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New evidence in technology scaling dynamics and the role of the formative phase

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Abstract

This paper presents the latest update for historical scaling dynamics research including new technologies such as general purpose technologies (e.g., steam engines) and small end-use technologies (e.g., cellphones, e-bikes). Scaling refers to technology growth that is rapid and extensive, occurring at different levels, both unit and industry. It also studies the importance of the formative phase in the historical diffusion of energy technologies. So, what are the characteristics of the formative phase in the case of fast and intense adoptions? What is the influence of the formative phase in the overall diffusion? Empirical analysis uses logistic models to explore the growth of energy technologies observed historically. The formative phase is defined here as the early stage of diffusion before technology up-scales at unit level; the operational criteria adopted is that formative phase ends when diffusion reaches 10% of cumulative total unit numbers. The historical evidence confirms that larger transitions require more time for experimentation and maturation in the formative periods, especially in the case of complex innovations with high infrastructure needs. In addition, small size technologies with high turnover rates present the fastest diffusion. More research is needed to refine the definition of the moment when the technology completes the formative phase and acquires enough maturity to pass on to mass-commercialization.

Keywords: technological change; innovation; economies of scale; logistic growth; formative phases.

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About the Author

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New evidence in technology scaling dynamics and the role of the formative phase

Nuno Bento

1. Introduction

The energy system has grown at an unprecedented rate over the last century: total energy use passed from 20 EJ in 1800 to 430 EJ in 2000, a 21-fold increase (Grubler, 2008), of which 16-fold were only in the 20th century when population knew a 4-fold augmentation (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). In addition, 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 had in the late 19th century.

The technology research community is increasingly studying the determinants 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 is starting to look at processes that occur during the formative phase of technologies and affect the overall diffusion (Wilson, 2012).

The transition to new technologies, from invention to widespread diffusion, was normally a long process that spanned over several decades (Grubler, 1998; 2012). The investigation 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. The former ones have more challenges to diffuse in terms of the installation of a larger production base, stricter objectives of performance and costs, etc., and so need more time to prepare for an intense up-scale and growth. For instance, wind power took almost two decades to grow while steam engines had to wait a century before widespread diffusion, but then their impact on the energy system was far more pervasive.[1] The extent-duration of diffusion relationship was shown to be very strong for a set of energy technologies (Wilson, 2009). Among other implications, it may point to the limits in the capacity of R&D investment and dynamic effects (e.g., economies of scale and learning) to accelerate technology penetration in the market (Wilson & Grubler, 2011).

The diffusion of larger and more powerful technologies amplifies their impact on the energy system. In fact, up-scaling at unit level allows the technology to deliver more services at lower costs by the effect of economies of scale. The historical evidence shows that the expansion of energy technologies typically evolved in a three phase process (cf. Wilson, 2012): i) a formative phase consisting on the production of many small scale units aimed at establishing a manufacturing base that reduce costs through learning; ii) an up-scaling phase by constructing ever larger units (e.g., steam turbines or power plants) to gather technological economies of scale; and finally, iii) 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 later stages depends on the processes occurring during the initial period of development.

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. 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), low penetration levels, unarticulated demand, and weak positive externalities (Bergek et al., 2008a; Abernathy & Utterback, 1978). In this formative period the innovation is tested in a specialized niche market which generates 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, as well as generate 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 (Wilson & Grubler, 2011).

[1] See Appendix 1 for more details on the history of steam engines.

Thus, experimentation and demonstration are two important features of the formative phase. Experimentation allows the technology to be "debugged" with the accumulation of experience (Ruttan, 2001). It is a means of promoting the articulation of designs, policies, markets, as well as user requirements and cultural significance of an innovation (Kemp et al. 1998). Demonstration is critical for commercialization by increasing confidence in innovation through providing evidence of the viability of scaling up lab size applications into commercial prototypes.

A more theoretical literature on functions of innovation systems considers that the formative phase and the entire lifecycle of an innovation takes place within a particular technology innovation system (Carlsson & Stanckiewicz, 1991; Jacobsson & Johnson, 2000) which is constituted by actors, networks and institutions (Bergek et al, 2008a; Jacobsson & Bergek, 2004). It has identified key functions or processes required for a successful maturation of the innovation during the early stage, among them are the formation of knowledge (learning), experimentation and the formation of markets (Bergek et al., 2008b; Hekkert & Negro, 2009; Jacobsson & Lauber, 2006). Interaction between functions accelerates innovation emergence and growth (Hekkert & Negro, 2009; Hekkert et al., 2007).

In these terms, the formative phase is marked by the 'co-evolution' between institutions and technologies, during which technology should articulate with its institutional and business context in order to grow (Bergek et al., 2008a; Jacobsson, 2008). Institutional alignment with the needs of the technology is critical. This means supporting diversity in the initial process of knowledge generation, reducing uncertainties through market formation, and increasing the legitimacy of the technology (Jacobsson & Bergek, 2004; Jacobsson & Lauber, 2006). Examples can be found in the diffusion of solar power in Germany (Jacobsson and Bergek, 2004), wind power in Germany and Denmark (Jacobsson & Lauber, 2006) and biomass digestion and gasification in Germany and the Netherlands (Hekkert & Negro, 2009).

So, the formative phase is the time required to set up the structure of the new innovation system and fulfill the system functions, enabling spillovers that accelerate cumulative causations and lead to widespread growth (Bergek et al., 2008b; Hekkert et al., 2007). This approach highlights a number of processes that are present during the formative phase which contribute to accelerate or constrain diffusion. For instance, the growth of a technology that is a ready substitute for incumbents may be faster than the diffusion of a radical innovation which requires the deployment of a new infrastructure, organizational reforms, etc., in a word a new system innovation, needing a longer period of development to get ready for diffusion.

Two propositions can be drawn from the aforementioned literature. Firstly, innovations with larger market impact require longer periods of formation to bring together all the necessary conditions (e.g., technical, institutional) for diffusion. Secondly, complex energy innovation systems with more infrastructural needs have longer formative phases.

This research aims to understand how technologies behave during the early stages of diffusion, and to what extent this phase influences technology growth. So: what are the characteristics of the formative phase in the case of fast and intense adoptions? The processes that occurred in the early stage are analyzed through a "meta-analytic" comparative study of observable transitions in the past. Logistic growth models are used to describe historical diffusion of a series of energy supply and end-use technologies. Firstly, data sources are presented and the methodology followed in the analysis. Secondly, the main findings are shown in terms of the patterns of technological change observed during the formative phases, diffusion phases and spatial diffusion. This research also updates and tests the robustness of the relations that were previously found in earlier scaling dynamics studies, which can be used for multiple applications such as scenarios validation against historical evidence or to explain cost dynamics. It is argued that a minimum time is required for technology to be experimented upon and further improved before it can be ready to grow in the market. In addition, it is analyzed the behavior of small, less complex, and short lifetime innovations in terms of the speed of up-scaling and widespread diffusion.

2. Data used

The diffusion of technologies is analyzed both in terms of unit numbers and capacity (megawatts), at unit and industry level, following the methodology developed in previous technology scaling dynamics (cf. Wilson, 2009, 2012).

Capacity captures the potential of a technology to contribute to the growth and transformation of the energy system. It reflects the service provided by the technology, e.g. the wattage of an electric bicycle is related to the mobility service provided; the horsepower of a steam engine is related to the (mechanical) force service provided. Information on capacity is widely available for energy technologies (e.g., power plants) or can be easily converted (e.g., horsepower of steam engines). And the choice of capacity is well suited to compare different energy technologies because it has a high degree of generality and is not affected by the differences between technologies in terms of efficiency, capital investment or labour productivity.

In addition, cumulative figures were preferred to annual additions or growth rates because they contain the whole history of production and capacity evolution, and smooth out short-term variability. Also it doesn't need to take into account capital turnover (replacement, retirement, substitution, etc.), which is case and time sensitive and so very difficult to calculate accurately at the industry level. See more explanations in Wilson (2009).

Therefore the cumulative number of units produced are used, as well as energy conversion capacity in MW, at both unit and industry (i.e., cumulative total capacity of all units) levels.

Table 1 presents the set of technologies surveyed by this study, as well as data sources. Historical time series were compiled and analyzed on both end-use and supply-side energy technologies. Data was collected from the year of first commercialization, or close to if data not available. More information about the data series and data sources can be found in supplementary material available online, or in individual research papers about the historical diffusion of bicycles (Bento, submitted for publication), electric bicycles (Bento, 2012a), and mobile phones (Bento, 2012b).

TABLE 1. HISTORICAL ENERGY TECHNOLOGIES INCLUDED IN THE ANALYSIS: SERIES, SPATIAL DISAGGREGATION AND LOGISTIC FITS (SEE TABLE NOTES FOR DATA SOURCES)

	Technology	Data & Units	Time Series			Regions	Main Sources[i]
			Unit Capacity	Unit Numbers	Industry Capacity		
Supply-Side Technologies	Oil Refineries[ii]	Total Capacity (bpd)	1940-2000 (average only)	*not available*	1940-2007	Core: OECD, (Former Soviet Union) FSU Rim2: Asia(excl.China), Mid.East,Lat.America Periphery: China, Africa Global	Oil & Gas Journal, BP, Enos
	Power - Coal	Capacity Additions (#, MW)	1908-2000 (max. & average)	1908-2000	1908-2000	Core: OECD Rim1: FSU Rim2: Asia, South Aftrica Periphery: Africa (exl. South Afr.), Lat.Am. Global	Platts
	Power - Nuclear	Capacity Additions (#, MW)	1956-2000 (max. & average)	1956-2000	1956-2000	Core: OECD Rim1: FSU Rim2: Asia Periphery: Africa, Lat.Am. Global	Platts
	Power - Natural Gas	Capacity Additions (#, MW)	1903-2000 (max. & average)	1903-2000	1903-2000		Platts
	Power - Wind	Capacity Additions (#, MW)	1977-2008 (average only)	1977-2008	1977-2008	Core: Denmark	DEA, BTM Consult
	Steam stationary	Total Capacity (#,hp)	1710-1930 (average only)	1710-1930	1710-1930	Core: UK, US Rim2: Continental Europe Periphery: Rest of the world (RoW) Global	Kanefsky, Woytinsky, US Census
End Use Technologies	Passenger Jet Aircraft[iii]	Aircraft Delivered (#, Model) & Engine Thrust (kN)	1958-2007 (max. & average)	1958-2007	1958-2007	Core: Boeing Rim2: Airbus Global: Boeing, McDouglas, Airbus	Jane's, aircraft databases
	Passenger Cars	Cars Produced (#) & Engine Capacity (hp)	1910-1960, 1960-2005	1900-2005	*calculated from unit data*	Core: US Rim1: FSU Rim2: OECD(excl.US) Periphery: Developing Global	AAMA, US NHTSA, ACEA
	Compact Fluorescent Light Bulbs	Light Bulb Sales (#)	*estimated*	1990-2003	*estimated*	Core: OECD (exc.Japan) Rim2: Asia Periphery: RoW Global	IEA
	Electric bicycles	E-bikes production (#)	*estimated*	1997-2010	*estimated*	Core: China Rim2: RoW Global	Weinert, Jamerson& Benjamin
	Steam locomotives	Installed Capacity (#, hp)	1830-1960 (average only)	1830-1960	1830-1960	Core: UK, US Rim2: Continental Europe Periphery: RoW Global	Woytinsky, US Census, Daugherty
	Steamships	Installed Capacity (#, hp)	1810-1940 (average only)	1810-1940	1810-1940		Mitchell, Woytinsky, US Census
	Motorcycles	Motorcycles production (#)	*estimated*	1900-2008	1900-2008	Core: UK, France, Germany, Italy Rim1: FSU Rim2: US, Japan Periphery: China, India, Indonesia Global (incl.RoW)	UN
	Mobile Phones	Cellphones sales (#)	*estimated*	1979-2010	1979-2010	Core: Scandinavia, Japan Rim2: OECD Periphery: RoW Global	Gartner
	Washing machines	Washing machines production (#)	*estimated*	1920-2008	estimated	Core: US Global	UN, Stiftung Warentest

