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Estimating the price (in)elasticity of off-grid electricity demand

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ABSTRACT

Community-scale power infrastructure may be the only electrification option for tens of millions households that remain out of reach from centralized power grids. The responsiveness of household electricity demand to price is a crucial design input for off-grid systems. While the price elasticity of electricity demand of grid-connected consumers has been abundantly studied, few studies focus on off-grid communities where substantial econometric challenges arise, including the absence of metered consumption data and electricity prices that are simultaneously determined by cost and demand considerations. This study attempts to address these challenges for the case of off-grid micro hydropower consumers. It makes two core contributions: First, we propose the surface area of the contributing hydrologic catchment as a new instrumental variable to estimate elasticity using a cross sectional dataset of existing micro hydropower infrastructure. Second, we provide a first price-elasticity estimate (−0.15) for off-grid electricity demand in Nepal. We surmise that the small (in absolute value) elasticity value found in this study arises from the low levels of consumption observed off-the-grid. We use a Monte Carlo analysis to show that failing to account for this disparity can lead to substantial financial losses caused by suboptimal power infrastructure design.

1. Introduction

The critical role of electricity as a driver of economic development is widely recognized (e.g., Dinkelman, 2011; Rud, 2012) and recent large-scale investments allowed 222 million people worldwide to gain access to electricity between 2010 and 2012 (International Energy Agency (IEA) and The World Bank, 2015). Yet 1.3 billion people, mostly in rural areas (International Energy Agency, 2013) remain unconnected, 620 million of whom will likely remain out of reach of national power grids due to remoteness, low population densities and prohibitive grid extension costs (International Energy Agency (IEA) and The World Bank, 2015). In this context, local power systems that are not connected to the national grids, but generate electricity near the point of consumption are a promising alternative for rural electrification (Narula et al., 2012). Such community-scale off-grid systems may be the only means of accessing electricity in the foreseeable future in many remote regions, notably in mountainous areas, where grid extension costs are compounded by accessibility challenges.

In contrast to large power grids, where electricity is generated at cost-optimal sites and transported to demand centers through high voltage transmission lines, off-grid systems can neither store nor export excess energy. Power generation in off-grid systems therefore has to match household electricity demand at the local level, meaning that the economic viability of the system is constrained by the total electricity demand of the community. In that context, the optimal capacity of a power system is jointly determined by the cost (i.e. the rate at which the unit cost of infrastructure [$ per kW] decreases with capacity) and demand curves. The slope of the demand curve is particularly critical and determined by the *price-elasticity* of energy demand, i.e. how responsive household level electricity consumption will be to changes in the electricity price. Without this information, designers are likely to either over or underestimate the optimal plant capacity, resulting either in capital costs that cannot be recovered by the local sale of electricity, or in forfeited income if a plant fails to supply local demand. Either situation can contribute to a lack of financial sustainability of designed local power supplies. The price elasticity of electricity demand, γ_p, is formally defined as the ratio of relative change in electricity demand kW to the corresponding relative change in price P:

$$\gamma_p = \frac{dkW/kW}{dP/P} \quad (1)$$

γ_p is typically negative (decreasing marginal utility of consumption)

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and, in the case of electricity, has an absolute value smaller than one, meaning that electricity demand is price-inelastic (e.g., Espey and Espey, 2004).

Determining the causal effect of price changes on electricity demand is an arduous task, particularly in the context of rural electrification in developing countries. The direct approach of simply asking community members (e.g., through dedicated techniques like contingent valuation (Thomas and Syme, 1988) is prone to hypothetical biases because the surveyed households have likely never experienced the level of electricity service they are asked to value. To date, there is no general theory of respondent behavior to characterize and control hypothetical bias (Loomis, 2011). An alternative set of methodologies, revealed preferences approaches, use observed behavior (as opposed to stated preferences) to determine elasticity. Recent efforts to privatize electricity markets worldwide increased research interest in assessing how households adapt their electricity consumption in response to price policies (see e.g., (Espey and Espey, 2004; Hondroyiannis, 2004), for a review). Numerous studies use residential power consumption data monitored by utilities to evaluate demand elasticity. However, few (if any) studies have been devoted to off-grid power generation in developing countries. This setting differs from centralized grids in two important ways.

First, because of their local scale, the capacity of off-grid power systems is tailored to local electricity consumption: household demand affects the size of the infrastructure, which, in turn, affects the unit cost of the produced electricity through economies of scale. It follows that price is simultaneously determined by demand and supply considerations in off-grid power systems. In that situation, price is endogenous,[1] and the effect of price on electricity demand is challenging to disentangle from the effect of infrastructure size, itself driven by electricity demand, on electricity costs. In developing countries, these difficulties are often compounded by data constraints: in this study, our inability to observe electricity price, income and electricity consumption at the household level (Section 2.3) may give rise to omitted variables and measurement errors[2] that add onto existing endogeneity concerns. In contrast, grid-connected consumers typically have a limited influence on electricity tariffs, which are exogenously imposed by large power utilities. While electricity prices can become endogenous if block tariffs are implemented [3] (Reiss and White, 2005), this effect appears to be marginal for grid-connected household consumption in developing countries and is largely ignored by previous studies (e.g., (Bose and Shukla, 1999; Tiwari, 2000; Chattopadhyay, 2004; Filippini and Pachauri, 2004).

