Formative Phase and Spatial Diffusion of Energy Technologies. (Part I: Definition of Formative Phases, Indicators and Comparative Analysis)

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July 2013

Draft

Paper to be presented at 13th European IAEE Conference Düsseldorf, August 2013

Abstract

The objective of this research is to identify historical patterns in the formative phases of energy technologies. The formative phase 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 penetrate into the market. This phase is particularly relevant in the diffusion of energy innovations because it prepares the technology for widespread growth. So, this investigation aims to develop an operational definition of formative phase to enable comparative technology analysis. The formative processes are firstly identified in the literature of technological innovation system and are then connected to a common set of indicators for characterizing the period of formation of new technologies. These metrics are tested using a comparative energy technology data set, including both supply-side and end-use innovations. The analysis shows that "10% of (estimated) maximum capacity of unit additions" is a good indicator of the real time progress of innovations and completion of the formative phase. This phase normally lasts a couple of decades (20-25 years in average) but it can be faster in the case of less radical innovations. Next step will focus on spatial diffusion of new technologies and the duration of the formative phase in other regions.

Keywords: innovation; technological innovation systems; economies of scale; formative phases.

Formative Phases of Energy Technologies: Definition, Indicators and Comparative Analysis

1. Introduction

The energy system has grown at an unprecedented rate over the last century with total energy use knowing a 16-fold increase, when population had a 4-fold augmentation (Grubler, 2008; Smil, 2000). This enormous expansion was possible thanks to the extensive diffusion of a series of energy supply and end-use technologies that made more services available at lower prices (Fouquet, 2011, 2008). At the same time, the technological progress permitted the diffusion of more powerful technologies that boosted their final impact on the energy system. For instance, today's 100 kW-car has roughly the same power as a room sized stationary steam engine in the late 19th century.

The research community has been increasingly studying the determinants of the rate of diffusion of energy technologies. A recent literature analyzes transitions with the focus on the scale up of technologies and industries (Wilson, 2012; Wilson & Grubler, 2011; Wilson, 2009). The scaling dynamics approach examines historical technology growth that is both rapid and extensive, occurring at different levels (unit and industry levels). It has been successful to describe the role of economies of scale in the historical diffusion of several energy technologies. Now this research has started to focus more on the processes that occur in the early stages of innovation which affect the overall diffusion (Wilson, 2012; Bento, 2013).

The formative phase designates the early stage of development (between the invention and the up-scaling phase) that sets up the conditions for the technology to emerge and penetrate into the market (Wilson, 2012). Initially, performance drives diffusion of new technologies that are crude, imperfect and costly (Rosenberg, 1994). They pass through a long time period of development, rarely shorter than a decade, that is marked by large uncertainties on designs, markets and uses (Bergek et al., 2008a).

In the early stage of formation, the innovation is tested in specialized niche markets which generate knowledge about its performance, efficiency, and attributes in terms of services provided and reliability (Kemp et al., 1998). The design and construction of many units permit identifying and solving a series of "youth" problems; it also generates incremental innovations and learning that reduce unit costs (Abernathy & Utterback, 1978). If successful, interrelated technologies may combine (clustering) and spillover to new markets, sectors, and countries (Grubler et al., 2012; Wilson & Grubler, 2011).

Therefore the formative phase is a crucial stage in the diffusion of energy innovations because it prepares the technology for up-scaling and widespread growth (Wilson, 2012). However, it is often loosely defined as 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). Hence, there is the need to establish the nature of the different phases of formation and growth of innovations.

The objective of this research is the identification of historical patterns in the formative phases of energy technologies. In particular, it is investigated an operational definition of formative phase which can derive a set of indicators to measure the innovation status. So, what are the processes that innovation needs in order to evolve in the early stages, and how can they be measured? Firstly, the conceptual framework is briefly presented using concepts from the innovation and transitions literature to reveal the main process that occur during the formative phase. Secondly, the methodology and data sources are explained. Thirdly, the main processes identified in the theoretical part are linked to a set of indicators for characterizing the end and duration of the formative phase. Finally, the article ends with a discussion of the main results. It is argued that a better understanding of innovation dynamics in the formative phase allows the design of more theoretically and empirically grounded policies to accelerate the dissemination of the next wave of sustainable energy innovations.

2. Formative phases and formative phase processes

In this section, it is analyzed the innovation development by focusing in the processes occurring during the formative phase of new technological systems. This issue is addressed with concepts and theories from three streams of the literature: technological change; scaling dynamics; and technological innovation systems.

2.1. General patterns of innovation and technological change

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 by the mean of user adoption and competitor imitation (Freeman, 1982, Grubb, 2004).

In the early years of “childhood,” technology is so crude and expensive that 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 and become dominant with the time (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.

A more empirical literature has identified a set of mechanisms that can accelerate or slow down the rate of technology growth (Grubler, 2012, 2008, 1998; Rogers, 1995): relative advantage; market size (scale); the existence of pre-existing markets; technology complexity; and infrastructure needs. Recent investigations of the scale of diffusion of several technologies revealed a strong relationship between the extent and the length of growth (Wilson & Grubler, 2011; Wilson, 2009). This means that technologies with a more pervasive effect in the market take more time 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 widespread diffusion which had a strong impact in the economy.

The historical evidence has also revealed that the expansion of energy technologies typically evolved in a three phase process (Wilson, 2012):

i) a formative phase consisting on 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 technological 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.

Therefore the success of a technology in the advanced stages of diffusion depends critically on the processes occurring during the initial years of development between the invention and the up-scaling phase. These processes are analyzed more in detail in the next section.

2.2. The formation of new technology innovation systems

2.2.1. Co-evolution of technology and innovation system

It is important to understand how technological change unfolds as innovation progresses through formative phase, up-scaling and growth. Particularly in the formative phase when the 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 main challenges raised during the early years of development are analyzed by the theory of *technological innovation systems* (TIS) which 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).[1]

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 to perform a particular task. There are different types of networks according to the nature of the goal: hence, some are more oriented around learning and knowledge creation and diffusion (e.g. university-industry links), others are more dedicated to specific tasks such as standardization and market formation, whereas political networks are formed by a group of actors that share a set of norms and beliefs

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[1] The concept of Technology Innovation System (TIS) was introduced by Carlsson & Stanckiewicz (1991) and defined as "…a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilise technology."

to influence policy making through advocacy coalitions (Sabatier, 1998). *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 of a technology by 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 starts during the formative phase and it is particularly important in the case of new and radical innovations, for which almost every component must be put in place. The innovation system evolutes through a cumulative process of small changes, which can last for decades, and ends by building-up an embryonic structure (Markard & Hekkert, 2013; Jacobsson, 2008; Van de Ven & Garud, 1989). A distinguishing feature of this stage is the emergence of strong positive feedbacks marked by "causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal process" (Myrdal, 1957:18). For instance, new entrants bring more resources and knowledge that enlarges networks, contributing to legitimize the technology and further influence the institutions (Jacobsson, 2008).

Therefore the formative phase is the time required to set up the structure of the new innovation system and fulfill basic processes, enabling spillovers effects that accelerate cumulative causations and lead to widespread growth (Hekkert et al., 2007). 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)). If the challenges in the early stages are mainly related with the creation of the supportive structure of the emerging innovation system, in the growth phase "…the need for 'resource mobilization' increases by orders of magnitude." (p.420). One of the advantages of the TIS approach is that highlights a number of processes (called functions) that are needed in the formation of the technology, which allows the assessment of the innovation system's performance.

2.2.2. Key functions of innovation systems in the formative phase

It has been identified seven functions of innovation system that influence the building up of a new system (Bergek et al., 2008b):

1) knowledge development and diffusion;
2) entrepreneurial experimentation;
3) influence on the direction of search;
4) market formation;
5) resource mobilization;
6) legitimation;
7) and development of positive externalities.

Next, the formative phase is analyzed by focusing on three functions: experimentation (and learning), legitimation (and institutional alignment), and knowledge development and spillover. These functions were recognized as important triggers of virtuous cycles in recent diffusions of energy technologies in Europe (Hekkert et al., 2007; Bergek et al., 2008b; Jacobsson & Lauber, 2006).

A) Experimentation and learning

Some system functions may be particularly important during the formative phase: experimentation and early market formation are among them (Hekkert et al., 2007, 2009). These processes relate to the development of a more tacit, explorative and applied knowledge from testing uncertain applications or discovering new opportunities (Bergek et al., 2008b).

The early phase of the innovation is characterized by large uncertainties on technologies, markets and uses (Kemp et al., 1998). At the same time, it is asked a high price for a crude and imperfect technology (Rosenberg, 1994). Not surprisingly, the innovation has low penetration rates and the innovation system shows weak positive externalities. In this highly uncertain context, it is crucial the realization of activities that generate learning and knowledge (Bergek et al., 2008b). From a social point of view, an essential way to handle uncertainty is to make sure that many entrepreneurial experiments take place (Jacobsson & Bergek, 2012). Experimentation is a primary source of learning and knowledge. The test of many new combinations develops knowledge on the technology, raising expectations about its potential. Without explorative trials, technical experiments and uncertain applications, the emergence of a new technology becomes more difficult.

Market formation is another essential process in the constitution of a new innovation system, especially when it has already passed the testing stage (Hekkert et al., 2009). This concerns the articulation of demand in a real market through demonstrations, niches and bridging markets. It gives a field of trial for the products, incentives for firms and the opportunity for cost reduction and growth (Jacobsson & Bergek, 2012). Firstly, the deployment in the market creates knowledge from the cooperation of actors, especially between producers and users, which improves the performances of the innovation (von Hippel, 2010; Rosenberg, 1982; Norberg-Bohm, 2003; Bergek et al., 2008a; Jacobsson & Bergek, 2008). Secondly, first niche markets generate resources for the firms to finance further experiments (Murphy & Edwards, 2003). Thirdly, the increase in production allows the identification and correction of technical problems and creates learning that leads to cost reductions (Thompson, 2010; Arrow, 1962).