[i] Main Sources: (described in detail in (Wilson, 2009): *Refineries* - (BP, 2008; Enos, 2002; OGJ, 1999, 2000); *Coal, nuclear, natural gas power* - (Platts, 2005); *Wind power* - (BTM_Consult, 2002; Danish_Energy_Agency, 2008); *Passenger jet aircraft* - (Jane's, 1998) with supplementary data from online sources including www.airliners.net, www.flightglobal.com, www.boeing.com, www.airbus.com; *Passenger Cars* - (AAMA, 1980, 1995, 1997) with supplementary data from online sources including US National Highways Traffic Safety Agency (www.nhtsa.dot.gov) and European Automobile Manufacturers' Association (www.acea.be); *Compact fluorescent light bulbs* – (IEA, 2006).

(new technologies surveyed in this study): *Electric bicycles* (Weinert, 2007; Jamerson & Benjamin, 2011; Pike Research, 2010) with supplementary data from online sources BOVAG-RAI (http://www.bovag-cijfers.nl); *Steam locomotives* (Wright, 1930; Hunter, 1985; Daugherty, 1933; US Census - Bicentennial Ed., 1975, 1997; US Census, 1865, 1870, 1880; Woytinsky & Woytinsky, 1953; Kaiserlichen - Germany Statistisches (various years); Fremdling, 1977; Smith 2009; Crouzet, 2000; Merger, 1989; Woytinsky, 1926), *Steam stationary* (Von Tunzelmann, 1978; Kanefsky, 1979; Kanefsky & Robey, 1980; Atack et al., 1980; Hunter, 1985; Woytinsky, 1926; Allen, 2009; US Census 1902, 1912); *Steamships* (Mitchell, 1980, 1993; US Census - Bicentennial Ed., 1975, 1997; Woytinsky, 1926); *Mobile phones* – (ITU, 2011; Gartner, annual reports: http://www.gartner.com/); Washing machines (UN, 2008, various years; U.S. Census Office, 1978) with unit capacity calculated from the average power of European machines cf. Stiftung Warentest (annual reports available at www.test.de). Even though the size of washing machines is not the same, the capacity is similar: the US machine is three times larger than the European one, though the former uses hot water from an external source, while the latter heats it up internally.
[ii] Industry level - installed capacity (not cumulative capacity). Unit level-US only (fluid catalytic cracking units).
[iii] Boeing, McDonnell-Douglas, Airbus only. We estimate that these 3 manufacturers have accounted for over 2/3 of total cumulative sales of large commercial jet aircraft (and currently account for over 90% of annual sales). Historically, the other main manufacturers were from the former Soviet Union (e.g., Tupolev, Ilyushin) but available data are incomplete. See Wilson (2009) for more details.

The diffusion of other technologies was surveyed with the same methodology. For instance the growth of bicycles was examined (see Bento, 2012a), but there was a clear problem with the conversion to energy capacity terms. Indeed the impact of diffusion was limited by the low capacity assumed for bicycles (100 watts per bicycle) due to the low efficiency of humans. However, the implications in terms of the service provided (mobility) in real life were much more important than what the analysis of capacity suggested, therefore it was decided to remove bicycles from the sample of technologies.

3. Method applied

The aim of this research is to investigate the importance of the formative phase in technology diffusion, and explain the process that occurs in the early stage through "meta-analytic" comparative studies of observable transitions in the past. The method consists of using logistic growth functions to describe historical diffusion data for a range of different energy supply and end-use technologies, and extract from them the rate and extent parameters. These parameters are then compared with the extent and duration of the formative phases of other technologies to find a pattern of technology growth over time. The objective of this analysis is to understand how successful technologies behave during the early stages of diffusion, and to what extent this phase influences technology growth.

The logistic growth model is used to fit actual data in order to identify patterns in the temporal growth of technologies. The examination of simple growth rates would be quite volatile and influenced by short-term variations, instead fitting data with logistic functions can more reliably identify long term tendencies.[2] There is a wide range of evidence supporting the use

[2] Other models, such as Gompertz or Sharif-Kabir, were tested with the help of the Logistic Substitution Model (LSM II) software developed at the International Institute of Applied Systems Analysis (IIASA) which is also

of the three-parameter logistic function to represent long term technological transitions, namely in the energy and transport field (Grubler, 1999, 1998; Marchetti & Nakicenovic, 1979). This function is inspired by the logistic model (Fisher & Pry, 1971)—a three parameter, S-shaped, model assuming symmetry around the inflection point—representing technological diffusion as follows:

$$y = \frac{K}{1 + e^{-b(t-t_0)}}$$

where:

K = saturation level (asymptote)

t_0 = inflection point at K/2

b = diffusion rate (steepness of the S-curve)

Δt = time period over which y diffuses from 10% to 90% (or similarly from 1% to 50%) of its saturation level (K), and Δt = (1/b).log 81

The logistic function provides information about the extent and the duration of diffusion. Figure 1 provides an illustration of the metrics using the diffusion of all steam machines in UK and US (included in the Core because of its role in the development of high pressure steam engines and its introduction in mobile applications). The parameter K gives the saturation level of diffusion, while the Δt is a measure of the time duration of diffusion—more precisely from 10% to 90% or from 1% to 50% of saturation—which is inversely proportional to the rate of diffusion with higher Δt values meaning slower diffusion. The parameters are fitted according to a criterion of quality (adjusted R^2 higher than 95%) and a minimum of observations to provide confidence to the real value of the saturation level (60% of the calculated K must be covered by historical data) (Wilson, 2009; Debecker & Modis 1994).

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available online at http://www.iiasa.ac.at/Research/TNT/WEB/Software/LSM2/lsm2-index.html?sb=3 . Although the logistic function gave the best results globally, and thus was chosen for this study. See Grubler (1998) for more details on diffusion models.

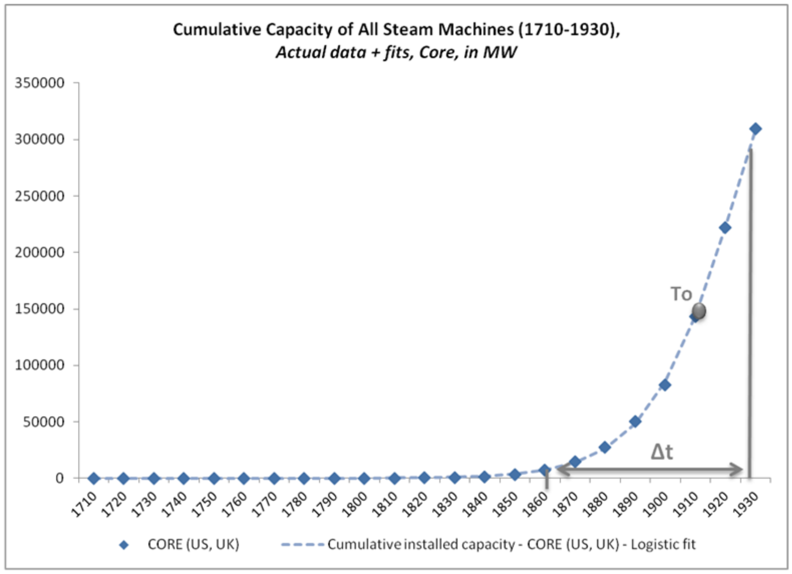

FIGURE 1. CUMULATIVE CAPACITY GROWTH OF ALL STEAM MACHINES IN UK AND US BETWEEN 1710 AND 1930, IN MEGAWATTS

It is important to remember that the logistic model provides descriptive parameters like the diffusion rate, only. The literature identified a few factors that can speed up or slow down the rate of diffusion or Δt (for a review see Rogers, 1995; Grubler, 1998). Among them are the scale or market size (i.e., the larger the technology system, the longer it takes to penetrate the market), technology complexity and infrastructure (i.e., complex and interrelated technology systems, needing a heavy and new infrastructure, will require more time to develop), and comparative advantage over the incumbent or replaced technology (meaning that a more efficient, performing and cheaper innovation will diffuse faster).

Patterns of spatial diffusion were investigated by disaggregating global numbers into different regions: corer, rim and periphery. Theoretical and empirical studies suggested that adoption originates in innovation centers within core areas and then spreads out via a hierarchy of sub-center, fast follower, regions (here called rim 1 and rim 2) until it ultimately reaches the periphery (Grubler 1998). Countries are classified by regions according to the moment they started adopting the technology in the sequence of widespread diffusion. The position of a country varies by technology, e.g., the United States (where automobiles were first mass commercialized) are core market for cars while the United Kingdom is core for steam engines for the same reason (though we assumed that the UK shares this position with the US because of the role of the latter in the development of the high pressure steam engines). There was often the need to separate between rim 1 and rim 2 areas to distinguish the diffusion in former soviet countries, where the decision process was more centralized (rim 1) than in other countries where adoption results from a more decentralized process (rim 2).

Since the impact of the technology depends on the scope of the market, the extent of diffusion is normalized by the size of the energy system at each moment in time (cf. Wilson, 2009). This was done by normalizing the extent of growth (K in MW) by the primary energy consumption (in EJ) at the inflection point (t0) of the fitted logistic function. The final result is an index allowing the comparison of technologies diffused at different moments in time.

