The impact of market concentration on solar home system installations in rural off-grid areas

Rafia Zaman* and Stefan Borsky**

*University of Graz, Institute of Systems Sciences, Innovation and Sustainability Research, Merangasse 18, AT-8010 Graz, Austria. *Corresponding author:* rafia.zaman@uni-graz.at

** University of Graz, Wegener Center for Climate and Global Change, Brandhofgasse 5, AT-8010 Graz, Austria.

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Abstract

This paper investigates the impact of market concentration on solar home system installations in rural off-grid energy markets. We use an extensive dataset that includes 4.11 million solar home systems installed in 503 markets over 15 years (2003-2017) under Bangladesh's market-based solar home system program. We show that an increase in the degree of market concentration reduces both the number and the total capacity of installed solar home systems after controlling for relevant demand and supply-side factors. The marginal effect is non-linear and is particularly strong at a higher degree of market concentration. Additionally, we find heterogeneous effects of market concentration depending on the size of the installed solar home system and customer group. It is particularly households buying small solar home systems, who are adversely affected by a lack of competition between the solar service providers. Our study implies that policy-makers, program implementing authorities, and development donors of market-based solar home system programs should all take the supply structure of rural off-grid energy markets into account when designing rural electrification policies to achieve universal electricity access.

Keywords: Rural electrification; solar home system; market concentration; competition; South Asia; Bangladesh.

JEL: D22; O12; O13; ; Q41; Q48.

1 Introduction

Achieving universal electrification, as a part of the UN sustainable development goals (SDG 7.1.1) is a pressing concern for developing countries. Around 671 million people living in rural off-grid areas still lack access to electricity (UN 2020). The expansion of grid electricity to remote rural villages, often characterized by scattered settlements in hill tracts and riverine islands, is expensive and technically challenging (Abdul-Salam & Phimister 2019). Distributed electricity systems, mainly solar home systems, are a cost-effective and promising off-grid technology for providing lighting and low-end energy services to rural households (GOGLA 2019, Sievert & Steinbuks 2020).[1]

Several off-grid energy programs, particularly in South Asia and Africa, promote market-based approaches in order to increase the scale of solar home system installations and, thereby, advance electricity access (Palit & Chaurey 2011, Turner 2019). A market-based approach involves subsidies and other facilitation mechanisms, such as consumer financing, to enable poor rural households to buy solar home systems at affordable prices. Furthermore, a market-based approach includes financial support, such as institutional grants for capacity building, market development, and awareness-raising activities, as well as low-cost loans for working capital requirements, in order to facilitate the supply of technologies and to encourage firms to participate in and compete for sales in rural off-grid energy markets (Pode 2013, Steel, Anyidoho, Dadzie & Hosier 2016).[2] Although several market-based off-grid energy programs have been implemented, it is only in relatively few countries lacking electricity access that commercial markets have been established (Joshi, Choudhary, Kumar, Venkateswaran & Solanki 2019).

One factor, inhibiting not only the further dissemination of the solar home system technology but also the long-run sustainability of the programs themselves, is the level of market maturity and competition in rural off-grid energy markets (Barrie & Cruickshank 2017, Moner-Girona, Solano-Peralta, Lazopoulou, Ackom, Vallve & Szabó 2018). Providing electricity access to poor households in remote rural areas requires a high initial investment and an extensive service infrastructure. High distribution costs and low investment returns associated with low energy demand often discourage firms from entering these markets. This leads to a situation in rural off-grid energy markets whereby only relatively few firms are in operation and there is often a lack of competition (Rehman, Sreekumar, Gill & Worrell 2017). Lack of competition allows firms to maximize their profit margins by charging higher prices or interest rates and providing poor service quality that primarily affects poor rural households (Hausman & Sidak 2004, Srinivasan 2009, Bollinger, Gillingham & Lamp 2017, Al-Azzam & Parmeter 2019, Turner 2019). This prompts a consequential policy concern about implementing purely market-based dissemination programs of solar home systems in the off-grid rural areas in order to ensure universal electricity access (Conway, Robinson, Mudimu, Chitekwe, Koranteng & Swilling 2019, Liao & Fei 2019, Grimm, Lenz, Peters & Sievert 2020).

[1] According to the Multi-Tier Framework proposed by the World Bank, tier 2-level electricity access comprises low-end energy services, including electrical lighting, air circulation, radio and television, and phone charging. For details, see https://openknowledge.worldbank.org/bitstream/handle/10986/24368/Beyond0connect0d000technical0report.pdf?sequence=1&isAllowed=y

[2] In this study, the term firm refers to installers, solar service providers, and partner organizations that provide solar energy services, interchangeably.