In short, the innovation progresses in the formative phase thanks to experimentation, testing and early production. The creation of more applied knowledge enables the correction of technical problems, preparing the technology for growth. The good indications from the first experiments and the introduction in early markets reinforce expectations, visions, etc, in one word, legitimacy, around the new technology. And legitimacy has been “widely” reported as a pre-requisite for the formation of a new TIS (Bergek et al., 2008a).

B) Legitimation and institutional alignment

In the formative period, a successful innovation gains social acceptation and constitutes itself as a credible alternative to the incumbent technology. This improves legitimacy and the capacity of the new technology to influence institutions in order to mobilize resources that are needed to acquire knowledge and start deployment in the market. Thus legitimation is of foremost importance because it is a matter of creating favorable expectations and acquiring institutional support.

Institutional change is at the heart of the development of the innovation system (Freeman & Louçã, 2002). For that, institutions must align with the needs of the emerging technology. This is only possible if the technology reaches a certain level of political strength and legitimacy 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). The creation of institutional capacity is necessary for the scaling up of technologies (to capture economies of scale at the unit level) and industries. One should expect more complex and radical innovations to need longer periods of formation of institutional capacity.[2]

Institutional alignment is important at least at two levels (Jacobsson, 2008). Firstly, it redirects the science and technology policy to create a variety of competing designs that can satisfy the same need (for instance, by supporting the research and experimentation on different types of solar technologies, simultaneously). This effort may need to start well in advance of the emergence of the first markets for the innovation (Bergek et al, 2008b). Secondly, regulative alignment such as regulation and fiscal policies, impact expectations, beliefs, visions, etc., that influence actors' strategy and affects the adoption of several technologies.

Actors of different TIS compete not only in the marketplace but also for institutional influence and legitimacy (Van de ven & Garud, 1989). Legitimacy is a key function in the development of the innovation system because it enables the fulfillment of other functions, such as resource mobilization and knowledge development, and stimulates virtuous interactions between functions (Hekkert et al, 2007, 2009). Hence, legitimation is central in institutional capacity build up and is considered one of the "motors" of innovation.

Additionally, institutions should align to the needs of the technology by taking into account the demands from the market. One of the reasons for the failure of the public programs to support the diffusion of wind power in Sweden was the emphasis on wind turbines in MW size, while the Danish choice to start supporting wind turbines of a smaller size proved to be more successful because it was possible to form a market for those machines (Jacobsson & Johnsson, 2000). A similar failure was the US federal project to promote large-scale wind power plants in the 1970s (Garud & Karnøe, 2003). The goal of the program was to build 3 to 5 MW machines, when the commercial wind

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[2] Janson 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.

turbines of that era were around 100 kW.[3] Therefore, the formative phase serves to reduce uncertainty about the technology and the demand requirements.

In conclusion, actors and networks act to strengthen the legitimacy of the technology and drive an institutional alignment in order to mobilize the resources needed to accelerate the formative phase. Public policies may work in the structure of the technology innovation system through different types of actors (e.g., suppliers, users), networks (e.g., standardization group, advocacy coalition) and institutions (both formal and informal) to reinforce the functionality and performance of the forming system.

C) Knowledge development and spillover

The function of 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 knowledge (Bergek et al., 2008b). The development and dissemination of knowledge depends on the actions taken and inter-relations established among the elements that compose the structure of the innovation system (actors, networks and institutions). These inter-relations influence the dynamics of the innovation system because of the existence of spillovers, i.e., side effects of changes in the structure (e.g., new entrants) or functions (e.g., knowledge creation) affecting other elements of the innovation system. The increasing interactions of functions can lead to “virtuous cycles’ that accelerate the formation of the new innovation system (Hekkert et al., 2007).

Spillovers can be of different forms: knowledge (e.g., technology developed by innovators freely available to other actors); regulation (e.g., innovators bear the cost of the creation of codes and standards for new technologies); skills (e.g., “followers” have access to trained labor without having contributed to the training costs); or complementary goods (e.g., no need to replicate the infrastructure that was created by pioneering companies). However, the existence of externalities delays the investment decision of “prime movers” (Griliches, 1992; Arrow, 1962). The innovator cannot appropriate all social benefits of his investment in R&D, infrastructure and marketing of new technology, which reduces the incentives for innovation.[4]

Another source of positive externalities can arise from the interactions with other innovation systems. The TIS may share knowledge or even structural elements with a competing TIS (Markard & Hekkert, 2013). As long as there are components shared, the emergent TIS may benefit from the functions performed in the related one. In Germany the feed-in law approved in 1991 was promoted by small scale hydropower producers and came unexpectedly to benefit the development of wind technologies (Bergek et al., 2008a; Jacobsson & Lauber, 2006). Exploiting overlaps between different TIS therefore potentiate knowledge spillovers at the structural level that opens up a more powerful

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[3] See more details in Norberg-Bohm (2000).

[4] Spillovers can be further categorized according to their applicability, origin and nature. See: Clarke et al., 2006.

'bottom-up' process of system growth than if each TIS is acting alone (Bergek et al., 2008b).

The tacit and applied knowledge that are generated from the experimentation and deployment of the technology in initial markets can spill over to other sectors or geographical areas. This explains why diffusion accelerates when the innovation reaches new markets (Wilson & Grubler, 2011): other regions benefit from knowledge spillovers from early diffusion in the core to progress faster in the adoption of the new technology. The resources (e.g., time, engineers, financial) devoted to perfect the technology and solve technical problems may not be replicated in other contexts. However the magnitude of that effect will depend on the institutional capacity of sub-center regions to absorb and take advantage of technology spillovers (Cohen & Levinthal, 1990, 1989). In these terms, spatial diffusion is a matter of knowledge spillovers between sectors and regions, as well as institutional alignment to accommodate the adoption of new technologies. The latter can be done by stimulating knowledge-based activities through more experimentation and the investment in local absorptive capacity.

In summary, the duration of the formative phase of technologies is constrained by the time required to set up the structure of the new TIS and to fulfill the functions of the innovation system including the creation and dissemination of knowledge. The interactions established among those elements enable spillovers which accelerate the positive feedback loops that, if successful, lead to the growth phase (Jacobsson, 2009; Hekkert et al., 2007). In the case of diffusion in other regions, strengthening the capacity to absorb spillovers is a particular case of institutional alignment which is needed to capitalize on spatial spillovers.

2.2.3. Phases of maturity of technological innovation systems

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

The technological innovation system passes from emergence to maturity through a number of modifications in technology, system structure and processes. 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 critical processes or functions of the innovation system evolutes with the stage of maturity of the technology. In these terms, it is possible to distinguish three phases: formative phase (from the start with a nascent TIS to the end when TIS is emerging); up-scaling phase; growth phase (corresponding to a mature TIS). See table 1.

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

The end of formative phase is characterized by the emergence of the TIS. This stage comprises both periods of "childhood" and "juvenile" of technology with the selection of first prototypes for testing and experimentation, and the concentration in a smaller number of designs in order to build up an early manufacture base. The innovation system becomes gradually more structured. There are an increasing number of actors bringing new resources and varieties into the innovation system, and higher rates of entry and exit of firms due to fierce competition. More networks of R&D, deployment, and lobby are formed, accompanied with the emergence of the first (formal) technology-specific institutions. Entrepreneurial experimentation has a key role in this very dynamic period.

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 a small number of designs	Dominant design; scaling up technology	Established product; Mass-production
Degree of structuration	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	R&D, deployment and other kinds of organizations	Different types of networks (cognitive and technological)	Established industry networks
Crucial processes (FIS)	Knowledge creation	Entrepreneurial experimentation	Resource mobilization/Legitimation +Market formation	[TIS established]

Adapted from Markard & Hekkert, 2013.

The up-scaling phase coincides with the moment of take-off of technology growth. It occurs when the structure of the innovation system is already consolidated and the industry concentrates into a very few number of distinct attributes or only one dominant design. Firms that produce other varieties of the technology leave the market which reduces the number of competitors and increases the share of surviving companies. Actors direct their search and investments towards the construction of larger units in order to improve performances and grasp economies of scale at unit level to reduce costs. The nature of networks is further diversified including knowledge and technical groups as well as suppliers, producers and consumers. Lobby networks are formed to shape expectations and influence more established technology-specific institutions. Institutional alignment is essential because technology up-scaling requires a large and diversified amount of resources (e.g. human, financial, knowledge), as well as the formation of markets for the new larger units that allow the build up of production chains anticipating mass-commercialization.

The growth phase reveals a mature TIS around an established product that is mass-commercialized like the automobile industry or wind turbines industry. There are a large number of actors and networks with different functions (e.g., suppliers, infrastructure providers, associations). Nevertheless, production can be concentrated in a limited number of producers to benefit from economies of scale in order to reduce costs and prices. The innovation system uses the political strength that has been acquired to consolidate the position of the technology in the market, namely against competing and emerging innovations. Stable institution structures aligned with the needs of the technology and actors play a key role to protect the innovation system.

This conceptualization of the stages of maturity of TISs is different than the one proposed by Markard & Hekkert (2013) because it is explicitly considered the intermediary stage between the formative phase and growth (cf. Wilson, 2012). The reason for isolating the up-scaling phase is explained by the particular behavior of the technology in this stage, as well as the needs of the innovation system in order to take out the full potential of the innovation and prepare for mass-commercialization. However, it is still not completely clear the separation between the end of the formative phase and the up-scaling phase in different regards like in the case of the "adolescent" period after the raise of a dominant design. Therefore a more applied analysis to the development 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 develop an operational definition of formative phases to enable comparative technology analysis. In particular, the analysis pretends to link formative phase processes highlighted in the technological change and innovation systems literature (see previous point) to a common set of indicators for characterizing the formative phase and defining its duration, as well as test the application of those indicators using a comparative technology data set. This will improve the understanding about the dynamics of energy technologies in the early stage and better delineate strategies to promote technology growth.

