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Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies

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ABSTRACT

Implementing the Paris agreement to prevent dangerous climate change requires energy system transformation and rapid diffusion of low-carbon innovations. In this paper we investigate both the temporal and spatial dynamics of formative phases by which energy technologies prepare for growth. Drawing on a review of diverse literatures, we offer a definition of the formative phase which clarifies its scope and duration, and identifies its main technological and economic determinants. We use parametric hazard models to assess the relative strengths of these determinants on formative phase durations for a sample of 15 energy technologies diffusing over time in their respective initial markets. We find that substitutability has stronger effects in accelerating the end of formative phases than installed capacity and prices. We extend our analysis using nonparametric models to analyze the spatial diffusion of formative phase durations from initial to follower markets. We find that formative phase durations are long outside initial markets as well, showing only signs of acceleration in latecomer regions. Our results imply risks for policies trying to accelerate the diffusion of large innovations without ready markets in both initial and follower markets.

1. Introduction

The historical diffusion of energy technologies shows long periods of emergence within changing energy systems (Fouquet, 2016; Grubler et al., 2016). Energy technologies often take several decades in the early phase of their life-cycle prior to mass commercialization (Fouquet, 2014; Smil, 2010, 2016). This period is also known as the formative phase which can be defined in the following terms: a period marked by high uncertainties (Van de Ven, 2017), during which the conditions (standardization, performance improvement, etc.) are created for a new technology to emerge and prepare for large-scale commercialization (Jacobsson and Lauber, 2006; Arthur, 2009; Bento and Wilson, 2016). This interactive process of testing and improvement, and aligning market and user needs, tends to occur in a small number of initial markets. At the end of the formative phase the technology becomes ready to leave the initial markets and diffuse out into new markets (Binz and Anadon, 2018; Binz et al., 2017; Grubler, 2012). Understanding both the temporal and spatial dynamics that shape the formative phase is important in the debate on how to accelerate energy innovation for climate change mitigation (Winskel and Radcliffe, 2014).

Different strands of the literature cover the dynamics and determinants of the formative phase. These include the identification of key changes in the type of innovation (e.g., product vs process) (Huenteler et al., 2016; Taylor and Taylor, 2012), the strategic management of new industries around innovations (e.g. changes in companies' demography) (Peltoniemi, 2011; Gustafsson et al., 2016), and the dynamics of emerging systems in socio-technical transitions (Bergek et al., 2015; Markard et al., 2012; Geels, 2005).

In terms of what determines the duration of formative phase, studies in management science emphasize the role of demand variables, such as heterogeneity in price sensitivity and adopters' risk avoidance (Golder and Tellis, 1997; Tellis et al., 2003, 2012; Peres et al., 2010). The diffusion of innovations literature shows that diffusion rates depend on the characteristics of both the technology and the adoption environment (Rogers, 2003). These factors include: relative advantage (Mansfield, 1968; Chandrasekaran et al., 2013); compatibility and complexity (Arthur, 2009); disruptiveness, inter-relatedness and infrastructural needs (Grubler et al., 1999); and market size (Wilson, 2012).

Technology growth out of the initial markets is typically investigated with the focus on the constraints to adoption like distance in

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economic geography (e.g. Comin et al., 2012; Griffith et al., 2013), or interactions with existing contextual structures in system theories (Bergek et al., 2015; Hansen and Coenen, 2015).

In this paper we pose the question: *What determines the duration of formative phases for energy innovations in different markets?* We are interested both in initial markets (also: core, lead, first mover, early adopter) where formative phases prepare technologies for mass commercialization, and in follower markets (also: periphery, lag, late adopter) where accelerated formative phases may benefit from diffusion and spillovers. To understand the temporal dynamics of energy innovation within initial markets (growth over time), we apply a hazard model to a time series dataset of 15 diverse energy technologies (including both new and old, energy supply and end-use). To understand the spatial dynamics of energy technology diffusion between markets (growth through space), we use Kaplan-Meier curves to compare the dynamics of formation in follower regions.

The paper is structured as follows. Section 2 reviews the relevant literature on formative phases to identify definitions, patterns and determinants. Section 3 explains the methodology including data sources, model and variables. Section 4 applies the concepts and methods presented in the previous sections to measure formative phase durations across regions and to estimate the effect of the determinants in accelerating formative periods. Section 5 concludes and derives policy implications.