The characterization of the formative phase of technologies is one of the main goals of this paper. This requires the definition of the formative period, especially the end point when the technology passes to the next stage of up-scaling. In previous analysis it was shown that diffusion is first pushed by the growth in unit numbers and by capacity later on (Wilson, 2009). Thus an operational criteria of 10% of the maximum number of units (cumulative unit numbers) is adopted here as the limit for the formative phase after which the up-scaling phase will start. For instance this pattern of growth was observed during the diffusion of wind power plants in Denmark (see Wilson, 2012). This criterion has the advantage of estimating the length of the initial phase of the technology, but has some limitations such as the link to the final number of units produced meaning that successful technologies will have formative phases characterized by large numbers of units.[3] Therefore it is important to remember that this formative phase definition is applied **ex post** and is a workable assumption intended to be reasonable for a first order study of the initial period of technology development. This is a first step in the attempt to quantify the formative phase of innovations, and more work should be done in the future to refine that definition. Table 2 provides a synthesis of main definitions and assumptions.

[3] Alternatively, one could estimate the year when unit capacity reaches 10% of the maximum, but this measure is not applicable to some technologies of our sample which do not up-scale (e.g., e-bikes, cellphones).

TABLE 2. MAIN DEFINITIONS AND ASSUMPTIONS

Formative phase	Definition: Early stage of diffusion before the technology up-scale at unit level. Criteria: ending at 10% of final (cumulative) maximum number of units (k)
Accuracy criterion for the logistic curve parameters	- minimum quality of fit (R^2) of 95% to insure accurately - sufficient historical data to estimate a reliable asymptote (at least 60% of K)
Definition of regions of diffusion	Temporal sequence of diffusion: - core, first(s) innovative market(s); - rim, fast followers (eventually separating FSU (rim 1) from other countries (rim 2)); - periphery, rest of the world.
Normalization of the extent of diffusion	Normalized K = K (in MW) / Primary energy consumption (EJ) at t_0

4. Findings

This section presents the main findings of the analysis to the growth of the technologies included in the sample considered in this research. The presentation is focused on the role of formative phases in the diffusion of different types of technologies. Thus results are first presented for the early stage of growth, then examine the influence in the dynamics of overall diffusion and finally the effect of (spatial) spillovers to enhance the impact of the technology.

4.1. Formative phases

What happens during the formative phase of technology diffusion? Is it possible to find similarities in the early stage among technologies of the same category? It is expected that complex and inter-dependent technologies, i.e., system integration requirements, show longer formative phases because they need the development of other technologies or areas (e.g., infrastructures) before they can penetrate into the market. This section analyzes the formative phases of several technologies.

The role of the formative phase in diffusion is analyzed in Figure 2 which presents the growth of the set of energy technologies surveyed in this study over the 20th century. The graph suggests that technological diffusion can take centuries, and depends on the market scale of the technology in the sense that innovations with higher impact will take more time to grow, which would confirm earlier results (Wilson & Grubler, 2011; Grubler et al., 2012). This is especially true in the case of new innovations compared to substitution technologies (e.g., cars vs. CFLs) which benefit from an already installed base support (e.g., infrastructure, knowledge, consumers) from the replaced technology to progress faster in the initial stage.

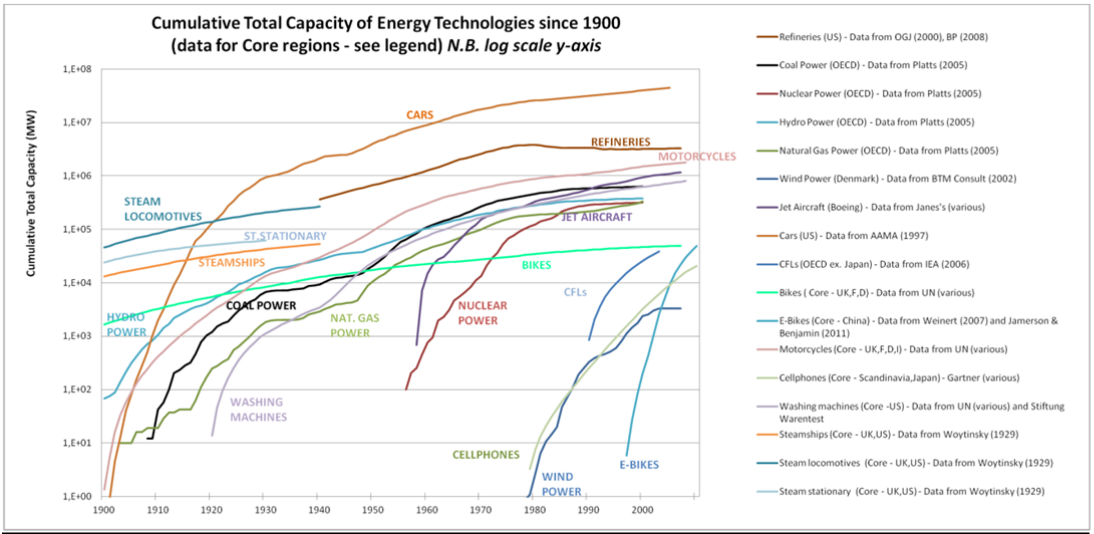

FIGURE 2. DIFFUSION OF ENERGY TECHNOLOGIES IN CUMULATIVE TOTAL CAPACITY TERMS SINCE 1900 (IN CORE REGIONS)

So, is it possible to associate a path of diffusion with a particular behavior during the formative phase of the technology? The next tables focus only upon the dynamics occurred during the initial stage of diffusion. The number of units produced in this period is an important measure of learning and depends on the characteristics of the technology. Therefore technologies were divided into two different tables according to the number of units produced in the early stage: hence, one table presents technologies that needed less than 1,000 units before passing to the subsequent phase; and another table shows data for technologies that experienced more than 1,000 units during the formative phase.

Each table contains information on the country where the innovation started (Core), the moment of the first commercialization, the year when 10% were reached both in terms of maximum unit numbers (here defined as the end of the formative phase) and capacity, the number of years of the formative phase and the number of units produced over that period, and finally the duration of the overall diffusion, i.e., Δt.

Table 3 summarizes the information on the formative phase of technologies that needed less than 1,000 units to pass on to the next phase of higher growth coinciding mostly with energy supply technologies.

TABLE 3. FORMATIVE PHASE OF ENERGY SUPPLY TECHNOLOGIES (IN CORE)

Technology	Core Market	First Commercial Capacity Installed	10% of Maximum Cumulative Total Numbers of Units	Formative Phase: Number of Years	Formative Phase: Number of Units	10% of Maximum Cumulative Total Capacity (MW)	Δt (10-90% max. MW)
Nuclear Power	OECD	1950s (1940s)[a]	1966	10-20	41	1973	20
Coal Power	OECD	1900s	1940	40	386	1957	33
Natural Gas Power	OECD	1900s	1949	45-50	456	1955	28
Wind Power	Denmark	1970s (1880s)[a]	1985	15-100	769	1991	11
Refineries [b]	*US*	*1860s-1870s*	.	*80-90*	*>500***	*1948*	*41*

[a] First nuclear installations on submarines date to 1940s; first wind power generators date to 1880s, but from 1970s in their modern form.

[b] Refineries data is indicative only because it is measured in installed capacity, not cumulative. Saturation capacity measured in terms of average rather than maximum capacities; **number of units are rough estimate.

According to the criterion that was retained in this paper, the formative phase ends when technology reaches 10% of its maximum unit numbers. In our sample that moment always happened before the point when technology attains 10% of total capacity, which confirms that in early years diffusion is pushed by the number of units and not by capacity (cf. Wilson & Grubler, 2011). Up-scaling occurs only after enough experience is gained in production.

The formative phase was more important in the case of new systems, such as refineries, for which the diffusion took almost a century to accelerate. However nuclear power passed through a relatively fast formative phase through a rapid unit up-scale in a more centrally planned and publicly funded R&D and deployment. The low number of units built during the initial stage of diffusion (i.e., around ten times less than for natural power plants and coal power plants) may be explained by the will to rapidly leapfrog to a much larger unit scale without passing through the phase of experimentation. That strategy was not without an important impact in costs as was demonstrated for the case of nuclear development in France (Grubler, 2010).

On the other hand, the set of technologies needed to build more than 1,000 units during the formative phase is shown on Table 4. This group coincides with general purpose technologies like steam engines and end-use energy technologies. The diffusion of steam engines demonstrates the importance of technology readiness to progress towards mass commercialization: it took more than a century between the invention of the steam engine and its spillover to other applications such as land and sea transportation. This example underlines the importance that knowledge creation and incremental innovations have to improve the technology and fulfill its potential. Indeed GPT are characterized by a wide scope of improvements, broad range of uses, and strong complementarities with other innovations (Rosenberg and Trajtenberg, 2004; Lipsey et al., 1998). A considerable activity of experimentation of thousands of units (more than 200 thousands of steam engines in the UK) was needed before the fundamental design and features of the technology stabilized (Abernathy & Utterback, 1978). The fact that 10% of cumulative total capacity was only reached very late at the end of the 19th century reveals that intensive up-scaling at unit level started to produce an effect by that time in terms of boosting capacity.

In the case of end-use technologies, it is possible to make a distinction between residential and transport systems because of the complexity and interrelation of the latter, requiring the installation of infrastructures, particular skills, etc. (Table 4). In the sample of technologies considered in this study, the growth of transport, such as cars or motorcycles, takes longer to materialize, while residential technologies only pass through the formative phase after the production of a large number of units - results indicate million, or even billion, units but this may be due to the definition of formative phases used which is linked to total unit numbers. For instance, technologies like cell phones, which have recently become the most popular technology, needed to produce a large number of units before mass diffusion and globalization, despite this they grew rapidly (Bento, 2012b).

TABLE 4. FORMATIVE PHASE OF END-USE TECHNOLOGIES AND GENERAL PURPOSE TECHNOLOGIES (IN CORE)

Technology		Core Market	First Commercial Capacity Installed	10% of Max. Cumulative Total Numbers of Units	Formative Phase: Number of Years	Formative Phase: Number of Units	10% of Max. Cumulative Total Capacity (MW)	Δt (10-90% max. MW)
GPT	Steamships	UK, US	1807	1880	73	24,022	1890	72
	Steam locomotives	UK, US	1825	1880	55	59,234	1900	63
	Stationary steam	UK, US	1710s	1861	150	157,939	1880	61
	All steam	UK	1710s	1870	160	229,738	1900	67
Transport	Jet aircraft	US	1958	1969	11	1,791	1973	49
	Motorcycles	West Europe	1900	1949	49	>12 million	1956	64
	E-bikes	China	1997	2005	8	>17 million	2005	8
	Cars	US	1890s-1900s	1937	40	>57 million	1955	67
Residential	Washing machines	US	1920	1951	31	>56 million	1962	54
	CFLs	OECD	1990	1994	4	>372 million	1994	15
	Cellphones	Nordic, Japan	1979	2001	22	>872 million	2002	17

In both tables it is interesting to note that the duration of the formative phase closely follows the rate of diffusion (Δt) across several technologies meaning that longer transitions need more time to form. It is surprising to see that the time needed to reach 10% of the maximum unit numbers (duration of formative phase) is more or less the same as to pass from 1 to 50% of the maximum capacity (equivalent to 10-90% max. of Δt), underlining the time required in the formative period of the technology as well as the role of up-scaling at the unit level to boost diffusion of capacity. However this might be explained by the high correlation between the number of units (from which the formative phase is derived) and capacity (from which Δt is calculated), even if the up-scaling at unit level is likely to weaken that link. More research is needed in terms of the definition of the formative phase and the influence it may have in the overall diffusion.