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

The formation period is essential for innovation to set up the conditions (e.g. technical, market demand) required to increase its unit size (up-scale) and prepare for up-scaling and mass commercialization (Wilson, 2009). However, the formative phase was loosely defined in early works (Bergek et al., 2008a) 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.

This paper aims to develop a range of indicators in order to define formative phases of innovations. These indicators are defined accordingly to the formative processes identified in the literature review. The discussion will focus essentially on the end limit because of its significance in the diffusion process.

Additionally, a set of indicators were assembled to identify the moment of beginning of the formative phase. Those measures were related with formative processes, such as: first 'embodiment' of technology; maximum RD&D expenditure; first application outside laboratory or first commercial application; first available data; first sequential commercialization; and invention and innovation dates (mostly according to innovation list).[5] The results will be presented in a separate work as this article is more focused on the end point and length of the formative phase.

3.3. Test indicators on comparative set of energy technologies

This research aims 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 test them in a comparative technology data set.

The technologies included in the analysis are shown in Table 2. For each technology is sought information on diffusion such as: cumulative unit numbers produced, unit-scale throughout the diffusion, and cumulative installed capacity expressed in MW. 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 a diversity of information related to the indicators used to characterize the formative phase. Those metrics are explained in the following section.

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[5] Such as Mensch (1979) and LOC innovation timeline available at http://inventors.about.com/ . It is followed the definition of Mensch for invention and innovation. The former designates the moment of discovery and technical knowledge accumulation, while the latter corresponds to “a technical event (…) 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." (Mensch 1979: 123).

Table 2 Technologies considered under this research

Type	**Technology**
Supply-Side Technologies	Oil Refineries
	Power - Coal
	Power - Nuclear
	Power - Natural Gas
	Power – Wind
	Steam stationary
	Work animals
End Use Technologies	Passenger Jet Aircraft
	Passenger Cars
	Compact Fluorescent Light (CFL) Bulbs
	Electric bicycles
	Steam locomotives
	Steamships
	Motorcycles
	Mobile Phones
	Washing machines

4. Results (I): end of formative phase

4.1. Alternative metrics

This section aims to develop a range of indicators in order to identify the end point of formative phase of innovations. These indicators are defined accordingly to the formative processes identified in the literature review, particularly the need of technology experimentation and learning, market formation, knowledge development and institutional alignment. Table 3 presents a summary of the indicators that are explained more in detail in the following points of this section.

Table 3 Summary table of proposed indicators to define end point of formative phase

Indicator	Metric	End Point of Formative Phase	Link to Formative Phase Processes	Rationale
a)	*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 size (identified ex post) 10% maximum average unit capacity (identified ex post)	knowledge development & institution capacity	knowledge and institutions necessary to support economies of scale are in place
c)	*Average cost reduction*	highest relative cost reduction first halving in cost	Knowledge development & institutional capacity (to benefit from learning gains) Knowledge spillovers (across sectors & economies of scope)	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). *Market share*: minimum of the four-firm concentration ratio (C4)	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)	*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)
f)	*User adaptation*	diffusion reaches 2.5% of maximum number of units in use or adherents ("innovators" group cf. Rogers, 1995) (identified ex post) existence or not of a lead user	knowledge development (feedbacks from users to developers / designers) & institutional capacity	evidence of users adapting technologies beyond designers intentions ('interpretive flexibility'). Learning by using enhances innovation's performance (Rosenberg, 1982)
g)	*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 (and production system) follows formative phase knowledge development & capacity building
h)	*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 and nation's innovative capacity needed to pass to the next stage in the growth process

In addition, it was investigated in a side work the start point of formative phases. The moment of invention and of the beginning of the development phase may not be coincident in time (Mensch, 1979). The former provide the "seeds" of the process, but is the latter that better characterizes the start of the formative phase. Meanwhile, inventors and other researchers make small advances that are important for the implementation of the initial idea but may not be enough to influence the formation of the technology.

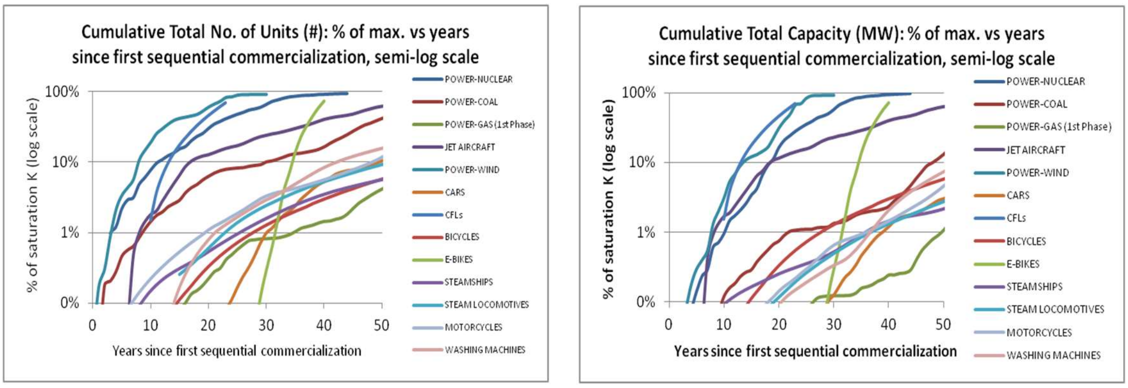
The first commercial application initiating successive new series of products (i.e., the beginning of consistent commercialization) was found to be a good proxy for the start of formative phase. The number of units commercialized in the first years are normally very low, less than 10 units, but this number can be higher in the case of more smaller-scale, less capital intensives, technologies like motorcycles or CFLs. In terms of technology lifecycle, this moment corresponds to the post-invention period and is characterized by the challenges raised by the more applied development stage.

4.1.1. 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. Previous researches have demonstrated that many energy technologies evolved in a three stage process (Wilson, 2009, 2012): formation period (with creation of the manufacturing base); up-scaling at unit level; and growth phase. In this perspective, the early period is the moment when the conditions are set up (i.e., technical, market, institutional) in order to upscale at unit level and prepare for mass commercialization. Until that point an intense period of *experimentation and learning* with many unit numbers takes place to mature the technology and scale up production.

In addition, the analyses on the historical dynamics of technologies have shown a close relationship between duration of growth and market size, underlining the role of economies of scale in diffusion (Wilson & Grubler, 2011; Wilson, 2012). The S-shaped patterns of growth justified the use of a logistic model, which (three) parameters describe the dynamics of diffusion: K expresses technology's saturation level; Δt denotes the time period over which adoption passes from 10% to 90% (or similarly from 1% to 50%) of K; and T_0 represents the moment of maximum growth rate coinciding with the inflection point (50% of K). This gives the basis for the first set of indicators of the end of formative phase, coinciding with the moment when diffusion reaches 10% of cumulative number of units or, alternatively, 10% of cumulative total capacity. These two measures are consistent with the definition of the rate of diffusion in the logistic model (Δt), which measures the period between 10 and 90% of saturation, suggesting that the real impact of innovation on the market starts after the end of the formative phase.

Figure 1. Formative phases measured by the growth of cumulative total number of units (left-hand) and cumulative total capacity (right-hand)*



** Sstationary steam engines are not shown in the graphs because they took more than 100 years to reach 10% of saturation in both cases.*

The application of these definitions to measure the end point of formative phases of the energy technologies in the sample shows a couple of interesting results (Fig. 1). On the one hand, the time needed to prepare the innovation for diffusion takes several decades and it is unusual to last less than a decade after first sequential commercialization. That duration can be even larger (more than a century) in the case of complex innovations, such as stationary steam engines, which diffusion had a great impact on the economy (Rosenberg & Trajtenberg, 2004). On the other hand, the formative period was much faster with CFLs, jet aircraft, wind and nuclear energy. In the case of nuclear, this is explained by political pressure to start building power plants of a larger size (Grubler, 2010). In the other examples, it seems that the production of a large number of units contributed to rapidly progress to the next stages.

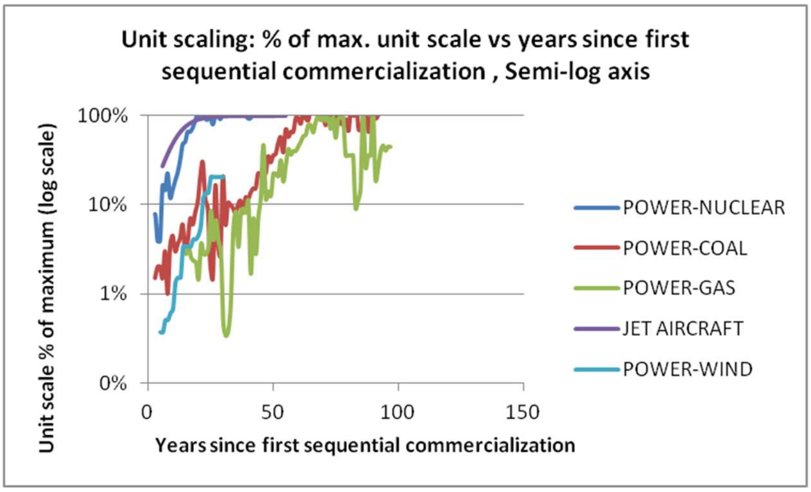
The analysis also shows that growth is initially driven by the production of many units. The comparison of the two graphs reveals that cumulative unit numbers reaches 10% of saturation slightly faster than cumulative capacity. This is particularly true in the case of technologies that upscaled (e.g., wind energy, jet aircraft), for which the growth in the installed capacity is more important after the production of units of a bigger size. In summary, these results reassert the importance of experimentation and (early) market formation in the development of a new innovation system by enabling more learning in production and demand creation.

