instruments). Sales, unit numbers. Installed capacity.	Establishing if sales growth is permanent and represents take-off.
Resource mobilisation	Financial investments. Human capital and complementary assets.	Quantifying human capital and complementary assets.
Legitimation	Recognition of societal benefits (e.g. awards, competitions, brochures). Technical assessment studies. Public debates (e.g. parliament, media). Lobbying activities. Alignment of science and technology policy, and other institutions.	Confining definition of legitimation. Quantifying social recognition, public debates or lobbying activities.

* Development of positive externalities is included as an additional innovation system function in some studies and refers to the exploitation of synergies with other innovation systems (Bergek et al., 2008b).

Table 2. Conceptualization of the formative phase

	Formative Phase in the Industry Lifecycle literature (e.g., Peltoniemi, 2011)	Formative Phase in the Technological Innovation System (TIS) literature (e.g, Bergek, 2008a; Hekkert et al., 2007)
Definition	Period of intense technical variation leading to the emergence of a dominant design	Time to set up constitutive elements and essential processes of the TIS
Mechanism	Improvement of technology quality and reduction of costs	System structuration and performance of key functions
Analytical focus	Technology	Innovation system (including institutions)
Main actors	Firms	Private and public organisations and relevant networks

2.3. Formative processes in the emergence of innovation systems

Formative phases within innovation system development is a relatively recent focus of research (Markard and Hekkert, 2013). A common approach for identifying the formative phase is to compare and contrast the changing state of the innovation system over time. Bergek et al. (2008a) distinguish between a formative phase when "… constituent elements of the new TIS begin to be put into place..." (p. 419) and a growth phase when "… the focus shifts to system expansion and large-scale technology diffusion through the formation of bridging markets and subsequently mass markets…" (p. 420).

Table 3 summarises the changes in innovation systems as they grow and evolve through different stages: nascent, emerging, strengthening, mature. During each stage, the innovation system is characterised by differences in technology characteristics, structural elements (actors, institutions, networks), and key functions (Markard and Hekkert, 2013). The "nascent" TIS in the start of the formative phase is marked by the existence of a large variety of ideas and concepts. The structure of the innovation system comprises a small number of actors organized mainly in networks dedicated to R&D activities and knowledge creation. Jacobsson (2008) and Markard and Hekkert (2013) consider early trials and demonstrations to also be part of the nascent stage of TIS development.

In contrast, the "emerging" TIS at the end of the formative phase is evidenced by a more stable technology design and a gradually more structured innovation system. The key processes that play a more influential role include market formation and strengthening expectations (guiding the direction of search). This process is complex and typically in competition with other technologies. An increasing number of actors also reinforces the political strength of advocacy coalitions helping to align institutions with the needs of the innovation system (Bergek et al., 2008a; Borup et al., 2006).

Table 3. Stages of maturation of technological innovation systems (adapted from Markard and Hekkert, 2013).

	Nascent TIS*	Emerging TIS	Strengthening TIS	Mature TIS
Technology	Post-invention; variety of ideas and concepts	"Childhood"; selection of first prototypes; retention of a small number of designs	Dominant design; scaling up technology	Standardised product; mass production
Degree of structuration	Low (or absent); early formation	Medium; late formation	Medium-high; transitional	High
- Actors	Very few actors: mainly inventors, private and public research labs, universities	Medium number of actors: private and public organizations; high entry/exit rates	Medium to large number of actors: more private organizations; decreasing number of firms; higher exit rates	Large number of actors: different kinds of organizations; small number of firms; low entry/exit
- Institutions	Very few; mostly informal and cognitive (ideas, expectations)	Dynamic number of technology-specific institutions	Stabilizing number of technology-specific institutions	Stable formal and informal technology-specific institutions
- Networks	Constitution of knowledge and R&D networks	Diversification of the type of networks (e.g., R&D, deployment, lobbying)	Different types of networks (cognitive and technological)	Established industry networks
Key functions	Knowledge creation, Experimentation, Direction of search	Knowledge creation, Experimentation, Direction of search, Market formation	Resource mobilisation, Legitimation, Market formation	All functions

* Including 'incubation time' of the innovation, i.e. the development time prior to introduction.

3. *Indicators of the start and end points of formative phases*

The previous section articulated the formative phase in terms of technology characteristics, innovation system elements and functions. This provides a clearer basis for choosing indicators that can measure formative phase durations in a standardised and comparable way. Estimating formative phase durations consistently across technologies allows the determinants of more rapid formative phases to be identified and tested. This has not been done to-date, yet is of major current policy interest in response to climate change mitigation challenges.

This paper proposes a range of indicators for the start and end of the formative phase, building on the formative phase processes shown in Table 3 and the indicators used in the literature to characterise innovation system functions shown in Table 1. Additional indicators are compiled using industry lifecycle characteristics including the number of firms, shake-out, and cost reductions.

3.1. Start point indicators

Table 4 presents the indicators and associated metrics for the start points of formative phases. The indicators are: (S1) first 'embodiment' of technology; (S2) first commercial application; (S3) first sequential commercialization. Linkages between each indicator and innovation system functions at the beginning of the formative phase are shown in Table 4. These include important system functions in early years such as knowledge creation, experimentation, and market formation.

First embodiment of technology (S1) was chosen because of the importance for technology development of learning obtained from the first trials (Hendry et al., 2010), and its correspondence with applied knowledge creation as a key innovation process. First commercial application (S2) has been considered in previous studies (e.g. Mensch, 1979) and is a mark in the development of innovation systems, particularly in the growth of entrepreneurial experimentation. First sequential commercialisation (S3) is an important indicator of transition from pre-commercial experimentation to more sustained production as a basis for learning and specifically for early market formation. Overall these indicators show the direction of search and mark the progress of the new technology, as well as the increasing dynamics of the emerging innovation system.

Additional indicators were considered but rejected due to lack of data. These include first peak in R&D expenditure (see Appendix B). They are explained in detail in a separate technical report (Bento and Wilson, 2014).

Table 4. Indicators to define start point of formative phase

	Indicator	Metric	Link to Innovation System Functions	Rationale
S1	*First 'embodiment' of technology*	- year of first significant prototype or demonstration of the innovation	knowledge creation, experimentation	learning derived from experimentation and trials articulates possibilities for producing and marketing the innovation (Harborne and Hendry, 2009; Garud and Karnøe, 2003)
S2	*First commercial application*	year of first application outside the lab or beginning of technology production	Experimentation, Knowledge creation	technology put into production for the first time, or market created, raises applied knowledge and confidence in a new product (Mensch, 1979)
S2a		- measured using innovation lists (e.g. Mensch, 1979)		
S2b		- measured using own research		
S3	*First sequential commercialization*	- year of first commercial application initiating successive series of product (i.e., not just a one-off)	knowledge creation, market formation	transition from pre-commercial experimentation enables decisive production and repeat market experience

3.2. End point indicators

Table 5 presents the indicators and associated metrics for the end points of formative phases. These include both indicators of technology supply and market demand.

