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Enabling diffusion: How complementary inputs moderate the response to environmental policy

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ABSTRACT

While policies encouraging diffusion of new technologies provide incentives for adopting the focal good, they typically ignore the ecosystem of complementary goods and services. Based on existing literature on indirect network effects, we argue that when there is less availability of complementary goods, policies have a smaller impact on diffusion. Using a natural experiment based on the establishment of state-level solar carve-out policies, we demonstrate that solar power installations increased substantially more after the policy in cities where a critical complementary good – qualified installers – was more available.

1. Introduction

Worldwide efforts to tackle climate change have included heavy investment in renewable sources of energy. Solar generation, though one of the smallest energy sources in terms of generating capacity, experienced the biggest leap in 2010: its installed base jumped 70% from the previous year (The Economist, 2011). While policy makers around the globe search for the most effective ways to accelerate renewable energy development, success and failure stories abound in the media (e.g., the effects of Chinese and U.S. policies supporting solar power development). In general, governments have two basic means at their disposal: regulations that rule out certain activities, and policies that provide incentives for private actors to engage in specific actions. When policy makers take the latter approach, they typically incentivize the focal activity but ignore the ecosystem of related activities that may facilitate or inhibit their policy objectives. Management literature on technology diffusion has long argued that the complementary goods and services that constitute the ecosystem may pose a challenge to the adoption and diffusion of new technologies (e.g., Katz and Shapiro, 1985; Schilling, 1998, 1999, 2002; Brynjolfsson, 1996; Wade, 1995; Angst et al., 2010). This paper explores the specific effect of solar carve-out policies that encourage the adoption of solar electricity generation technology in the U.S., and demonstrates that the effect of carve-out policies was significantly larger in the presence of a complementary market of qualified installers.

Management literature has focused on understanding the conditions under which new technologies diffuse across a population of potential adopters. Early scholars of this phenomenon have generally agreed on the familiar S-curve of diffusion (Griliches, 1957; Mansfield, 1961; Rogers, 1962), which was attributed to several factors: heterogeneous benefits across consumers (David, 1969; Davies, 1979), learning benefits from a larger installed base (Attewell, 1992; Kapur, 1995), and real-option valuation results from the decision to invest in adoption (Stoneman, 1983, 2002). More recent literature on diffusion has considered the effects of direct and indirect network externalities (Church and Gandal, 1993; Farrell and Saloner, 1985, 1986; Gandal, 1994). We suggest an additional distinct case of indirect network externalities in which the benefits of adoption depend on the availability of complementary

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goods or services *at the time of the adoption decision* (e.g. availability of installers of the focal technology). Such goods or services are complementary inputs.

Complementary inputs share certain features with complementary products such as software and services. In both cases, the utility derived from the focal good depends on consuming not only the focal good but also the complementary good. As with other indirect externalities, the (expected future) availability and price of complementary inputs depends on the number of prior adopters of the focal good. The main difference between complementary goods and complementary inputs, however, is that complementary inputs are consumed *at the same time as* the focal good. In other words, the focal good (e.g., new buildings adopting LEED or new solar power generation assets) and the complementary input (e.g., local building professionals with LEED accreditation or installers of power generation equipment) are complements in the sense that *they must be used together* to generate utility, and they are used simultaneously at the time of adoption. This distinguishes complementary inputs from other complementary products and services that are consumed in conjunction with the focal good for periods *after* the initial adoption (i.e., buying video games for several years after purchasing a video game console). As our theoretical model and empirical results below demonstrate, this modifies the established theory of diffusion.

One common challenge associated with studying complementary goods, services, and inputs is the endogeneity of these markets: one would expect that complementary inputs would be developed in anticipation of adoption of the focal product; therefore, the observation that there is greater adoption of the focal good in the presence of more complementary inputs could reflect the development of those complementary inputs in anticipation of high levels of adoption. In this study, the natural experiment provided by our empirical context allows us to address the potential endogeneity concerns that plague studies of indirect network externalities. In particular, we exploit an exogenous shock – specifically, to the demand for new installations of solar generating systems after a state enacts a new solar carve-out policy – to examine how the pre-existing availability of installers influences the magnitude of the response to the (positive) demand shock. We demonstrate that the increase in adoption of solar generating systems following the policy shock is substantially larger when there is more availability of the complementary input (i.e. installers).