The existing literature dealing with off-grid electrification still lacks an explicit focus on the development of rural off-grid energy markets and supply-side competition. Many studies are primarily based on a qualitative assessment of solar home system program design and policies across implementing countries. Sovacool (2013), for example, reports several factors, such as capacity building, financing, marketing and awareness, stakeholder engagement and ownership, and technical standardization when describing the performance of solar home system programs implemented in ten different countries, including Bangladesh, Sri Lanka, Nepal, China, Nepal, Laos, and others. In a similar vein, single case studies focusing on India and Sub-Saharan African countries highlight several critical factors, such as community participation, technical defaults, and performance of installed solar home systems, customer awareness, and affordability, which all work to limit the dissemination of solar home systems in rural off-grid areas (e.g. Azimoh, Klintenberg, Wallin & Karlsson 2015, Urpelainen & Yoon 2015, Atsu, Agyemang & Tsike 2016, Baurzhan & Jenkins 2016, Joshi et al. 2019). Based on experimental evidence, several studies find that poor rural households have only a limited ability to pay the full product price in a purely market-based solar home system program (e.g. Grimm et al. 2020, Lee, Miguel & Wolfram 2020, Sievert & Steinbuks 2020). They suggest subsidizing solar home system prices to ensure that system costs are covered and that firms expand their services in rural off-grid areas. However, a small body of qualitative literature reports supply-side factors as being primary problems constraining the growth of rural off-grid energy markets (Urpelainen & Yoon 2017). For instance, solar home system markets in Tanzania and Fiji remain less competitive than markets in Kenya due to the relatively low number of participating firms. The authors argue that the lack of competition in these markets led to an increase in product and service costs of solar home systems (Urmee & Harries 2012, Ondraczek 2013).

In this paper, we provide empirical evidence for the impact of market concentration on the number and capacity of new solar home systems installed in a market over time. Additionally, we follow Shrieves (1978) and O'Shaughnessy (2018*a*) and extend our analysis to investigate the effect of market concentration on solar home system size and customer group. We base our analysis on an extensive dataset covering the whole universe of around 4.11 million installed solar home systems under the IDCOL[3] program in Bangladesh across 503 markets over 15 years (2003-2017). We focus on Bangladesh as this is one of the key countries that have achieved noticeable progress in off-grid solar electrification in the last decade (IEA, IRENA, UNSD, WB & WHO 2020). To measure the degree of market concentration, we construct a normalized Herfindahl-Hirschmann Index based on market share information for each of the 60 active solar service providers in Bangladesh. To account for the count data characteristics of our dataset, we apply a Poisson fixed effect model, which is estimated using a Poisson pseudo maximum likelihood estimator, as suggested by Silva & Tenreyro (2006).

Our results show that a one percentage point increase in the degree of market concentration reduces the average number of new solar home system installations by 0.37 percent and the total capacity of installed solar home systems by 0.31 percent in a market. Put differently, a one standard deviation increase in the degree of market concentration decreases the number

[3] Infrastructure Development Company Limited (IDCOL), the principal implementing authority; for details, see http://idcol.org/home/solar

of installed solar home systems by 11.9 percent and the total capacity of installed solar home systems by 9.9 percent. Additionally, we observe that, in particular, it is the highly concentrated solar home system markets, which drive this negative relationship. We further show that the degree of market concentration has a stronger influence on small solar home system installations ($\leqslant$50 watts) compared to that on large solar home system installations (>50 watts). A one percentage point increase in the degree of market concentration reduces the number of installed small and large solar home systems by 0.43 percent and 0.13 percent, respectively. Finally we find, that market concentration only affects the installations undertaken by household owners, but not those of non-households owners, such as in offices, restaurants, and shops.

Our study contributes to the growing literature on off-grid electricity access in developing countries. We are the first, to the best of our knowledge, who conduct an empirical investigation on the role of market structure, in particular, on competition between firms, in the diffusion of solar home systems in the rural off-grid energy market context. Researchers have recently started to investigate the relationship between market concentration and the price of grid-connected solar photovoltaic systems, but only in the context of the US residential markets (Gillingham, Deng, Wiser, Darghouth, Nemet, Barbose, Rai & Dong 2016, Bollinger et al. 2017, O'Shaughnessy 2018*b*, O'Shaughnessy 2019). In the present paper, we complement these studies by providing evidence on the relationship of market concentration and sales in an off-grid developing country setting. Our study also contributes to the recent call for sustainability transition studies to address the importance of market-related structure and processes in enabling clean energy transition (Boon, Edler & Robinson 2020).