Technology supply indicators reveal growth in production capacity (e.g., the entry of actors, development of networks, build-up of value chains, alignment of regulation - reflecting an increasingly structured TIS), as well as indirectly show a technology's design maturity. The indicators are: (E1) numbers of units produced and capacity installed; (E2) up-scaling. These indicators were demonstrated empirically in a study of wind power development (Wilson 2012). In both cases, a 10% threshold is used. Marchetti and Nakicenovic (1979) first proposed a metric for time durations of technological substitution, with the changeover time, Δt, being the time to grow from 10 to 90% market share. 10% of eventual saturation is therefore a recognised milestone. As an example, Grubler (2012) finds that at the global level, characteristic changeover times in primary energy span 80 to 130 years. The indicators relate to specific innovation system functions. The number of installations indicate market formation, and technology up-scaling reveals the choice of design or standard which reinforces the direction of search.

Market demand indicators provide information about learning-by-using and on the market readiness of a technology. The indicators are: (E3) market structure; (E4) cost reduction; (E5) user adoption. These indicators have been widely applied in technology lifecycle and management studies (Klepper 1997; Agarwal and Bayus, 2002; Rogers, 2003). Linkages to innovation system functions include: number of companies indicating resource mobilisation; learning and cost reduction evidencing market formation; and adoption by the "innovators" group demonstrating legitimation. Additional indicators were considered but rejected due to lack of data. These include number of patents, dominant designs, and production scale up (see Appendix C). They are explained in detail in a separate technical report (Bento and Wilson, 2014).

Although most of the indicators can be tracked as a technology progresses through the formative phase, the two technology supply indicators (E1 & E2) can only be identified *ex post* as shares of observed market saturation levels.

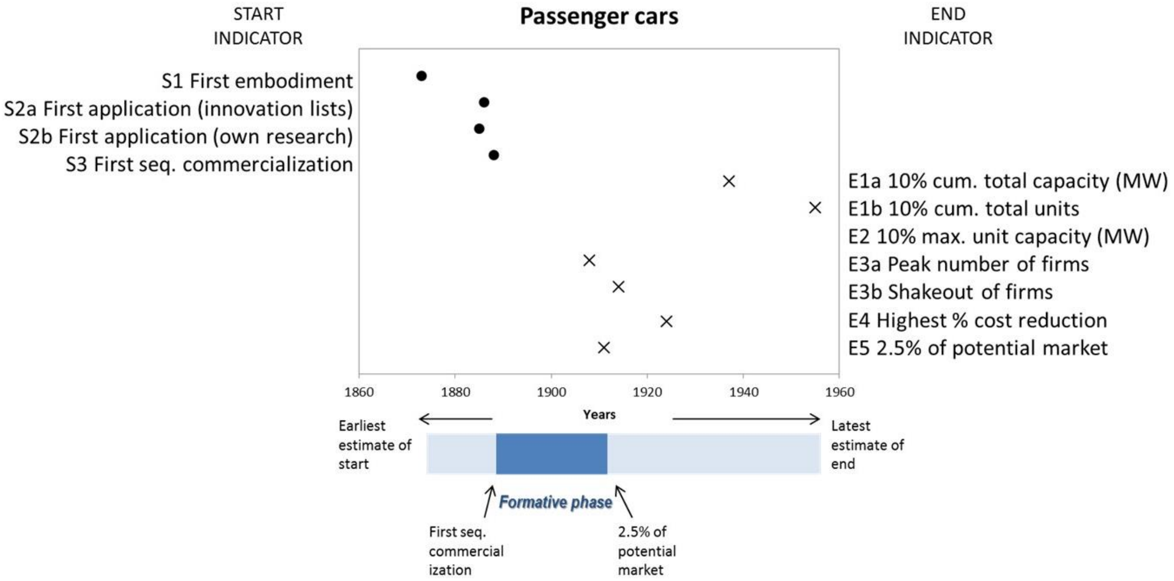
Table 5. Indicators to define end point of formative phase

Type		Indicator	Metric	Link to Innovation System Functions	Rationale
Technology Supply Indicators	*E1* *E1a* *E1b*	*Units produced and capacity installed*	year when 10% of eventual saturation level is reached (identified *ex post*) - cumulative total unit numbers - cumulative total installed capacity	legitimation, resource mobilisation, market formation	transition from experimentation with many unit numbers to mature market growth and production scale up (Wilson, 2012)
	E2	*Up-scaling of unit size*	- year when 10% of maximum unit capacity is reached (identified ex post)	direction of search, legitimation	knowledge and institutions necessary to support economies of scale are in place (Winter, 2008)
Market Demand Indicators	*E3* *E3a* *E3b*	*Market structure*	year when numbers of firms peaks or changes - number of firms peak - pronounced (>30%) and sustained fall in number of firms from peak (termed "shake-out" by Klepper, 1997:165)	market formation, resource mobilisation, legitimation	expectations become more robust, lowering risk in scale investments; increasing competition and resource requirements mean firms exit market (Klepper, 1996)
	E4	*Cost reduction*	- year of highest relative year-on-year cost reduction	market formation, legitimation	learning-by-doing (Arrow, 1962); institutional capacity established to support learning economies
	E5	*User adoption*	- year when 2.5% of maximum potential adopters have adopted ("innovators" category identified by Rogers, 2003)	legitimation, market formation	learning-by-using; reduction in perceived technological uncertainty and adoption risk (Rosenberg, 1982)

3.3. Estimating durations

Formative phase durations can be estimated by differencing the start and end point indicators. Figure 1 provides an example for passenger cars in the US. Results from all available indicators are compared to find the earliest estimate of the start point (minimum or leftmost dot) and the latest estimate of the end point (maximum or rightmost cross). This sets the upper bound for formative phase duration (light blue bar), expressing the uncertainties associated with competing indicators. A central estimate of formative phase duration (dark blue bar) spans the time period between preferred indicators of start and end points which are consistent across all technologies (see below). This narrows the gap to a more plausible interval that can be comparable across technologies.

Figure 1. Estimating formative phase durations and uncertainties, using passenger cars in the US as an example.



