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Bento, N. and Wilson, C.

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International Institute for
Applied Systems Analysis
Schlossplatz 1
A-2361 Laxenburg, Austria

Tel: +43 2236 807 342
Fax: +43 2236 71313
E-mail: publications@iiasa.ac.at
Web: www.iiasa.ac.at

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Formative Phase Lengths for a Sample of Energy Technologies Using a Diverse Set of Indicators

Nuno Bento
Charlie Wilson

Approved by

Arnulf Grubler
Transitions to New Technologies (TNT) Program

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Contents

Abstract

The objective of this research is to identify historical patterns in the formative phase of energy technologies. This period designates the early stage of development (i.e., between the invention and the up-scaling phase) that sets up the conditions for the technology to emerge and prepare for widespread growth. This investigation aims to develop an operational definition of formative phase to enable comparative technology analysis. A review of the literature, particularly the technological innovation system one, reveals a set of formative processes which are then connected to a common set of indicators for characterizing the development of new technologies. The results show that "2.5% market potential" is a good metric of the completion of the formative phase as early demand helps to reduce uncertainties (technology, market and institutions) and improve performances. This phase is often long, taking at least a decade in the more optimistic estimates. It can be shortened in the case of less disruptive innovations or by a simultaneous promotion of technology supply and demand.

Keywords: diffusion; technological innovation systems; up-scaling; formative phases.

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About the Authors

Nuno Bento was a Postdoctorate Scholar at the International Institute of Applied Systems Analysis (IIASA), Austria, between February 2011 and March 2012. He is currently a researcher at the DINÂMIA'CET of ISCTE – University Institute of Lisbon, working in a project financed by the Portuguese research council about the diffusion of energy technologies and their adoption in Portugal. Nuno received his Ph.D. degree in 2010 in Economics from the University of Grenoble, France, following a research on new energy technologies conducted at the Laboratoire d'Economie de la Production et de l'Intégration Internationale (LEPII-EPE-CNRS).

Charlie Wilson is a Lecturer in Energy and Climate Change in the Tyndall Centre at the University of East Anglia (UK). His research interests lie at the intersection of technology, policy, behavior and decision making. After completing his PhD at the University of British Columbia (Canada) on the social and behavioral determinants of energy use, Dr. Wilson has held teaching and/or research positions at the London School of Economics (UK), Chalmers University (Sweden), and IIASA. Prior to his academic career, Dr. Wilson worked for a number of years in the private sector on renewable energy finance and climate change policy.

Formative Phase Lengths for a Sample of Energy Technologies Using a Diverse Set of Indicators

Nuno Bento and Charlie Wilson

1. Introduction

The development of new low-carbon technologies is essential in order to mitigate climate change. Recent studies note the dangerous continuation of current trends of energy consumption and emissions unless there is a major change in behaviors and technologies to reduce carbon emissions in the following decades (IPCC, 2013; GEA, 2012). The acceleration of energy innovations is also important to lower the overall cost of reaching long-term climate goals (Weyant, 2011; Newell, 2010). To this end, emissions policy to increase demand for new technology needs to be combined with innovation policy, comprising a well-targeted R&D program that can boost innovations as they are being formed through their early stages (Henderson & Newell, 2011). The understanding of the dynamics that occur during the formative phase of technologies is essential for the design of better policies in order to accelerate innovation.

The formative phase designates the early stage of development that sets up the conditions for the technology to emerge and penetrate into the market (Wilson, 2012; Wilson & Grubler, 2011). In these terms, it corresponds to the period that runs between the invention and the up-scaling phase, i.e. the moment when larger size versions of the innovation start to be produced in order to grasp economies of scale at unit level. In the innovation system perspective (Bergek, 2008a; Hekkert et al., 2007; Jacobsson & Bergek, 2012), this is the time required to set up the constitutive structure of the new innovation system. However, the formative phase is often loosely defined in the literature as the period marked by large uncertainties on technologies, lasting rarely shorter than a decade and corresponding to a volume of diffusion that is a fraction of the estimated potential (Bergek et al., 2008a). Previous empirical studies on the introduction of 30 product innovations in the US estimated the average time between invention and commercialization as approximately 30 years, with 14 years more before sales take-off (Agarwal & Bayus, 2002, see also Tellis et al., 2003; Golder & Tellis, 1997; Mensch, 1979).

Formative phases have been defined functionally, conceptually, but not empirically. The objective of this research is to develop and empirically test an operational definition of formative phases in order to enable comparative technology analysis. The consistent cross-technology indicators of formative phase duration are a key contribution to existing research.

So, what are the processes that innovations need in order to evolve in the early stages, and how can they be measured? An important part of this work consists of studying the main characteristics of the development period of several technologies and relating them with the duration of that stage. The report is structured as follows. First, the conceptual framework is presented using concepts from the innovation and transitions literature in order to reveal the main processes that occur during the formative phase. Second, the methodology and data sources are explained for a sample of energy technologies on which formative phase indicators are tested. Third, the main processes identified in the literature review are linked to a set of indicators for characterizing the end and duration of the formative phase, preceding a brief discussion on the main drivers of innovation in practice in early years. The major results from the analysis are summarized in the concluding section.

2. Formative phases and formative processes

This section analyzes the development of new technologies by highlighting the processes occurring during the formative phase. This issue is addressed with concepts and theories from three streams of the literature: innovation and technological change; historical diffusion and scaling dynamics; and technological innovation systems.

2.1. Stages of the innovation process

Technological change is usually represented in the literature through the Schumpeterian vision of a succession of stages (more or less linear) of invention, innovation, and diffusion – the latter by the mean of user adoption and competitor imitation (Freeman, 1982, Grubb, 2004).

An influential model for the understanding of the innovation process is the Product life cycle (PLC) presented by Abernathy and Utterback (1978). [1] In the early years of "childhood," technology is so crude and expensive that it can only penetrate in a few niche markets (Rosenberg, 1994, Kemp et al. 1998). There is a lot of uncertainty surrounding the evolution of the technology and the market, thus several models are experimented within a very dynamic environment (Abernathy & Utterback, 1978). The "adolescence" period is marked by a concentration of the industry in few numbers of designs, which present better attributes, until one becomes dominant turning into the standard of the industry and enabling mass-commercialization (Utterback, 1994; Abernathy & Utterback, 1978; Murmann & Frenken, 2006). Later on, the technology reaches "maturity" and growth rates slowdown, becoming more difficult to introduce incremental innovations. At that stage, competition is focused more on price and costs reductions, and production is concentrated in a few number of producers trying to benefit from scale economies.

The research community has been increasingly studying the determinants of the rate of diffusion of energy technologies. A set of mechanisms were identified that can accelerate or slow down the rate of technology growth, such as (Grubler, 2012, 2008, 1998; Rogers, 1995): market size (scale); relative advantage; the availability of pre-existing markets; technology complexity; and infrastructure needs. A recent empirical

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[1] For a recent review of the industry life-cycle literature, see Peltoniemi (2011).

literature particularly focuses on the effect of scale in the historical growth of energy technologies. The study of scaling dynamics revealed a strong relationship between the extent and duration of growth (Wilson & Grubler, 2011; Wilson, 2009). That is, technologies with a more pervasive impact in the market take longer to diffuse than those that have a smaller potential of penetration. For instance, wind power took two decades to grow, while steam engines had to wait a century before diffusion have a strong impact on the economy.

The historical evidence has also shown that the expansion of energy technologies typically evolved in a three-stage sequential process (Wilson, 2012):

i) a formative phase consisting of the experimentation and production of many small scale units;

ii) an up-scaling phase by constructing ever larger units (e.g., steam turbines or power plants) to gather economies of scale;

iii) and a growth phase characterized by mass production of large-scale units, reaping economies of scale (and also learning economies) at the manufacturing level.

This makes it important to analyze the formative phase processes that seem to underpin the subsequent up-scaling and growth of energy technologies. These processes are analyzed more in detail in the next section.

2.2. The formation of new technological innovation systems

2.2.1. Co-evolution of technology and institutions

In the formative phase innovation is involved in many uncertainties in terms of technologies, markets and regulation (Kemp et al., 1998; Jacobsson & Bergek, 2004; Meijer et al., 2007).

The theory of technological innovation systems (TIS) considers that the entire lifecycle of an innovation takes place within a particular innovation system (Jacobsson & Johnson, 2000; Jacobsson & Bergek, 2012). Innovation is understood as an interactive process involving a network of companies and economic agents (e.g., users), acting within an environment marked by institutions and policies that influence technology, adoption behavior and performance, bringing new products, processes and organization structures into economic use (Nelson & Winter, 1982; Freeman & Perez, 1988; Lundvall, 1992). This theory is therefore helpful to understand the main factors that affect the development of new innovation systems.

The emergence of a new technological innovation system is characterized by the implementation of a structure composed of three main elements (Bergek et al., 2008a; Jacobsson & Bergek, 2004): actors, networks and institutions. Actors include firms and other organizations (e.g. universities, industry associations) along the value chain (Bergek et al., 2008a). Networks are the result of links established between fragmented components (i.e. actors) to perform a particular task. Institutions structure political, economic and social interactions (North, 1990, 1991). They consist of formal rules (e.g., laws and property rights) and informal norms (e.g. tradition and culture). Institutions have three roles in innovation systems (Edquist & Johnson, 1997): to reduce uncertainty by providing information; manage conflicts and promote cooperation; and provide incentives for innovation. Those roles are particularly important during the formative phase by providing the context in which actors start aligning in networks –namely through fostering the dynamics of networks, promoting knowledge creation and dissemination, and allowing for market formation.

The genesis of a new TIS involve three basic structural processes (Bergek et al., 2008a; Jacobsson, 2008): entry of firms and other organizations; formation of networks and institutional alignment. This process is particularly important in the case of new and radical innovations, for which almost every component must be put in place (Hekkert et al., 2007). The innovation system evolves through a cumulative process of small changes, which can last for decades, and ends by building-up an embryonic structure of the future system (Markard & Hekkert, 2013; Jacobsson, 2008; Van de Ven & Garud, 1989).

According to this view formative phase is the set of structural processes needed to initiate and develop a TIS. Yet these processes take time, so the formative phase can be identified as a duration. Bergek et al. (2008) 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)). One of the advantages of this approach is that it highlights a number of processes (called functions) which are needed for the good functioning of the innovation system (Markard et al., 2012; Bergek et al, 2008b; Hekkert et al., 2007).

2.2.2. Key functions of the innovation system in the formative phase

It has been identified seven functions of innovation system that are involved in and are provided by the building up of a new system (Bergek et al., 2008b):

a) knowledge development and diffusion;
b) entrepreneurial experimentation;
c) influence on the direction of search;
d) market formation;
e) resource mobilization;
f) legitimation; and
g) development of positive externalities.

Three functions were particularly recognized as important "triggers" of virtuous cycles of growth in recent diffusions of energy technologies (Hekkert et al., 2007; Bergek et al., 2008b; Jacobsson & Lauber, 2006): knowledge development and diffusion; experimentation (and learning), and legitimation (and institutional alignment).

Knowledge development and diffusion is crucial in the emergence of the innovation system. It concerns the creation and consolidation of an essential scientific and technical knowledge base, as well as its propagation across sectors and regions (Jacobsson & Bergek, 2012). The main sources of knowledge creation are scientific and research policies for more formal and fundamental knowledge, as well as experimentation and market penetration for the creation of a more tacit and applied type of knowledge (Bergek et al., 2008b).

Experimentation is a primary source of learning and knowledge (Bergek et al., 2008b). The early phase of innovation is characterized by large uncertainties on technologies, markets and uses (Kemp et al., 1998). These uncertainties may be handled by making sure that many entrepreneurial experiments take place (Jacobsson & Bergek, 2012). The test of many new combinations develops applied knowledge on the technology as well as allows the identification and correction of technical problems. Market formation is another essential process in the constitution of a new innovation system (Hekkert et al., 2009). This concerns the articulation of demand in a real context through demonstrations, niches and bridging markets (von Hippel, 2010; Rosenberg, 1982; Bergek et al., 2008a; Jacobsson & Bergek, 2008).

Finally, legitimacy has been widely reported as a pre-requisite or a key function of the innovation system for the formation of a new TIS (Bergek et al., 2008a; Hekkert & Negro, 2009; Hekkert et al., 2007). It is a matter of gaining social acceptance and turning the innovation into a credible alternative to the incumbent technology. This is necessary in order to align institutions with the needs of the emerging innovation. For that, the technology must reach a certain level of political consensus through a socio-political process of actions taken by actors and networks that lead to the formation of expectations and visions in the early stages of the innovation (Bergek et al., 2008a; Borup et al., 2006). The legitimation process should take longer in the case of more disruptive technologies given the complexity and the level of resources (e.g. financial, technical) involved.[2]

2.2.3. Phases of maturity of technological innovation systems

This section synthesizes the previous points by schematically characterizing the main features of the innovation systems along different stages of development.

The technological innovation system passes from emergence to maturity through a number of modifications in technology, system structure and processes (Markard & Hekkert, 2013). The innovation is gradually refined with the first prototypes being successively substituted by more perfected versions. At the same time the structure of the innovation system is consolidated with the arrival of new actors, the creation of more networks and the development of supportive institutions. Finally, the nature of the key functions changes with the stage of maturity of the technology. It is especially interesting to investigate the main features of the innovation system in the beginning and end of the formative phase.

Table 1 maps Markard and Hekkert's (2013) stages of progress in TIS on to the simple sequence of formative, up-scaling and growth phases (Wilson, 2012). The nascent and emerging stages of a TIS are included within the formative phase which is separated from the mature stage of a TIS by the up-scaling phase. The analysis in this report mainly focus on the formative phase.

