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Opportunities for behavioral energy efficiency and flexible demand in data-limited low-carbon resource constrained environments

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HIGHLIGHTS

- First flexible demand and behavioral energy efficiency pilot in Latin America.
- 60 participants from low-middle income neighborhoods of Managua, Nicaragua.
- Wireless sensor networks enabled flexible demand and high-resolution feedback.
- 9% behavioral energy savings and ≥ 80% participation in flexible demand events.
- Co-benefits included improved energy literacy and financial management.

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ABSTRACT

Sensor networks, information and communication technologies, and advances in behavioral science can allow for the design and implementation of inclusive information and automation systems for ongoing low-carbon transitions. Here, we present results of the first randomized pilot providing tandem behavioral energy efficiency and flexible demand services through the use of distributed sensor networks in Latin America (Managua, Nicaragua). We show that the houses and micro-enterprises randomly assigned to the intervention reduced their energy consumption by nine percent relative to the control group, and participated at length in peak-shaving flexible demand events (≥80% of events). Identified social co-benefits included increased energy literacy, financial management and user empowerment, and find that improved access to energy information was more important than cash when incentivizing project participation with a high user willingness to pay. Several challenges may hinder the success of smart systems in resource constrained environments, including temporal and financial scarcity at the household level, lack of institutional support, and a panoply of top-down misaligned incentives. We document the multiple barriers to scale flexible demand and energy efficiency strategies, including bottom-up (e.g., appliance financing) and top-down (e.g., decoupling) challenges and discuss ways to overcome them. As more low, low-middle income countries transition away from fossil fuels, the use of sensor networks and information and communication technologies for building smart and inclusive smart systems will become increasingly necessary and attractive.

1. Introduction

The ongoing global transition towards renewable energy is now occurring across all regions, incomes and levels of human development – with most new renewable energy capacity being installed in low, low-middle, and middle-income countries [1]. At the same time, access and ownership of cellphones, smartphones and information and communication technology (ICTs) has spanned the globe. Currently, there are more active mobile connections than people in the world (7.8 billion SIM connections vs. 7.6 billion people), and the number of 3G/4G users is expected to double by 2020 (2.5 billion users) [2]. The combination of these two trends presents a unique opportunity to develop and use low-cost information and communication technologies to address the inherent challenge in managing increasing penetrations of uncertain and variable renewable energy, particularly in data-limited contexts without a smart grid. However, despite the cost reductions in efficient appliances, renewable energy technologies, and ICTs, there are very few pilot demonstrations in low, low-middle and middle-income

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economies that harness the synergy of these technologies.

Energy efficiency has a large potential role in reaching global goals related to energy security [1,2,3], economic efficiency [3,4], local pollution reduction, and climate abatement [5–7]. However, the size of the efficiency resource is not well understood. Some estimates suggest that there is vast economic potential with two-thirds of the resource remaining unfulfilled [2,5], while other analyses suggest that the resource is significantly smaller due to physical constraints, risk and opportunity costs, costs to project participants, and unobserved factors that can reduce the effectiveness of energy efficiency interventions (e.g., behavioral aspects) [8–10].

There is also widespread interest in using flexible demand as a means to reduce electricity system operation and infrastructure costs [9,10]. Within this area, there is a deep literature that provides (i) reliability, optimization and engineering analyses of load flexibility [2,11–20], (ii) evaluations for available sensing, actuation and control solutions [2,21–24], and (iii) pilots to validate theoretical assumptions, and understand the physical engineering aspects, and business opportunities that can inform large-scale deployments [2,21,25–29]. The role of user behavior and engagement, however, is an often overlooked yet crucial factor that will critically affect the success of these programs [30–33]. Behavioral science research has developed a diversity of theories explaining the many reasons why and how energy efficiency programs succeed and fail [34–36]. Social comparisons and access to information [34], social cognitive theory and moralized consumer choice [34,35], the role of autarky and self-determination [37], sustainability leanings [38], political ideology [39], and monetary incentives and loss aversion [40], have all been used to explain the mechanisms through which individuals (or households) chose to participate and remain engaged in renewable and energy efficiency programs [41–43].