4. Formative phase durations of energy technologies

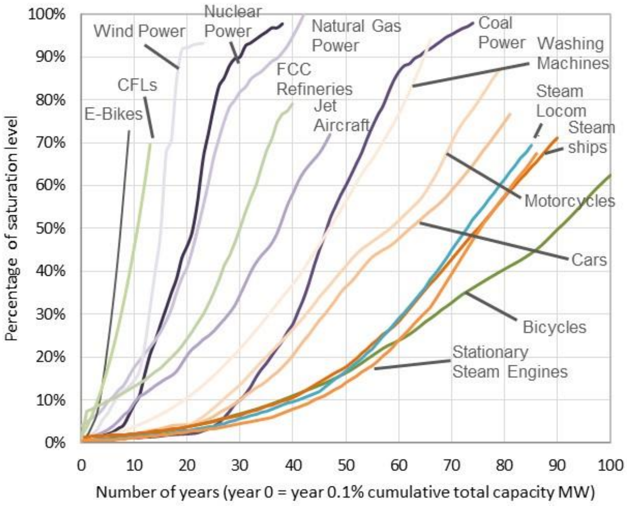
4.1. Applying the indicators

To demonstrate how the proposed indicators can be used to consistently measure formative phase durations across diverse technologies, we compiled data characterising a sample of 16 energy technologies that have diffused into the mass market and so transitioned out of their formative phases. The sample was not designed to be exhaustive but to cover a diverse range of technologies. It comprises: (1) energy supply and end-use, (2) large and small technologies, and (3) historical and current technologies (see Appendix A). Following Murmann and Frenken (2006), technologies are defined as the highest level of complexity and aggregation of component parts excluding distribution infrastructure and commercialization (e.g., power plants rather than electricity systems or steam turbine units). Unless otherwise mentioned, the spatial scale of analysis always corresponds to the initial markets of first commercial application for each technology in which the formative phases marked the emergence of a new innovation system. As examples, wind power is analysed in Denmark, cars in the US, e-bikes in China (see Appendix A for details). A synthesis of all relevant data and sources is included in Appendices B and C, and elaborated in detail in a separate technical report (Bento and Wilson, 2014).

The diffusion dynamics of sampled technologies in their initial markets are shown in Figure 2. The graph shows rising market shares in these initial markets from the point when each technology passed a threshold of 0.1% of its eventual maximum installed capacity. This makes it easier to compare between technologies and removes the annual growth volatility of the very early diffusion period. Maximum capacities or saturation levels are either observed (e.g., steam engines) or estimated using fitted logistic functions to observations, subject to goodness of fit criteria (e.g., wind power). Saturation levels are only estimated in the mature initial markets of first commercialisation. Full details of the saturation level estimations are provided in a separate technical report (Bento and Wilson 2014).

The sample includes technologies showing relatively fast diffusion (e.g. e-bikes, compact fluorescent lamps or CFLs) as well as those with much slower market progression (e.g. motorcycles, cars, bicycles). Mobile phones are not included in Figure 2 as the saturation level is still uncertain.

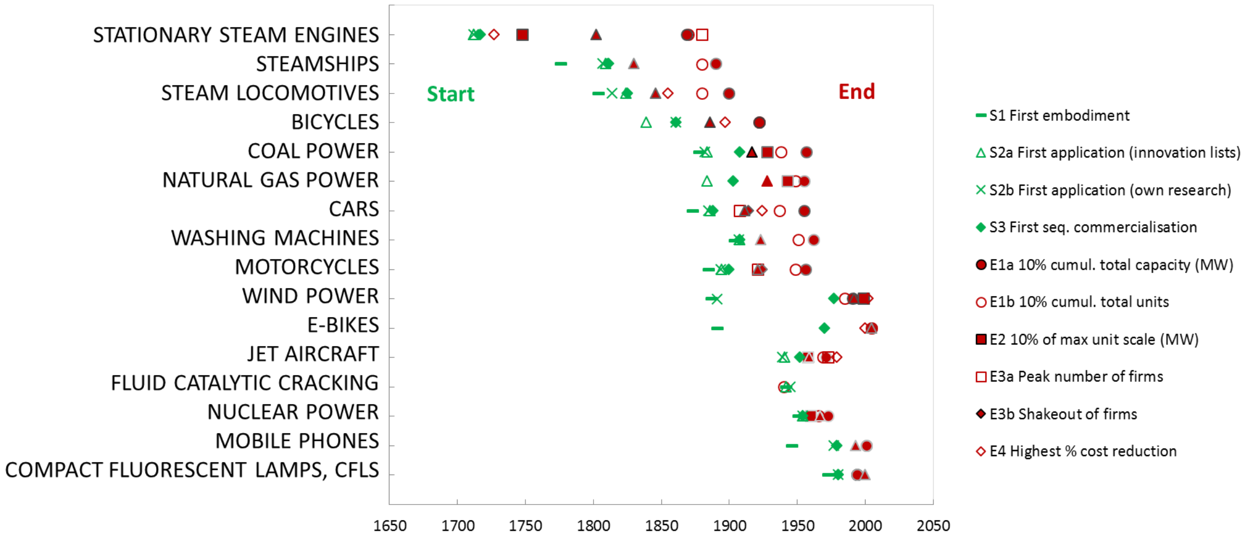
Figure 2. Diffusion of energy technologies in their initial markets



4.2. Selecting preferred indicators

Different indicators of the start and end points of the formative phase are shown in Figure 3 for the sampled technologies ordered historically by the year of invention, from the earliest (at the top) to the latest (at the bottom). The periods between start and end indicators reveal long formative phases spanning several decades. Durations are longer in the case of older, general purpose technologies like steam engines which had to wait for the development of complementary innovations before their pervasive impact across several sectors of the economy could be achieved (Rosenberg and Trajtenberg, 2004).

Figure 3. Indicators of the start and end points of formative phases in initial markets. (Technologies ordered historically by year of invention).



Of the indicators for the start point of the formative phase, (S1) 'first embodiment' is generally the earliest date whereas (S2) 'first application' and then (S3) 'first sequential commercialization' provide later estimates, as expected. The start point indicators tend to converge, apart from in certain cases such as wind power and e-bikes. For both technologies, initial innovation and first applications were in the 1890s but the first sequential commercialisation observed in the data did not begin until almost a century later in Denmark and China respectively.

A single preferred indicator is needed for consistency when comparing formative phases across technologies. Three criteria were used to select a preferred indicator: (i) correspondence with formative phase processes identified in the literature; (ii) available data for most technologies; (iii) consistency with other indicators (i.e., not an outlier). The (S3) 'first sequential commercialisation' indicator best meets these criteria. First, it is strongly related to formative innovation processes as the start of commercialization applies knowledge created to intensify production and materialise a technology. Second, data are available for all but one technology. Third, the indicator correlates strongly with the average of the other two indicators (r=0.93). The main drawback of the (S3) 'first sequential commercialisation' indicator is that it does not take into account early development and experimentation activities (including the 'incubation time') which might be important formative processes prior to serial production (Markard and Hekkert, 2013; Jacobsson, 2008).