In summary, the data seems to confirm our initial expectations about the duration of the formative phase in long-term transitions, especially in the case of more complex and interrelated technologies such as GPT which need to wait for the invention of other technologies to spillover to other applications and fulfill all of its potential. Energy supply-side technologies and transport systems showed longer formative phases, while residential end-use technologies progress through intensive production in a shorter period of time. The scale of the technology also matters. The variability of situations observed inside the same category points out the importance of unit scale — we come back to this point later. Since it is not possible to build as many nuclear power plants as wind power plants to test the innovation, the length and the number of units produced during the formative phase must adapt to the type of technology. The next section studies the impact of different types of technologies on diffusion.

4.2. Diffusion phases

The aim of this section is to investigate the impact of different types of technologies on the pattern of diffusion. In the previous section it was shown that the duration and the intensity of the formative phase are both influenced by the characteristics of the technology, such as use and size, which might also have an effect over the entire growth. So, it is expected that the diffusion of new innovations takes more time than for substitute technologies, or the penetration of smaller and modular end-use technologies might be faster than larger and rigid energy supply technologies.

Previously, mentioned was the importance of technology scale upon the speed of diffusion. Former studies found a strong relationship between the market size and the rate of diffusion, the so-called extent-duration (k-Δt) relationship (Wilson, 2009; Wilson, 2012). For the present analysis, the historical data sets were updated with more technologies, such as supply-energy technologies from the past (e.g., steam engines, work animals), transport and communication technologies (e.g., electric bicycles, motorcycles, cellphones), and household appliances (e.g., washing machines). So, technologies that presented long formative phases, such as supply-side energy technologies and transport, are expected to show a higher (k-dt) relationship than for substitution end-use technologies. Figure 3 shows the results for the complete sample of technologies.

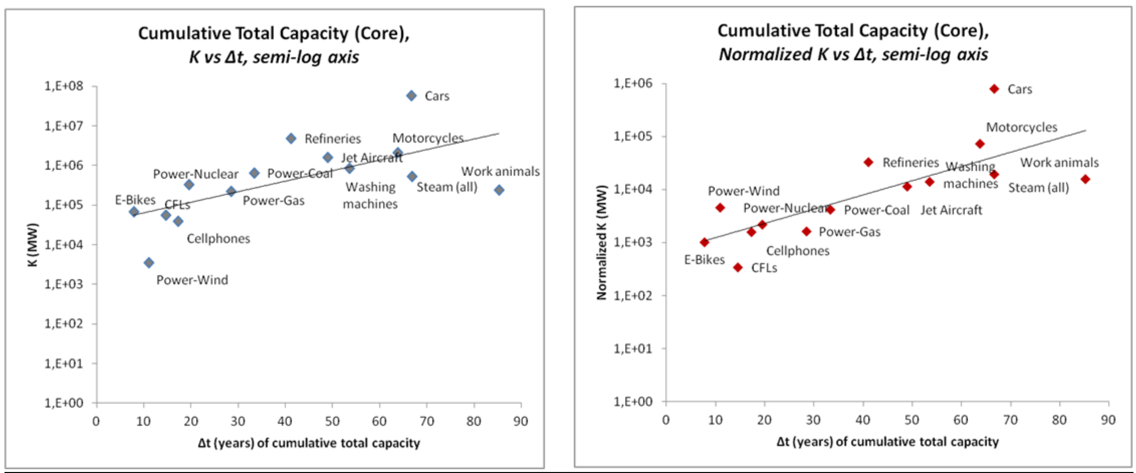

FIGURE 3. EXTENT - RATE OF TECHNOLOGY DIFFUSION RELATIONSHIP

The technologies considered in this figure are: steam engines (all); refineries; nuclear power plants (pp); coal pp; natural gas pp; wind pp; CFLs; cellphones; washing machines; jet aircraft; cars; e-bikes; motorcycles; and work animals.

The left-hand graph shows the extent-duration of diffusion relationship using saturation values directly taken from the fitted curves to actual data, while the right-hand graph uses normalized Ks to account for the difference in the size of the energy system in to which each technology diffused. From a comparison of both graphs, it is possible to confirm that normalization does not affect results (i.e., the gradient of the trend curve remain unchanged), only the scale of the values is altered. The most important finding is the reiteration of the positive relation between market size and duration of diffusion, meaning that technologies with larger potential (i.e., maximum cumulative capacity) take more time to diffuse.

However, these graphs offer a very aggregated picture of diffusion that hides the dynamics of change across several groups of technologies. Therefore a more detailed analysis is needed in order to look closer at particular patterns of diffusion according to different categories of innovations.

The impact was tested on the extent-duration of diffusion relationship of the categorization of technologies by:

- use;
- up-scaling dynamics;
- the length of the formative phase;
- lifetime;
- and granularity (unit size).

There is some discussion in the literature about the speed of diffusion of energy end-use technologies compared to energy supply technologies (see for instance Grubler, 2012). This would be motivated by a higher relative advantage of end-use technologies. A study about historical transitions in the UK, Fouquet (2011, 2008) showed evidence of a much faster decline in the energy service prices (e.g., lighting, transport) than in the energy input prices (e.g., electricity generation), mainly due to improvements in the efficiency of end-use conversion. Thus a fast diffusion of end-use technologies would be explained by economic reasons.

Figure 4 analyzes the effect of distinction of technologies by use in technology growth. The sample of technologies is divided into: general purpose technologies, energy-supply technologies, end-use transport and end-use residential technologies.

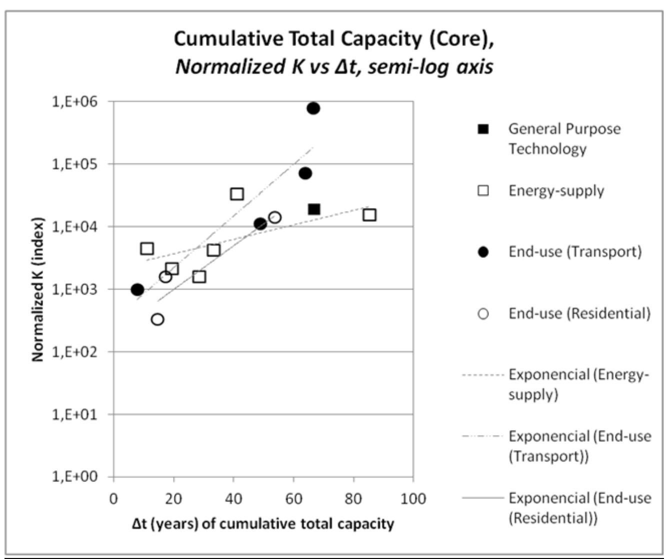

FIGURE 4. CATEGORIZATION OF TECHNOLOGIES (1) BY USE

Two main conclusions can be drawn from the analysis of the effect of technology use on diffusion. Firstly, the K - Δt representation shows a steeper gradient for end-use technologies suggesting that those technologies diffuse faster for a given amount of market penetration or capacity expansion. Secondly, residential technologies and energy supply technologies (empty circles and squares) in the sample penetrated quicker than transport and general purpose technologies. That may be explained by the complexity of transport systems and GPTs which often need complementary technologies such as infrastructures (roads, rails, etc.). For instance steam machines (stationary and mobile) took a long time (around 60 years) to grow because of the high level of interdependence of technologies and the various spillovers of their development.[4] The penetration of steam engines in manufacturing needed many inventions in other areas like in power transmission; its diffusion in mobile applications was dependent on the progress made in the power capacity of the engine as well as inventions in ships, locomotives and railways technologies (Von Tunzelmann, 1978; Allen, 2009).[5]

The trajectory of diffusion may be influenced by changes occurred at the unit scale of the technology. Up-scaling enhances the impact of the technology's diffusion, but it presupposes institutional capacity and learning to support the construction of larger unit sizes in order to capture scale economies. It is likely that technologies that have considerably up-scaled at some point will present higher saturation levels, as well as longer diffusion than technologies that have not up-scaled. In addition those technologies might have needed a longer formative phase to put together all the conditions (e.g., resources, knowledge) that made it possible for the construction of larger units.

The impact of up-scaling at unit level in technology growth is investigated in Figure 5. This figure compares technologies that up-scaled intensively (e.g., nuclear power plants), moderately (e.g., motorcycles), or even not at all (e.g., CFLs), since the beginning of the diffusion. The criteria followed to distinguish between « medium » and « high » upscale was whether or not the last unit scale reported (or the maximum scale if different) was ten times higher than the first commercial introduction.

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[4]Coinciding with longterm macroeconomic Kondratiev cycles (Freeman & Louçã, 2002; Freeman & Perez, 1988).
[5]For a brief history of the diffusion of steam engines, see Appendix 1.

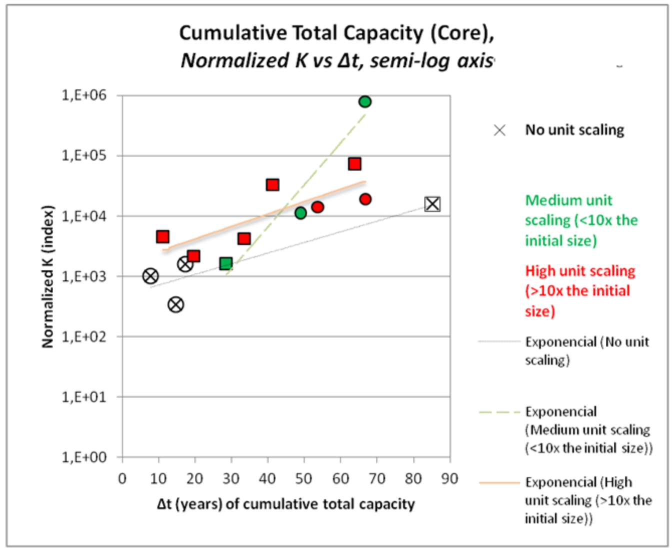


FIGURE 5. CATEGORIZATION OF TECHNOLOGIES (2) BY UP-SCALING

Note: squares indicates supply-side technologies (including GPT) and circles end-use technologies. High unit scaling technologies are signalled with red colour, medium scaling with green and no unit scale by crosses.