The early years of the "nascent" TIS marks the start of the formative phase. This stage begins in the period after invention and is marked by the existence of a large variety of

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[2] Jansson et al. (2013) use the analogy of the innovation diffusion to study the transitions from and to democracy. The authors found that "patience increase the likelihood of success" and contributes to the consolidation of democratic institutions. It was observed that the longer the transition (up to 12 years), the longer the survival of the resulting democracy.

ideas and concepts. The structure of the innovation system is still embryonic containing very few elements. There are a small number of actors (e.g. inventors, private or public research laboratories, universities) mainly organized in networks dedicated to R&D activities and knowledge creation. The restricted number of institutions is mostly informal and sharing ideas about the technology. Knowledge creation is the crucial process at this stage.

Conversely, the end of the formative phase is characterized by the emergence of the TIS. This stage comprises both the periods of "childhood" and "juvenile" of technology development according to the PLC model, with the concentration in a small number of designs in order to build up an early manufacture base and prepare the innovation for up-scaling. In addition, the innovation system becomes gradually more structured. There are an increasing number of actors bringing new resources into the TIS, and higher rates of entry and exit of firms due to fierce competition. More networks of R&D and deployment, as well as advocacy coalitions are formed, accompanied with the emergence of the first (formal) technology-specific institutions, which are important to support the actors technically and politically. Entrepreneurial experimentation has a key role in this very dynamic period to prepare the next stage through the development of the technology and articulation of demand.

Table 1. Stages of progress of technological innovation systems

	Formative phase		**Up-scaling phase**	**Growth phase (Mature TIS)**
	Nascent TIS (start)	**Emerging TIS (end)**		
Appearance of 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	Established product; Mass-production
Degree of structuration of the TIS	Low (or absent)	Medium	Medium-high	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 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 sharing ideas about techn.	Dynamic number of technology-specific institutions	More stable number of technology-specific institutions	Stable formal and informal technology-specific institutions
Networks	Knowledge and R&D networks constitution	R&D, deployment and other kinds of organizations	Different types of networks (cognitive and technological)	Established industry networks
Crucial functions	Knowledge creation	Entrepreneurial experimentation	Resource mobilization/Legitimation +Market formation	[TIS established]

Adapted from Markard & Hekkert, 2013

Although Table 1 is expressed in terms of structural elements, processes and functions, it is silent on the time dimension of the formative phase. Time is important because of the need to accelerate innovation of low-emission technologies for climate mitigation and to improve modeling of technological change. Hence, linking the characteristics of the TIS, at its nascent and emerging stages, to observable outcomes in terms of innovation diffusion enables to infer the empirical determinants of formative phase duration. Therefore, a more applied analysis to the growth of several technologies over time may help to better define the frontiers of the formative phase.

3. Methodological issues

3.1. Comparative analysis of formative phase characteristics

The aim of this research is to establish an operational definition of formative phases and to apply this definition empirically to estimate formative phase durations historically for energy technologies. The contribution of this investigation is to enable comparative technology analysis. An important part of this work consists on studying the main characteristics of the development period of several technologies and relating them with the duration of that stage.

The literature review presented above showed that the period of formation is essential for the innovation system to set up the structure and perform key functions (e.g. basic and applied knowledge development, experimentation, legitimation, market formation) required for up-scaling and mass commercialization (Wilson, 2009, 2012). However, the formative phase was loosely defined in early works as lasting rarely shorter than a decade and corresponding to a volume of diffusion and economic activities that is a fraction of the estimated potential (Bergek et al., 2008a). Therefore it is necessary the identification of major features of the formative phase in order to be able to track and compare the innovation progress during the early years.

3.2. The need of indicators to define formative phase consistent with formative phase processes

This investigation develops a range of indicators in order to define duration of formative phases of innovations. Hence, a set of indicators to measure start and end of formative phase was identified which are coherent with the concepts and theories presented in the literature review, particularly the key processes or functions of the innovation system (Bergek et al., 2008b; Hekkert et al., 2007, 2009).

The discussion will focus especially on the end part of that phase because of its importance for up-scaling and the transition to large scale diffusion. Additionally, a set of indicators were assembled to identify the moment of beginning of the formative phase. Those measures were related with the start of formative processes, such as first commercialization or invention and innovation dates. These metrics are explained more in detail in the following sections.

3.3. Test indicators on comparative set of energy technologies

This research intends to improve our understanding about the processes that occur in the early years of innovation by defining a range of indicators that characterize the formative phase and testing them on a comparative technology data set.

Different data sources were compiled and compared for each indicator, using a sample of energy technologies from both supply and end-use. The technologies included in the analysis are shown in Table 2. Data were collected to describe diffusion of each technology including cumulative unit numbers produced, unit-scale throughout the diffusion, and cumulative installed capacity expressed in MW. Most data describe diffusion in each technology's market of first introduction as this captures the initial formative phase for the technology. In spatial diffusion terms, these markets of first introduction from which technologies and knowledge can subsequently spill over are called 'core' markets (Grubler et al. 1999). Unless otherwise mentioned, the spatial scale of analysis always corresponds to the initial market for each technology (see Table 2). The time series data and all sources and procedures followed to collect the numbers are explained in a technical report (Bento, 2013). In addition, it was collected information on the historical development of each innovation regarding different aspects like important dates (invention or innovation), demonstrations or relevant models.

The choice of the optimal indicator for the start and end points of the formative phase is made according to the three following selection criteria:

i) links to formative phase processes which were identified in the literature;
ii) data is available for potentially all technologies (very few missing information);
iii) consistent and not an outlier.

Some metrics are only possible to track ex post, but others can be estimated ex ante as well. This is the case for the year when 2.5% of market potential or 10% maximum unit capacity are reached as long as market potentials or maximum unit scales can be approximated (e.g., by technology feasibility studies). These two indicators directly measure technology progress and market formation. The use of ex ante metrics is of a great importance as enables the application of the formative phase definitions prospectively in innovations that are starting to emerge.

The analysis therefore enables to estimate the duration of formative phases of the technologies in the sample. The results can then be compared and explanatory variables identified that may elucidate about the differences in formation periods, giving stronger empirical basis for theories about the emergence of innovations.

Table 2. Energy technologies included in the sample: time series and data sources, ordered historically (by year of invention)

Technology		Data & Units	Time Series			Initial markets	Main Sources
			Unit Capacity	Unit Numbers	Industry Capacity		
Steam stationary	S	Total Capacity (#,hp)	1710-1930 (average only)	1710-1930	1710-1930	UK, US	Kanefsky, Woytinsky, US Census
Steamships	D	Installed Capacity (#, hp)	1810-1940 (average only)	1810-1940	1810-1940	UK, US	Mitchell, Woytinsky, US Census
Steam locomotives	D	Installed Capacity (#, hp)	1830-1960 (average only)	1830-1960	1830-1960	UK, US	Woytinsky, US Census, Daugherty
Bicycles	D	Bicycles production (#)	estimated	1861-2010	estimated	UK, France, Germany	UN, UK and US Census, INSEE, DIW
Coal Power	S	Capacity Additions (#, MW)	1908-2000 (max. & average)	1908-2000	1908-2000	OECD	Platts
Natural Gas Power	S	Capacity Additions (#, MW)	1903-2000 (max. & average)	1903-2000	1903-2000	OECD	Platts
Passenger Cars	D	Cars Produced (#) & Engine Capacity (hp)	1910-1960, 1960-2005	1900-2005	calculated from unit data	US	AAMA, US NHTSA, ACEA
Washing machines	D	Washing machines production (#)	estimated	1920-2008	estimated	US	UN, Stiftung Warentest
Motorcycles	D	Motorcycles production (#)	estimated	1900-2008	1900-2008	UK, France, Germany, Italy	UN
Wind Power	S	Capacity Additions (#, MW)	1977-2008 (average only)	1977-2008	1977-2008	Denmark	DEA, BTM Consult
Electric bicycles	D	E-bikes production (#)	estimated	1997-2010	estimated	China	Weinert, Jamerson& Benjamin
Passenger Jet Aircraft	D	Aircraft Delivered (#, Model) & Engine Thrust (kN)	1958-2007 (max. & average)	1958-2007	1958-2007	Boeing	Jane's, aircraft databases
Oil Refineries	S	Total Capacity (bpd)	1940-2000 (average only)	not available	1940-2007	OECD, Former Soviet Union (FSU)	Oil & Gas Journal, BP, Enos
Nuclear Power	S	Capacity Additions (#, MW)	1956-2000 (max. & average)	1956-2000	1956-2000	OECD	Platts
Mobile Phones	D	Cellphones sales (#)	estimated	1979-2010	1979-2010	Scandinavia, Japan	Gartner
Compact Fluorescent Light Bulbs	D	Light Bulb Sales (#)	estimated	1990-2003	estimated	OECD (exc.Japan)	IEA

Note: "S" – Energy Supply Technologies "D" – End-Use Technologies.
For more details, see Bento (2013) and Wilson (2012).

4. Results (I): start of formative phase

4.1. Alternative metrics

The moment of invention and of beginning of the development phase is normally not coincident in time. The former provides the "seeds" of the process, but is the latter that better characterizes the start of the formative phase.

This section aims to identify an operational definition for the start of formative phase. It is discussed a set of different metrics consisting in information about the year of first ‘embodiment’ of technology, the first application outside laboratory, the first commercial application, and the first sequential commercialization. Additionally, it is discussed the usefulness of indicators that measure inputs to the innovation process.

4.1.1. indicator (a) First 'embodiment' of technology

The first embodiment of technology is a mark in the innovation process. It concerns especially the moment of appearance of the first prototypes or the demonstration of their use in the real world. This often means that major technical barriers have already been solved and innovation is consolidating towards a technologically viable design. The learning derived from first embodiment may also be decisive to develop knowledge concerning the possibilities of production and marketing of the innovation, which can accelerate its penetration in the market later (Hendry et al., 2010; Von Hippel, 2010; Rosenberg, 1982).

The main weakness of this indicator in practice deals with the fact that many technical trade-offs may remain unsolved at the end of a few demonstration units. Although the first embodiment of the technology may represent the beginning of the formative phase by contributing to raise the credibility and dynamics of innovation, it is still unclear whether its impact is large enough to trigger the other processes inherent to the formative period.

4.1.2. indicator (b) First application outside laboratory or first commercial application

The first real scale application outside laboratory is a decisive moment in the progress of the technology and in the transition from the laboratory to the market. Often, this moment coincides with the first commercial application or first ‘useful’ appliance delivering a function or end-use service. For instance, the first steam engines were directly used to pump water out from coal mines in the UK (Von Tunzelmann, 1978). The experimentation outside laboratory also enables the reception of feedback from users, allowing the adaptation of the artifact (or concept) to the needs of demand. This may help innovators to solve technical trade-offs or find new services for the technology which were not initially expected (von Hippel, 2010).

Mensch (1979) provides a list of innovation dates, defining innovation as "a technological basic innovation when the newly discovered material or newly developed technique is being put into regular production for the first time, or when an organized market for the new product is first created.” [3] Dates of invention and innovation for missing technologies are found in other reference lists. In particular the data set created in Silverberg and Verspagen (2003) which combines the data sets of other (still) state-

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[3] We found similar definitions in other data sets. This is the case of Haustein and Neuwirth (1982) which associate the date of invention to the first major patent application or other (list) sources, and the date of innovation to the moment of first production or market introduction.

of-the-art innovation timelines of Haustein and Neuwirth (1982) and Van Duijn (1983).[4] Finally, influential publications and patent information were used to establish the dates of invention and innovation for not listed technologies.

Table 3 presents the time interval between invention and innovation of twelve different technologies according to the innovation. The results show that it takes in average almost three decades to pass from invention to innovation, in agreement with the literature (e.g. Agarwal et al, 2002).

Table 3. Time interval between invention and innovation of twelve different energy technologies ordered historically, by year of invention

Technology	Invention Date	Innovation Date	Interval between invention and innovation (years)
STEAM STATIONARY	1707	1712	5
STEAMSHIPS	1707	1809	102
STEAM LOCOMOTIVES	1769	1824	55
BICYCLES	1818	1839	21
COAL POWER	1842	1884	42
NATURAL GAS POWER	1842	1884	42
CARS	1860	1886	26
WASHING MACHINES	1884	1907	23
MOTORCYCLES	1885	1894	9
JET AIRCRAFT	1928	1941	13
FLUID CATALYTIC CRACKING (in refineries)	1929	1942	13
NUCLEAR POWER	1943	1954	11
CFLs	1972	1980	8
		Mean (standard deviation):	28.5 (26.9)
		Median:	21 [i]

[i] If the highest value for Steamships is not taken into account, the mean lowers to 22.3, the standard deviation to 16.1, and the median to 17 years.

Source: Mensch (1979), Silverberg and Verspagen (2003), own research (see Appendix 1).

The main advantages of using well-established lists of innovations are the simplicity and confidence that brings to the choice of the starting point of formative phases, especially when the criteria is clearly defined in the source list. However, this indicator ignores all activities that had been deployed before that date which were important for the development and emergency of the technology (e.g. R&D activities, training of personnel). Thus, it can be seen in practice as a late bound of the real moment of start of the formative phase.

4.1.3. indicator (c) First sequential commercialization

A third indicator for the start of the formative phase is the moment of first commercial application initiating successive series of products (i.e., not just a one-off, but the beginning of a consistent commercialization). This corresponds to a later stage of experimentation when the innovation is gradually introduced into the market and starts

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[4] When there was a difference in the date of the invention or innovation between the lists (Silverberg and Verspagen, Haustein and Neuwirth and Van Duijn) there has consequently been chosen for the earliest date.

to have a first competitive pressure. On the one hand, the development of a manufacture base to support initial production may necessitate firm prospects about the development of demand. For instance, the start of manufacturing of CFLs or cellphones required solid perspectives on the demand for the first thousand units being produced. On the other hand, looking at successive years of market deployment avoids the risk of considering early 'one-off' test applications that need already significant fundamental R&D as formative phase start point.