The different indicators for the end point of the formative phase diverge more clearly in some cases (see Figure 3). The measures for stationary steam engines, for example, range over a 150 year period from 1727 to 1880 for (E4) 'highest % cost reduction' and (E1a) '10%

cumulative total units' respectively. However, there is less divergence for more recent technologies.

Clear links to theory, available data, and consistency, were again applied as criteria to select a preferred indicator. The (E5) ‘user adoption’ indicator, measured by a 2.5% share of market potential being reached, best met the criteria. First, it links directly to the initial segment of market demand identified by Rogers (2003). It is consistent with the formative phase ending since technology risks, uncertainties and market misalignments are reduced such that adoption moves from ‘innovators’ to the subsequent and larger group of ‘early adopters’. Second, data were available for all but one technology (fluid catalytic cracking or FCC in oil refineries). Third, correlations with the average of all the other indicators was high (r=0.95).

To measure this indicator, assumptions have to be made about the potential market within which the innovation is adopted and gains market share. To measure the (E5) ‘user adoption’ indicator, actual market growth (e.g., units sold or capacity installed) is divided by the potential market size for the corresponding year (see Appendix A). Other methods for inferring thresholds of market take-off compare sales growth rates either with market penetration rates (Tellis et al., 2003), with annual sales (Golder and Tellis, 1997), or with annual net entry rates (Agarwal and Bayus, 2002). Using a 2.5% share of market potential is comparatively simple, less data demanding, and applies to a broad set of technologies.

One drawback of the ‘user adoption’ indicator is that it does not directly measure a technology’s maturity at the end of the formative phase. The (E2) ‘up-scaling of unit size’ indicator, measured by a 10% threshold of maximum unit capacity being reached, was selected as a complementary technology indicator. This conveys important information on the readiness of the technology for commercialisation at larger scales. However, data are only available for those technologies that up-scaled significantly (mainly energy supply technologies). Moreover, the indicator could only be estimated *ex post* once the unit capacity frontier for each technology had been revealed, unless reliable *ex ante* estimates could be made based on physical principles. *Ex post* indicators were suitable for this study of historical technologies in their initial markets for which market saturation is either observed or is being approached.

Of the two preferred indicators, (E5) ‘user adoption’ generally gives slightly earlier estimates of the end point of the formative phase, up to a decade earlier than the (E2) ‘up-scaling’ indicator (see Figure 3).

4.3. Average durations

Using (S3) ‘first sequential commercialisation’ and (E5) ‘user adoption’ as the preferred start and end point indicators respectively, Table 6 shows the central estimates of formative phase duration for each technology. The mean central estimate of formative phase duration across the 16 technologies in the sample is 22 years from a range of 4 – 85 years. Table 6 also shows the longest estimates of formative phase duration from the earliest start point indicator to the latest end point indicator which vary for each technology. This upper bound on formative phase duration has a mean of 75 years across the technologies in the sample from a range of 4 – 168 years.

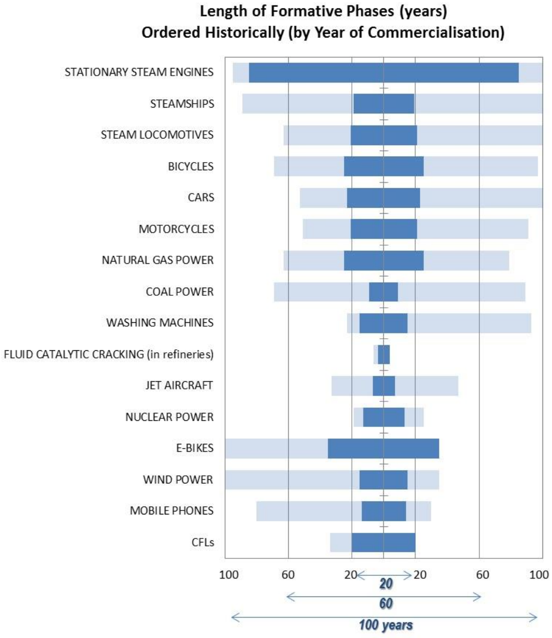
Table 6. Formative phase durations in years. (Technologies ordered historically by year of invention).

Energy technology	*Central estimate*	*Longest estimate*
Stationary Steam Engines	85	168
Steamships	19	114
Steam Locomotives	21	96
Bicycles	25	83
Coal Power	9	79
Natural Gas Power	25	71
Cars	23	82
Washing Machines	15	58
Motorcycles	21	71
Wind Power	15	115
E-Bikes	35	114
Jet Aircraft	7	40
FCC, Fluid Catalytic Cracking (refineries)	4	5
Nuclear Power	13	22
Mobile Phones	14	55
CFLs, Compact Fluorescent Lamps	20	27
Mean (all technologies)	**22**	**75**
Median (all technologies)	**20**	**75**

Figure 4 shows the central estimates (dark blue bars) and the longest estimates (light blue bars) of formative phase durations for the technologies ordered historically by year of commercialisation rather than by year of invention, as in Table 6. This reorders wind power and e-bikes to their later commercial time periods. Three observations can be made. First, formative phase durations for older technologies are more uncertain, particularly in terms of their end points. Second, longer formative phases are more uncertain in duration, which includes those for the steam technologies, passenger cars and natural gas power plants.

Third, even though stationary steam engines passed through a long formative phase in the 18th century, there is no clear trend indicating an acceleration in formative phases for more recent technologies. This result contributes to the debate on accelerated diffusion. Studies of multiple consumer durables show no evidence of a shorter incubation time (Kohli et al., 1999) or of diffusion acceleration over time (Stremersch et al., 2010; Peres et al., 2010). However, Golder and Tellis (1997) find evidence of decreasing time to takeoff of products introduced after World War II, and Meade and Islam (2006) similarly discuss studies that suggest an increase of diffusion speed over the past century.

Figure 4. Formative phase durations: central and longest estimates. (Technologies ordered historically by year of commercialization). Note: The origin of the x-axis is set equal to the midpoints of the central estimates for each technology (dark blue bar). Uncertainties in start point are shown to the left of the origin; uncertainties in end point are shown to the right of the origin (light blue bars).



