Technology Adoption and the Timing of Environmental Policy: Evidence from Efficient Lighting · Sarah Armitage, Harvard University

Avoiding catastrophic consequences of climate change will require a dramatic transition in energy technologies. This paper analyzes how the trajectory of clean technology development interacts with the type and timing of policies. I use the market for efficient lighting to examine how incentivizing the deployment of earlier-generation clean technologies may inhibit the long-run transition away from dirty technologies.

Early incentives for clean technologies may negatively affect the development of later-generation clean technologies (Sivaram, 2017). Anecdotal examples include competition between silicon-based solar PV and solar cells made from other materials or between lithium ion batteries and other battery chemistries; in these cases, public support for the early technology may have hindered the development of later technologies with potentially greater long-term technical promise (Sivaram, 2017). Given the scale of emissions reductions needed for climate change mitigation, hindering the development of potentially superior clean energy technologies may substantially increase the long-term social cost of climate change mitigation efforts.

Economic theory can help to illuminate why the timing of environmental policy may have implications for the long-run efficiency of climate change mitigation. A profit-maximizing firm will develop a new technology only if expected profits are greater than the fixed cost of investment. Subsidies for early clean technologies encourage the immediate adoption of durable products and may therefore reduce the market size for later-generation technologies. Even if market size eventually increases due to stock turnover, theoretical and empirical research suggest that time-to-profitability is an important factor in firms' willingness to invest in new technologies (Stein, 1989; Budish et al., 2015). Therefore, using subsidies and related tools to promote the deployment of early-generation clean technologies may exacerbate firms' tendency to underinvest in superior later-generation clean technologies.

To analyze this issue, I study the market for efficient lighting, where the later-generation efficient technology (LEDs) has competed with both the earlier-generation efficient technology (CFLs) and a more efficient version of the incumbent technology (halogens). Developed following a scientific breakthrough in the 1990s, LEDs for general purpose lighting are now superior to CFLs across virtually all characteristics of interest – cost, light quality, energy efficiency, lifetime, or opportunities for complementary products. In their first years of commercialization, however, LEDs competed actively with CFLs, which were well-established in the efficient lighting market, and LEDs continue to compete with halogens for market share. The lighting market provides an ideal setting for investigating the technology transition process, as this process has advanced further than for many other energy technologies. Furthermore, this market is also independently important given the technical potential of LEDs to reduce global electricity consumption (Davis, 2017).

Two key policies have influenced the development the efficient lighting market in the United States. First, numerous state and utility programs have provided product rebates to counteract the higher upfront cost of efficient bulbs. Second, federal lighting efficiency standards removed most traditional incandescent bulbs from the market over 2012 to 2014, precipitating the introduction of halogen bulbs that relied on the same basic incandescent technology but achieved approximately 30% greater efficiency. Through my analysis of con-

sumer purchase decisions, I simulate the development of the efficient lighting market given different policy scenarios, asking how much faster (slower) did LED cost reductions need to occur to achieve the same growth in the LED market relative to a world without subsidies or standards.

To conduct this analysis, I build a structural model of the residential lighting market over 2010-2017 to determine the impact of subsidies and standards on the penetration of different technologies. As a baseline, I use a static demand model following Berry et al. (1995), where each consumer's indirect utility depends on observable product characteristics such as light output, technology type, light color, price, available rebates, expected bulb lifetime, and unobservable product quality. Instruments include manufacturer and retailer cost shifters, Hausman-type instruments, and differentiation instruments developed by Gandhi and Houde (2019). To estimate the model, I rely primarily on retail sales data from Nielsen, which provides quantities of light bulbs sold and prices at the week-store-UPC level, at thousands of retailers across the U.S.

Because light bulb lifetimes vary significantly by technology type, ranging from 1,000 hours for an incandescent bulb to 25,000 hours for an LED bulb, I also model endogenous coming-to-market to capture how the distribution of potential customers depends on the past history of technology adoption. This component of the analysis is essential to account for the impact of longer light bulb lifetimes on the size of the residential lighting market, with a nearly 50% decline in general purpose lighting shipments observed over the study period; it is also necessary to account for different preferences of early adopters of efficient lighting technology relative to the general population. To implement endogenous coming-to-market in my empirical estimation, I modify the standard fixed point algorithm used in BLP and related literature to model the changing distribution of customers over time, using engineering estimates of lighting failure rates by technology type to determine product lifetimes. While previous papers have accounted for coming-to-market as part of complex dynamic demand systems (Lee, 2013), to the best of my knowledge this paper is the first to account for this issue as part of economists' workhorse discrete choice demand model. A secondary goal of my project, therefore, is to provide proof-of-concept for this approach to modeling evolving demand for new technologies.

Using the estimated parameters of my demand system, I then perform counterfactual policy simulations that vary the timing of federal efficiency standards and the phase-out of subsidies for CFLs. To implement alternative timing of standards, I hold fixed the incandescent and halogen products available on the market in 2011, the year before the actual standards came into effect nationally. I then estimate the resulting consumer surplus, producer surplus, and overall environmental externality for each counterfactual policy timing. For each of these policy simulations, I also examine the sensitivity of my results to the relative lifetimes and the relative externality associated with each technology. Finally, I consider how the impact of standards and subsidies compares to that of a carbon tax that increases the operating cost of lighting differentially by technology. These analyses together seek to illuminate how policymakers should evaluate tradeoffs between the benefits of emissions reductions from early-generation efficient products and the potential cost of delaying adoption of later-generation technologies.

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Author Disclosure Statement · Sarah Armitage, Harvard University

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I declare that I have no other relevant or material financial interests that relate to the research described in this paper.