The main drawback of this indicator is the fact that it does not take into account the activities of development and experimentation of the technology, which are important formative processes, prior to the beginning of serial production. Thus, it may give a late estimate for the starting point of the formative phase.

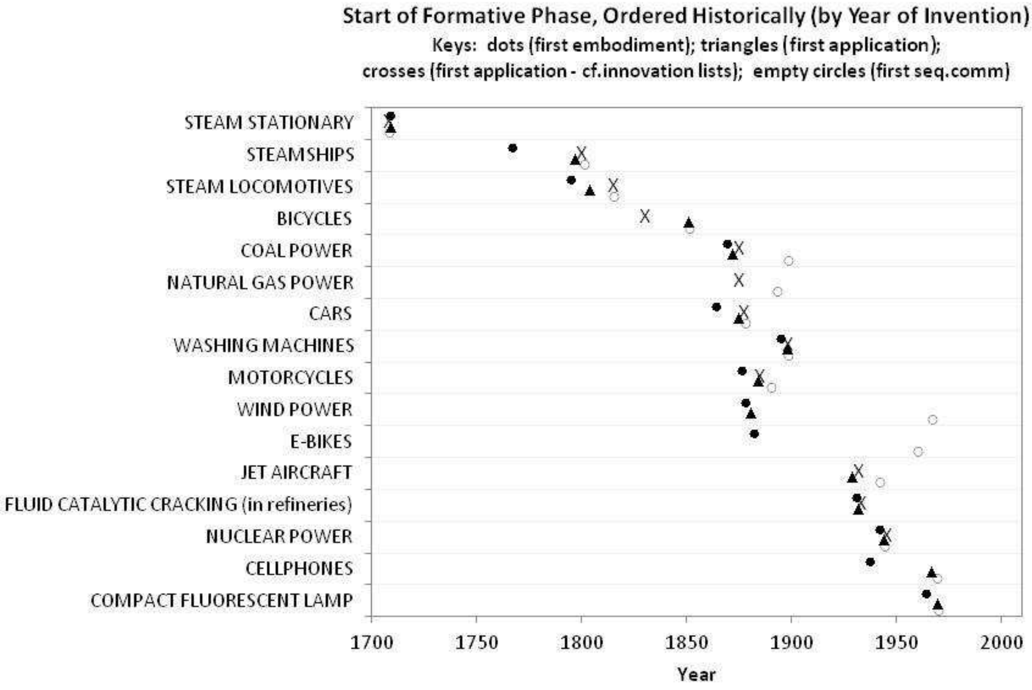
4.2. Comparing different indicators

This section applies the above operational definitions to the sample of technologies in order to find the start points of formative phases (see Table 4 for a synthesis of all indicators). Appendix 3 suggests additional potential indicators that can be considered to track the start of formative phases in future researches. Ideally, different indicators would converge in a precise date or a sufficient short period of time that marks the beginning of the relevant functions (e.g. creation of formal knowledge, experimentation) for the development of the innovation. Figure 1 presents all the estimates of the beginning of the formative phase according to the measures defined earlier. A synthesis of all the data and sources can be found in Appendix 1.

Table 4. Summary table of proposed indicators to define start point of formative phase

Indicator	Indicator	Metric	Link to Formative Phase Processes	Rationale
a)	First 'embodiment' of technology	Year of first significant prototype or demonstration of the innovation	knowledge development experimentation & learning	the learning derived from experimentation and trials is decisive to understand the real possibilities of production and marketing of the innovation (Hendry et al. 2010)
b)	First application outside lab or commercial application	B1) Cf. Innovation List (e.g. Mensch 1979) B2) Own research (Year and model)	entrepreneurial experimentation materialization (first investments in production)	technology is being put into regular production for the first time, or a market is first created for the new product (Mensch, 1979). This raises applied knowledge and confidence in the new technology that boosts its development
c)	First sequential commercialization	Year of first commercial application initiating successive series of product, i.e., not just a one-off	knowledge development materialization market formation	transition from experimentation with some unit numbers to early market penetration enables decisive production and market experience

Figure 1. Start of formative phase of technologies according to different indicators in markets of first introduction



In most cases, the results of the indicators roughly converge in the moment of start of the formative phase, but the estimate can differ slightly according to different measures. The 'First embodiment' of technology presents generally the earliest date, while more applied indicators of "First application" and especially "First sequential commercialization" give later estimates as expected. The difference between the latter and the other indicators is particularly large in the case of wind power. However, this is explained by the stage of diffusion covered in the sample. Wind power refers to the commercialization of modern turbines in Denmark which started more intensively in the 1970s, whereas the technology was invented and first demonstrated almost a century before – but not commercialized in successive years, i.e. had only isolated applications.

The three selection criteria (theoretical foundation, data availability and consistency) explained in the methodological section are applied to select the preferred indicator. "First sequential commercialization" is the one that is closer to meet the three criteria. This indicator is coherent with the literature in the sense that start of commercialization is expected to intensify the production of more applied knowledge about the technology and the demand. The information on the year of beginning of sequential commercialization is generally available (the only exception was FCC in refineries for which there was no clear indication of that date). Finally, the indicator is consistent with the results of the other measures, especially when wind turbines are not considered because of the reasons explained above.

The consistency of "first sequential commercialization" is further tested by correlating the results with the average of the other two indicators. It was found that "First sequential commercialization" highly correlates with the average of the other two indicators (r=0.93). Therefore, first commercial application initiating successive new series of products (i.e., the beginning of consistent commercialization) is the preferred metric for the start of formative phase.

5. Results (II): end of formative phase

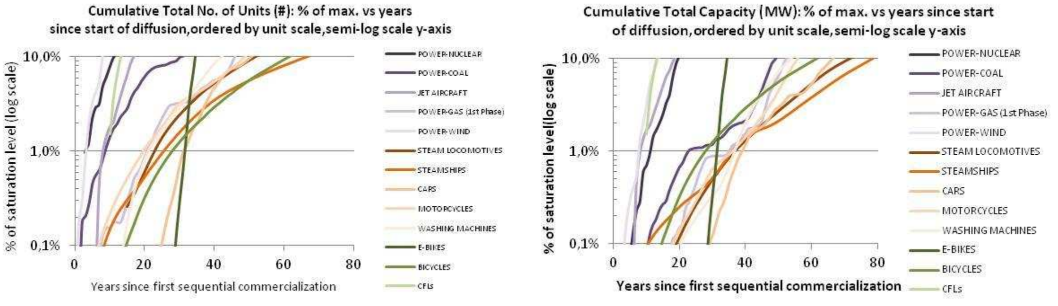
5.1. Alternative metrics

This section aims to develop a range of indicators in order to identify the end point of formative phases of innovations. These indicators are defined accordingly to the formative processes identified in the literature, particularly the need of technology experimentation and learning, market formation and institutional alignment.

5.1.1. indicator (a) numbers of units produced and capacity installed

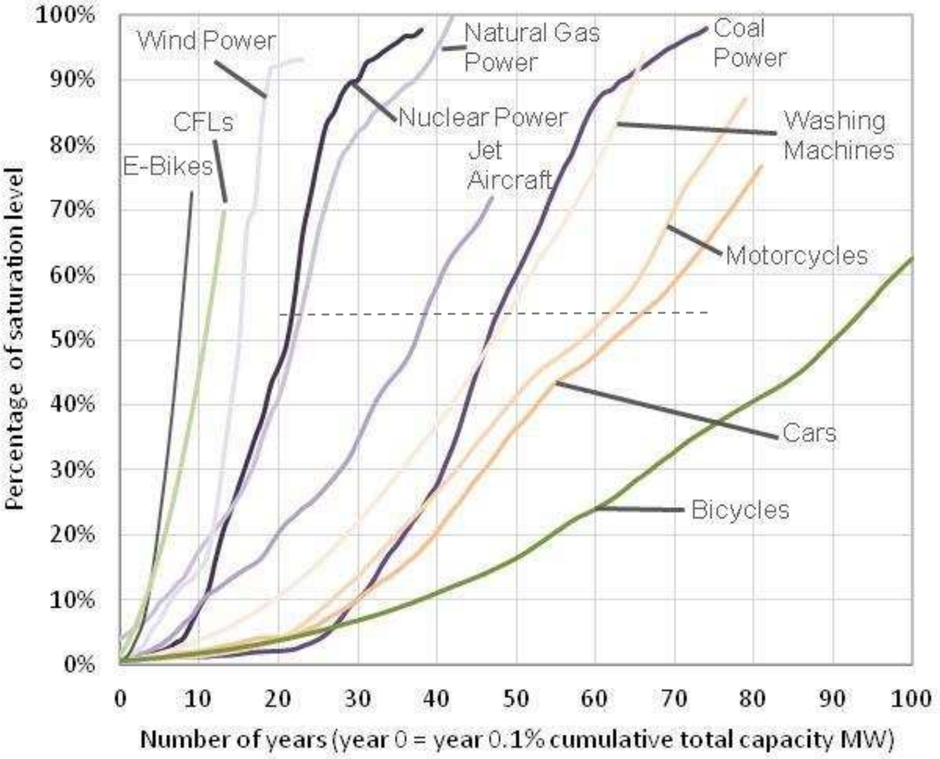
The first indicator of the end of formative phase is straightly connected to the number of installations of the innovation. In this perspective, the formative phase is the moment when conditions are set up (i.e., technical, market, institutional) to enable both technology and industry growth. This often comprises an intense period of experimentation and learning with many unit numbers (Hendry et al., 2010). The number of installed units grows rapidly, and the total installed capacity also expands (affected additionally by up-scaling). Two indicators are estimated to measure when the number of units reaches 10% of their eventual saturation level, and when the installed capacity reaches 10% of its eventual saturation level. 10% is used as the cut-off point to describe the end of the formative phase so it dovetails with Δt parameter widely used to describe the 'turnover time' or main growth phase of technologies from 10 - 90% of saturation (Grubler et al. 1999). As diffusion saturation levels are needed for both these indicators, they can only be estimated ex post, i.e., once the full diffusion lifecycle is observable.

Figure 2. Early diffusion of technologies during formative phases shown as growth of cumulative total number of units (left-hand) and cumulative total capacity (right-hand) since year of first sequential commercialization in initial markets, ordered by unit scale, semi-log scale y-axis *



* Graphs show actual data in percentage of estimated saturation levels (K). In purple are technologies larger than 1MW, in orange between 1MW and 1KW, and green for those less than 1KW.

Figure 3. Growth of cumulative total capacity since year when 0.1% of saturation is reached, in initial markets



The application of these indicators to measure the end point of formative phases of the energy technologies in the sample shows a couple of interesting results (Fig. 2-3). On the one hand, the data reveals that the formative phase usually comes to an end several decades after introduction in the market – following either first sequential commercialization as shown in Fig. 2 or 0.1% saturation like in Fig.3 (0.1% was chosen for the beginning of the plot to remove the visual skew of technologies before that point). The time needed to prepare the innovation for growth can be even larger (more than a century) in the case of more complex innovations, such as stationary steam engines, which diffusion had a great impact on the economy (Rosenberg & Trajtenberg, 2004). On the other hand, the end of the formative phase was much faster for ready substitute technologies such as CFLs (light green in the graph), as expected.

Therefore, the use of observable outcomes of technology diffusion –in terms of unit numbers or installed capacity – can give valuable information about the duration of the formative phase. Still, the ex post nature of the indicator limits its application in the case of emerging innovations.

5.1.2. indicator (b) up-scaling of unit size

The second indicator focuses on the growth dynamics of innovations at unit level. Many energy technologies have increased in size and energy conversion capacity over the past century. For instance the engine power of cars knew an enormous progress over time, passing from 10 horsepower of the Olds' Curved Dash to 20 hp of the model-T Ford, in the early 20th century, to 140 hp of the average new vehicle in the US (see more examples and data in Wilson, 2012 and Smil, 2008). Another example is jet aircrafts which up-scaled (in terms of engine capacity) through successive models of the Boeing 707 from 1958, then through successive models of the Boeing 747 from 1969, eventually saturating with the Airbus A380 introduced in 2007.[5] One of the main advantages of up-scaling at unit level is the capture of available scale economies in order to lead to reductions in average unit costs from the production of larger units. However this is often accompanied with important technical and system integration challenges that must be solved before it becomes possible to build units of a larger size. Hence, the formative period is needed to support structural processes – e.g. knowledge development, in particular of more applied nature – and networks and institutions development. In these terms, larger technologies that up-scaled intensively are expected to develop more slowly.

The indicator of the end of the formative phase, and the concomitant beginning of the up-scaling phase, is based like in the previous case in the Δt from 10-90%, but this time applied to unit size. This is normally estimated ex post but can also be forecasted from technical feasibility studies for new technologies. Figure 4 presents the evolution of the unit scale of power-plants and jet aircrafts.

The application of this indicator to our sample of technologies shows a couple of interesting results. Some technologies needed more than 20 years to reach 10% of maximum unit capacity after first sequential commercialization. In other cases, the formative phase came to an end much faster, such as: jet aircraft and nuclear energy. The experience with the propeller aviation would arguably have contributed to the rapid progress of the former, while political pressure explains the behavior of the latter – at the price of lock-in to inferior technology (Cowan, 1990). Yet a practical drawback of this indicator is the limited number of time series available for examining the evolution of the unit scale over time as many technologies – particularly energy end-use - do not upscale. In addition, more analyzes are needed to understand the impact of up-scaling challenges on the dynamics of technological development.