Evidence suggests that technologies with no unit scaling diffuse faster than the others - the only exception is the historical diffusion of work animals (mostly horses) in the US which took decades to penetrate the market. These are mostly small and diffuse technologies (e.g., cellphones, e-bikes), which raises the question of whether the size of the technology influences diffusion — the effect of « granularity » (i.e., smaller unit-scale, short life, technologies) is analized more in detail later. On the other hand, it is plausible that no up-scaling allows to pass through the formative phase faster, ceteris paribus, since the innovation does not face the same challenges (technical, institutional, and market) of building larger size units. In addition there is some evidence that up-scaling at unit level enhances the extent of growth because red circles and squares are normally above the other technologies of the sample. More examples are needed in the future to confirm (or disprove) this result which links up-scaling with the ultimate impact of the innovation directly.

The relation between unit scale dynamics and the length of the formative phase can be assessed through the comparison between Tables 3-4 and Table 5. Energy supply technologies such as power plants show high rates of up-scaling after passing through long formative phases. In addition transport technologies that significantly scaled at unit level also knew long formative periods. Therefore the evidence suggests that innovations with a large potential of up-scaling will need longer formative periods to set up all the conditions (e.g., technical, market, financial, institutional) that are necessary for the growth in scale.

TABLE 5. SIZE AND UNIT SCALING RELATIONSHIP

Technologies (in Core)	Δt	Unit scale at X moment (kW) First scale	To (mid-point)	Last scale	Δ(Last/First scale) (%)	Formative phase duration cf. Tables 3-4 (Number of years)
-No unit scaling						
CELLPHONES	17	0.0045	0.0045	0.0045	0%	22
CFLs	15	0.018	0.0153	0.018	0%	4
E-BIKES	8	0.39	0.39	0.39	0%	8
WORK ANIMALS	85	0.56	0.56	0.56	0%	-
-Medium unit scaling (<10x of initial size)						
JET AIRCRAFT	49	85000	118000	86000	1%	11
POWER - GAS (1st Phase)	28	10000	71000	76000	660%	45-50
CARS	67	15	90	140	833%	40
-High unit scaling (>10x of initial size)						
WASHING MACHINES	54	0.19	2.71	2.3	1111%	31
REFINERIES (FCC)	41	460000	7809000	10288000	2137%	80-90 *
POWER - NUCLEAR	20	50000	892000	1516000	2932%	10-20
MOTORCYCLES	64	1	12	37	3700%	49
POWER - COAL	33	12000	437000	467000	3792%	40
STEAM MACHINES (all)	67	3	-	141	4600%	160
POWER - WIND	11	30	680	1410	4600%	15-100

* Refineries data are indicative only because it is measured in installed capacity, not cumulative, and number of units are rough estimate.

It is now time to investigate the relationship between the length of formative phases and diffusion. It is expected that a longer formative phase leads to more pervasive diffusion, i.e., longer growth cycles (ΔT) and so higher K-ΔT relationships. The effect of the formative phase in the extent-duration relationship is shown in Figure 6. The formative phase goes from the moment of first commercialization until diffusion reaches 10% of cumulative total unit numbers. Technologies are distributed in different groups according to the duration of the formative phase: rapid, less than 20 years of formative phase; medium, 20 to 40 years; and long, more than 40 years.

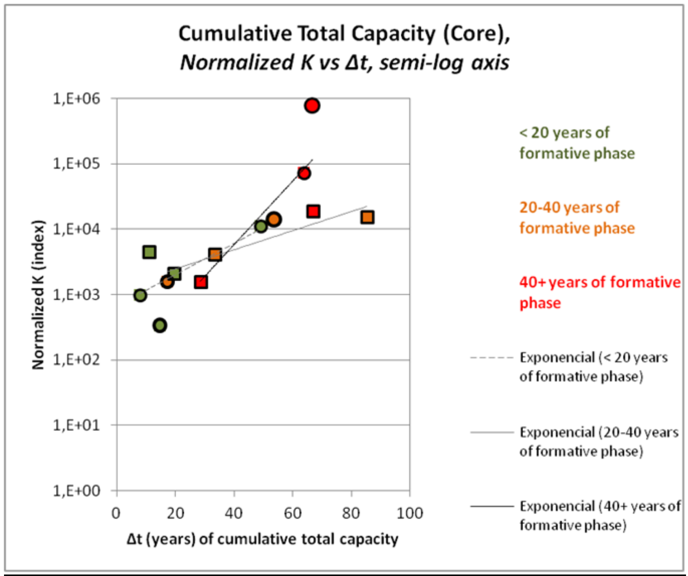


FIGURE 6. CATEGORIZATION OF TECHNOLOGIES (3) BY LENGTH OF FORMATIVE PHASE

Note: longer formative phases are signalled with red, medium formative phases with orange and shorter formative phases with green. Squares indicates supply-side technologies (including GPT but excluding refineries because it is measured in installed capacity and numbers are indicative) and circles end-use technologies.

The results seem to confirm the intuition that long formative phases are associated with technologies that penetrated with a great extent in the energy system. More radical and complex innovations (e.g., cars or steam machines) diffused extensively after having passed through long formative phases. Conversely, technologies with a shorter formative phase grow faster. The only exception was nuclear power plants (the second leftmost square with a cross) which experienced a longer diffusion despite the short formative phase motivated by the public's will to quickly up-scale at unit level in order to speed up installed capacity and production. Therefore the diffusion of new innovations with a high transformative potential may require even more time to prepare.

It is interesting to note that technologies like CFLs or e-bikes are ready for mass-commercialization quicker and then diffuse more rapidly. Those technologies are known for being small, with a short lifetime and rapidly replaced, enabling more experimentation and allowing for fast progress in the learning curve. Thus it has been tested that short life expectancy technologies grow faster than others. The impact of the technology lifetime on the diffusion extent-duration relationship is examined in Figure 7.

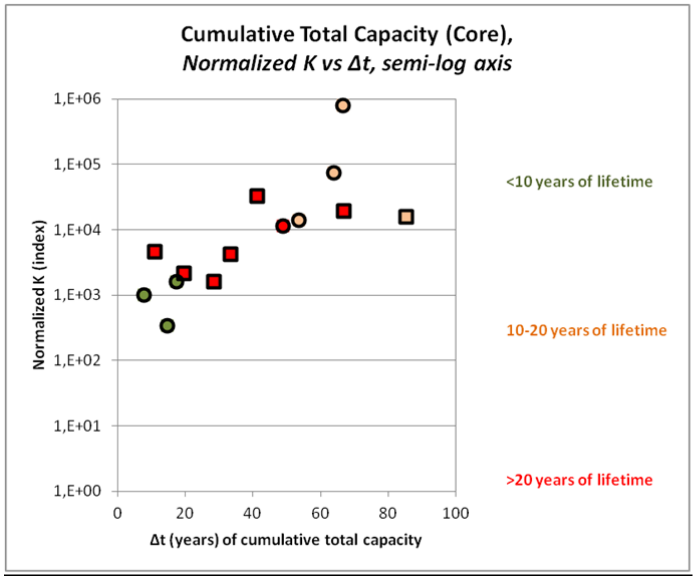


FIGURE 7. CATEGORIZATION OF TECHNOLOGIES (5) BY TECHNOLOGY LIFETIME: HIGH VERSUS SHORT RATE OF REPLACEMENT

Note: longer lifetime technologies are signalled with red, medium lifetime with orange and shorter lifetime with green. Squares indicates supply-side technologies (including GPT) and circles end-use technologies.

Figure 7 confirms that technologies with a short lifetime (less than 10 years) reach their market potential rapidly, needing less time to grow (high rates of diffusion) compared to technologies that last longer. Another interesting feature shown in the graph is that technologies with life expectancies longer than 20 years tend to diffuse faster than middle-range 10 to 20 years lifetime ones. This might be explained by the fact that long life expectancy technologies take a considerable amount of resources (human, financial, time, infrastructure, etc.) to build and so need a long time to recover from the initial investment. Thus they last longer without the need for replacement. For instance, nuclear power plants are a typical example because they need to operate for a long time period which can reach 40 years (or more) in order to justify the resources spent in their construction and dismantlement. The low turnover may "lock in" the market due to high sunk costs invested in the first generation models (Frankel, 1955), blocking the penetration of improved versions of the technology that limits the final impact of the diffusion.

In addition by comparison of Figures 6 and 7 it is possible to conclude that short lifetime technologies normally present fast formative phases. The only exception is cellphones, which have a short life expectancy but had slightly more than 20 years of formative phase (i.e., 23 years).

The relationship between the size and the life expectancy of technologies is analyzed in Figure 8. It is possible to see that both lifetime and unit size correlate strongly, meaning that bigger technologies last longer or vice-versa smaller technologies are replaced more rapidly. This is an important finding because it determines the chances that innovations have for experimentation during the formative stage. Thus smaller « granular » technologies allow for more units being produced and used because of the lower capital needs, giving more opportunities for experimentation that accelerates identification and resolution of technical problems, as well as the progression in the learning curve. They are also less susceptible to "lock in" motivated by the resistance to premature retirement of capital stock, which becomes less of an issue in the case of technologies with high turnover rates.

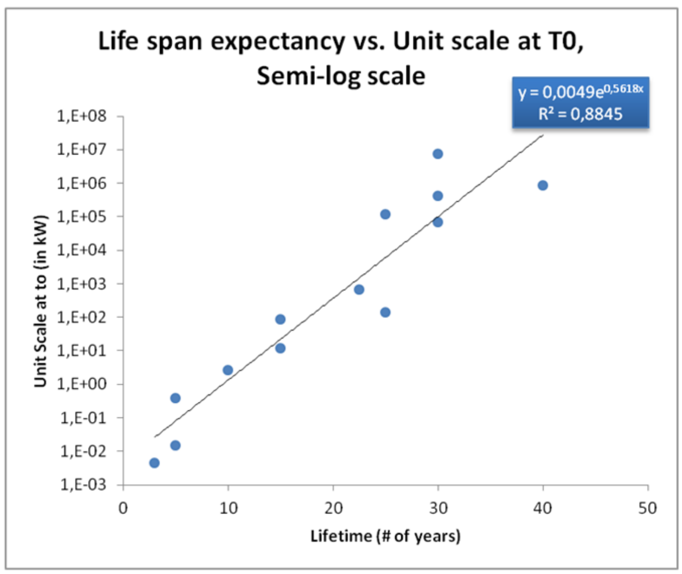


FIGURE 8. LIFE SPAN EXPECTANCY VS UNIT SCALE RELATIONSHIP

Large scale technologies are expected to take longer to grow than smaller ones because experimentation is more challenging for the former—both technically and financially—as well as their needing more time to obtain the right conditions (technology, institutions, markets) required to start deployment.