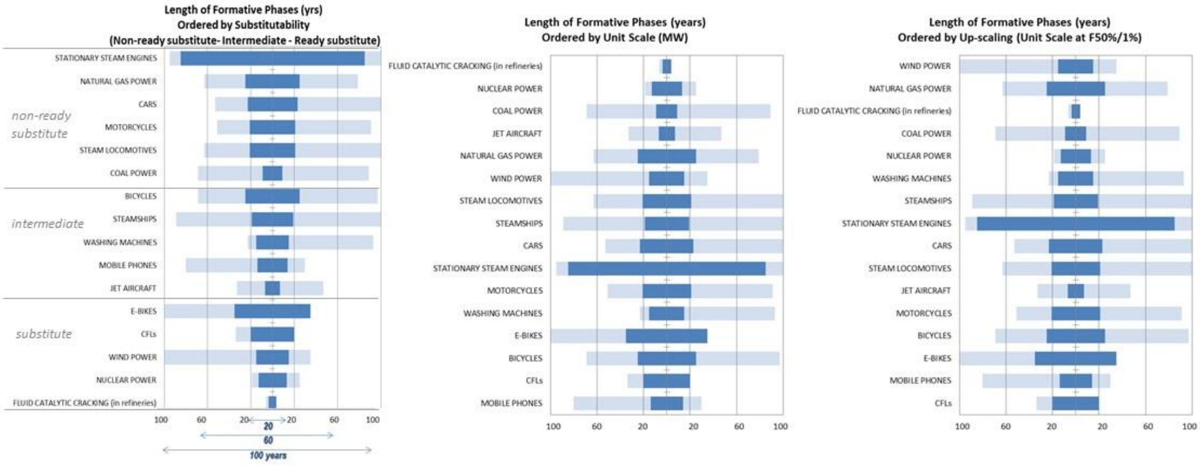
4.4. Determinants of duration

Measuring formative phase durations consistently allows a comparative analysis across technologies of the effect of technology and market characteristics. Although the innovation systems literature identifies key formative processes, it does not generalise how long these processes tend to last nor what the determinants of formative phase duration may be.

In contrast, the factors that explain the duration of diffusion are more clearly understood. These include: relative advantage, complexity, compatibility (Rogers, 2003; Golder and Tellis, 1997; Fabrizio and Hawn, 2013); substitutability, inter-relatedness and infrastructure needs (Grubler et al., 1999); and market size (Wilson et al., 2012).

By signalling important characteristics of the technology and market, similar factors may affect the duration of formative phases as well. For example, technologies which are not ready substitutes for incumbent technologies may require longer formative phases to align supporting institutions (legitimation) and to stimulate user demand in forming markets (Hekkert et al., 2007). Other factors explaining formative phase duration may include unit scale, which affects the risks and resource requirements for experimentation with multiple units, and the up-scaling of unit sizes, which is associated with convergence on a dominant design and a clearly articulated market demand. Figure 5 presents formative phase durations sorted by these three factors: substitutability, unit scale and up-scaling.

Figure 5. Formative phase durations in years, ordered by substitutability (left panel), by unit scale (middle panel) and up-scaling (right panel).



a) *Substitutability*

Technologies in the sample vary in the extent to which they are ready substitutes for incumbent technologies. Diffusion processes are slower for non-ready substitutes that need new institutions and infrastructures to develop to enable commercialisation (Grubler et al., 1999). The potential to share structural elements with other innovation systems may also be more limited for technologies that are not ready substitutes. This constrains the positive externalities which enable more rapid innovation system development (Bergek et al., 2008b, 2015).

As an approximation of substitutability, the 16 energy technologies in the sample were subjectively assigned to one of three categories (non-ready substitutes, intermediate, ready substitutes) based on the extent to which their market deployment depended on demand for novel services and changes in user practices, or new infrastructures and supporting institutions. As examples, steam engines brought new energy services in mines and industry (non-ready substitute), whereas wind power diffused into already existing electricity networks and markets (ready substitute).

Figure 5 (left panel) indicates relatively rapid formative phases in the case of ready substitute technologies for which ancillary infrastructure (airports, electricity grids, refuelling stations, etc.) was already in place. Non-ready substitute technologies, including stationary steam engines, passenger cars, coal and gas power, needed longer to develop the requisite knowledge, institutional capacity and infrastructure to mature commercially and scale up.

b) Unit scale

Figure 5 (middle panel) shows formative phase durations ordered by unit scale (in MW) with larger sized technologies at the top. Although no overall pattern is observed, very large technologies including fluid catalytic cracking, nuclear power plants and jet aircraft, show relatively rapid formative phases. This result is unexpected considering the significant challenges, resource requirements, and risks involved in the deployment of these large-scale technologies. However, the formative phases of all three technologies were linked to the unique institutional environment around World War II, including strong demand-pull, price insensitive military users, and sharing of intellectual property (Delina and Diesendorf, 2013). This raises the possibility that formative phases can be compressed or accelerated in extreme demand environments with simultaneous market-pull and technology-push efforts, and low sensitivity to risk.

c) Up-scaling

Figure 5 (right panel) shows formative phase durations ordered by up-scaling of unit sizes, with larger up-scaled technologies at the top. Up-scaling is measured by the growth in unit size up until the midpoint of the diffusion curve. There is no clearly observable relationship between up-scaling and formative phase duration. Some technologies that barely scaled up had long formative phases (e.g., washing machines); others that up-scaled intensively passed through a fast period of formation (e.g., nuclear power).

d) Other determinants

Table 7 summarises the formative phase durations for subsets of technologies grouped by substitutability, unit size, and up-scaling. Differences in the mean formative phase durations between groups were tested for significance, using an 80% confidence interval appropriate for small heterogeneous samples (Boland et al, 2001). Tests confirm the patterns observed in Figure 5, especially for ready substitute technologies which have significantly shorter formative phases. However, given the small sample, wide confidence intervals, and the subjective classification of substitutability, results at this stage are considered to be indicative only.

Technologies are also grouped according to their applications: energy supply vs. end-use; transport vs. non-transport; and environmental vs. non-environmental technologies. End-use technologies might be expected to have shorter formative phases if their smaller unit sizes allow more rapid learning cycles, whereas transport technologies and environmental technologies might be expected to have longer formative phases if their commercialisation is strongly dependent on dedicated infrastructure or regulation respectively. Tests of difference shown in Table 7 support these expectations only in the case of environmental technologies. Other differences were found to be not significant, even if the direction of difference was consistent with expectations.

Table 7. Determinants of formative phase duration. Notes: means show average durations per subset of technologies using central estimates for each technology. Significance of t-test statistics use 80% confidence intervals (see text for details).