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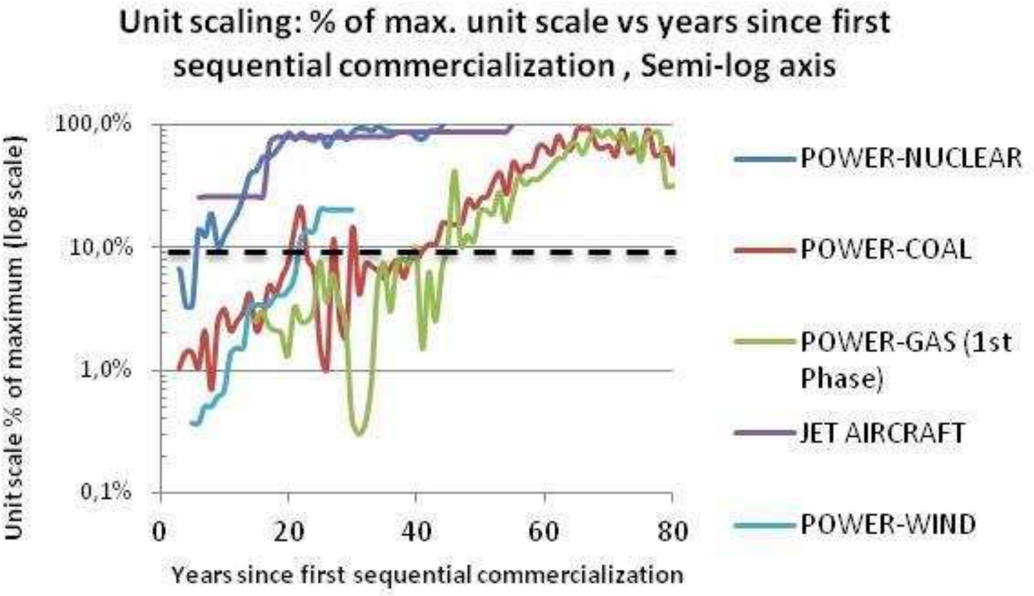
[5] As the first jet aircraft model (the Boeing 707-100) was already a medium capacity aircraft, the observed up-scaling in terms of maximum unit capacities introduced each year is compressed (see Figure 4).

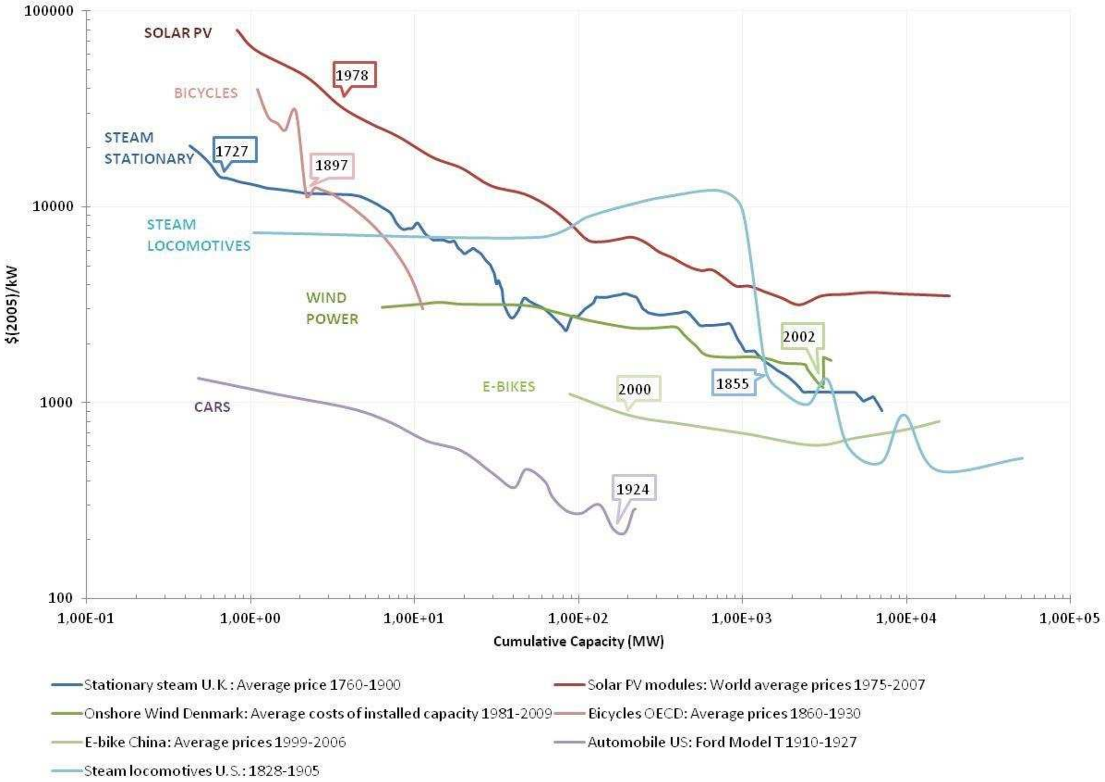
Figure 4. The end point of formative phase measured by the moment when innovation reaches 10% of maximum unit scale of new additions



5.1.3. indicator (c) average cost reduction

The third type of indicators measure directly the competitive preparedness of the innovation. The first prototypes are normally so crude and expensive that they can only find demand in very specific niches (Rosenberg, 1994; Kemp et al., 1998). Firms explore the first market opportunities to increase production and improve the quality of the innovation. Costs are expected to significantly decrease thanks to the development of knowledge and institutional capacity that is yielded with the increase of production (Arrow, 1962). In addition, the existence of spillovers, i.e., side effects triggered by knowledge creation, produce positive effects which further contributes to enhance the competitiveness of the emerging concept. The development of high pressure steam engines enlarged its application to ships and locomotives, contributing to further decrease the cost of the technology (Rosenberg & Trajtenberg, 2004). Therefore the learning-by-doing gained during the formative phase are likely to lead to major cost reductions, progressing faster towards to the end of that phase.

Figure 5. Learning curves of energy technologies in initial markets (year of max. cost reduction in text box)



Sources: [Stationary Steam UK] Kanefsky, 1979; Crafts, 2004; Fouquet, 2008; [Onshore Wind Denmark] Grubler et al., 2012; [E-Bikes China] Weinert, 2007; [Steam locomotives US] White, 1968; [Solar PV Modules world] Nemet, 2009; Grubler et al., 2012; [Bicycles OECD] Herlihy, 2004; Lloyd-Jones & Lewis, 2000; Perry, 1995; [Automobile US] Abernathy et al., 1974.

The use of learning curves is a promising tool for the identification of different stages along the innovation lifecycle (Fig. 5). Solar photovoltaic was added to the analysis for the sake of comparison with available cost dynamics of technologies of our sample. The graph shows the year when maximum relative cost reduction was registered, coinciding with the steepest slope of the learning curve (see text boxes). This year was reached later for technologies such as steam locomotives, wind power and cars. In contrast, steam stationary, bicycles and solar PV, saw their highest rates of cost reductions in the early stage of commercialization.

The use of indicators based on the highest relative cost reduction can inform about the end of formative phases. Still, it is important to understand to which extent the results are affected by the choice of technologies in the sample as well as the availability of data for early years. More work is needed on the metrics that analyze the dynamic of costs in order to gauge the status of technologies in the innovation process.

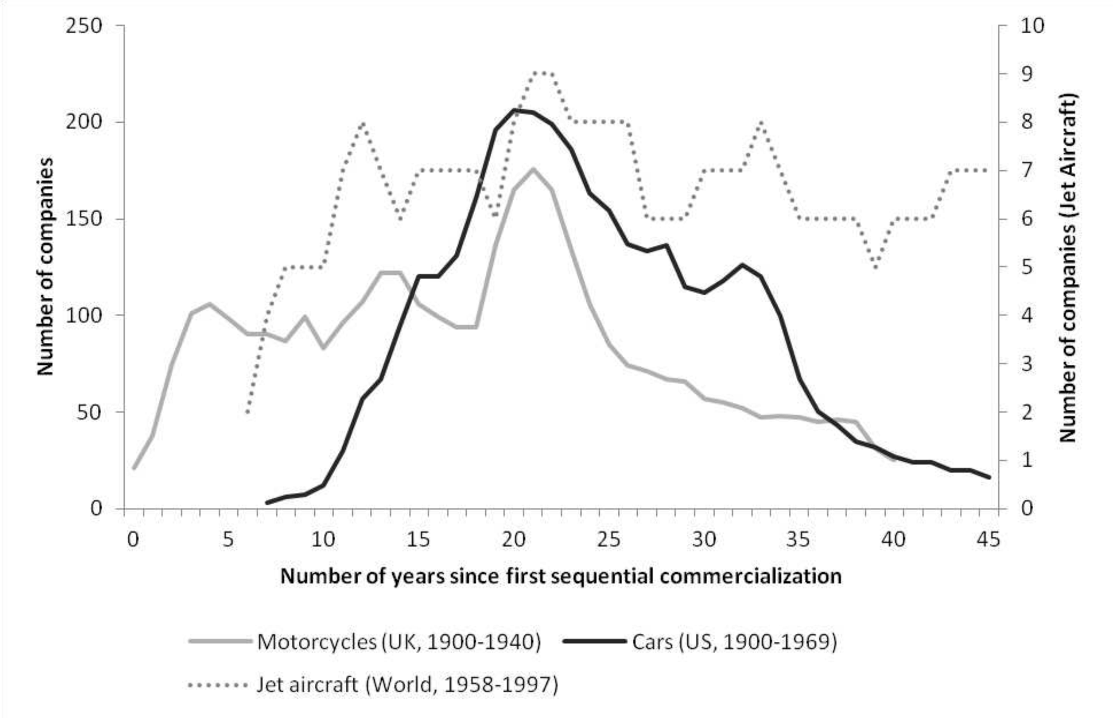
5.1.4. indicator (d) the patterns of entry/exit (market structure)

This indicator aims to identify the end of the formative phase through the analysis of changes in the market structure over time (Abernathy & Utterback, 1978; Klepper, 1997). The market structure reflects the dynamics occurring in the product lifecycle

(PLC). As Klepper (1997, p.149) pointed out: "the essence of the PLC is that initially the market grows rapidly, many firms enter, and product innovation is fundamental, and then as the industry evolves output growth slows, entry declines, the number of producers undergoes a shakeout, product innovation becomes less significant, and process innovation rises". These movements are often associated with knowledge development and knowledge spillovers among many competing innovators (Agarwal et al., 2010). Thus, formative phase is expected to end as market expectations become robust, lowering risk in scale investments, and once smaller firms leave the market. The formative phase is therefore likely to precede market concentration.

The end of formative phase may be found through the analysis of the demography of companies, particularly when there is a "shakeout" in the number of firms (Klepper, 1997). According to the literature, this occurs whenever the fall in the number of firms N is pronounced (at least 30% from the peak) and sustained (not rising subsequently to 90% of the peak, cf. Klepper, 1997:165).

Figure 6. The evolution of the number of companies since the start of diffusion of several technologies



Source: [Cars] Smith, 1968; [Motorcycles] Wezel, 2002; [Jet aircraft] Bonaccorsi & Giuri, 2003.

The number of automakers in the US is compared to the evolution of the industrial demography of motorcycles in the UK and jet aircrafts globally (Fig. 6). An interesting finding in this figure is that the number of companies tends to peak almost at the same point in the three industries here considered. In fact, the technologies converge in attaining an absolute maximum around two decades after first sequential introduction. This finding seems to confirm the literature on the evolution of the number of firms during the technology lifecycle (see a review of empirical studies in Peltoniemi, 2011).

5.1.5. indicator (e) user adoption

This indicator directly focuses on the development of demand as a metric for the end of the formative phase. The technology would passe to the next stage of the innovation process when it reaches a certain share of the expected market.

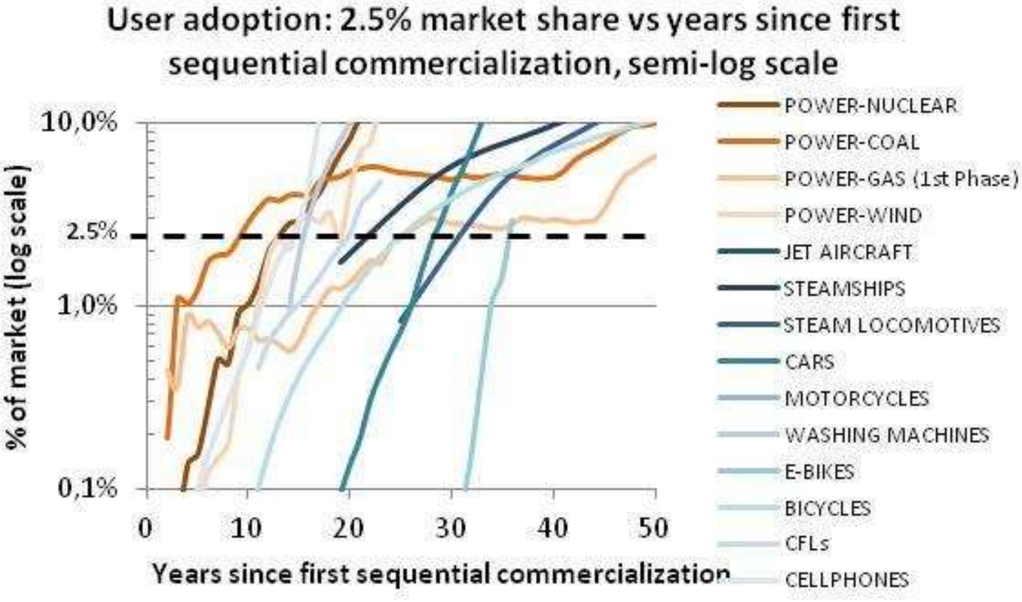
On the one hand the experimentation of the new technology by an increasing number of adopters generates “learning by using” that enhances innovation’s performances (Rosenberg, 1982). On the other hand it contributes to increase the level of knowledge that developers and designers have about the innovation through the feedbacks they receive from users (von Hippel, 2010).