4.1.2. 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 graphs in Wilson, 2012 and Smil, 2008). 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 (i.e., from the production of larger units, not confounding with learning which derivates from the manufacturing of many units of the same size). However this is often accompanied with important technical and marketing challenges that must be solved before it becomes possible to build units of a larger size.

Thus the formative period would be the time needed to develop knowledge and put in place the institutions needed to support economies of scale. In many technologies surveyed in previous articles (Bento, 2013; Wilson, 2012) the up-scaling at unit level starts around the moment when production reaches 10% of maximum capacity of unit additions. Hence this metric is used to identify the end point of formative phases of the energy technologies surveyed in the sample (Fig. 2).

Figure 2. The end point of formative phase measured by the moment when innovation reaches 10% of maximum unit scale of new additions

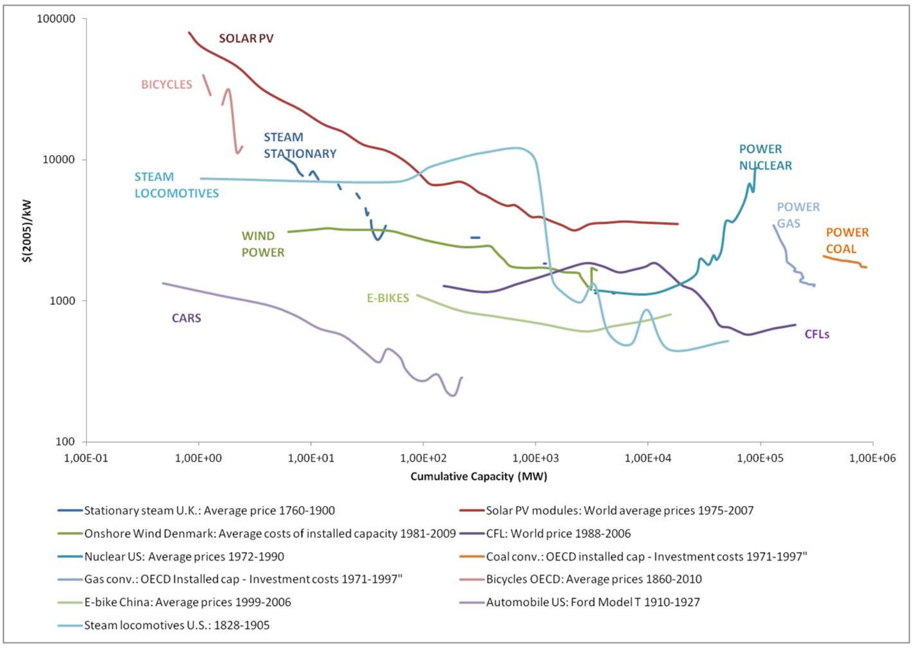


The application of this indicator to our sample of technologies shows a couple of interesting results. The most common pattern is the end of the formative phase around 25 years after first sequential commercialization. During that period actors build up knowledge and institutional capacity to prepare the up-scaling of unit capacity. They produce many units to enlarge production capacity and learn about the technology. This corroborates with the observed regularity of the three sequential stages of growth in energy technologies. However, the transition to the next stage was much faster in two specific cases: jet aircraft and nuclear energy. The experience with the propeller aviation would have contributed to the rapid progress of the former, while political pressure explains the behavior of the latter. Nevertheless, the rapid up-scaling of nuclear power plants had an unexpected impact on the evolution of costs later on, with reports of negative learning in the case of the French nuclear program (Grubler, 2010).

4.1.3. indicator (c) average cost reduction

The third type of indicators measure directly the competitive preparedness of the innovation. The first models 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. Cost is reduced to competitive levels thanks to the development of knowledge and institutional capacity during the formative phase that enable learning economies (Arrow, 1962). In addition the existence of spillovers, i.e., side effects triggered by knowledge creation or a new entrant in the field, may produce positive effects across sectors as well as economies of scope which further contributes to enhance the competitiveness of the emerging concept. Therefore the formative phase precedes major cost reductions. Hence, the end of this period might coincide with the highest rates of cost reductions or the first halving in costs.

Figure 3. Learning curves of energy technologies in the core



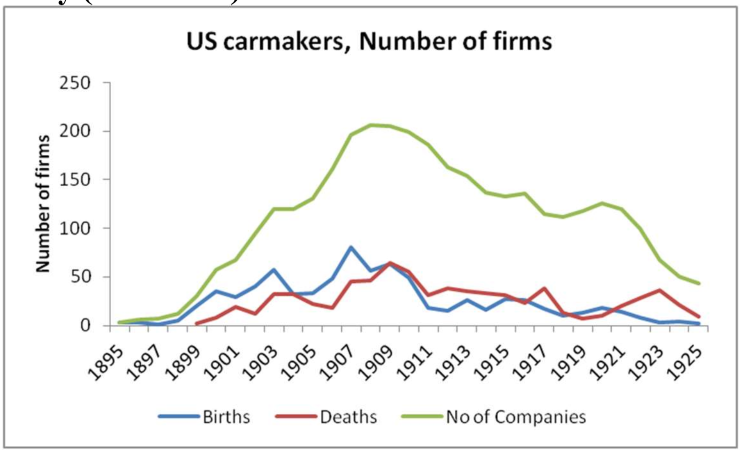
Sources: [Stationary Steam UK] Kanefsky, 1979; Crafts, 2004; Fouquet, 2008; [Onshore Wind Denmark] Grubler et al., 2012; [Nuclear US] Grubler et al., 2012; [Power Gas Conventional OECD] European Commission, 2005; [E-Bikes China] Weinert, 2007; [Steam locomotives US] White, 1968; [Solar PV Modules world] Nemet, 2009; Grubler et al., 2012; [CFLs world] Weiss et al., 2010, 2008; [Power Coal Conventional OECD] European Commission, 2005; [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 the different growth stages of a technology (Fig. 3). The analysis to the cost evolution of steam locomotives revealed a halving around 1855 which is a coherent estimation for the end point of the formative phase. However, these metrics were unable to provide robust results in many other technologies. A clear example is onshore wind energy, for which there was no halving in costs (in a yearly basis). The highest cost reduction (in percentage) occurred in 2002, well after the up-scaling of unit capacity and during the growth stage. In this case a more accurate measure would be the end of the first wave of cost reductions which came about the year 1990. More work is needed on the indicators that analyze the dynamic of costs to inform about the status of technologies in the innovation process.

4.1.4. 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 innovation lifecycle (Abernathy & Utterback, 1978). These movements are often associated with knowledge development among many competing innovators prior to scale up. Formative phase is expected to end as market expectations become robust lowering risk in scale investments and once smaller firms leave the market. In that sense formative phase precedes market concentration. Therefore that moment can be found through the analysis of the demography of companies, in particular when there is a "shakeout" in the number of firms (Klepper, 1997). The "shakeout" occurs when 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). In addition, it is surveyed the market shares of the main group of companies, particularly the year when the four-firm concentration ratio (C4) reaches the first minimum.

Figure 4. The number of carmakers in the US and of new entrants and companies leaving the industry (1985-1925)



Source: Smith, 1968.

The reconfiguration of the industrial structure was more intensively studied in the case of automobiles in the US, for which there are data available for the early period (Fig. 4). In this case the first "shakeout" occurred in 1914, almost coinciding with the year of minimum concentration ratio C4, 1911.[6] That is respectively four and two years after the introduction of the model-T Ford, which came to revolutionize the car industry by introducing mass-production in assembly lines and new management methods (Klepper, 1997).

In the case of the others technologies of the sample, the number of companies actively operating in the market decreased for different reasons, such as institution barriers or

[6] Murmann & Frenken (2006) pointed that the entry and exit patterns can be different within the same technology, according to the level of analysis. For instance, the number of automakers in the US peaked in 1909, whereas the number of tire producers reached a maximum in 1922.

industry consolidation. The number of firms manufacturing stationary steam engines may have peaked for the first time around 1869 by the effect of Watt's patent enforcement that had prevented other firms of using compounding cylinders afterwards (Allen, 2009). On the other hand, the jet aircrafts industry knew a "shakeout" in 1979 after having known the first peak in 1973. This was three years later than the foundation of Airbus, the major competitor of Boeing in the aircraft manufacturing market.

4.1.5. indicator (e) 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. Its establishment has such a powerful impact that switches the focus of R&D from product innovations to process innovation (Abernathy & Utterback, 1978).[7] This is also a major risk for the population of firms that until then progresses the technology by trial and error (Murmann & Frenken, 2006).

The standardization into a dominant design is only possible thanks to knowledge development that allow the creation of variety and alternative designs (variation) (Saviotti, 1996; Dosi, 1982). The selection of a particular standard (retention) may enable significant knowledge spillovers by systematic exploitation of economies of scope (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); the existence of network externalities (Katz & Shapiro, 1985); or resulting from a negotiation process (Tushman & Rosenkopf, 1992).

The selection among various competing designs lowers the uncertainty in the product class and enables scale investments. Therefore the formative phase precedes dominant design and is characterized by the co-existence of many competing varieties. Once established, the dominant design has to diffuse almost completely throughout the industry (Abernathy, 1978: 61-62). Hence, the year of introduction is here defined as the moment after which the number of competing designs reduces to a main standard, meaning that the fundamental trade-offs between technical and service characteristics were already settled. However, the dominant design may only be possible to identify in retrospect (ex post) and not in real time (Anderson & Tushman, 1990).