Technology or market characteristic	Number of technologies (n)	Mean formative phase duration (years)	Expectation	Result
Technology characteristics				
Substitutability			shorter for substitute technologies	expectation supported
Non-Ready Substitute	6	31		
Ready Substitute	5	17		
		*t=1.09 **		
Unit scale			shorter for small unit scales	expectation not supported
Above 1MW	12	22		
Below 1MW	4	24		
		t= .28		
Up-scaling			shorter for low up-scaling	expectation confounded (opposite result)
High (higher than 5x)	5	13		
low (less than 1x)	4	24		
		*t=1.82 ***		
Initial cost			shorter for lower initial cost	expectation not supported
High (more than $1,000)	3	42		
Low (less than $1,000)	4	25		
		t= .71		
Technology lifetime				
Long (equal or more than 20 years)	9	22	shorter for shorter lifetime	expectation not supported
Short (less than 20 years)	7	22		
		t= .01		
Application of technology				
End-use	10	20	shorter for end-use technologies	expectation not supported
Supply	6	25		
		t= .41		
Transport	7	*22*	shorter for other technologies	expectation not supported
Non-Transport	9	*22*		
		t= .07		
Environmental	4	*24*	shorter for other technologies	expectation supported
Non-Environmental	6	*15*		
		*t=1.57 ***		
Diffusion characteristics				
Diffusion duration			shorter for rapid diffusion	expectation supported
Very slow (more than 50 years)	7	30		
Rapid (20 years or less)	5	19		
		*t=1.03 **		
Diffusion pervasiveness			shorter for lower pervasiveness	expectation confounded (opposite result)
High (more than 10,000 MW)	6	15		
Low (less than 10,000 MW)	10	26		
		*t=1.41 ***		

* significant at 0.2 level, ** significant at 0.1 level, *** significant at 0.05 level. [a] Environmental technologies comprise CFLs, e-bikes, bicycles, and wind power; non-environmental technologies include jet aircrafts, motorcycles, cars, refineries, coal power, and gas power.

Table 7 also includes tests for other potential determinants of formative phase duration. All else being equal, longer formative phases might be expected for technologies that diffuse more pervasively, have higher initial costs and longer lifetimes. These latter two characteristics imply fewer or more costly opportunities for rapid experimentation and learning cycles during the formative phase.

More rapid formative phases were found for technologies with pervasive impacts in the market. These unexpected results which confounded expectations are again influenced by the presence in these two subsets of technologies of nuclear power and fluid catalytic cracking linked to accelerated formation during a time of war. In sum, the results show that certain technology characteristics, technology applications and overall diffusion can have an effect in the duration of formative phases.

5. Discussion and conclusion

The objective of this research was to develop an operational definition of the duration of formative phases to enable comparative technology analysis. The formative phase designates the early stage of technology development that prepares an innovation for up-scaling and widespread growth. It was shown that a set of indicators can be developed from signs of innovation maturity and formative processes identified in the literature and then be consistently applied to a diverse sample of technologies.

The year of first sequential commercialization is a decisive mark at the start of the formative phase by showing the innovation's readiness to fulfil expectations of initial demand. Distinguishing a clear end point for the formative phase is more uncertain. Diffusion passing an adoption threshold of 2.5% of its market potential is an important milestone as it coincides with the adoption of a new technology by risk-taking "innovators" whose user experiences contribute to lowering perceived risks and aligning the technology with market needs (Rogers, 2003). For a subset of technologies that up-scale, a 10% threshold of the unit capacity frontier being reached is a complementary metric of a maturing technology that correlates well with the user adoption metric.

Applying these start and end point indicators to a sample of 16 energy technologies shows that formative phases are long, lasting on average over 20 years. Establishing a functioning innovation system to support a technology's diffusion takes time. Formative phase durations are significantly longer for technologies that are not ready substitutes and that provide novel energy services. Steam engines are the clearest example. Crude and expensive initial designs required lengthy cycles of knowledge creation, testing and refinement to address uncertainties on designs, markets, and applications (Craft, 2004). Other technologies that created new service demands and markets, including cars and coal power from the early 20th century, require not just an extended period of experimentation and knowledge development, but also an extensive institutional process of legitimation to overcome the “liability of newness” (Bergek et al., 2008a).

More generally, institutional context was found to be decisive in the formation of new technologies. The sample comprised a set of complex, large-scale technologies, including nuclear power and jet aircraft, whose formative phases were compressed due to aggressive innovation efforts combining market-pull and technology-push under the extreme environment of WWII (Delina & Diesendorf, 2013). This reinforces the importance of understanding the role of contextual influences in TIS development (Bergek et al., 2015).

There were few other consistent influences of market and technology characteristics on formative phase durations. Expectations that smaller unit scale, less cost intensive, energy end-use technologies might have shorter formative phases given the more numerous opportunities for experimentation and learning were not supported in the data. The only significant determinants of relatively rapid formative phases in line with expectations were substitute technologies with short market diffusion times and non-environmental technologies. Given the small size of the data set, this latter finding needs further research to test how regulation or policy can support environmental technologies as part of broader system transitions.

However, the central finding of formative phases averaging over two decades in duration corroborates the importance of accumulative processes identified in the innovation systems literature, including experimentation in the initial years of the formative phase, as well as legitimation and market formation at a later stage (Bergek et al. 2008a; Markard and Hekkert, 2013).

This highlights the risks inherent in current efforts to accelerate the commercialisation of low carbon technologies (Winskel and Radcliffe, 2014; Henderson and Newell, 2011). The stringency of climate change mitigation targets has led to calls to compress the formative phases of a wide portfolio of novel energy supply and end-use technologies from carbon capture and storage (Haszeldine 2009) and next generation nuclear power (Grimes and Nuttall, 2010) to cellulosic biofuels and electric vehicles (Tran et al., 2012).

The historical evidence analysed in this research shows that compressed formative phases are only characteristic of technologies that are ready substitutes for incumbents (e.g. compact fluorescent lamps, wind power). Centralised low carbon power production and hybrid-electric vehicles meet these criteria for rapid formation more closely than carbon capture and storage (CCS) with its requirements for new CO_2 pipeline infrastructure (Smil 2010) or electric vehicles with their requirements for reshaped user expectations and driving practices (Tran et al. 2012). As CCS systems at industrial scales have not been sequentially commercialised over two or more years (de Coninck and Benson, 2014), it is even arguable whether CCS has yet begun its formative phase.

History thus offers a cautionary note on the potentials and risks of policy efforts to accelerate formative phases. Policies pushing to commercialise pre-mature technologies by picking a technical design or shortcutting key formative processes can result in failure. Examples from the early 1980s include the breeder reactor and synfuel production in the US, and the rapid up-scaling of wind turbines in Germany and the Netherlands (Grubler and Wilson, 2014). A systemic and sustained approach to technology formation, supported by stable and consistent policy, is more likely to help accumulate knowledge and experience from experimentation while building and aligning market demand.