Formative processes are concentrated during diffusion in the first group of consumers, the so-called “innovators” in Rogers’ sequential adoption model approximated as the first 2.5% of all adopters (Roger, 1995). The theory associates the first adopters to persons that are more willing to take risks. Potential market size is estimated using either targeted demand (in case of diffusion of new innovations, e.g. number of households for washing machines) or relative to market size of existing, competing technologies (in case of substitution technologies, e.g. sales of all light bulbs for CFLs). Table 5 presents the definition of potential market size for each technology. To construct the market share indicator, the actual market growth (e.g., units sold or capacity installed) is divided by the potential market size for the corresponding year. (Potential market sizes thus tend to grow as a technology diffuses). Figure 7 summarizes this market share indicator. The figure shows the number of years after commercialization that each technology needed to reach 2.5% of maximum potential adopters.

Table 5. Definition of the potential market of adopters for each technology (in core, unless mentioned otherwise)

TYPE	TECHNOLOGY	DEFINITION OF THE POTENTIAL MARKET	DATA SOURCE
Energy supply	Nuclear Power	Total installed capacity (in MW).	Platts
	Coal Power	Total number of power plants in use.	Platts
	Natural Gas Power	Total number of power plants in use.	Platts
	Wind Power	The Danish electricity generation mix.	Danish Energy Agency (2013)
	Steam Stationary	Total power provided by different sources in UK.	Fouquet (2008)
Energy end-Use	Jet Aircraft	Number of air carriers in service in the US.	US DoT (1960)
	Passenger Cars	Total number of households.	US Census Bureau
	CFLs	Sales of all light bulbs.	(various) McKinsey (2012), IEA (2006)
	Bicycles	Total population.	Angus Maddison online db
	E-Bikes	Total number of households.	Chinese Statistical Yearbooks
	Steamships	Total US merchant vessel fleet. (The prime movers considered are: sail, steam and motor. Unit: Gross tonnage).	Nakicenovic (1984)
	Steam Locomotives	Passenger traffic on railways (in millions passengers. Maximum number estimated ex post).	Mitchell (1992)
	Motorcycles	Total number of households in Great Britain.	UK DfT statistics, ONS
	Mobile phones	Total population.	United Nations (2011)
	Washing Machines	Total number of households.	US Census Bureau

Figure 7. End of formative phase coinciding with the adoption of the innovation by the "innovators" class (i.e., 2.5% of market share). Energy supply technologies in orange and energy end-use technologies in blue, ordered respectively by unit scale



Almost all technologies needed more than a decade after commercialization to reach 2.5% of adopters in their potential market (only coal power plants attained the threshold in less time, i.e. nine years). Two technologies took more than twenty-five years to attain that threshold: e-bikes (thirty-five) and steam stationary (eighty-five, not shown in the graph). The commercialization of e-bikes in China starts in the 1970s but diffusion only becomes significant since late 1990s. In the case of stationary steam engines, the diffusion was longer because it had to wait for the development of complementary technology to apply all its potential in different sectors of the economy (Rosenberg & Trajtenberg, 2004).

This metric based on a fraction of adoption is very versatile and intuitive. It suggests that the new technology is ending the formative phase since technology risks, uncertainties and issues were reduced to a point where it was ready for early adopters. The advantage of the market penetration approach is that it can be estimated ex ante as a new technology is diffusing to test whether the 2.5% threshold has been reached.

Other methods for inferring whether market take-off thresholds have been reached for a particular technology compare sales growth rates with market penetration rates (Tellis et al., 2003) or against annual sales (Golder & Tellis, 1997) or even annual net entry rates (Agarwal et al., 2002). Using a 2.5% of market potential indicator is comparatively simple, less data demanding, and applicable to a broad set of technologies.

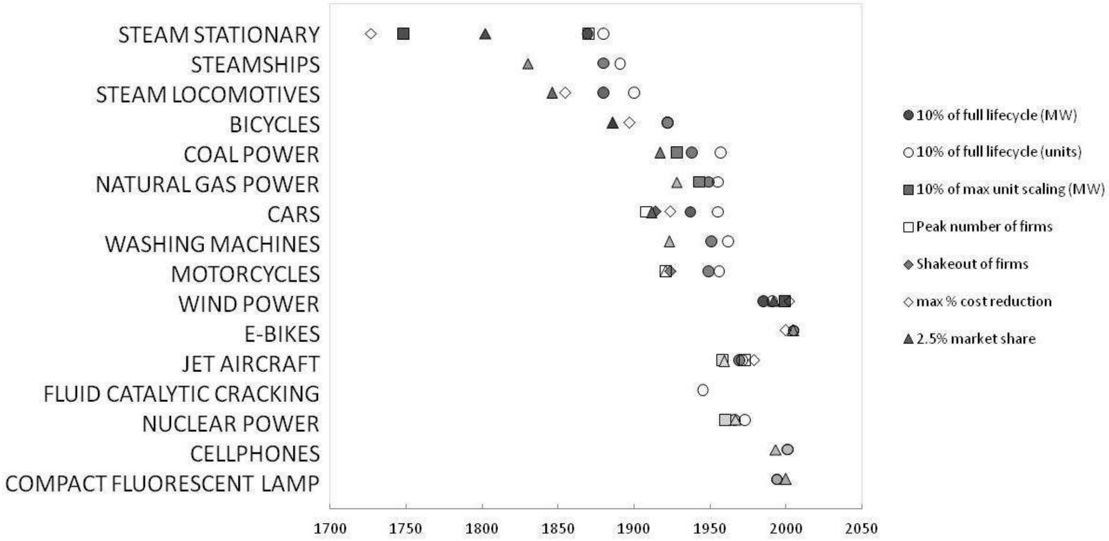
5.1.6. Additional indicators to be considered in the future

Three additional potential indicators are proposed that can provide good measures about the end of formative phases: patent applications; dominant design; and production scale up. They are explained with more detail in Appendix 4. However, they were not included in the analysis because of the lack of (reliable) data for a majority of technologies.

5.2. Comparing different indicators

At this point it is possible to compare the results of all indicators of the end of formative phases. Figure 8 presents all the estimates according to the different metrics used in this study. The end of the formative phase is more difficult to define as the plausible interval is broader than previously in the case of the starting point (see point 4.2). Stationary steam engines are a good example of that as different metrics give estimations for the end of the formative years which span from 1727 (maximum relative costs reduction) to 1880 (10% full lifecycle units), i.e. 150 years.

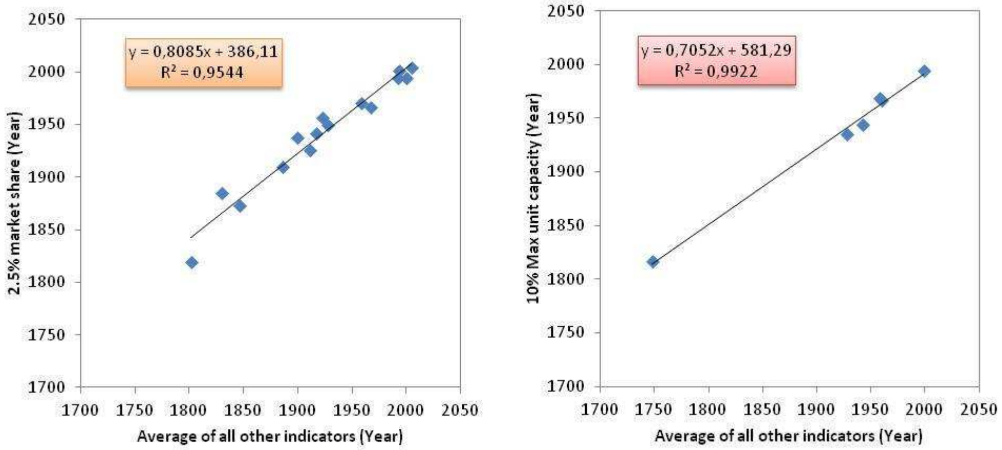
Figure 8. End of the formative phase of technologies according to different indicators, ordered historically (by year of invention)



Once again, the use of alternative metrics was unable to reveal an unequivocal date for the end of formative phases. Similarly to what was previously done for the starting point, a preferred metric is chosen that meets the three criteria set out earlier: coherence with the literature on formative phases; consistency (not to be an outlier); data available for potentially all technologies. In these terms, there were two metrics that emerged as possible good measures for the end of formative phases: 2.5% share of potential market and 10% of maximum unit capacity. As for the coherence with the literature, the former is a good indicator of early demand development, whereas the latter gives important information on the evolution of the supply – particularly for those technologies that up-scale intensively. Both measures give consistent and reasonable estimates without providing outliers (2.5% of market share gives slightly earlier estimates with a decade of difference at maximum). Finally, they can be used almost in all technologies. For instance, it was found data for all technologies (except refineries) in the case of 2.5% share of potential market. However, in the case of 10% of maximum unit capacity, data was found for technologies that up-scaled or increased significantly in unit scale which can only be identified ex post.

The indicators are in addition compared against the simple average of all other metrics (Fig.9). It was found that technology up-scaling presents the highest correlation with the average of all indicators; however, the metric based on user adoption seems more reliable as it shows a very close degree of correlation with much higher number of observations (i.e. fifteen against six).

Figure 9. Correlation between the average of all indicators of end of formative phase by technology and estimates of the year when “2.5% of market share” (left-hand) and “10% of maximum unit capacity” (right-hand) were reached, respectively



Therefore, 2.5% share of potential market (or maximum potential adopters) is the preferred metric of the end of formative phases. In the case of technologies for which data on market potential is very uncertain or cannot be calculated, an alternative metric could be 10% maximum unit scaling (particularly if the technology scales rapidly). Table 6 synthesizes all indicators and measures that were presented above. More details about the data can be found in Appendix 2.

The use of a metric which focus directly on demand gives good indications about the way that a market perceives the maturity/readiness of a new technology. At last, the success (failure) of an innovation depends on the existence (or not) of a market for it. Thus, an indicator that tracks market progress is of great interest to situate the new technology in the formative phase. In addition, using metrics that can be projected ex ante, such as a fraction of the potential market, allows the estimation of formative phase lengths and diffusion rates for very recent innovations (for which there is no forecasted saturation).

Table 6. Summary of proposed indicators to define end point of formative phase

Indicator	Type	Indicator	Metric	Link to Formative Phase Processes	Rationale
a)	**Technology Supply Indicators**	Numbers of Units Produced and Capacity Installed	10% maximum of cumulative unit numbers (identified ex post) 10% maximum of cumulative installed capacity (identified ex post)	experimentation & learning materialization (first investments in production)	transition from experimentation with many unit numbers to mature market growth and production scale up
b)		Up-scaling of unit size	10% maximum unit capacity (identified ex post) 10% maximum average unit capacity (identified ex post)	knowledge development institutional alignment (legitimation) experimentation resource mobilization	knowledge and institutions necessary to support economies of scale are in place
c)	**Market Indicators**	Average cost reduction	highest relative cost reduction	knowledge development legitimation knowledge spillovers (across sectors & economies of scope) market formation	links to learning economies (Arrow, 1962). Cost is reduced to competitive levels thanks to the development of knowledge and institutional capacity during the formative phase that enable learning economies (i.e., formative phase precedes major cost reduction)
d)		Market structure	demography: the fall in the number of firms N ("shakeout") is pronounced (at least 30% from the peak) and sustained (not rising subsequently to 90% of the peak, cf. Klepper, 1997:165)	knowledge development (among many competing innovators prior to scale up)	links to market structure over innovation lifecycle (Abernathy & Utterback, 1978). Formative phase ends as market expectations become robust lowering risk in scale investments and smaller firms have left the market (i.e., formative phase precedes market concentration)
e)		User adoption	diffusion reaches 2.5% of market potential or of maximum number of adopters ("innovators" cf. Rogers, 1995)	knowledge development (feedbacks from users to developers / designers) institutional alignment	reduction in the perceived technological uncertainty/risk. Learning by using enhances innovation's performance (Rosenberg, 1982)

6. Results (III): duration of formative phase

6.1. Comparison of all formative phase lengths given different metrics

This last part analyzes the duration of the formative phase of innovations following the identification of starting and ending points in the previous section. The mean length of formative phase for all technologies is shown in Table 7.

The table exhibits both the central and longest estimate of the duration of formative phases by technology. The results show that formative phases are long, lasting several decades in average. It can even take centuries like in the case of general purpose technologies such as stationary steam engines, or other type of innovations such as wind power and e-bikes – in these latter cases, the unusually long interval stems from the fact that those technologies started to be deployed only decades after innovation and first commercialization.

The results also show no clear difference of formative duration between energy supply and end-use technologies. The reason why innovations are distinguished in this way is because there can be differences in the processes involved in their formation – e.g. entrepreneurial experimentation and market formation in larger size technologies in energy sector versus consumer goods - which could have affected the formative phase lengths.

Table 7. Summary of formative phase lengths: central and longest estimates. Technologies ordered historically (by year of invention)

Technologies	Central	Longest estimate
Stationary Steam	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
Fluid Catalytic Cracking (In Refineries)	4	5
Nuclear Power	13	22
Cellphones	14	55
Compact Fluorescent Lamp	20	27

The formative phases of all technologies in the sample are further compared graphically through the procedure that is presented in Fig. 10 with the example of passenger cars in the US. For each technology, the results from all available indicators are contrasted in order to find the earliest (minimum or the leftmost dot) estimate of the starting point of formative phase, as well as the latest (maximum or the rightmost cross) date of the ending point. These two estimates set the boundary of the largest possible interval for the formative phase (light blue bar) expressing the uncertainties about the different estimations given by the indicators. Additionally, the central estimate is defined by comparing the preferred metrics of start and end of formative phases. The first sequential commercialization sets the lower-bound of the dark blue bar whereas 2.5% market share the upper-bound, and thus, the bar corresponds to the best estimate of the formative phase length. This procedure is followed for all technologies and the blue bars are then put side by side in Fig.11.