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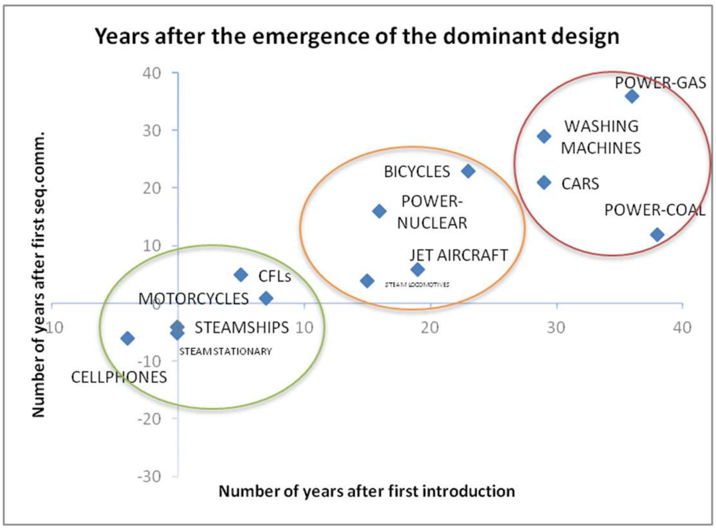
[7] "…a dominant new product synthesized from individual technological innovations introduced independently in prior products. This dominant design has the effect of enforcing standardization so that production economies can be sought. Then effective competition begins to take place on the basis of cost as well as of product performance. ... Technologies which lift fundamental technical constraints..; Designs which enhance the value of potential innovations...; Products which assure expansion into next markets." (Abernathy & Utterback, 1978: 46).

Figure 5. The emergence of dominant designs: comparing the number of years after first introduction and first sequential commercialization



The emergence of dominant designs is investigated for the technologies in the sample through the comparison between the number of years after first introduction and the number of years since first sequential commercialization. The inclusion of the former indicator is explained by the fact that it was also a good proxy of the start of the formative phase together with the latter, and it might be closer to the moment of establishment of a dominant design.

The analysis shows three different cases (Fig. 5). The first one, highlighted with a green circle in the graph (bottom-left), is characterized by a very dynamic innovation process that lead to close historical events among dominant design, first introduction and sequential commercialization. It includes small and granular technologies (e.g., CFLs and cellphones) as well as mobile applications of steam technologies and motorcycles. These group of technologies progressed substantially after the introduction in the market and through the production of many unit numbers. The second group of technologies (yellow circle, in the middle) needed more time to stabilize the features of the product, around 20 years after first introduction or 10 to 20 years since first sequential commercialization. This category includes general purpose technologies (such as stationary steam engines), jet aircrafts, nuclear power plants and bicycles. Finally, the third set of technologies (red circle) is characterized by a slow innovation process that had to wait long time (30 to 40 years after first introduction) for the emergence of a dominant design. This is the case of natural gas power plants, coal power plants, washing machines and automobiles.

In the case of cars, many technologies and designs had to be invented and tested before the introduction of the model-T by Ford (Klepper, 1997). This model showed technological and economy superiority against its competitors, obliging all other carmakers to imitate the same product (Abernathy & Utterback, 1978).

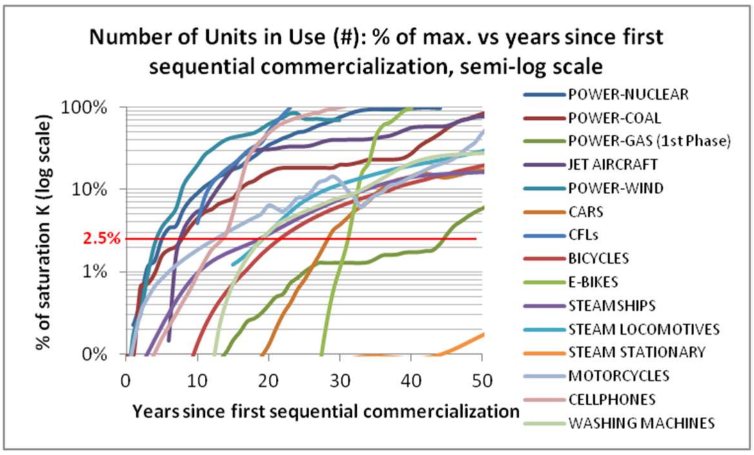
Therefore, the complexity of the innovation influence the levels of knowledge development and institutional capacities that are needed to progress in the innovation process. Hence it contributes to delay or advance (in case of a more simple technology) the emergence of a dominant design.

4.1.6. indicator (f) user adaptation

The end of the preparation period can be marked by raising evidence of users adapting technologies beyond their initial purpose (i.e., interpretive flexibility). The experimentation of the new technology by an increasing number of consumers enables "learning by using" which enhances innovation's performances (Rosenberg, 1982). It also contributes to increase the level of knowledge that developers and designers have about the innovation through the feedbacks they receive from users. In the extreme, user-innovations develop new functionalities which become commercially more attractive. It is particularly the case in the presence of a lead-user. As noted by Von Hippel: "…[lead users] are ahead of the majority of users in their populations with respect to an important market trend, and they expect to gain relatively high benefits from a solution to the needs they have encountered there. .." (Von Hippel, 2010: 416).

In this study the largest influence on innovation is considered to take place during diffusion in the first group of consumers, which is called "innovators" in Rogers' sequential adoption model (Roger, 1995). This class was statistically identified with the first group of 2.5% of all adopters, here approached by the maximum number of units in use. Figure 6 shows the results for the technologies in the sample.

Figure 6. End of formative phase coinciding with the adaptation of the innovation to user requirements after diffusion in the "innovators" class (i.e., 2.5% of maximum number of units in use)



According to this definition, the formative phase ends less than 25 years after first sequential commercialization for all technologies except for e-bikes, natural gas energy and steam stationary. For technologies that up-scaled at unit level, the average number of years before reaching 2.5% of units in use varies between 5 and 8 years, except for natural gas (45 years).

This metric is very versatile and the rational intuitive, meaning that the end of the formative phase coincides with the final adaptation of the technology to user requirements. In addition, it is a simple measure that can be used for new technologies in terms of whether they reach the threshold of 2.5% of total population. That point can also be seen as the "critical mass" after which diffusion becomes self-sufficient.

Nevertheless, the stage at which this critical point occurs is highly dependent on technology and cultural context, and it is influenced by the type of adopters and the decision process (Rogers, 1995). It can be attained when innovation reaches the class of innovators alone (2.5%) or with early adopters (representing themselves 13.5% or 16% with innovators) as well. More information about each technology (for instance, the evolution of its functionalities) should be analyzed to better judge about the end of the formative period.

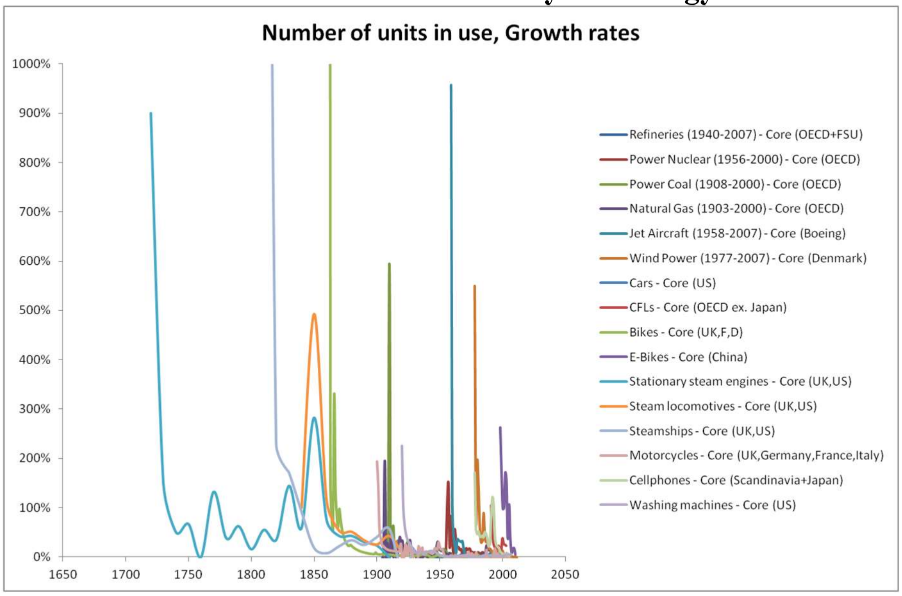
4.1.7. indicator (g) production scale up

The final goal of the formative phase is to prepare both the new 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.

The creation of a manufacture base requires the development of sufficient 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 all knowledge development and experimentation of different prototypes to finally reach a more stable design. On the other hand, a new production system must be put in place which demands a certain level of resources available (human skills, financial and other complementary assets) and capacity building. At the end of the process all knowledge and competencies created during the development stage are likely to spillover to other sectors and regions.

Therefore the formative phase is considered to arrive at the end when production scales up. The first investment in large-scale manufacturing is assumed to occur whenever there is a 10 fold increase of production and the number of units produced is larger than a thousand. Alternatively, it is taken the year of highest relative production growth (%). Figure 7 shows the growth in the number of units in use of the technologies from the sample.

Figure 7. Growth in the number of units in use by technology



The first metric (a 10 fold increase of production) is very plausible, but is more limited in terms of the coverage of our sample of technologies. In fact, there is only data on production up-scale for jet aircrafts (1959 or seven years after first sequential commercialization) and steamships (at some point in the 1810s). The second metric gives more information about the growth of production. The highest growth of production in relative terms often occurs a couple of years – between 5 and 10 years - after first sequential commercialization. The exception is steam technologies, especially fixed steam engines, which needed more time (almost a century) to prepare for mass production. A closer look to the data reveals that more radical and complex technologies need slightly more time to pass to the mass manufacturing stage (e.g., cars took thirteen years, while motorcycles only one). Therefore results suggest that more complex innovations take longer to stabilize design and to set up production.