There are various fruitful avenues for further research. First, results can be validated on a larger sample of technologies and additional indicators can be used to track the start and end points of formative phases (e.g., number of patent applications, dominant designs, R&D expenditures). Data availability may be an issue in both cases. Second, further testing is needed to detect robust explanations of formative phase durations across diverse technologies, particularly for those factors where results confounded expectations (e.g., up-scaling, diffusion pervasiveness). Multivariate models controlling for other influences may be possible for larger samples. Third, it would be interesting to explore whether shorter formative phases are more strongly associated with lock-in to a dominant design that ultimately proves inferior, as has been argued for technologies such as the pressurised water reactor in the nuclear industry (Cowan, 1990). Finally, the characteristics of formative phases for innovations that failed to diffuse in the market should also be examined.

Acknowledgments

The research on which this article is based was supported by a grant from the International Institute for Applied Systems Analysis (IIASA), and Harvard Kennedy School. The authors would also like to thank Arnulf Grübler for valuable insights throughout the research, as well as Henry Lee, Laura Diaz Anadon and Luís Cabral.

Supplementary material

The spreadsheets containing the data series and all the analysis can be found at http://webarchive.iiasa.ac.at/~bento

Appendix A. Data compiled for 16 energy technologies. (Technologies ordered historically by year of invention). See Appendices B and C for details.

Technology *		Data & Units	Time Series			Initial Markets (scale of analysis)	Market Potential **	Main Sources
			Unit Capacity	Unit Numbers	Industry Capacity			
Stationary Steam Engines	Su	Total Capacity (#,hp)	1710-1930 (average only)	1710-1930	1710-1930	UK, US	power provided by different sources	Kanefsky, Woytinsky, US Census
Steamships	Ed	Installed Capacity (#, hp)	1810-1940 (average only)	1810-1940	1810-1940	UK, US	gross tonnage of merchant vessel fleet (sail, steam, motor)	Mitchell, Woytinsky, US Census
Steam Locomotives	Ed	Installed Capacity (#, hp)	1830-1960 (average only)	1830-1960	1830-1960	UK, US	rail passenger traffic (million passengers)	Woytinsky, US Census, Daugherty
Bicycles	Ed	Production(#)	*estimated*	1861-2010	*estimated*	UK, France, Germany	population	UN, UK and US Census, INSEE, DIW
Coal Power	Su	Capacity Additions (#, MW)	1908-2000 (max. & average)	1908-2000	1908-2000	OECD	number of power plants in use	Platts
Natural Gas Power	Su	Capacity Additions (#, MW)	1903-2000 (max. & average)	1903-2000	1903-2000	OECD	number of power plants in use	Platts
Passenger Cars	Ed	Production (#) & Engine Capacity (hp)	1910-1960, 1960-2005	1900-2005	*calculated from unit data*	US	number of households	AAMA, US NHTSA, ACEA
Washing Machines	Ed	Production (#)	*estimated*	1920-2008	estimated	US	number of households	UN, Stiftung Warentest
Motorcycles	Ed	Production (#)	*estimated*	1900-2008	1900-2008	UK, France, Germany, Italy	number of households	UN
Wind Power	Su	Capacity Additions (#, MW)	1977-2008 (average only)	1977-2008	1977-2008	Denmark	electricity generation mix	DEA, BTM Consult
Electric Bicycles (E-bikes)	Ed	Production (#)	*estimated*	1997-2010	*estimated*	China	number of households	Weinert, Jamerson & Benjamin
Passenger Jet Aircraft	Ed	Production (#, Model) & Engine Thrust (kN)	1958-2007 (max. & average)	1958-2007	1958-2007	Boeing	number of air carriers in service	Jane's, aircraft databases
Fluid Catalytic Cracking (FCC) in Oil Refineries	Su	Total Capacity (bpd)	1940-2000 (average only)	*not available*	1940-2007	OECD, Former Soviet Union (FSU)	-	Oil & Gas Journal, BP, Enos
Nuclear Power	Su	Capacity Additions (#, MW)	1956-2000 (max. & average)	1956-2000	1956-2000	OECD	total installed capacity	Platts
Mobile Phones	Ed	Sales (#)	*estimated*	1979-2010	1979-2010	Scandinavia, Japan	population	Gartner
Compact Fluorescent Light Bulbs (CFLs)	Ed	Sales (#)	*estimated*	1990-2003	*estimated*	OECD (exc. Japan)	light bulb sales	IEA

* Su = energy supply technologies, Ed = end-use technologies.

** Market potential used for end point indicator (see text for details). Data for same initial markets as time series, except for: stationary steam engines (UK); jet aircraft (US); steamships (US); motorcycles (UK).

Appendix B. Start of formative phase: Data synthesis

Formative Phase	INDICATOR	UNITS	STATIONARY STEAM ENGINES	STEAMSHIPS	STEAM LOCOMOTIVES	BICYCLES	WIND POWER	COAL POWER	MOTORCYCLES	CARS	E-BIKES	NATURAL GAS POWER	WASHING MACHINES	CFLs	FLUID CATALYTIC CRACKING (in refineries)	JET AIRCRAFT	NUCLEAR POWER	MOBILE PHONES
Reference Points	**Invention (cf. invention lists)**	Year	1707	1707	1769	1818	1888	1842	1885	1860	1897	1842	1884	1972	1929	1928	1943	1973
		Source	Haustein & Neuwirth	Haustein & Neuwirth	Mensch	Mensch	Gipe	Mensch	Van Duijn	Mensch	US Patent 596,272	Mensch	Van Duijn	IEA (2006)	Enos (1962)	Mensch	Haustein & Neuwirth	US Patent 3,906,166
Ex Ante START POINTS	**First 'embodiment' of technology**	Year	1712	1776	1804	n/d	1887	1878	1885	1873	1891	n/d	1904	1973	1940	n/d	1951	1946
		Model	Newcomen	Jouffroi's Palmipède	Trevithick's locomotive	n/d	First wind turbine	First power station in Bavaria	Daimler-Maybach's Reitwagen	Bollé's 1st steam vehicle	Electric tricycle by A.L. Ryker	n/d	First electric washing machine	GE invents spiral CFL	Pilot plant in Louisiana	n/d	EBR-I Idaho	First mobile phone in a car
	First application outside lab / commercial application (I)	Year	1712	1809	1824	1839	1891	1884	1894	1886	n/d	1884	1907	1980	1942	1941	1954	n/d
		Source (innov.list)	Von Tunzelmann (1978)	Silverberg & Verspagen; Haustein & Neuwirth	Mensch	Mensch	Gipe	Mensch	Silverberg & Verspagen; Van Duijn	Mensch	n/d	Mensch	Silverberg & Verspagen; Van Duijn	IEA (2006)	Silverberg & Verspagen	Mensch	Silverberg &Verspagen; Haustein &Neuwirth	n/d
	First application outside lab / commercial application (II)	Year	1712	1807	1814	1861	1891	1882	1894	1885	n/d	n/d	1908	1980	1942	1939	1954	1977
		Own Research	Newcomen	Robert Fulton's Clermont	Stephenson's Locomotion	Michaux's Velocipède	La Cour	Edison Electric Light Station	H&W motorcycles	Benz	n/d	n/d	Thor washer	Philips model SL	Enos (1962)	von Ohain's first flight	USSR's Obninsk plant	Prototype cellular system
	First sequential commercialization	Year	1717	1811	1825	1861	1977	1908	1900	1888	1970	1903	1908	1980	n/d	1952	1954	1979
		Number of Units	5	1	4	2	2	1	1330	n/d	n/d	1	n/d	100000	n/d	10	1	n/d
		Model	Newcomen	Paddle wheel and sail	Locomotion No 1	Michaux's Velocipède	Danish 3-blade (26kW)	Turbo generators	Werner (UK)	Benz car	n/d	n/d	Thor	Philips SL	n/d	Comet	APS-1 OBNINSK	First commercial system in Japan
Additional Indicators	**First maximum in *public* R&D expenditure**	Year	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	1971	1983	1987
		Public R&D in 2005$ million	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	11185	3963	15726