Figure 10. Illustration of the identification procedure of formative phase lengths and uncertainty ranges with the example of passenger cars in the US

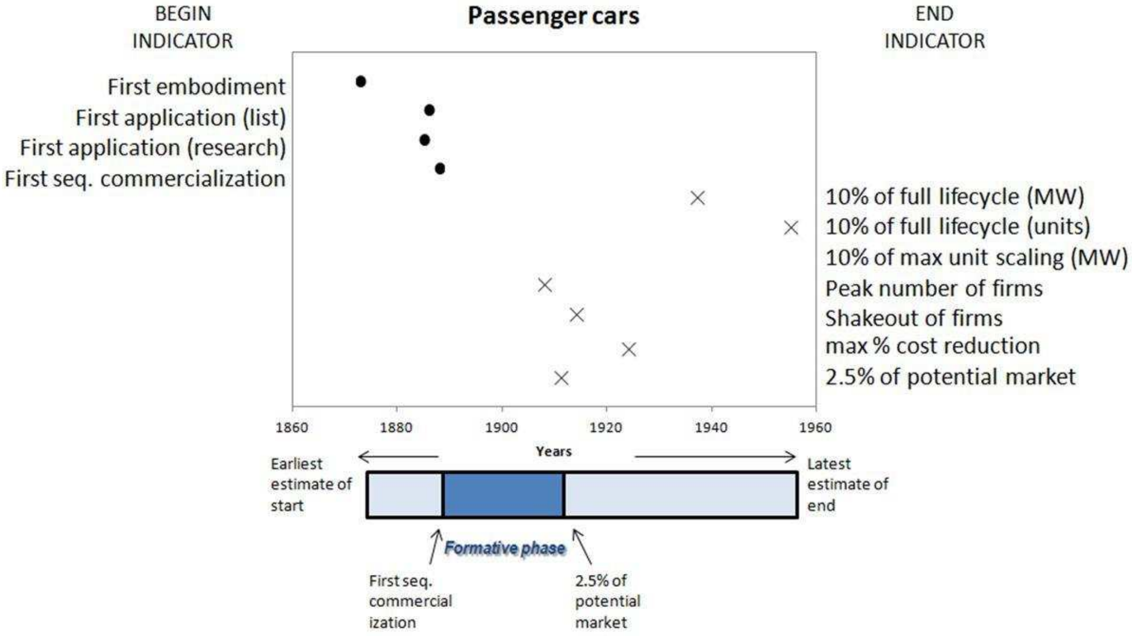
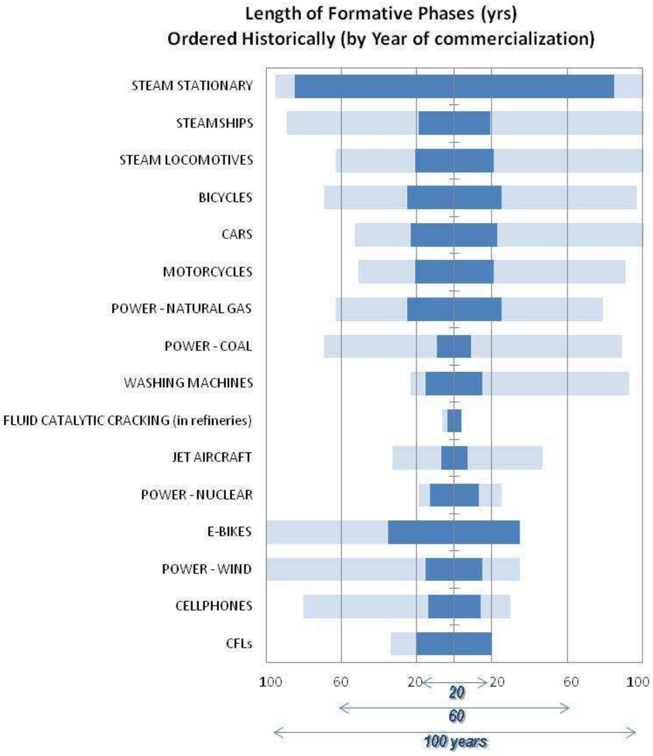


Figure 11. Formative phase lengths by technology ordered historically (by year of commercialization), in years

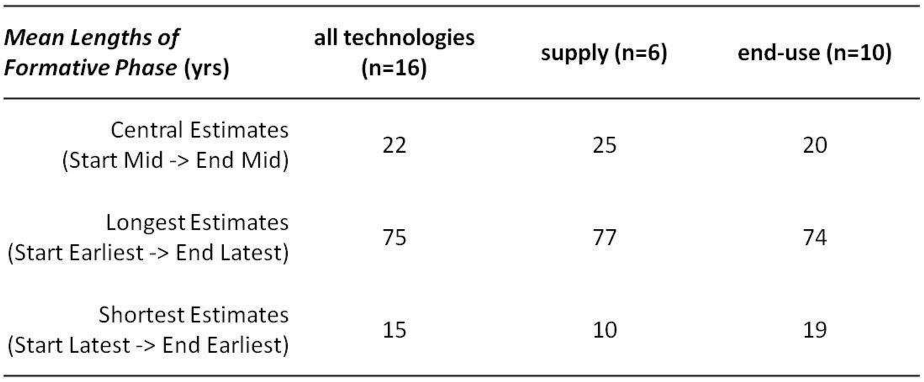


Note: The origin of the graph is set equal to the midpoint of the dark blue bar. If the extremities of that bar touch the line of “20” on the left and “20” on the right like for CFLs, it signifies that the best estimate of the formative phase for that technology is 20 years.

Two main insights can be derived from the analysis of Fig.11. The first important finding concerns the progress of formative phase lengths over time. Even though stationary steam engines passed through a long formative period in the 18th century, there is no clear trend indicating development acceleration for modern technologies. The second finding is that it is more difficult to identify the beginning and (especially) the final point in the case of long formative periods, especially of older technologies. In fact, a wider dispersion of values was found in technologies that passed through a long development process (i.e., larger bars) such as steam technologies, cars or natural gas power plants.

Table 8 displays the formation lengths by type of technology and nature of estimate. End-use energy technologies present more rapid (i.e. low values) “central” and “longest” estimates, whereas energy supply technologies have quicker “shortest” durations. It is therefore unclear the effect of different types of technologies in these values. Several other variables may affect the duration of formative phases, as well. In particular, the effect of innovation’s characteristics which is further investigated in section 6.2.

Table 8. Mean lengths of formative phase for all technologies and by type, in years



Mean Lengths of Formative Phase (yrs)	all technologies (n=16)	supply (n=6)	end-use (n=10)
Central Estimates (Start Mid -> End Mid)	22	25	20
Longest Estimates (Start Earliest -> End Latest)	75	77	74
Shortest Estimates (Start Latest -> End Earliest)	15	10	19

6.2. Comparative analysis of technology characteristics and formative phases using different metrics

The formative lengths calculated above are now related to the type of innovations to understand the effect of technology characteristics in short or long formative phases. The literature review revealed several technology features that influence the diffusion duration, such as: market potential, relative advantage (in terms of efficiency and costs), and complexity (Grubler, 2012, 1998; Rogers, 1995). Therefore the comparison of the formative time spans of different technologies allows testing the effect of these factors in the extension of these early periods.

First, more radical innovations are expected to take longer formative periods. In contrast with substitution innovations, which benefit from the structure inherited from the old technology, radical innovations need to set up the structure of the new technological innovation system and fulfill basic processes, including institutional alignment (Hekkert et al., 2007).

Second, high unit scale technologies which need to intensively up-scale before they are ready for mass deployment may take longer formative periods. The mobilization of a larger amount of resources (e.g. human, financial, and technical) might be necessary to build up units of a higher scale. On the other hand this presupposes an advanced state of knowledge as well as several positive experimentations. The latter would raise legitimate expectations about the benefits of technology up-scaling, influencing the direction of search towards the construction of units of a larger size – confirming scaling as a common "heuristic" of production according to Winter (2008).

Third, the size of the market can be an important constraint in the speed of technology growth as technologies which have higher impact in average take longer to diffuse (Wilson, 2009, 2012). Similarly, innovations that have a larger potential may take longer to form and prepare for commercialization.

The remainder of this section analyzes the effect of factors such as technology disruptiveness, unit scale, up-scaling dynamics, and market potential, on formative phase lengths.

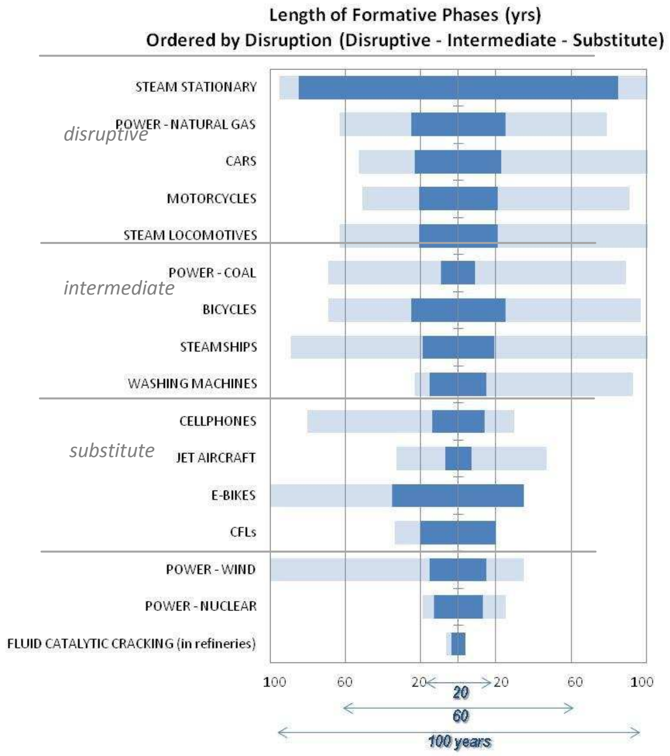
6.2.1. Relationship between formative phase length and technology disruptiveness

The effect of technology disruption in duration of the formative phase is analyzed in Figure 12. Technologies are assigned to one of the categories (disruptive, intermediate, substitute) based on the extent to which their diffusion depends on novel markets and practices, rely on new infrastructures, etc. Overall, the analysis to the data gives mixed results.

The formative phase is relatively more rapid in the case of substitute technologies for which the ancillary infrastructure (airports, electricity grids, refueling stations) is already in place in the beginning of diffusion (e.g., the adoption of fluid catalytic cracking in refineries) than for more radical innovations.

More complex and disruptive technologies, such as stationary steam engines, need more time to develop knowledge, infrastructures and institutional capacity to pass to the next stages of up-scaling and growth. E-bikes also present an exceptional long formative phase, but in this case the reason lays on the period of time that mediated the invention and first applications of the technology and the beginning of adoption as a serious alternative mode of transportation in China. Similarly, the uncertainties on the start of the formative phase of wind power stems from the fact that diffusion in Denmark takes off many decades after innovation in 19th century. In the other cases the length of formative phases slightly increases with disruptiveness, especially when the analysis includes the uncertainty in the measurements (light blue bar).

Figure 12. Formative phase lengths by disruptiveness, in years

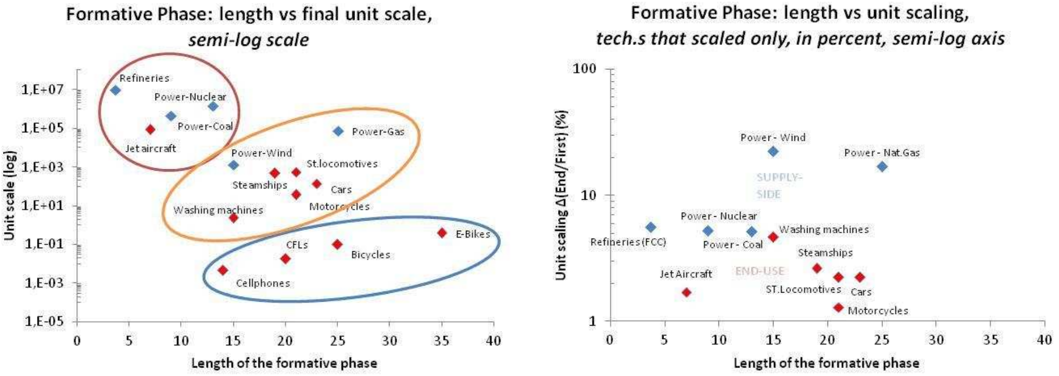


Note: The origin of the graph is set equal to the midpoint of the dark blue bar. If the extremities of that bar touch the line of “20” on the left and “20” on the right like for CFLs, it signifies that the best estimate of the formative phase for that technology is 20 years.

6.2.2. Relation between formative phase length and technology up-scaling

The relation between technology scale and duration of formative periods is analyzed in Fig. 13 (left-hand). It is possible to distinguish three groups of technologies in the graph. The first group is composed essentially of smaller and granular technologies (e.g. cellphones, CFLs, bicycles) and presents relative long formative periods with wide dispersion of values. The second group includes power technologies as well as end-use innovations in transport (e.g. steamships, steam locomotives, cars) and household appliances (e.g. washing machines). This group contains technologies of a higher unit scale that passed through a similar period of formation (15-25 years). The third group is composed of very large technologies, such as nuclear power plants or refineries. It distinguishes itself from the other two groups by presenting a fast emergence (i.e. shorter duration formative phase), which was unexpected considering the complexity, large amount of resources (namely financial) and risk, that were involved in the deployment of those innovations.

Figure 13. Comparing formative phase lengths with technology unit scale (left-hand) and unit scaling (right-hand)*



Note: Red diamonds represent energy end-use technologies and blue diamonds energy supply technologies. Formative lengths correspond to the central estimates using the preferred metrics, i.e. the year of first sequential commercialization and the year of 2.5% share of potential market for start and end points, respectively.