Second, costs and operational challenges often prevent the installation of household connection meters (Rosa et al., 2012; Casillas and Kammen, 2011). While substantial recent progress has been made in the installation of household metering devices (Lee et al., 2016; Pueyo, 2015), many off-grid power systems remain unmetered. In Nepal, off-grid micro-hydropower schemes are typically operated on capacity-based tariffs (Fulford et al., 2000; Ghale et al., 2000), whereby households pay a fixed fee per unit of electric capacity (e.g. 70 Nepalese Rupees per month for a 100W inlet (Joshi and Amatya, 1996). Without connection meters, household electricity consumption cannot be monitored in many off-grid power supply schemes. This causes a fundamental data problem and requires proxy variables to assess electricity consumption. Another important consequence is that households cannot be billed on their energy consumption, but pay a fixed fee determined by the capacity of their connection (Baral et al., 2012). Electricity consumption choices therefore represent *long-term* decisions, driven by the ownership of electrical appliances and limited by the connection capacity, usually enforced via sealed current limiting devices installed by the utility. This delays the effect of exogenous shocks (e.g., climate, prices and income) on the household's decision to change their level of consumption (Iimi, 2011), and renders short-term dynamic elasticities irrelevant. It also means that existing identification strategies to address price endogeneities in large power grids (i.e. panel adjustment techniques (Alberini and Filippini, 2011) and instrumental variables based on the enforced tariff structure (McFadden et al., 1977; Reiss and White, 2005) cannot be readily transferred to unmetered micro grids because the required detailed information on individual household consumption and pricing structure is generally unavailable.

These estimation challenges limit the use of existing econometric approaches to determine γ_p for off-grid, unmetered households. Local price elasticities are frequently overlooked by practical design manuals, which assume that electricity prices are exogenous and constant (e.g., Junejo et al., 1999; Fraenkel et al., 1991; Junejo, 1997). This assumption is valid for grid-connected plants benefitting from feed-in tariffs (e.g., Basso and Botter, 2012), but may lead to over-designed infrastructure off-grid because it neglects the possibility that excess power generation will saturate local demand, in which case prices will drop substantially. Poor sizing is listed among the likely reasons explaining the low sustainability (i.e. high failure rate) of off-grid infrastructure in developing countries (e.g. Khennas and Barnett, 2000), for micro hydropower).

To address this gap, we propose a method to estimate the price-elasticity of off-grid, unmetered electricity demand. The study focuses on Nepal and uses recorded information on the costs and salient features of subsidized micro hydropower schemes to determine average, community-level consumption (in connection capacity, kW) and price (in $\$/kW$ connection fee). Micro hydropower in Nepal is a good example of scantly sustainable off-grid infrastructure despite very favorable conditions. Thanks to the low level of technology of its components, micro hydropower often emerges as the most cost effective rural electrification option for mountainous regions globally (Müller et al., 2016). Nepal has an enormous hydropower potential, a large rural population without access to the power grid, substantial local hydropower expertise, favorable institutions and 50 years of implementation experience. Nonetheless, about 30% of existing micro hydropower plants are not in operation (Khennas and Barnett, 2000). We use an instrumental variable approach to address endogenous pricing and base our identification strategy on the fact that hydropower generation, and therefore electricity price, is strongly affected by water availability, which itself relates to upstream topography. We present evidence in Section 4.1 that the considered instrument – the area of the contributing watershed – is exogenous, i.e. it does not directly affect electricity demand, and is sufficiently correlated to infrastructure costs to provide unbiased (though noisy) estimates of γ_P. Although the relation between infrastructure costs and upstream topography is specific to hydropower, which limits the applicability of this particular method, the general approach of leveraging supply-side environmental constraints as instrumental variables may be extended to characterize demand for other off-grid renewable sources.

We find that the estimated elasticity is significantly lower (in absolute value) than long-run elasticities found elsewhere in the literature. Three important differences come to mind immediately and set this study aside from previous estimations of γ_p. First, isolated micro grids are more prone to outages and voltage fluctuation than larger grids because of their small size and undiversified power source (Vaidya, 2015). Second, the absence of connection meters in the Nepalese dataset sets the marginal cost of consumption (in terms of appliance usage) to zero. Third, off-grid electrification primarily concerns rural communities, which typically have much lower levels of income, appliance ownership and electricity consumption than their urban counterparts. We discuss these particularities and their possible implications on demand elasticity that may explain its lower absolute value (Section 4.2).

[1] An independent variable of a regression model is endogenous if it is correlated to the error term.

[2] For instance, price and consumptions are mismeasured in our study if costs are not completely recovered or if the infrastructure is not used at its full capacity.

[3] Consumers can affect their marginal price by choosing their level of consumption.