Legend: n/d (no data), not applicable (n/a)

Sources (not exhaustive): Innovation lists: Mensch (1979), Haustein and Neuwirth (1982), Van Duijn (1983), Silverberg and Verspagen (2003). Steam stationary: Von Tunzelmann (1978), Kanefsky and Robey (1980), Kanefsky (1979). Steamships: U.S. Census Office (1978); Nakicenovic (1984). Steam locomotives: Mitchell (1992). Bicycles: Perry (1995). Power-Wind: Gipe (1995), Danish Energy Agency (2012). Power-Coal: Termuehlen and Emsperger (2003). Motorcycles: Wezel (2002). Cars: Abernathy and Clark (1985), Abernathy et al (1983), Argyres et al. (2011). E-Bikes: Weinert (2007). Power-Natural Gas: Mowery and Rosenberg (1989). Washing machines: Maxwell (2009). CFLs: IEA (2006). FCC refineries: Enos (1962). Jet Aircraft: Mowery and Rosenberg (1989), U.S. Department of Transportation (1960). Power-Nuclear: IAEA (2012). Cellphones: National Science Foundation (2012). For more details on the data see Bento and Wilson (2014).

Appendix C. End of formative phase: Data synthesis

Formative Phase	INDICATOR	UNITS	STATIONARY STEAM ENGINES	STEAMSHIPS	STEAM LOCOMOTIVES	BICYCLES	WIND POWER	COAL POWER	MOTORCYCLES	CARS	E-BIKES	NATURAL GAS POWER	WASHING MACHINES	CFLs	FLUID CATALYTIC CRACKING (in refineries)	JET AIRCRAFT	NUCLEAR POWER	MOBILE PHONES
Ex Post END POINTS	**Fraction of full technology lifecycle**	Year of 10%K (cumul.#)	1870	1880	1880	1922	1985	1938	1949	1937	2005	1968	1951	1994	n/d	1969	1966	2001
		Year of 10%K (cumul.MW)	1880	1890	1900	1922	1991	1957	1956	1955	2005	1976	1962	1994	1945	1971	1973	2001
	Up-scaling of unit size	Year of 10% K (max. unit capacity)	1748	n/d	n/d	n/d	1999	1928	n/d	n/d	n/d	1943	n/d	n/d	n/d	1958	1960	n/d
Ex Ante END POINTS	**Market structure**	Year of peak in number of firms	1869	n/d	n/d	n/d	n/d	n/d	1921	1908	n/d	n/d	n/d	n/d	n/d	1973	n/d	n/d
		Year of "shakeout" (N falls -30% from the peak)	n/d	n/d	n/d	n/d	n/d	n/d	1924	1914	n/d	n/d	n/d	n/d	n/d	1979	n/d	n/d
		Year of min. market concentration ratio (CR4)	n/d	n/d	n/d	n/d	n/d	n/d	n/d	1911	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
	Cost reduction	Year of first 50% reduction in cost	n/a	n/d	1855	1897	n/a	n/a	n/d	n/a	n/a	n/a	n/d	n/a	n/d	n/d	n/a	n/d
		Year of max. % cost reduction	1727	n/d	1855	1897	2002	n/d	n/d	1924	2000	n/d	n/d	n/d	n/d	n/d	n/d	n/d
		% (max. cost reduction)	30%	n/d	85%	63%	15%	n/d	n/d	25%	22%	n/d	n/d	n/d	n/d	n/d	n/d	n/d
		Description (model, mass prod.)	Newcomen	n/d	4-4-0	Safety bike	Danish model	Conventional coal PP	n/d	Ford Model T	mass prod.	Conventional gas PP	n/d	n/d	n/d	n/d	PWR	n/d
	User adoption	Year of 2.5% potential market	1802	1830	1846	1886	1992	1917	1921	1911	2005	1928	1923	2000	n/d	1959	1967	1993
Additional Indicators	**Patent application**	Year of first peak	n/d	n/d	n/d	n/d	1980	n/d	n/d	1897	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
		Year of start of 2nd wave of increase	n/d	n/d	n/d	n/d	1996	n/d	n/d	1914	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
	Production scale up	Year of 10-fold increase in production	n/a	1820	n/a	1862	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	no/n.a.	n/a	n/a
		Year of highest growth	1720	1820	1850	1862	1978	1938	1901	1946	1998	1945	1921	1991	1956	1959	1993	1980
		%	838%	3417%	560%	7000%	450%	267%	194%	328%	263%	275%	132%	42%	7%	863%	700%	33%
	Dominant design	Year	1764	1807	1829	1884	1957	1920	1901	1909	1946	1939	1937	1985	1942	1958	1970	1973
		Model	Watt engine	Fulton's Clermont	Stephenson's Rocket	Safety bike	Gedser wind turbine	Pulverized coal system	"diamond frame"	Ford T	Tucker's Wheel motor unit	BBC Velow plant	Bendix automatic wash.mach.	Electronic ballast	Fluid Catalytic cracking	B707/DC-8	LWR (PWR)	Cooper's portable handset
	User adoption	Lead user? (Yes/No)	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes	No
	Up-scaling of unit size	Year of 10% K (avg. unit capacity)	1730	1830s	1840	n/d	1990	1926	1941	1918	1990s (late)	1906	1943	n/d	1942	<1958	1961	n/d

Notes: n/d = no data, n/a = not applicable

Sources: see Appendix B

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