Thus far, the majority of research exploring residential and small-business flexible demand focuses on modeling, as well as regulatory and technical innovation [42]. There is little work focusing on users' physical, temporal, and budget constraints and even less emphasis on understanding the barriers and drivers that have been uncovered by advances in behavioral science [30,43–47]. A deeper understanding of these issues could be leveraged to use flexible demand programs as a tool for inclusive and social participatory engagement. Motivations for participating in demand-side management (e.g., monetary, environmental, altruistic, community-oriented) could be as varied as concerns towards it (e.g., health, privacy, costs) [48], and more research is needed to develop approaches and technologies that can reach the greatest number of people. Furthermore, there is very little applied and interdisciplinary research that informs how to evaluate and narrow the energy efficiency and smart infrastructure gap in data-limited low-carbon resource constrained environments. This research is crucial, however, as most future electricity demand will occur in emerging economies and the rising south [49–51].

Here, we present what we believe to be the first randomized pilot of a behavioral energy efficiency and flexible demand intervention in low, low-middle income neighborhoods in Latin America. Behavioral energy efficiency is defined as messaging grounded on behavioral science to produce simple, actionable messages to motivate end-users to save energy [52]. Flexible demand is defined as the use of communication and control technology to shift electricity demand across time (e.g., seconds, minutes, hours) while delivering end-use services (e.g., cooling, heating, electric vehicle charging) [53]. There are several notable findings and contributions from our approach. First, we demonstrate that low-cost wireless sensor networks can be used to achieve large monetary savings through flexible demand and behavioral energy efficiency in data-limited resource-constrained environments. We find that the houses and micro-enterprises (MEs) randomly assigned to our intervention reduced their energy consumption by nine percent relative to a control group, and participated at length ($>$ 80%) in peak-shaving flexible demand events. Second, we use state-of-the-art analysis to characterize both the parameters and uncertainty of our estimates through Bayesian Inference and Markov Chain Montecarlo (MCMC), a novel approach that could significantly benefit many pilot projects with small sample sizes across the world. Third, our pilot uncovered many co-benefits to smart grid interventions that had previously not been identified or discussed at large in the literature, including improvements in energy literacy, knowledge creation, household and small-business management, small business and women empowerment, as well as reducing perceived stress of energy expenditures. Finally, our pilot implementation suggested that under some circumstances, monetary incentives are not the preferred or the most successful method of encouraging end-user project participation – even in resource constrained environments. When given the option to choose a reward for program participation of either detailed energy information or direct cash payments, most participants chose information over cash, consistent with literature that suggests that non-monetary rewards can be equally or more effective than financial incentives at motivating behavioral change. We discuss all these themes at length throughout the paper.

2. Materials and methods

2.1. Study design and recruitment

Nicaragua has one of the highest penetrations of non-large hydropower renewable energy among countries in the Western Hemisphere (~%60) [54]. While it has significantly improved access to basic services and quality of life after decades of civil unrest, Nicaragua still has relatively high electricity prices and relatively low scores on ease of doing business and infrastructural quality [54–56]. In January 2015, we implemented a baseline survey (N = 435) to collect household and small-business characteristics (e.g., age, education level, gender, and appliance ownership) on neighborhoods of similar social demographics (overcrowding, access to basic services, housing quality, education level, economic dependency and poverty), performed a basic needs assessment, and gained insight on local perspectives of climate change, energy costs and grid adequacy, the perceived usefulness of energy information, and a variety of local energy management perspectives. Our surveys and interviews included 216 households and 219 micro-enterprises (e.g., butcheries, chicken shops, corner stores).

The pilot's baseline survey elucidated many themes that allowed us to design adequate project invitation mechanisms, and later, effective information technology systems to retain our project participants. Energy, food, and access to basic services were the top three self-perceived present concerns in our sample (23%, 20%, and 12% of the sample ranking an issue as a top concern, respectively) with most members finding it very-hard (18% of sample) or hard (43% of sample) to pay their monthly electricity bill. The combination of relatively high electricity prices (0.21$/kWh) and low incomes created a constant source of stress in the sampled neighborhoods, with 60% of the sample checking their energy meter on a daily basis and keeping an energy calendar, or simply taking "energy notes" (energy meters are sometimes located outside houses, and other times located with other energy meters on a street corner) in an attempt to control their energy consumption. Furthermore, 72% of the surveyed households and micro-enterprises unplugged their refrigerator once a day, or at different times of the day in an attempt to reduce their energy consumption. Many of the households and MEs perform this practice on a daily basis while explicitly acknowledging that they don't know if their strategies are being successful. An additional incentive for a careful energy management approach by our project participants is that a monthly consumption below 150 kWh leads, on average, to a 60% reduction in the unit cost of energy $US/month (cost of energy for 150 kWh/month vs. 300 kWh/month). Many of our participants were actively engaged in attempts to save energy to receive a subsidized cost per unit of electricity, albeit many of them doing so unsuccessfully.