4.1.8. indicator (h) patent applications

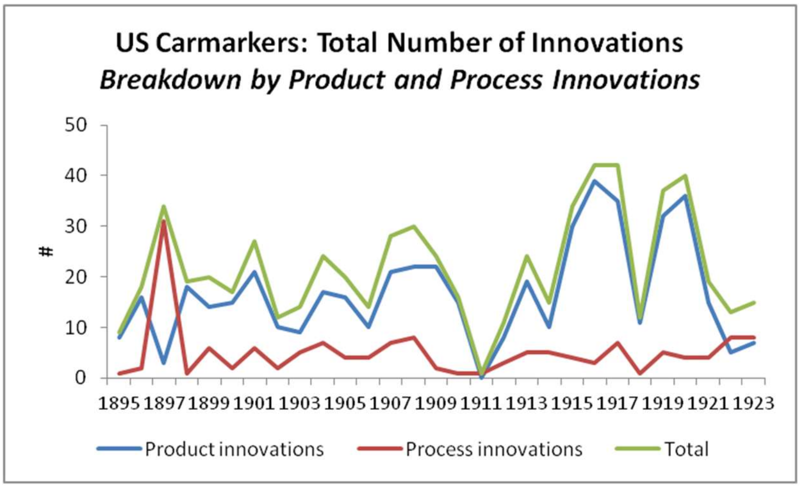
Another way to assess the status of development of a new technology in the innovation process is through the analysis to patenting dynamics. Patents are a well-known (intermediate) output measure of innovation mostly derived from R&D-based activities (Kleinknecht et al., 2002). It is an important source of information about the state of knowledge in a certain domain or technology. Still, 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 adopt a technology (Kleinknecht et al., 2002). Nevertheless, patent applications give important information about institutional capacity building. Knowledge accumulation improves nation's innovative capacity which contributes to accelerate the preparation of innovations.

Therefore the end of the formative phase is approached by the completion of the first wave of patent applications. This period may be marked by more complex innovations than in later periods when innovations would be more of an incremental type. Thus the year of first peak in patent applications is likely to be a good indicator of the end of formative phase. As a complementary metric it is taken the year of start of the second period of sustained growth of the number of patents (i.e., maintained at least in the three following years).

It was possible to find enough data on patent activities only for two technologies: automobiles in the US (Fig.8) and wind energy globally (Fig.9). In the first case, the number of patent applications knew a first peak around 1897 whereas the second sustained wave of patent application started in 1914. This corresponds to nine and twenty-six years after first sequential commercialization, respectively. In the case of wind energy, the first peak was reached in 1980 and the second wave of patenting in 1996, or three and nineteen years after first sequential commercialization, respectively.

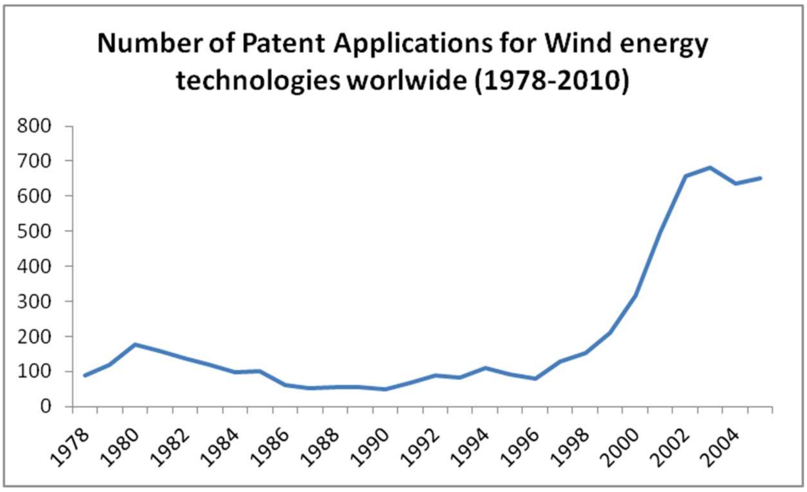
Interestingly, the year of start of the second wave of patenting is coincident with important changes that occurred in the innovation context. In 1914 there was a major "shakeout" in the number of carmakers in the US following the introduction of the Ford Model T in 1908. In the case of wind energy, the result (1996) is close to the moment of introduction of larger size 500kW wind turbines (Spliid, 2013). So, there is an apparent correlation between the second wave of patent applications and the up-scaling of the innovation. More analyzes to other technologies are needed in the future to share light about the pertinence of the patent activity as an indicator of the end of the formative phase.

Figure 8. Number of patents in the automobile sector in the US (Core)



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

Figure 9. Number of patents in wind energy globally

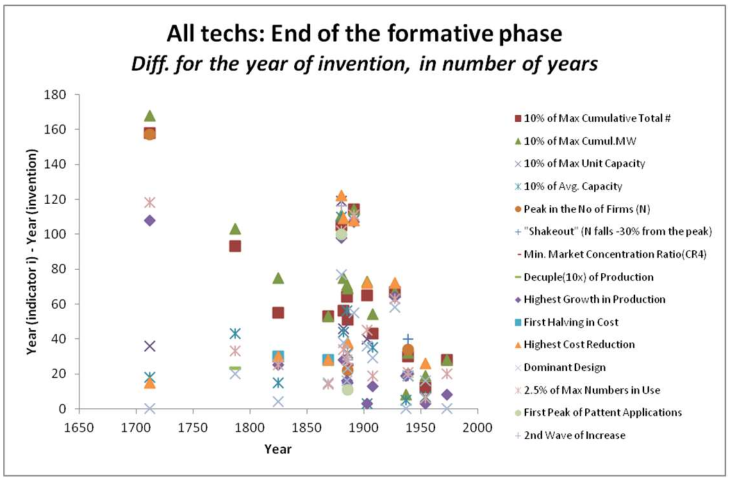


Source: WIPO, 2010.

4.2. Comparing different indicators

At this point it is possible to compare the results of all the indicators of the end of formative phases. Figure 10 shows all the estimates according to the different metrics used in the analysis and in terms of the number of years after invention. There is a great dispersion of values and it is difficult to identify a clear pattern in the graph.

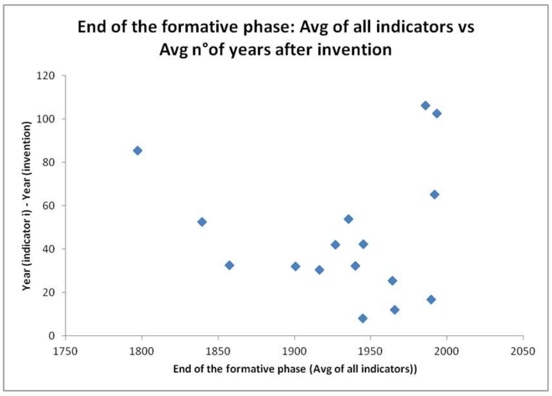
Figure 10. End of the formative phase of technologies according to different indicators and against the moment of invention

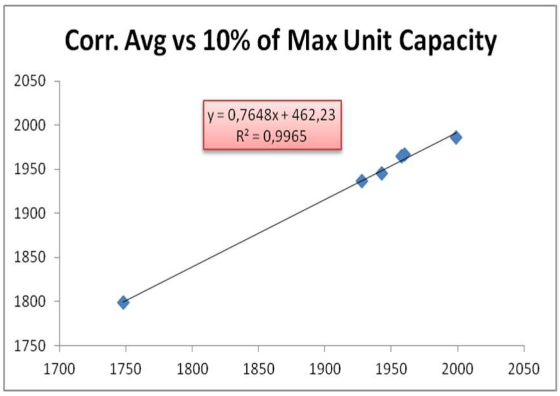


Additionally, the indicators are compared by using the simple average of all metrics as a proxy of the real moment of the end of the formative. Each indicator evaluates an important feature of the innovation process and the average makes use of all available information. First it was computed the average of all estimates of the end of the formative phases for each technology, then the results were compared to each indicator in order to find the one that correlates the most with the central value.

Figure 11 (left-hand) shows the average of all indicators by technology as well as the average difference to the year of innovation. It was found that the "10% of Maximum unit capacity" has the highest correlation with the average of all indicators (Fig. 11, right). Therefore, it seems that the indicators related with innovation up-scaling are well suited to track the end of the formative phases.

Figure 11. Average of all indicators of end of formative phase by technology (left-hand) and correlation with "10% of Maximum unit capacity" (right-hand)





5. Results (II): lengths of formative phase

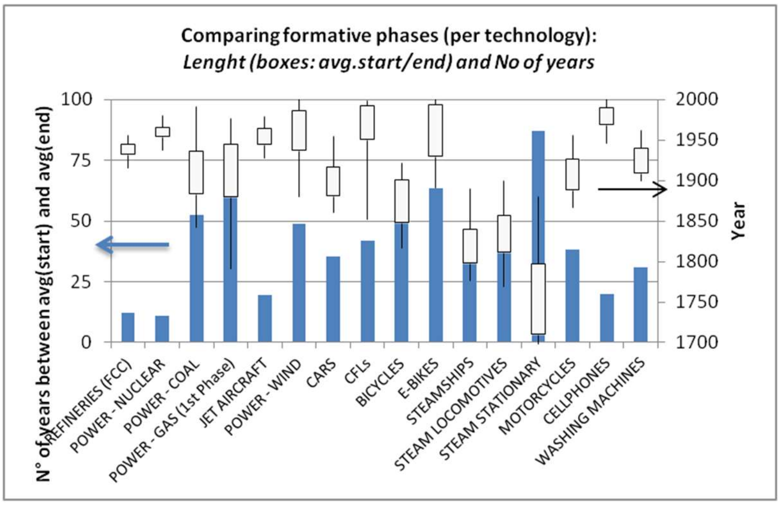
5.1. Comparison of all formative phase lengths given different metrics

In this last part, it is analyzed the duration of the formative phase of innovations following the identification of possible starting and ending points in the previous section.[8]

The length of formative phases by technology is analyzed in Fig. 12. The graph shows minimum estimates of the start of formative phases, as well as maximum estimations of their end. The white boxes are respectively defined by the average of all indicators of start of the formative phase (low-bound) and the average end of the formative phase (upper-bound). The blue bars show more clearly the length of formative phases derived from the comparison of average end and average start points. Additionally, in a separate graph was compared the year of first sequential commercialization and the year when 10% of maximum unit capacity was reached corresponding to proxies of the start and end of formative phases, respectively. The results are similar to the ones that are shown in Figure 12 but with a fewer number of technologies.