2. The formative phase

2.1. Definition

The term formative phase appears in the technological innovation system literature to designate the early period of diffusion during which new technologies are first used, improved and prepared for commercialization: “the value of this very first phase” is “in the opportunities [given] for experimentation, learning and the formation of visions” (Jacobsson and Lauber, 2006: 271). A similar concept is’era of ferment’ which is used in the industry life-cycle literature to designate the period of intense rivalry and competition among variations, initiated by a technological breakthrough and eventually leading to the selection of a single dominant design (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Murmann and Frenken, 2006). Other terms have been suggested in marketing studies such as the ‘time to take off’ (Golder and Tellis, 1997; Tellis et al., 2003; Tellis and Chandrasekaran, 2012), which designates the period from product introduction to “substantial” growth. A related concept is the ‘incubation time’ (Kohli et al., 1999) which includes product development as well. Other terms are used in the innovation literature to designate the first period of development and commercialization including: ‘embryonic’ (Taylor and Taylor, 2012), ‘nascent and emerging’ (Markard and Hekkert, 2013), ‘nurturing’ (Smith and Raven, 2012), and ‘installation’ (Perez, 2002). The content of all these definitions can change in terms of the scope of technological change and the types of activities included.

The *scope* of technological changes expected to occur during the formative phase vary across different streams of the literature. The industry life-cycle literature focuses on modifications to the technology, the nature of innovation, and industry structure (Peltoniemi, 2011; Gustafsson et al., 2016). A technological opportunity introducing a new product encourages the entry of a large number of firms that will improve the quality of production and reduce prices (e.g. Agarwal and Bayus, 2002). According to this perspective, the transition to technological maturity is typically characterized by a shift from product to process innovation as product variety decreases and eventually a design becomes dominant (Abernathy and Utterback, 1978; Klepper, 1997).

The technological innovation systems (TIS) perspective considers the coevolution of technologies and context (Bergek et al., 2015). Bergek et al. (2008: 419–420) distinguish a formative phase in which “the constituent elements of the new TIS begin to be put into place, involving entry of some firms and other organizations, the beginning of an institutional alignment and formation of networks” from a growth phase when “the focus changes to system expansion and large-scale technology diffusion through the formation of bridging markets and subsequently mass markets”. While traditional TIS studies emphasize changes in the structure of innovation systems (e.g. Jacobsson, 2008), more recent work provides a functional analysis of influential processes in the early period including: knowledge creation, entrepreneurial experimentation, and influence on the direction of search (Hekkert et al., 2007; Bergek et al., 2008; Markard et al., 2012).

The innovation literature emphasizes some characteristics of the formative period such as: lengthy process (Klepper, 1997); experimentation (Arrow, 1962; Jacobsson and Lauber, 2006); coexistence of a range of competing designs (Abernathy and Utterback, 1978); high uncertainty regarding technologies, markets and institutions (Van de Ven, 2017; Kemp et al., 1998; Bergek et al., 2008). The focus on one or several of those formative features distinguishes theoretical approaches.

2.2. Duration

How long formative phases last depends on what is included in their scope. The *delimitation* of the formative phase also has a wide range of interpretation in the literature (see also Gustafsson et al., 2016).

Jacobsson and Lauber (2006: 260) suggest that the end of the formative phase “may occur when investments have generated a large enough, and complete enough, system for it to be able to ‘change gears’ and begin to develop in a self-sustaining way”. Indicators of formative phase end point include the establishment of dominant designs (Abernathy and Utterback, 1978; Anderson and Tushman, 1990), industry “shake-outs” (Klepper, 1997), sales take-off—identified either by analyzing the evolution of annual rates (Agarwal and Bayus, 2002) or by comparing them with an empirically-derived take-off curve (Golder and Tellis, 1997; Tellis et al., 2003). Other studies estimate the end of the formative phase using a threshold like 2.5% market share, corresponding to the innovator segment of potential adopters (Rogers, 2003). This is consistent with research on new consumer products which shows evidence of market take-off at an average market penetration of 2.5–3% (Tellis et al., 2003; Golder and Tellis, 1997). Other thresholds such as 10–20% of total adoption have also been used to approximate the point of self-sustaining market growth (Mathur et al., 2007).

Clearly identifying a start point for formative phases is also problematic as definitions vary from recognized date of invention (Agarwal and Bayus, 2002; Hanna et al., 2015), or start of development (Kohli et al., 1999) to first commercialization (Golder and Tellis, 1997; Tellis et al., 2003; Smil, 2010).

Bento and Wilson (2016) test different indicators for the duration of the formative phase for a sample of technologies in their initial markets (Fig. 1). The central estimates assume the formative phase starts in the year of first sequential commercialization, and ends when diffusion reaches 2.5% of potential adopters (in line with Rogers’ (2003) definition of “innovators”). Alternative indicators of formative phase start and end points reveal the uncertainty ranges. Results show the long time scale of formative phases, rarely shorter than a decade, varying from 4 years for fluid catalytic cracking in refineries to 85 years for stationary steam engines.

2.3. Determinants of duration

The duration of formative phases is shaped by both technology and market context. It is thus important to understand the factors associated with shorter and longer formative phases. Systemic theories such as the TIS perspective (Markard et al., 2012; Bergek et al., 2015) are concerned with structural elements underlying the emergence of new technologies, but are less clear on how these factors affect the duration