The impact of the technology size on the overall diffusion is analyzed in Figure 9. Technologies are now classified by their unit size—the last unit scale reported—in three groups : « watt scale », for technologies smaller than a kilowatt ; « kilowatt scale », for unit sizes between one kilowatt and one megawatt ; and « megawatt scale », for technologies bigger than one megawatt at the unit level.

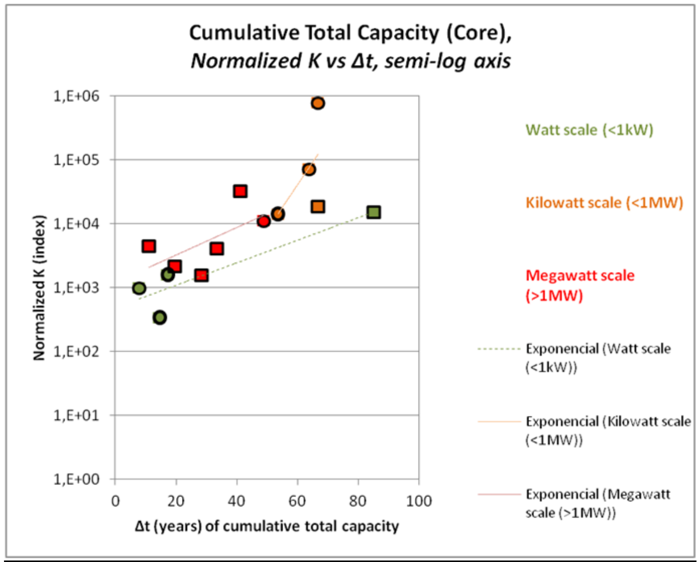


FIGURE 9. CATEGORIZATION OF TECHNOLOGIES (6) BY GRANULARITY: WATT VERSUS MEGAWATT

Note: watt scale technologies are signalled with green, kilowatt scale with orange and megawatt scale with red. Squares indicate supply-side technologies (including GPT) and circles end-use technologies.

The results show a strong relation between the extent-duration (K-dT) of diffusion and the size of the technology, with smaller systems diffusing faster than larger ones. The only difference is again work animals in the US that took several decades to diffuse and whose growth had other types of constraints linked with the reproduction of animals. Surprisingly, megawatt scale technologies are the second fastest group to grow. One explanation might be that intense up-scaling at unit level allows a faster achievement of the maximum installed capacity than for smaller technologies. This is particularly the case for large and centralized technologies like power plants that diffused faster than more interrelated decentralized technologies such as cars, motorcycles or steam machines. Another explanation might be that resources and costs needed to build very large plants constrains the final number of units being deployed, permitting a fast progression towards that number. These results on the effect of the size on diffusion were also expected because it correlates with technology lifetime (Figure 8) which was shown to influence the extent of diffusion (see Figure 7).

In the last few paragraphs stronger evidence has been presented which confirms the relation between the duration and the extent of diffusion. The analysis of the technologies by different characteristics (i.e., use, up-scaling dynamics, length of formative phase, lifetime, and size) showed that less complex end-use technologies take shorter to form and diffuse than highly complex and interdependent technologies which frequently need further up-scaling to reach higher levels of growth. In addition technologies that presented high up-scaling at unit level needed longer formative phases. The paradigm case is for general purpose technologies like steam engines which passed through a long formative period to ameliorate the technology and give time to create new innovations before spillover to mobile applications. The size of the innovation is another important determinant for diffusion. In fact "granular" technologies are particularly well positioned to diffuse faster because their development is less costly, and more units can easily be manufactured. Moreover, shorter life expectancy implies very high replacement rates which put more pressure on production. The experience gained in production and utilization of the technology allows faster improvement upon the first generation models, fostering the formative phase towards a quicker expansion of the innovation. Conversely, the deployment of innovations of a bigger size can lock in the market to the first units because they require a long time to recover initial costs, and they are more expensive to be replaced.

In summary, the duration of the formative phase follows the length of diffusion with longer transitions requiring more time and patience to prepare. The formative phase enables spillovers that accelerates the cumulative causations and fosters diffusion. In the next section the role of a particular set of spillovers, i.e. spatial spillovers, in technology growth is analyzed.

4.3. Spatial diffusion

This final point analyzes the patterns of spatial diffusion after the moment when the innovation gets out from the core and starts to penetrate new regions. In particular, the role of spillovers from the growth in the core in the speed of diffusion in subsequent areas—here called "rims" (fast followers) and "periphery"—is investigated.

The innovation reaches new markets in a different stage of its development, which may give an impulse to the speed and the extension of diffusion. There are some theoretical and empirical studies sustaining that diffusion accelerates when the innovation reaches new regions, but the extension of the penetration is lower than in the first "core" area (Grubler, 1998). In the following analysis countries are distributed among regions (core, rims or periphery) according to the moment they entered into the sequence of adoption. The difference in the patterns of growth are then compared to the behavior of diffusion in the early stage, the formative phase, which is expected to be faster in subsequent areas in the presence of knowledge externalities from the diffusion in the previous markets.

Firstly, the rate of diffusion may change as the technology enters into new markets with the experience gained from the progress obtained in the previous regions. The growth of several technologies by region is analyzed in Appendix 2. The diffusion is generally more rapid (steeper curve) in the rim and the periphery than in the core. Figure 10 tests the effect of spatial acceleration by comparing the inflection point (t_o) to the rate of diffusion (Δt) of those technologies in each region. The graph confirms that diffusion tends to accelerate (lower Δt) when it passes from core to rim and to periphery. This might be explained by the fact that technologies are not obliged to pass through the same formative phase in sub center regions as in the core.

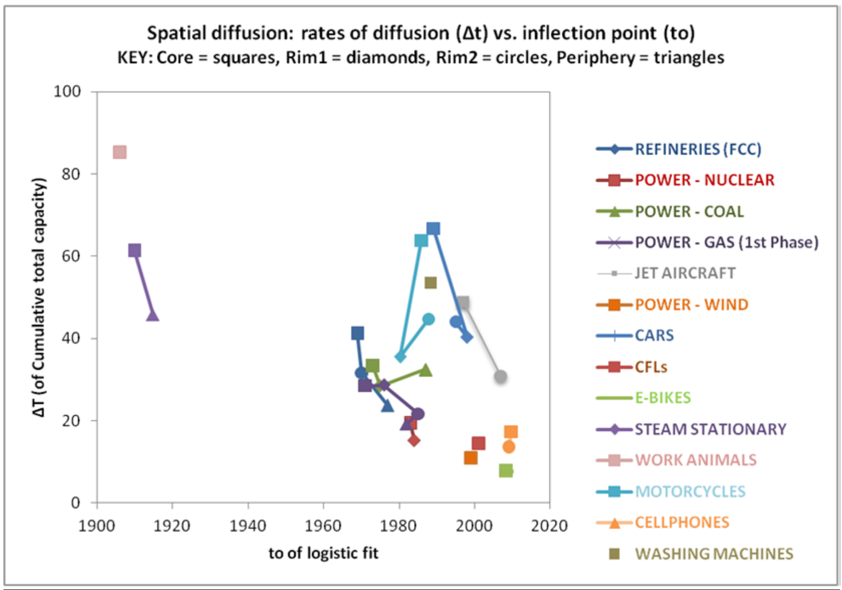


FIGURE 10. SPATIAL ACCELERATION OF DIFFUSION

Table 6 shows the length of the formative phase in center and sub center regions. The formative phase is defined in this paper as the period before the moment when diffusion reaches 10% of cumulative unit numbers.

The length of the formative phase in sub center regions is faster than in the core in 7 out of 11 technologies for which we have data on diffusion in various regions (not including the composite category "Steam machines (all)").[6] The analysis confirms the acceleration of the formative phase in rims and periphery by the existence of knowledge and learning spillovers from the early diffusion in the core. These numbers compare with the speed of growth during the rest of diffusion (i.e., the period between 10% and 90% of maximum cumulative capacity,

[6]See the effect of spatial diffusion in terms of the lower cumulative unit numbers in subsequent regions during the formative phase in Appendix 3.a. These raw numbers are presented with the purpose of illustration of the formative phase acceleration in subcenter regions, they are not controlled for the different size (e.g. energy system, economy, population) of the regions.

see Appendix 3.b.). The acceleration effect is much clearer in this case with diffusion accelerating (i.e., lower Δt) in subsequent regions in 9 out of 11 technologies. Therefore evidence suggests that it might be more difficult to short-circuit the accumulation of human and institutional capacity in the formative stage than to accelerate diffusion once formation is completed.

TABLE 6. LENGTH OF THE FORMATIVE PHASE BY REGION

	Duration (N°. of years)				
Technologies / Regions	*GLOBAL*	*CORE*	*RIM 1*	*RIM 2*	*PERIPHERY*
POWER - NUCLEAR	10	10	7	n/a	n/a
POWER - COAL	40	32	35	n/a	38
POWER - GAS (1st Phase)	52	46	27	20	31
POWER - WIND	n/a	8	n/a	n/a	n/a
JET AIRCRAFT	15	11	n/a	19	n/a
STEAMSHIPS	n/a	73	n/a	40	60
STEAM LOCOMOTIVES	55	55	n/a	50	30
STEAM STATIONARY	158	149	n/a	70	50
STEAM MACHINES (all)	158	158	n/a	70	50
E-BIKES	8	8	n/a	n/a	8
MOTORCYCLES	n/a	49	31	64	n/a
WASHING MACHINES	n/a	31	n/a	n/a	n/a
CARS	62	37	50	66	n/a
CFLs	n/a	4	n/a	n/a	n/a
CELLPHONES	n/a	22	n/a	21	n/a

n/a: not available.

Secondly, the speed of spatial transfer may have an effect in the final extension of diffusion. A more rapid penetration in new markets could increase the pressure in production and generate more positive externalities (e.g., experiment, knowledge, scaling and learning economies), thus enlarging the market for the technology. The speed of "contagion" among regions can be measured by the difference in terms of the number of years between the moment when the inflection point occurred (t_0) in the region i (i= rim1, rim2 or periphery) and in the core. A low number means that technology transition to sub center regions was rapid and vice versa. A high number signifies that the innovation took some time to penetrate other regions. Figure 11 shows the impact of spatial diffusion in terms of enlarging the market for the technology. The extent of diffusion is measured in terms of global cumulative capacity, which was normalised to account for the different size of the energy system across time—see normalization procedure in Wilson (2009).