[8] See Appendix 1 for a synthesis table. It is also presented the estimates of the start points of the formative phase according to different metrics. This was elaborated in a separate work and it was not developed in the current article.

Figure 12. Length of formative phases (by technology)



Two main insights can be derived from the analysis to the graph. The first important finding is that it is more difficult to identify the beginning and the final points in the case of long formative phases. In fact, a wider dispersion of values was found in technologies that passed through a long period of formation (i.e., larger white boxes or equivalently higher blue bars).

The second finding links more directly the length of formative phases with the type and characteristics of innovations. More complex technologies, such as stationary steam engines and coal or natural gas power plants, tend to present longer formative phases. This fact may be explained by the time needed to develop enough fundamental and applied knowledge as well as to build institutional capacity that is required for the innovation to pass to the next stages of up-scaling and growth. E-bikes also show an exceptional long formative phase, but in this case the reason seems to lay on the period of time that mediated the invention of the technology and the beginning of its use as a serious alternative mode of transportation in China. The effect of innovation's characteristics in the length of the formative phase is further investigated in the next sections.

5.2. Similarities and differences between metric definitions

The previous point showed how uncertain is still the measurement of formative phases, especially when technologies need a long period to set up technology and institutional conditions in order to grow up. It is now investigated the main convergences and divergences between indicators, as well as possible explanations for the observed patterns.

In terms of the definition of the starting point of the formative phase, the metrics tend to converge when they are close to the invention date and conversely diverge when they occur longer after the moment of invention.[9] So, there is lower uncertainty about the

[9] See Appendix 1 for more details.

beginning of the formative phase when the activities connected with that stage start just after invention. In addition, the following metrics present very similar results between each other and with the average of all indicators: “year according to the list of innovation”, “first application outside laboratory or first commercial appearance” and “first sequential commercialization”. This observation points to the importance of materialization and experimentation in the early years of the innovation. On the contrary, the “first available data” and “maximum of R&D expenses” showed more divergent (and later) estimates of the beginning of the formative phase, which may be a sign of biased (upward) indicators.

In terms of the definition of the ending point of the formative phase, the metrics related to the completion of precise targets present the most similar results (Fig. 10).[10] This is the case of the indicators belonging to the following categories: “total milestones”, “up-scaling of unit size” and “lead user”. Most of these metrics are only possible to track *ex post*, but there are a few of them that can be used *ex ante,* as well. This is the case of the year when it is reached 2.5% maximum number of units in use (one could take total population as a proxy) or 10% maximum unit capacity of the technology (in that case, by using studies on technological feasibility of unit scaling). These indicators measure directly the progress in terms of experimentation of new prototypes (e.g., up-scaling metrics), and market formation. However, other milestone indicators such as “10% maximum cumulative capacity”, and in a smaller extension “10% maximum cumulative unit numbers”, are frequently more pessimistic about the completion of the formative phase (i.e., presenting later estimates). The explanation for these outliers may be related with the sequential process of unit and industry scaling that was found previously in earlier researches (see Wilson, 2012). For instance, the development in the overall installed capacity may only kick off after the beginning of the up-scaling stage, and so after the end of the formative phase.

Two main features emerge from the comparison of similarities and differences between indicators of start and end of the formative phase, respectively. On the one hand, in both cases the metrics that evaluate technology experimentation are important indicators about the status of development of the innovation. On the other hand, the dispersion of the indicators is much more important in the case of the ending point than of the starting point (Fig. 1 and Fig. 10). Therefore, if the beginning of the formative process is not straightforward to identify, the results show that the recognition of the end of that phase is a much more difficult task.

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

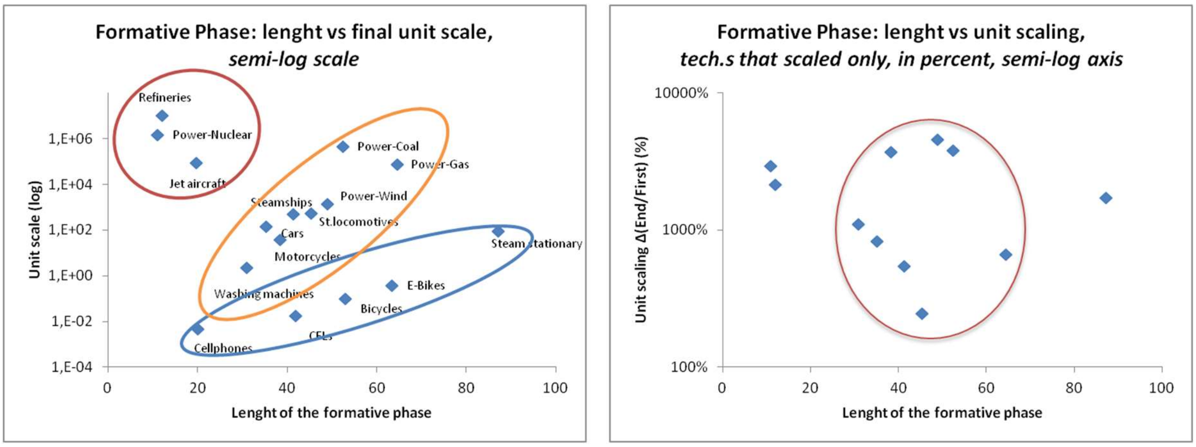
In this last point, the length of formative phases is compared to the type of innovations to know the effect of the characteristics of technologies on the preparation for growth.

It was previously shown that more complex innovations are often associated with longer formative periods (section 5.1). In addition, the beginning of unit scaling – here defined as the moment when unit capacity reaches 10% of the final maximum - is often a good indicator of the end of the formative phase (section 5.2 and section 4.2). Therefore the

[10] See Appendix 1 for more details.

analysis will focus particularly on comparing scaling dynamics of technologies with formative phases.

Figure 13. Comparing the length of formative phases with technology unit scale (left-hand) and unit scaling (right-hand)



The relation between technology scale and duration of formative periods is analyzed in Fig. 16 (left-hand). It is possible to distinguish three groups of technologies in the graph. The first group composed essentially of smaller and granular technologies (e.g. cellphones, CFLs, bicycles) presents relative long formative periods and a wider dispersion of values. The second group includes power technologies as well as end-use innovations in transport (e.g. steamships, steam locomotives, cars, motorcycles) and in household appliances (e.g. washing machines). This group contains technologies of a higher unit scale than the first one with identical duration of the formative period. The third group is composed of very large unit scale technologies, such as nuclear power plants or refineries. It distinguishes itself from the other groups by the faster period of formation. Therefore, high unit scale technologies tend to be associated with shorter formative periods.

This finding might be explained by the longer lifetime of those technologies and higher unit costs, which makes replacements less frequent. Thus the progress towards the next stage may be more rapid with the experimentation of a fewer number of units.

The comparison of the length of the formative phase with the dynamics of unit scaling of technologies is shown in Fig. 16 (right-hand). Hence, the graph only compares technologies that scaled up unit capacity during the innovation process. The results show that the length of formative phases took normally long time around 30 to 60 years. Interestingly, the outliers are refineries and nuclear power plants which passed very fast the early period, and stationary steam engines in the opposite side. If in the case of nuclear energy the intensive public investment led to a quicker up-scaling of the power plants, the case of steam engines is a typical case of the development of a general purpose technology that needed long time for the invention of other innovations in order to fulfill all its technical potential (Rosenberg & Trajtenberg, 2004).

In conclusion, the analysis suggests that high scale technologies tend to progress faster in the formative phases. However, it is less clear the influence of the potential for technology up-scaling at unit level in the length of the formative period.

6. Discussion & conclusions

This investigation aims to reveal historical patterns in the formative phases of energy technologies. For that, it was searched an operational definition that can derive a set of indicators to measure the status of innovation development and to enable comparative technology analysis. A revision of the innovation and technological innovation system literatures highlighted a certain number of processes that were linked to a set of indicators for characterizing the end and duration of the formative phase. These metrics were tested using a comparative energy technology data set, including both supply-side and end-use innovations. In addition, a separate work was undergone to define the start point of the formative phase. The first commercial application initiating a successive new series of products (i.e., not just a one-off commercialization) showed to be a good proxy of the beginning of the formative period. This underlines the importance of experimentation and knowledge obtained from production (learning) for the development of the innovation.

The most reliable indicator of the end of the formative phase was found to be the moment when innovation reaches "10% of maximum unit capacity". In our sample of technologies, this occurs around 25 years after first sequential commercialization. This result has two main significations. On the one hand, the formative phase is a long process which takes a couple of decades, between two and three decades in average. On the other hand, this period is important to build up knowledge, legitimacy and institutional capacity in order to prepare for up-scaling of unit capacity. This involves the development of a more applied knowledge through experimentation and testing. It also requires the mobilization of resources (e.g., human, financial) enabling the production of more units to enlarge manufacturing capacity and learning. However, one major inconvenient is that the metric is only suitable for technologies that are likely to scale during the innovation lifecycle.