High unit scale technologies with short formative phases, such as FCC refineries, nuclear power and jet aircraft, were all heavily influenced by exogenous disruption to innovation environment by World War II (e.g., strong demand-pull, price insensitive military, sharing of intellectual property). This suggests that formative phase can be compressed or accelerated in extreme demand environments (with low sensitivity to risk) with simultaneously demand “pull” and supply “push” efforts.

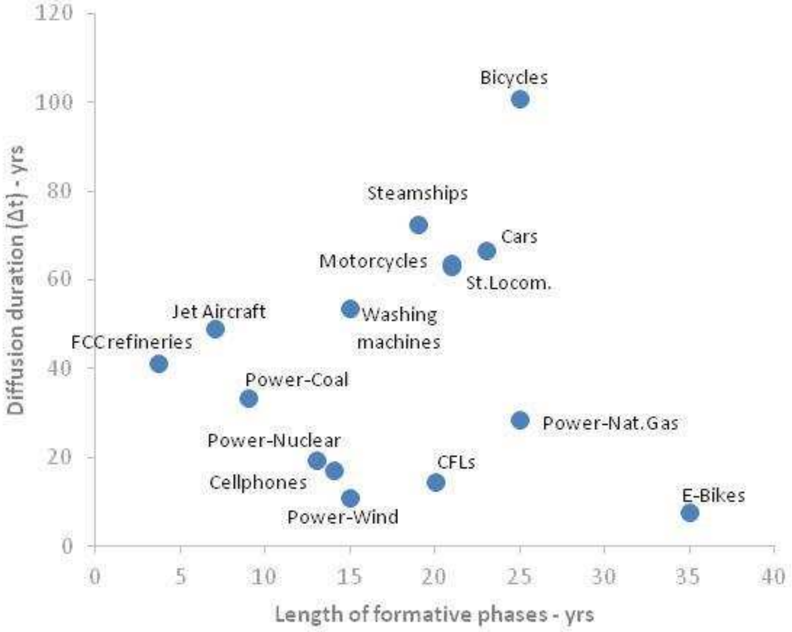
The effect of unit scaling dynamics of technologies in the formative phase lengths is analyzed in Fig. 13 (right-hand). Only innovations that scaled up over their entire technology lifecycle are shown in the graph. In theory, technologies which scaled-up intensively may present longer formative phases in order to prepare for the technological and economical challenges of up-scaling, other things equal. However, this relation is only verified for energy supply innovations for which formative phase tends to lengthen with unit scaling. The history of wind power, which up-scaled significantly, gives a good illustration of this with the success of the more patient Danish strategy that preferred to develop smaller wind turbines in the 1970s and 1980s, at the same time that other countries like the US and Germany tried to build up large (MW) scale turbines what ultimately turned out to be a failure (Garud & Karnøe, 2003; Hendry & Harbonne, 2011; Grubler et al., 2012).

The formative phase of end-use technologies seems less affected by the extent of up-scaling of unit size. A plausible explanation is that mass commercialization followed almost immediately the formative phase and technology up-scaled continuously over time (e.g. cars, washing machines), rather than large jumps to capture scale economies at unit scale in the beginning.

6.2.3. Relation between formative phase length and overall diffusion

The relation between formative lengths and the duration of the full technology lifecycle is presented in Fig.14. The diffusion durations (delta t or Δt) were extracted from earlier studies which analyzed the diffusion of these technologies with logistic growth functions (see Bento, 2013 and Wilson, 2012). Surprisingly, almost no correlation was found between the length of the formative phase and the duration of diffusion. Yet it is possible to observe that several end-use technologies with long formative phases are associated with elongated diffusion processes (e.g. washing machines, steam locomotives, cars, steamships and bicycles).

Figure 14. The relation between formative lengths and technology diffusion



Note: Stationary steam is not shown in the graph because it is clearly an outlier.

6.2.4. Synthesis

Table 9 summarizes the determinants of the formative phase according to the literature review and the main findings from the empirical analysis presented above. The effect of a number of factors (e.g. history, type of technologies) is still unclear and needs further research. Similarly the simultaneous impact of several variables, such as unit scaling in the case of energy supply technologies or long diffusion processes in the case of end-use technologies, should be more explored in order to get a better understanding about the formative requirements according to different innovation characteristics. However, the evidence presented is consistent with the assumption that less complex and disruptive technologies tend to be associated with shorter formative lengths.

Table 9. Synthesis table about the effect of several variables on formative lengths: theoretical hypothesis and empirical evidence

Factors	**Hypothesis** Formative phase tends to take **longer** *with technologies that are…(see* literature review)	**Empirical results**
History	older	.
Disruption	more disruptive and radical	+
End-use vs. Supply	(undetermined)	.
Unit scale	larger	-
Up-scaling	highly scalable	. (supply only +)
Diffusion duration	related to long time diffusions	. (end-use only +)

Hypothesis is confirmed by data: ++ strongly; + generally; "." no clear correlation; - rather the opposite effect; -- strong evidence of the opposite effect.

Statistical tests on the significance of differences in mean formative lengths of technologies were performed by determinant (see results in Appendix 5). These tests confirm that formative phases of disruptive technologies are significantly longer than those of substitutes (based on our subjective assignation of disruptiveness). The formative phase durations of technologies (energy supply or end-use) that penetrate slowly in the market were also longer. Conversely, the formative phase of technologies that strongly up-scaled were shorter. (The particular case of rapid up-scaling during war time is discussed in section 6.2.3). Finally, formative phase durations have declined after World War II for the set of technologies in the sample.

7. Discussion and conclusions

The objective of this research was to develop an operational definition of the duration of formative phases to enable comparative technology analysis. For that, it was identified a set of processes that innovations need to perform in order to evolve in the early stages, which were then linked to a group of indicators defining the start and end of the formative phase. The innovation and transitions' literature was used to reveal the main functions of the innovation system associated with technology formation. A database was constructed which systematically compile many information about the formative phase of a sample of energy technologies. This work departs from the assumption that a better understanding of the dynamics occurring in the formative phase enables the design of more effective policies to accelerate the diffusion of sustainable innovations.

The formative phase designates the early stage of development (i.e., between the first application or commercialization and the up-scaling phase) that sets up the conditions for the technology to emerge and penetrate into the market. This phase is particularly relevant in the diffusion of energy innovations because it prepares the technology for up-scaling and widespread growth. Innovations pass through a long time period of development and experimentation that is marked by significant uncertainties on designs, markets and uses.

The literature review showed that innovation progresses in early years thanks to a combination of scientific and technological advances enabled by formal research and experimentation, as well as market developments in terms of demonstration projects or niche markets enabling learning-by-use and adaptation to the needs of demand. Hence, the year of first sequential commercialization was chosen as the preferred mark of the beginning of the formative phase. At that point, the original concept is sufficiently consolidated to enter into a new stage of development that will prepare the innovation for market growth.

The year when diffusion reaches 2.5% market potential was defined as the best estimate for the ending point of the formative phase. This milestone coincides with the adoption of the new technology by the first group of "innovators" which is often determinant to improve performances and reduce costs. These two metrics are good proxies of the formative phase because they can inform about the progresses made on both technology development and market formation. Alternatively, it can be used 10% maximum unit capacity as a second-best proxy of the end-point of the formative phase and beginning of the next (up-scaling) stage.

Two main features emerge from the application of the indicators of start and end of formative phases. On the one hand, the metrics that evaluate market deployment like first commercialization are important indicators about the status of development of the innovation by showing its readiness to fulfill the expectations of the early demand. On the other hand, the dispersion of the indicators is much more significant in the case of the ending point than of the start (Fig. 1 and Fig. 8). Therefore, the end of the formative phase should be identified with even more caution and taking into account all the information available concerning the evolution of both technology and demand.

The formative phase duration was found by comparing the preferred metrics of start to end of formative phase. It was shown that formative phases are long, rarely taken less than a decade, and are influenced by the disruptiveness of the new technology. That is, the formative phase is relatively slower in the case of disruptive technologies for which the ancillary infrastructure is absent in the beginning of diffusion (e.g., steam engines, cars). In addition, the results suggest that formative phases become longer with the extent of unit scaling in the case of supply side technologies, which may be explained by the need of more inputs (e.g. knowledge, technical, financial, organizational) in order to start building larger unit sizes. However, there is also evidence of exceptionally large scale innovations that passed through a short formative period. It was the case of FCC refineries, nuclear, and jet aircraft, which were influenced by exogenous disruption to innovation environment by World War II. This case suggests that the formative phase can be accelerated in extreme contexts with demand "pull" and supply "push" together.

The duration of formative phases was also compared to the speed of overall diffusion. It was found little correlation between formative lengths and diffusion time-span. Still, it was observed that long formative phases were associated with several lengthy diffusion processes in the case of end-use technologies. Furthermore, the results point to the effect of disruptiveness, general purpose and slow diffusion processes, in elongating formative periods.

More analyzes are needed to confirm the effect in formative lengths of factors, such as market extent of the innovations and industrial organization (e.g. competition degree, regulation, standards). An interesting hypothesis to test in further research is whether short formative phases are more likely to be associated to lock-in to inferior designs. That is, the dominant design is "agreed" too rapidly as scale-up of manufacturing needs a standardized technology like in the case of the pressurized water reactor in the nuclear industry.

Supplementary material

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

Appendix 1. Start of formative phase: Data synthesis

Formative Phase	INDICATOR	UNITS	STEAM STATIONARY	STEAMSHIPS	STEAM LOCOMOTIVES	BICYCLES	POWER - WIND	POWER - COAL	MOTORCYCLES	CARS	E-BIKES	POWER - NATURAL GAS	WASHING MACHINES	CFLs	FLUID CATALYTIC CRACKING (in refineries)	JET AIRCRAFT	POWER - NUCLEAR	CELLPHONES
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: Innovation lists: Mensch (1978), Haustein & Neuwirth (1982), Van Duijn (1983), Silverberg & Verspagen (2003). Steam stationary: Von Tunzelmann (1978), Usher A.P. (1954), Kanefsky & Robey (1980), Kanefsky (1979). Steamships: U.S. Census Office (1978); Fletcher (2012), Wikipedia, http://en.wikipedia.org/wiki/Steamship#cite_note-2 (accessed in 30/11/2012). Nakicenovic (1984). Steam locomotives: White (1868), Simmons (1997), White (1968), Mitchell (1992). Bicycles: Herlihy (2004), Perry (1995). Power-Wind: Gipe (1995), Patel (2011), Vestergaard, Brandstrup & Goddard (2004), WIPO (2010), Danish Energy Agency (2012), Power-Coal: Termuehlen & Emsperger (2003). Motorcycles: Wezel (2002). Cars: Abernathy & Clark (1985), Abernathy, Clark & Kantrow (1983), Abernathy & Wayne (1974), Suarez & Utterback (1995), Argyres N., Bigelow L., Nickerson J.A. (2011). E-Bikes: Weinert. Power-Natural Gas: Mowery & Rosenberg (1989), http://web.mit.edu/aeroastro/labs/gtl/early_GT_history.html (accessed 12 December 2012). Washing machines: Maxwell (2009), Cowan (1997). CFLs: IEA (2006, Vorsatz et al. (1997). FCC refineries: Enos (1962). Jet Aircraft: Bonaccorsi & Giuri (2003), Mowery & Rosenberg (1989), U.S. Department of Transportation (1960). Power-Nuclear: IAEA (2012), Nuclear Energy Institute (2011). Cellphones: Encyclopaedia Britannica (1992), National Science Foundation (2012). For more details on the data on the full lifecycle of technologies, see Bento (2013).

Appendix 2. End of formative phase: Data synthesis

Formative Phase	INDICATOR	UNITS	STEAM STATIONARY	STEAMSHIPS	STEAM LOCOMOTIVES	BICYCLES	POWER - WIND	POWER - COAL	MOTORCYCLES	CARS	E-BIKES	POWER - NATURAL GAS	WASHING MACHINES	CFLs	FLUID CATALYTIC CRACKING (in refineries)	JET AIRCRAFT	POW NUC
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	19
		Year of 10%K (cumul.MW)	1880	1890	1900	1922	1991	1957	1956	1955	2005	1976	1962	1994	1945	1971	19
	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	19
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
		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
		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
	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
		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
		% (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
		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	PV
	User adoption	Year of 2.5% potential market	1802	1830	1846	1886	1992	1917	1921	1911	2005	1928	1923	2000	n/d	1959	19
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
		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
	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
		Year of highest growth	1720	1820	1850	1862	1978	1938	1901	1946	1998	1945	1921	1991	1956	1959	19
		%	838%	3417%	560%	7000%	450%	267%	194%	328%	263%	275%	132%	42%	7%	863%	70
	Dominant design	Year	1764	1807	1829	1884	1957	1920	1901	1909	1946	1939	1937	1985	1942	1958	19
		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	L (P
	User adoption	Lead user? (Yes/No)	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Y
	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	19

Legend: n/d (no data), not applicable (n/a)
Sources: (see on sources of Appendix 1).

Appendix 3. Additional potential indicators that can be used to track the start of formative phases

The investment in research activities is necessary in order to develop knowledge that augment the probability of discovering new ideas and innovations. This is particularly the case of fundamental investigation – essential for the fulfillment of the function of the innovation system related to the creation of formal knowledge - which is very risky but has important externalities and spillovers to the economy, therefore relying almost exclusively on public funding (Jaffe, 2005). Hence, the first peak in public R&D expenses can be seen as a turning point after which some signs appear of the start of a more applied phase of technology testing and experimentation. At that point, the focus of innovative activities tends to shift from knowledge creation to the manufacture of the first prototypes and learning from the production of first units. In these terms, it is a good indicator of the beginning of the formative phase.