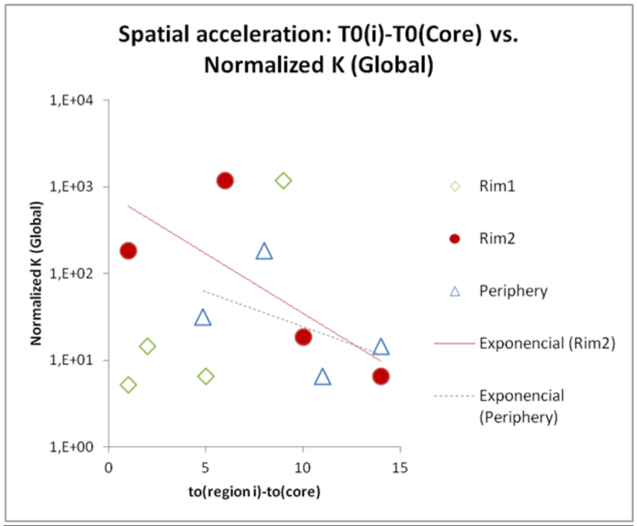


FIGURE 11. THE EFFECT OF SPATIAL TRANSITION IN THE EXTENSION OF DIFFUSION

The results are not clear, however, they seem to indicate that a fast transition to new regions can enhance the market impact of the innovation. This effect is clearer in rim2 which presents a clear negative trend meaning that faster spatial diffusions (lower values in the x-axis) are associated with more pervasive growth (higher values in the y-axis). This finding is very relevant due to the importance of this "fast follower" region—including large OECD markets—in the historical diffusion of technologies. The only exception in the positive benefits of a fast transition is Rim1, which comprises mainly of the Former Soviet Union where the diffusion was historically more centralized. In short, there are strong indications that innovations can diffuse faster and attain a higher potential by speeding up diffusion in other areas, though more research is needed to confirm this result.

5. Conclusion

What is the importance of the formative phase in the historical diffusion of technologies? Two propositions were considered in this study: firstly, larger transitions demand longer periods of formation of the technology; secondly, complex energy innovation systems need more time for the formative phase. The historical evidence reasserts market size as important determinants of diffusion rates. Large system technologies need a long formative period to prepare for up-scaling and growth, and take more time to diffuse. Many factors influence the rate and extent of diffusion in early years including institutional alignment, technological complexity and interrelatedness, and knowledge spillovers. Firstly, institutions should align with the needs of the emerging innovation in order to progress in the formative phase and make the diffusion possible. Secondly, innovations with greater inter-dependences like general purpose technologies need complementary technologies which are not available initially and must be invented in the meanwhile to materialize all their potential. Thirdly, knowledge formation and experimentation during the formative phase is necessary to allow up-scaling and widespread diffusion. Therefore a policy aiming to stimulate the innovation during the formative phase would support experimentation and R&D activities to improve the technology, as well as the deployment in early niche markets.

In an advanced stage of the formative phase the technology may need to enlarge markets and penetrate abroad. The study confirms that diffusion in sub center markets was generally quicker than in "Core" markets, which is explained by the spatial and knowledge spillovers from the development of the technology in "Core" markets. There are signs that fostering the transfer of technologies to other regions and/or improving the absorptive institutional capacity (e.g., human resources, financial, knowledge) may stimulate the rate and extent of diffusion, but more research is needed in this topic in the future.

The scaling dynamics of technologies was studied against different characteristics of technologies and dynamics of the technological process. The main lessons that were drawn from this analysis are summarized as follows: (i) small scale, less capital-intensive, and short lifetime technologies can diffuse faster (shorter Δt) than more centralized and complex energy supply technologies; (ii) end-use technologies can reach high levels of cumulative capacity when compared to supply-side energy technologies; and (iii) a favorable context for unit level up-scaling will expedite the formative phase.

More research is needed on the dynamics occurring over the formative phase of technologies. In particular, a more refined definition of formative phase is necessary to test the impact of the main processes involved at this stage of technology development and diffusion. In addition, the duration and extent of the diffusion relationship should be enriched with a more in depth study of the economic factors that influence the position of technologies in the overall scaling trend, such as the relative cost advantage of the technology and the impact on learning and unit costs. Finally, other metrics aside from capacity should be tested—in terms of services provided, for instance—to measure the scaling of smaller technologies that present low efficiencies and high learning rates.

Supplementary material

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

Appendix 1. Brief history of technology development and diffusion of steam machines

The economic growth throughout history has been marked by a number of important technological breakthroughs that have had a strong impact on the economy for several decades. The notion of general purpose technologies (GPTs) serves to distinguish a few of them which diffusion had a deep effect in all sectors of activity, such as the steam engine in the 19th century, electricity in the early decades of the 20th century, and information and communication technologies (ICT) in our era (Edquist & Henrekson, 2006). Bresnahan & Trajtenberg (1995) suggested the GPT concept for innovations that play a decisive role to increase long-term productivity of the economy as the new technology is widely adopted throughout the sectors. A GPT is normally characterized by the following four "distinctive" features (Bresnahan, 2010; Lipsey et al., 1998): i) wide scope for development and improvements; ii) potential of use across a broad range of applications; and iii) strong complementary with other technologies.

The steam engine is a particular example of GPT (Rosenberg & Trajtenberg, 2004): firstly, it was characterized by a general applicability into a large number of production processes; secondly, it exhibited a continuous innovative dynamism that increased over time its efficiency, which benefited the using sectors as well as enlarged the number of possible applications; and thirdly, technical advances in steam engines turn more profitable for the using sectors to innovate and ameliorate their own technologies and production process.

As for other GPTs, the steam engine passed through a long formative period marked by a sequence of innovations that improved dramatically upon the first design (Crafts, 2004). Rosenberg & Trajtenberg (2004: 2) pointed out that "…the engines that powered locomotives were radically different from those that pumped water out of mines early on…". The first successful steam engine was invented by Thomas Newcomen in 1712; it was mainly used to pump water out of the mines despite its very high price (more than 20,000$ per kW in current prices) and the consumption of large amounts of coal (Von Tunzelmann, 1978). Half a century later, James Watt developed a new version of the steam engine with a separated condenser which was patented in 1769. The Watt engine allowed fuel-savings that could be fourfold comparing to the first Newcomen engines, or half of it if compared to contemporary atmospheric engines (Kanefsky, 1979; Crafts, 2004). Hence steam power could be used almost everywhere and not exclusively in locations where coal was abundant and cheap (Von Tunzelmann, 1978; Frenken & Nuvolari, 2004). Still low pressure Watt engines had important limitations in terms of efficiency which were resolved through the introduction of reliable high pressure engines after the works of Arthur Woolf in the early 19th century in Cornwall—a British region with high coal prices, where engines were mostly used in mining—and the invention of the Lancashire boiler (Cratfs, 2004). Therefore steam power could be deployed in a larger scale and wider number of applications including transportation (land and sea). A further improvement was brought by the invention of the Corliss engine around 1850, disposing of more advanced valves that allowed for a much lower fuel-consumption as well as a stable and uninterrupted flow of power, which was very important in sectors such as textile and metallurgy (Rosenberg & Trajtenberg, 2004).

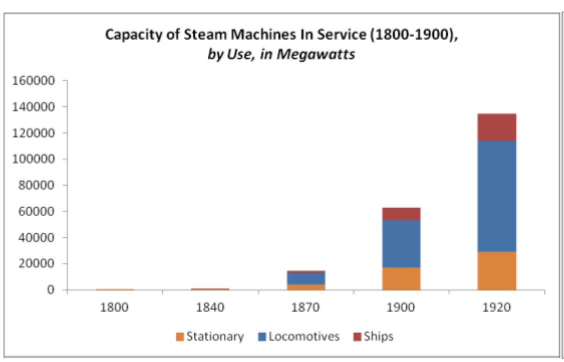
It was only after a long process of development that steam power started realizing its full potential by entering into a broader range of uses. This was possible thanks to the move to high pressure steam engines that halved coal consumption (per hp per hour) compared with the Watt engine (Kanefsky, 1979), and reduced the size of the engine for the same power output. These attributes were particularly important to let steam engines propel mobile applications, starting with ships in early 19th century and locomotives in the 1820s. Concerning steam ships, the continuous improvements in the fuel efficiency of engines across the 19th century—through the work at higher pressures—had reduced coal consumption and the need to carry onboard more fuel, enlarging the range of economic viable voyages. Early engines operated at 6-7 p.s.i. and consumed 10 lb of coal per hp per hour. The consumption further decreased to 5 lb in 1850s, 2.5 in 1870s and 1.25 in 1914 with pressures around 200 p.s.i. (Crafts, 2004). In addition the progress in metallurgy in the second half of the 19th century made available cheap and high-quality steel which reduced hull weights and allowed the construction of even larger ships. Regarding railways, diffusion also benefited from developments in the engine–which became more powerful and efficient by that time–and innovations in supply sector such as metallurgy. Finally the adoption of many complementary inventions such as braking, track design, and signalling was also important for the exceptional growth that steam engines knew in the last decades of the century.

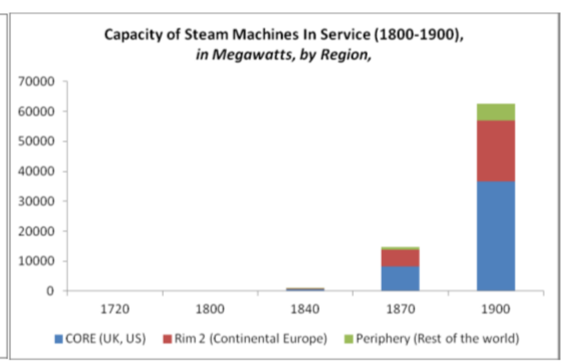
The diffusion of the steam engine was market by strong complementarities with innovations not just in transport but also in dynamic sectors of the economy such as textile and metallurgy. The introduction of the Corliss steam engine resulted in substantial improvements in fuel efficiency in the 1860s. Steam power became more economical than water power, thus fostering a process of massive industry relocation from isolated locations into urban centers that further enhanced agglomeration economies and population growth (Rosenberg &

Trajtenberg, 2004). In addition it made possible a much larger scale of production that allowed the realization of economies of scale turning Corliss into the dominant design in manufacturing in the course of the second half of the century. The smooth and responsive delivery of power was especially important in cotton textiles industries, whereas the larger scale and the capacity to handle drastic fluctuations in power requirements gave it a critical enabling role for rolling mills (rail mills), and therefore for the diffusion of railroads (Rosenberg & Trajtenberg, 2004). The impact on transportation, industrialization and urbanization suggests that steam power played an important part in the economic growth in the late years of the century (Crafts, 2004).