2. Complementary inputs: theory and predictions

The adoption and diffusion of new technologies has been examined from various theoretical perspectives, from innovation economics to institutional theory. Although these theories may appear to address the phenomenon from different vantages (with the former focusing on the utility derived from the adoption decision and the latter investigating diffusion as a social process) both innovation economics and institutional theory predict that network effects influence the diffusion of innovation. Institutional literature views diffusion of innovation as a process of social contagion (Angst et al., 2010) and cultural work (Strang and Soule, 1998), determined by the characteristics of innovation, innovators, and the environmental context (Wejnert, 2002). The economics of innovation, on the other hand, extends these ideas with models of diffusion processes in which network effects are theorized as direct and indirect network externalities.

In particular, Katz and Shapiro (1985) offer three categories of externalities that influence diffusion: (1) direct externalities (more users of the focal product enhance its value to all users); (2) indirect externalities from hardware and software, where the (current and future) availability of software enhances the value of hardware; and (3) indirect externalities in a durables market where the (future) availability of services enhances the value of the durable good. In both cases of indirect externalities, the expectation is that more availability of the complementary good (software) or service will lead more buyers to adopt the focal technology (hardware or durables). As the theoretical models of these markets suggest, however, the expected adoption of the focal good will lead to the development and availability of the complementary good or service (Schilling, 1999), making it difficult to empirically test the impact of complementary products and services on diffusion (Schilling, 1998, 2002).[1]

Existing studies have wrestled with this problem using a variety of approaches, from instrumental variables (Corts, 2010; Corts and Lederman, 2009; Gandal et al., 2000) to temporal patterns (Clements and Ohashi, 2005; Goldenberg et al., 2010; Stremersch et al., 2007, 2010). Several of these studies reveal a positive correlation between adoption of the focal good and the availability of the complementary good or service, while others produce mixed findings. Thus, although this literature has progressed in addressing the hardware–software endogeneity problems with the help of econometrics, it is still limited due to the required assumptions about the validity of instruments and the foresight of focal and complementary good providers; moreover, it suffers from the lack of a natural experiment – some form of exogenous shock that can be used to identify a causal relationship.

Following this prescription in the most recent attempt to address the hardware–software endogeneity problem, Corts (2010) examined the impact of mandated government fleet adoption of flex-fuel vehicles (FFVs), where the exogenous demand shock (from government procurement) for FFVs provided a natural experiment for the effect on alternative fuel retail infrastructure. The empirical results demonstrated support for the prediction that increasing demand for alternative fuel increases the availability of fuel infrastructure. However, Corts found inconclusive evidence that the government mandate had, in turn, increased retail demand for FFVs. Thus, while Corts demonstrated that the exogenous shock in demand for hardware led to greater availability in software, it remains an open question whether a greater availability of software increases the demand for and adoption of hardware.

In addition to addressing this empirical challenge, this paper adds an additional category of externalities that influence technology adoption: complementary inputs. Because complementary inputs (unlike complementary goods) are consumed *at the time a focal good is adopted*, it alters the theoretical model in an important way: rather than evaluating the installed base of hardware adopters providing the market for software, we must consider the current set of adopters that provide the market for the complementary input. This category of externalities, therefore, deserves independent theoretical and empirical treatment in the literature.

We are aware of only one existing study that empirically investigates the importance of complementary inputs in the diffusion of technology: Gruber and Verboven (2001), which examined the diffusion of mobile telecommunications in Europe.[2] These authors demonstrate that the transition from analog to digital technology,

[1] The services/durables category has been the subject of much less empirical work, but theoretically is the same as the hardware/software case.

[2] Another recent (as yet) unpublished study that addresses the endogeneity of complementary good markets and highlights the role of complementary inputs is by Simcoe and Toffel (2012). The authors examine the effect of public procurement policies on the diffusion of the U.S. Green Building Council's LEED standard for sustainable building practice among the private-sector real estate developers and LEED accredited professionals. Using novel methods of matching, their study inspects two samples: one consisting of Green Policy adopters and their quasi-control group, and another consisting of Green Neighbors (at the city level) and their quasi-control group. The results show the significant positive effects of public procurement policies on the increase in LEED-accredited professionals in cities with such policies