The indicators related to the completion of precise targets, such as "total milestones", "up-scaling of unit size" and "lead user", are other good proxies of the end of the formative phase. In particular, the metrics related with diffusion milestones showed that growth is initially driven by the production of many units. In fact cumulative unit numbers increases slightly faster than cumulative capacity in the early years. This finding reasserts the importance of experimentation and early market formation in the development of an innovation by enabling more learning in production and demand creation. In addition, some indicators can be also used *ex ante* (e.g. "2.5% maximum of units in use"), which has the advantage of enabling the assessment of innovation progress in real time.

The length of the formative phases of the technologies analyzed in this research was rarely lower than 20 years. However there are still many uncertainties surrounding the measurement of the duration of the formative phase because of the dispersion of values concerning the indicators of start and end. In particular, the analysis shows that it is more difficult to identify the ending point than the starting point of formative phases. In both cases, the indicators that evaluate technology experimentation revealed to be important metrics about the status of development of the innovation. In addition, tThe analysis suggests that high scale technologies tend to progress faster in the formative phases. Nevertheless, it is less clear whether the potential for technology up-scaling at unit level influences the length of the formative period.

This study enables a better understanding of the dynamics of technological diffusion during the formative phase, which allows the design of more theoretically and empirically grounded policies to accelerate the diffusion of innovations. It seems to support the claim under which policy should stimulate experimentation and testing in the beginning, and in a later stage early market formation for the innovation. However, the long duration of the formative phases reported here and the drawbacks of past experiences with innovations that rapidly passed the formation period (e.g., nuclear energy) show the limits of policies to speed up new technology development in the early years.

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Appendix 1. Formative phase: Synthesis table

Formative Phase	Characteristic	Unit/Measure	REFINERIES (FCC)	POWER - NUCLEAR	POWER - COAL	POWER - GAS (1st Phase)	JET AIRCRAFT	POWER - WIND	CARS	CFLs	BICYCLES	E-BIKES
STARTING POINT	Invention (cf.invention list)	Year	1915	1938	1842	1791	1928	n.a.	1860	1852	1818	n.a.
		Source	Mensch [34]	(LOC)[9]	Mensch [34]	[25]	Mensch [34]	n.a.	Mensch [34]	Mensch [34]	Mensch [34]	n.a.
	Innovation (cf.innovation list)	Year	1937	1954	1882	1903	1939	1880	1886	1927	1869	1891
		Source	(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]	Mensch[34]/(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]
	First 'embodiment' of technology	Year	1851	1951	1878	n.a.	1930	1887	1873	1973	1817	1895
		Model	First refinery	EBRn.a.I Idaho	First power station in Bavaria	n.a.	Whittle's turbojet engine	First wind turbine	Bollé's 1st steam vehicle	GE invents spiral CFL	Draisine	Ogden Bolton Jr.
	Max.R&D expenditure [1,5]	Year	n.a.	1979	n.a.	n.a.	1967	2010	n.a.	n.a.	n.a.	n.a.
		in millions 2005$	n.a.	3963	n.a.	n.a.	24398	45	n.a.	n.a.	n.a.	n.a.
	First applicat° outside lab/ first commercial application	Year	1856	1954	1882	1903	1939	1891	1880	1980	1861	1897
		Description	First large refinery	USSR's Obninsk plant	Edison Electric Light Station	A.Elling 's gas turbine	von Ohain's first flight	La Cour	Siegfried Marcus / Benz	Philips model SL	Michaux's Velocipède	Hosea W. Libbey
	First available data	Year	1947	1954	1908	1903	1958	1977	1900	1990	1861	1997
		units	361	1	1	1	8	2	8000	83300000	2	15000
	First sequential commercialization	Year	n.a.	1954	1908	1903	1952	1977	1888	1980	1861	1970
		Units	n.a.	1	1	1	114	2	n.a.	100000	2	n.a.
		Model	n.a.	APSn.a.1 OBNINSK	Turbo generators	A.Elling ?	Comet	Danish 3n.a.blade (26kW)	Benz car	Philips SL	Michaux's Velocipède	n.a.
ENDING POINT	Total milestones	Year of 10%K (cumul.#)	n.a.	1966	1938	1968	1969	1985	1937	1994	1922	2005
		Year of 10%K (cumul.MW)	1945	1973	1957	1976	1971	1991	1955	1994	1922	2005
	Up-scaling of unit size	Year of 10% K (max. unit capacity)	n.a.	1960	*1928*	*1943*	<1958	1999	n.a.	n.a.	n.a.	n.a.
		Year of 10% K (avg. unit capacity)	*1942*	*1961*	*1926*	*1906*	<1958	1990	1918	n.a.	n.a.	1990s (late)
	Market structure	Year of peak in the No of firms (N)	n.a.	n.a.	n.a.	n.a.	*1973*	n.a.	1908	n.a.	n.a.	n.a.
		"shakeout" (N falls -30% from the peak)	n.a.	n.a.	n.a.	n.a.	1979	n.a.	1914	n.a.	n.a.	n.a.
		Year of min. market concentration ratio(CR4)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1911	n.a.	n.a.	n.a.
	Production scale up	Year of decuple(10x) of production	no/n.a.	no/n.a.	no/n.a.	no/n.a.	1959	no/n.a.	no/n.a.	no/n.a.	no/n.a.	no/n.a.
		Year of highest growth	1956	1957	1910	1906	1959	1978	1901	1991	1862	1998
		%	7%	150%	595%	195%	958%	550%	85%	105%	7095%	263%
	Cost reduction [2]	Year of first halving in cost	n.a.	no/n.a.	no/n.a.	no/n.a.	n.a.	no/n.a.	no/n.a.	no/n.a.	1897	no/n.a.
		Year of highest relative cost reduction	n.a.	1980	*1991*	1975	n.a.	2002	1924	1999	1897	1999
		% (max. cost reduction)	n.a.	19%	2%	17%	n.a.	15%	25%	21%	63%	22%
		Description (model, mass prod.)	n.a.	PWR	Conventional coal PP	Conventional gas PP	n.a.	Danish model	Ford Model T	n.a.	Safety bike	mass prod.
	Dominant Design [5]	Year	1937	1970	1920	1939	1958	1957	1909	1985	1884	1946
		Model	Catalytic cracking	LWR (PWR)	Pulverized coal system	BBC Velow plant	B707/DCn.a.8	Gedser wind turbine	Ford T	Electronic ballast	Safety bike	Tucker's Wheel motor unit
	User adaptation	Lead user [3]? (Yes/No)	No	Yes	No	No	No	No	No	No	No	No
		Year of 2.5%K (in use)	n.a.	1960	1916	1948	1960	1982	1917	~1990	1883	2002
	Patent applications	Year of first peak	n.a.	n.a.	n.a.	n.a.	n.a.	1980	1897	n.a.	n.a.	n.a.
		Year of start of 2nd wave of increase	n.a.	n.a.	n.a.	n.a.	n.a.	1996	1914	n.a.	n.a.	n.a.
Sources:				[29],[30]	[28]	[26]	[6],[25]	[24],[33],[38]	[7],[13],[23],[31],[32]	[22]	[20],[21]	[19]

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STEAMSHIPS	STEAM LOCOMOTIVES	STEAM STATIONARY	MOTORCYCLES	CELLPHONES	WASHING MACHINES
n.a.	1769	1698	1867	1947	1900
n.a.	Mensch [34]	(LOC)[9]	(LOC)[9]	(LOC)[9]	[36,37]
1787	1825	1712	1885	1973	1908
(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]	(LOC)[9]
1776	1804	1712	1885	1946	1904
Jouffroi's Palmipède	Trevithick's locomotive	Newcomen	Daimlern.a.Maybach's Reitwagen	First mobile phone in a car	First electric washing machine
n.a.	n.a.	n.a.	n.a.	1987	n.a.
n.a.	n.a.	n.a.	n.a.	15726	n.a.
1807	1814	1712	1894	1977	1908
Robert Fulton's Clermont	Stephenson's Locomotion	Newcomen	H&W motorcycles	Prototype cellular system	Thor washer
1810	1835	1710	1900	1979	1927
8	35	4	1330	23482	760000
1811	1825	1717	1900	1979	1908
1	4	5	1330	n.a.	n.a.
Paddle wheel and sail	Locomotion No 1	Newcomen	Werner (UK)	First commercial system in Japan	Thor
1880	1880	1870	1949	2001	1951
1890	1900	1880	1956	2001	1962
n.a.	n.a.	1748	n.a.	n.a.	n.a.
1830s	1840	1730	1941	n.a.	1943
n.a.	n.a.	*1869*	n.a.	n.a.	n.a.
n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1810s	no/n.a.	no/n.a.	no/n.a.	no/n.a.	no/n.a.
1720	1850	1820	1901	1981	1921
900%	493%	3442%	194%	171%	226%
n.a.	*1855*	no/n.a.	n.a.	n.a.	n.a.
n.a.	1855	1727	n.a.	n.a.	n.a.
n.a.	85%	30%	n.a.	n.a.	n.a.
n.a.	4n.a.4n.a.0	Newcomen	n.a.	n.a.	n.a.
1807	1829	1712	1901	1973	1937
Fulton's Clermont	Stephenson's Rocket	various designs	"diamond frame"	Cooper's portable handset	Bendix automatic wash.mach.
No	Yes	No	No	No	No
1820s	1850	1830	1913	1993	1927
n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
[12],[14],[15]	[11],[16],[17]	[8]n.a.[10]		[18],[27]	[36],[37]