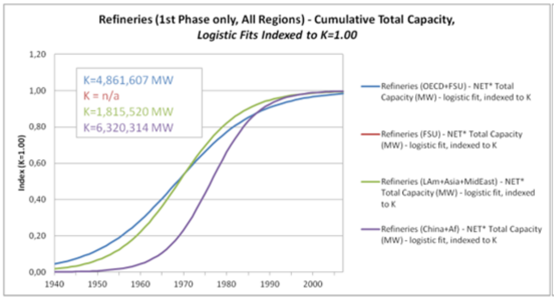
Nevertheless, the contribution of steam power to economic growth took a long time to materialize. It had little effect in British growth until 1830, but it accelerated productivity with the advent of the high pressure steam in 1850, i.e., 140 years and 80 years after the invention of the Newcomen's engine and Watt's engine, respectively (Edquist & Henrekson, 2006; Crafts, 2004). In a first era the steam engine was more developed and applied in a small-scale carried out for the specific needs of a local market. Localized and path-dependent nature of learning constrained technological spillovers and knowledge transfers among regions and applications. This explains the uneven rates of technological growth across applications, which restricted the impact of steam engines on the economy in the first half of the 19th century (Nuvolari & Verspagen, 2009). However, the introduction of the high pressure steam engine and of the Corliss design invention later on led to further advances in a broad spectrum of applications, increasing in turn the demand for the steam engine itself. This made it worthwhile to invest in further refinements of the engine turning it even more productive in the using sectors (Rosenberg & Trajtenberg, 2004), therefore closing a positive loop that fostered the diffusion of the steam engine in different applications and amplified its impact on the economy (Figure 12).

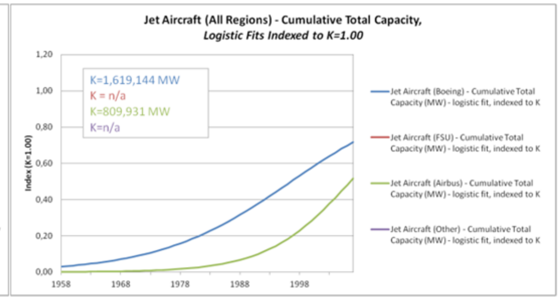
FIGURE 12. CAPACITY OF ALL STEAM MACHINES IN USE

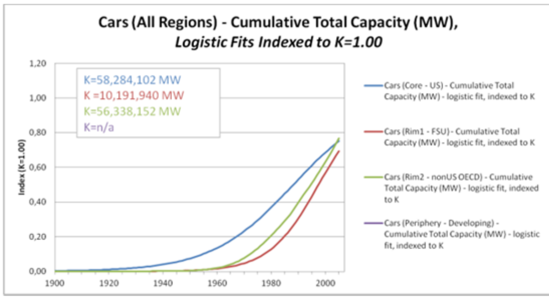


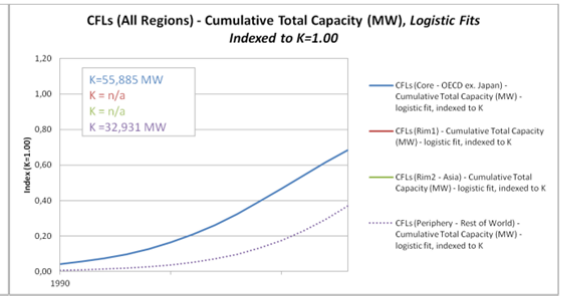


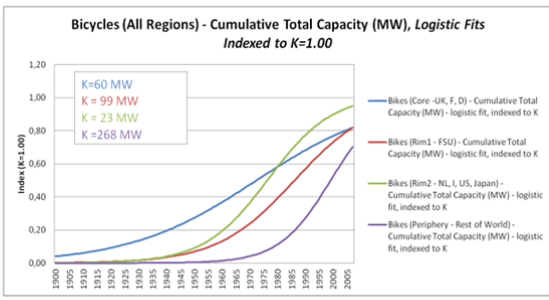
Appendix 2. Formative phase and cumulative capacity growth by region

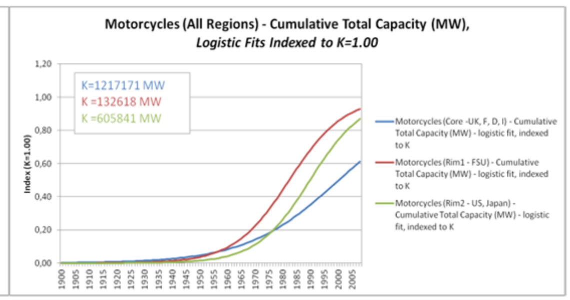


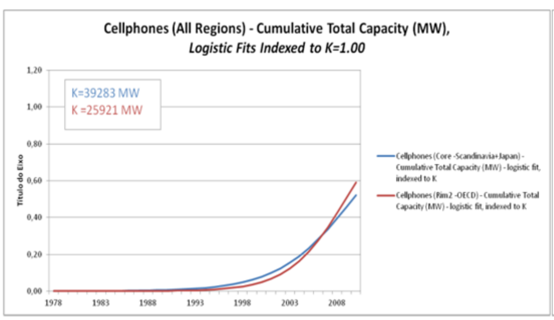


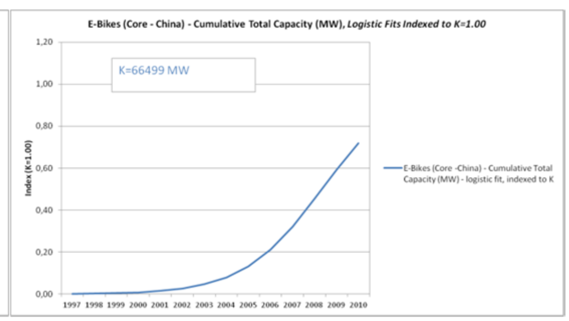


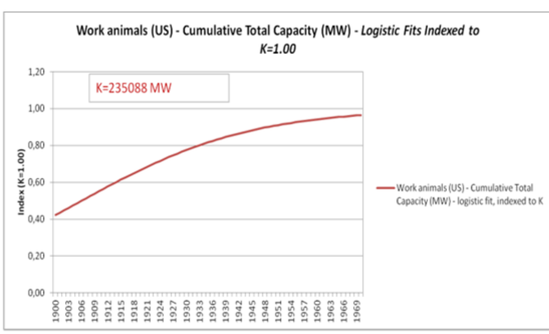


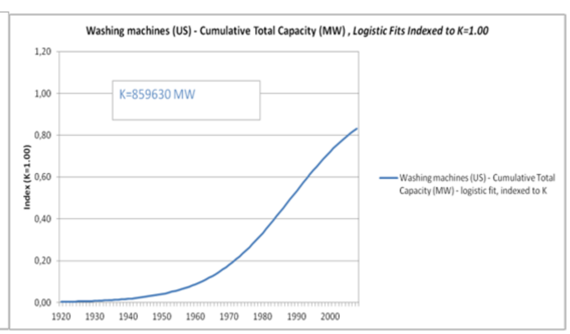












Appendix 3. Extent and duration of diffusion: synthesis tables

Appendix 3.a. Cumulative total unit numbers and length of the formative phase (at 10% of the total number of units) by region

	Duration (N°. of years)					*Total Unit Numbers*				
Technologies	*GLOBAL*	*CORE*	*RIM 1*	*RIM 2*	*PERIPHERY*	*GLOBAL*	*CORE*	*RIM 1*	*RIM 2*	*PERIPHERY*
POWER - NUCLEAR	10	10	7	n/a	n/a	54	41	9	n/a	n/a
POWER - COAL	40	32	35	n/a	38	730	386	124	n/a	28
POWER - GAS (1st Phase)	52	46	27	20	31	927	456	45	57	144
POWER - WIND	n/a	8	n/a	n/a	n/a	n/a	769	n/a	n/a	n/a
JET AIRCRAFT	15	11	n/a	19	n/a	3 353	1 791	n/a	1 025	n/a
STEAMSHIPS	n/a	73	n/a	40	60	n/a	24 022	n/a	6 135	2152
STEAM LOCOMOTIVES	55	55	n/a	50	30	91 653	59 234	n/a	28 398	7 877
STEAM STATIONARY	158	149	n/a	70	50	247 508	157 650	n/a	75 314	14 543
STEAM MACHINES (all)	158	158	n/a	70	50	369 111	229 738	n/a	110 195	24 651
E-BIKES	8	8	n/a	n/a	8	17 876 000	17 161 000	n/a	n/a	715 000
MOTORCYCLES	n/a	49	31	64	n/a	n/a	28 952 333	4 064 286	16 396 670	n/a
WASHING MACHINES	n/a	31	n/a	n/a	n/a	n/a	56 424 600	n/a	n/a	n/a
CARS	62	37	50	66	n/a	227 179 166	57 524 103	14 531 108	96 253 991	n/a
CFLs	n/a	4	n/a	n/a	n/a	n/a	372 566 600	n/a	n/a	n/a
CELLPHONES	n/a	22	n/a	21	n/a	n/a	880 749 015	n/a	601 230 566	n/a

n/a: not available.

Appendix 3.b. Cumulative total unit numbers and number of years between 10% and 90% (or alternatively from 1% to 50%) of *cumulative installed capacity*

	Duration (N°. of years)					*Total Unit Numbers*				
Technologies	*GLOBAL*	*CORE*	*RIM 1*	*RIM 2*	*PERIPHERY*	*GLOBAL*	*CORE*	*RIM 1*	*RIM 2*	*PERIPHERY*
POWER - NUCLEAR	19	20	15	n/a	n/a	404 414	323 401	53 388	n/a	n/a
POWER - COAL	40	33	28	n/a	32	1 146 150	644 575	125 535	n/a	73 521
POWER - GAS (1st Phase)	31	28	29	22	19	376 690	222 670	68 890	17 872	64 687
POWER - WIND	n/a	11	n/a	n/a	n/a	n/a	3 562	n/a	n/a	n/a
JET AIRCRAFT	51	49	n/a	31	n/a	2 771 415	1 619 144	n/a	809 931	n/a
STEAMSHIPS	64	72	n/a	61	35	111 764	74 135	n/a	26 878	10 880
STEAM LOCOMOTIVES	n/a	63	n/a	66	56	n/a	383 101	n/a	95 472	25 614
STEAM STATIONARY	63	61	n/a	n/a	46	135 906	76 487	n/a	n/a	7 880
STEAM MACHINES (all)	n/a	67	n/a	66	56	n/a	533 723	n/a	172 108	50 010
E-BIKES	8	8	n/a	8	n/a	69 270	66 499	n/a	2 771	n/a
MOTORCYCLES	63	64	36	45	n/a	450 117	59 895	23 396	99 236	267 589
WASHING MACHINES	51	54	n/a	n/a	n/a	6 272 064	859 630	n/a	n/a	n/a
CARS	64	67	40	44	n/a	163 079 055	58 284 102	10 191 940	56 338 152	n/a
CFLs	n/a	15	n/a	n/a	n/a	n/a	55 885	n/a	n/a	n/a
CELLPHONES	n/a	17	n/a	14	n/a	n/a	39 635	n/a	27 055	n/a

n/a: not available.

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