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Measuring the duration of formative phases for energy technologies

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ABSTRACT

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

1. Introduction

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

Two streams of the literature address the challenges faced by a new technology during the formative phase. First, the formative phase has a parallel with the concept of 'era of ferment' in the literature on industry lifecycles (Abernathy and Clark 1985; Abernathy and Utterback, 1978; and for a recent review, Peltoniemi, 2011). An era of ferment is a time of

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intense technical variation and selection, initiated by a technological breakthrough and culminating with the emergence of a dominant design (Anderson and Tushman, 1990). During this period, the number of firms increases while sales remain relatively low as potential adopters wait for the emergence of a new standard before purchasing. This can be a lengthy process. As an example, 30 product innovations in the US were found to take on average 30 years to move from invention to commercialization, with 14 years more before sales take-off (Agarwal and Bayus, 2002; see also Tellis and Chandrasekaran, 2012; Tellis et al., 2003; Golder and Tellis, 1997). However this literature tends to overlook the systemic conditions (e.g., investment in the production chain, supportive institutions) that often accompany the emergence of new technologies.

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

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

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

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

2. Innovation processes during the formative phase

2.1. Industry lifecycles

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

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

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

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

In the specific case of energy technologies, the end of the formative phase is also marked by a transition from experimentation and production of many small scale units to an up-scaling phase which can see rapid increases in the maximum