Nevertheless, the expenses in public R&D may be subject to other influences, such as general public budget cuts, which are not directly connected with the development of the innovation (Kleinknech et al., 2002). In addition, the phase of experimentation and formation of the technology may not follow immediately the first peak in R&D expenses. It is possible that some time lag exists between the research and the more applied formation of the technology because the conditions are not yet set to build up demonstration prototypes or to produce the first units. This indicator was not included in the analysis also given the difficulties to find data on public spending in R&D for all technologies, especially for the older ones like steam engines in the 19th century.

Appendix 4. Additional potential indicators to be considered in future analysis

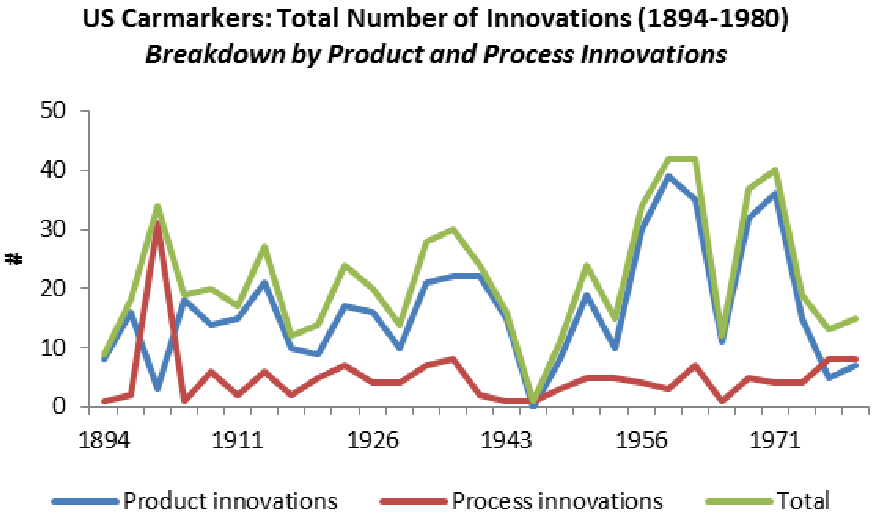
- indicator (f) patent applications

Patents are a well-known (intermediate) output measure of innovation mostly derived from R&D-based activities (Kleinknecht et al., 2002). It is an important source of information about the state of knowledge in a certain domain or technology. Yet there are a number of questions about the exactitude of patent figures because not every innovation is patentable and it can be used strategically by firms to prevent a competitor to use a certain technology (Kleinknecht et al., 2002). Nevertheless, patent applications give significant information about institutional capacity building and knowledge accumulation which improves the technological capacity of the innovation system that contributes to accelerate the development and adoption of new technologies (Bergek et al., 2008a; Cohen & Levinthal, 1989).

Hence, the end of the formative phase may be approached by the year of first peak in patent applications. Patent peaks are associated with transitions in knowledge generation activities towards a more applied innovation, guided by market prospects, with a more incremental nature (Grubb, 2004; Murphy & Edwards, 2003). As a complementary metric it is taken the year of start of the second period of sustained growth (i.e., maintained at least in the three following years) of the number of patents.

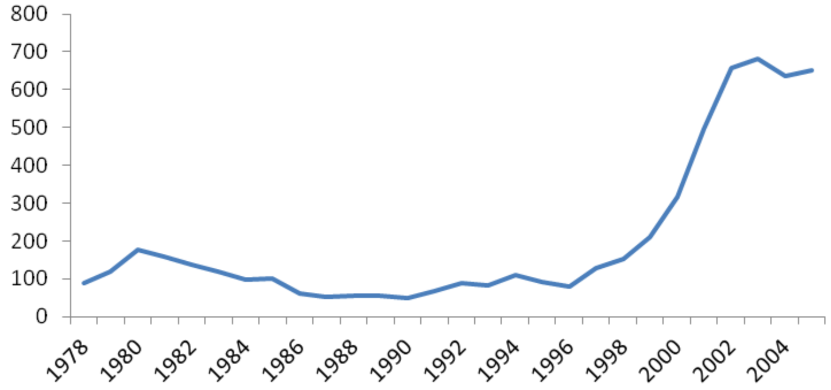
Enough data on patent activities were only found for two technologies: automobiles in the US (Fig.15) and wind energy globally (Fig.16). Interestingly, the year of start of the second wave of patenting is in both cases coincident with important changes that occurred in the innovation context. In 1914 there was a major "shakeout" in the number of carmakers in the US following the introduction of the Ford Model T in 1908. In the case of wind, this moment (1996) is close to the introduction of larger size (500 kW) turbines which had a great impact on the diffusion of wind power (Spliid, 2013). More analyzes are needed in the future to other technologies in order to share light about the relation between patent activity and other indicators of the end of the formative phase.

Figure 15. Number of patents in the automobile sector in the US (initial market)



Source: Abernathy, Clark & Kantrow, 1983: Appendix D, pp.150-179.

Figure 16. Number of patent applications for wind energy worldwide (1978-2010)



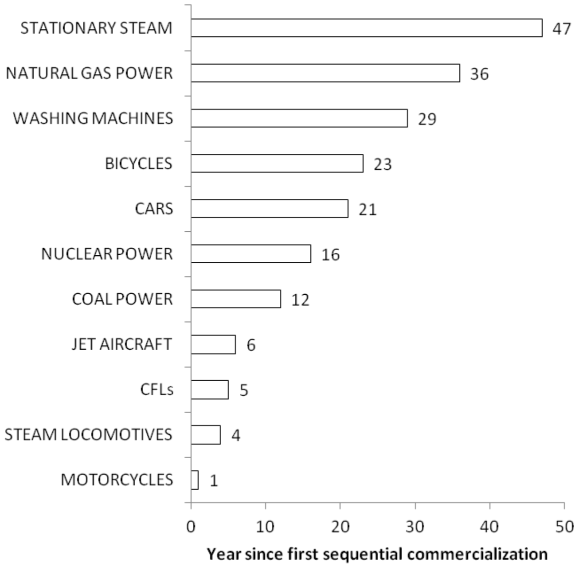
Source: WIPO, 2010.

- indicator (g) dominant design

The emergence of a dominant design is a turning point in the early years of a new technology and marks definitively the innovation lifecycle. It has such a powerful impact that switches the focus of R&D from product innovations to process innovation. Abernathy & Utterback (1978, p.46) pointed out: "…dominant design has the effect of enforcing standardization so that production economies can be sought. Then effective competition begins to take place on the basis of cost as well as of product performance." The authors further characterize those technologies as the ones that lift fundamental technical constraints, expand the market for the product and enhance the value of potential innovations.

The standardization into a dominant design occurs generally after a period of development and experimentation, enabling the creation of variety and alternative designs (variation) (Saviotti, 1996; Dosi, 1982). The selection (retention) of a particular standard enables significant knowledge spillovers by systematic exploitation of economies of scope, meaning that the fundamental trade-offs between technical and service characteristics were already settled (Murmann & Frenken, 2006). There are several reasons that can explain the dominance of a particular design, such as: it offered the best technological trade-off forcing all competitors to imitate (Abernathy & Utterback, 1978); the need of economies of scale that are only possible through standardization (Klepper, 1997) and the existence of network externalities (Katz & Shapiro, 1985); or resulting from a negotiation process (Tushman & Rosenkopf, 1992). All these reasons are further related to the functions of innovation system that were previously presented, respectively: knowledge development and diffusion; development of positive externalities and legitimacy and institutional alignment. However, the dominant design may only be possible to identify in retrospect (ex post) and not in real time (Anderson & Tushman, 1990).

Figure 17. Year of first appearance of the design that become dominant in terms of the number of years after first sequential commercialization



It was searched information on the year of introduction of the model that became dominant in technology histories. Figure 17 compares that moment expressed in terms of the number of years after first sequential commercialization. The graph shows that the dominant standard can first appear several years after the beginning of commercialization (e.g. motorcycles). It can also take many decades after commercialization.

The use of the year of introduction of the dominant model as a proxy of the moment of establishment of the dominant design should be made with caution. In some cases that moment is straightforward as when the diamond-frame was introduced in motorcycles (Wezel, 2002), whereas in other cases like cars there is less consensus on the date – estimates change depending on the launch date of the model-T (Abernathy & Utterback, 1978) or the impact on the number of competing firms or market concentration (Suarez & Utterback, 1995; Utterback, 2007; Argyres, Bigelow & Nickerson (2011).

- indicator (h) production expansion

The final set of innovation processes in the formative phase involves market formation, i.e. preparing both the technology and the production capacity for growth in the main markets. Thus the enlargement of production is an important sign of advancement in the innovation process.

According to the technological innovation system approach (Bergek et al., 2008a; Jacobsson & Bergek, 2012), the creation of a manufacture base requires, among other things, the development of knowledge (especially of a more applied type), resource mobilization and institutional capacity. On the one hand, mass production is only possible with a standardized product following experimentation of different prototypes to finally reach a more stable design (Abernathy & Utterback, 1978). On the other hand, a new production system must be put in place which demands a certain level of resources availability (e.g. human skills, financial and other complementary assets) and technological capacity. In this perspective, the stepwise expansion of technology production would give a sign of the progresses made towards the completion of the formative phase.

Several metrics were computed to search for the first year of significant increase in production. For instance, it is taken the year of highest relative production growth found ex post because of the meaning in terms of market growth. The highest growth of production in relative terms often occurs a couple of years (between 5 and 10 years) after first sequential commercialization. However, most of the highest rates were (artificially) found in the early years and were very volatile, turning difficult to distillate a pattern from the analysis of growth rates.

Alternatively, it was computed growth rates averaged over three and five years in order to reveal more clearly long term trends in production. In addition, it was excluded the start of the time series which presented naturally high growth rates, and a measure of volatility (standard deviation) was added to the analysis. Figure 18 reports the results of five year average growth rates in cumulative total capacity, as well as standard deviations, for the technologies in the sample. The five year growth rates become relatively more stable when they are lower than 10% (excluding start of time series). Similarly, volatility of growth rates stabilizes after passing under the 10% level. Table 10 summarizes all the additional indicators suggested here for future researches.

Figure 18. Five year average growth rate (left-hand) and five year standard deviation of growth rate (right-hand) in cumulative total capacity

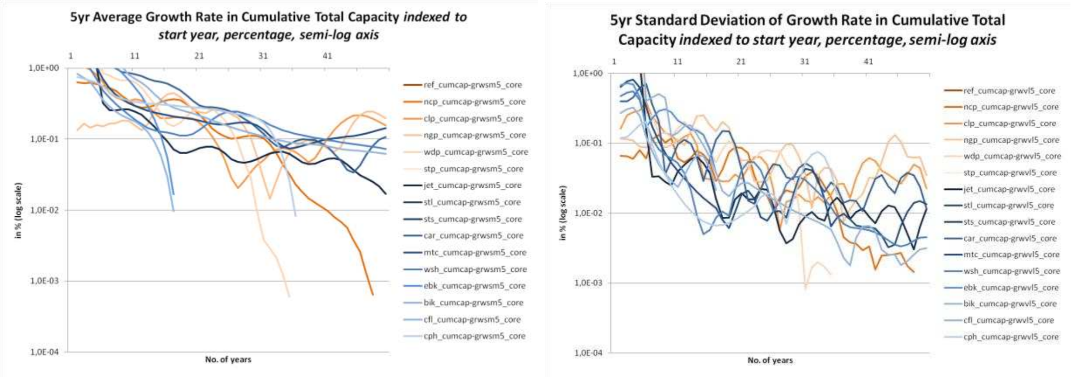


Table 10. Summary of proposed additional indicators to define end point of formative phase

Additional indicators					
f)	**Technology Supply Indicators**	Patent applications	start of the 2nd period of increase in the number of patents in a sustained way (at least in the 3 subsequent years)	(Formal) Knowledge development & institution capacity (derived from R&D-based activities)	indicator of innovation (output), knowledge accumulation needed to pass to the next stage in the growth process. The 2nd wave of patents may be associated with more applied research, privately financed and market-oriented
g)		Dominant design	competing designs = 1 (fundamental trade-offs between technical and service characteristics are settled) identified in retrospect (ex post) cf.Anderson & Tushman (1990)	knowledge development (centered on variety and alternative designs) knowledge spillovers (economies of scope)	links to variety and selection among competing designs (Saviotti, 1996; Dosi, 1982), converging on dominant design for scale investments (i.e., formative phase precedes dominant design - many competing varieties)
h)		Production scale up	first investment in large-scale manufacturing assumed to occur whenever there is a 10 fold increase of production highest production growth (%)	manufacturing economies rely on sufficient knowledge, resource mobilization & institutional capacity knowledge spillover (to other sectors & regions)	mass production requiring standardized product (Abernathy & Utterback, 1978) follows formative phase - knowledge development & capacity building (Bergek et al., 2008a,b)

Appendix 5. Statistical tests to the significance of differences in the duration of formative phases according to several technology characteristics (T-statistics in parentheses)

Technology characteristic	Number of observations	Mean formative length	
	n	Years	
Disruptiveness			
Disruptiveness	6	15	
substitute	5	9	
		(1.089)	*
Type of technology			
End-use	10	10	
Supply	6	13	
		(0.413)	
Commercialization			
Before WWII	9	14	
After WWII	6	9	
		(1,188)	*
Unit scale			
Above 1MW	12	11	
Below 1MW	4	12	
		(0.217)	
Up-scaling			
High (higher than 5x)	4	7	
low (less than 1x)	5	12	
		(1.685)	**
Diffusion duration			
Very slow (more than 50 years)	7	30	
Rapid (20 or less years)	5	19	
		(1.033)	*
Diffusion extension			
High (more than 10,000 MW)	6	15	
Low (less than 10,000 MW)	10	26	
		(1.411)	**
Initial cost			
High (more than $1,000)	3	42	
Low (less than $1,000)	4	25	
		(0.764)	

* difference significant with 80 percent confidence level. See Boland et al. (2001) for the discussion about using such low confidence levels for analyses involving small samples.

** significant at 0.1 level.

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