With regard to achieving universal electricity access, the insights of this study have important policy implications. A competitive rural off-grid energy market is instrumental in driving prices and service costs down, and thus, in increasing the scale of off-grid solar electrification. However, an increasing number of firms do not necessarily lead to an increase in market competition as the relative size distribution of the active firms might not change (Bresnahan & Reiss 1991, Manuszak 2002). Therefore, program implementing authorities and development donors should keep the market structure in rural off-grid energy markets in focus, when implementing solar home system dissemination policies in these areas. In a recent study, Grimm et al. (2020) find that poor rural households have a limited ability to pay for solar home systems in purely market-based programs. At the same time, this is exactly the customer group who is most affected by a lack of competition in the rural off-grid energy markets. When designing rural electrification policies and off-grid energy programs, it is important to provide subsidies to rural households alongside developing commercial markets for solar home systems.

2 Case background

At the beginning of the 20^{th} century, the rural electrification rate in Bangladesh was less than 25 percent (World Bank 2013). As a part of a universal electrification policy, the Bangladesh government, supported by the World Bank and other development donors, started a market-based solar home system program in 2003 (Palit & Chaurey 2011, Pode 2013, World Bank 2013). IDCOL, a state-owned financial intermediary company, is the main implementing authority of the solar home system program. This program combines market-based incentives and commercial elements in order to deliver cost-efficient energy services to poor rural households. Today, Bangladesh is one of the largest solar home system markets worldwide. In 2018, around 14 percent of the rural population was provided with access to electricity as a result of the installation of over four million solar home systems (World Bank 2018).

IDCOL implements the program through its local partner organizations and, thereby, leveraging their extensive distribution networks in rural off-grid areas. At the start of the program, IDCOL selected several local microfinance institutions and non-governmental organizations with a long-standing presence in the rural community as partner organizations. In 2010, rural off-grid energy markets for solar home systems were liberalized and commercial firms were allowed to enter the market (Wimmer 2018). The partner organizations are responsible for installing, financing, and maintaining solar home systems in rural households.

To support the development of rural off-grid energy markets, IDCOL provides partner organizations with several financial support schemes. Partner organizations receive capital subsidies for each solar home system they sell, which reduces the market price of the solar home system. Initially, these subsidies remained fixed regardless of the size of the solar home system. Later, IDCOL changed the subsidy scheme and now provides subsidies only for small solar home systems with a capacity of up to 30 watts. Additionally, partner organizations receive soft loans, which are loans with a below-market rate of interest, in order to finance the extension of their business operations (Khandker, Samad, Sadeque, Asaduzzaman, Yunus & Haque 2014). And finally, grants are also provided for training, awareness-raising, and quality assurance activities (Khandker et al. 2014, Marro & Bertsch 2015).

Partner organizations under the IDCOL program have to procure the components of solar home systems, such as solar panels, batteries, and converters, from several IDCOL-designated suppliers (World Bank 2012, Marro & Bertsch 2015, Wimmer 2018). Based on this procurement the partner organizations then set the price for solar home systems. The interest rates depend on the costs and risks associated with the loans disbursed to rural households.

Overall, IDCOL aims to create commercial solar home system markets, which can operate without donor grants and capital subsidies and continue expanding electricity access beyond the project duration. Thus, IDCOL gradually withdraws capital subsidies and reduces the option of receiving soft loans for partner organizations as the market volume increases over time. IDCOL, additionally, adopts open market principles to foster competition in the market. For instance, the partner organizations can freely choose any market or a group of geographical markets in which they want to start or expand their operations.

3 Data

For the purposes of our study, upon placing an official request, we obtained panel data from the IDCOL's solar home system program for 15 years (2003-2017). The original solar home system data contains 2,200,159 observations of different ownership groups, such as households, educational institutions, mosques, restaurants, shops, and offices. This is aggregated at the village level and contains information on the total number of new solar home system installations, the total capacity of the installed solar home systems, the name of the installing partner organization, and the name of the village. It covers the whole universe of solar home systems installed under the IDCOL program, comprising 4.11 million solar home systems in 2017.

During data pre-processing, the names of administrative areas, i.e. districts and thanas, are crossed-checked and harmonised using three different sources, namely geo-referenced boundary information provided by the GADM project[4], and new and old census geocode information published by the Bangladesh Bureau of Statistics[5].

Following Stigler & Sherwin (1985) and Fletcher & Lyons (2016), we define a relevant geographic market as an area in which the economic forces of supply and demand determine the price of a solar home system. Competitive conditions tend to ensure that prices are uniform within a given area. In Bangladesh, a thana consists of several villages and is considered to be a sub-economic zone after the district level. The partner organizations have their offices in each thana in order to store solar home system components. The respective thana office delivers solar home systems to the households in the local villages once the sales agreements are arranged. Hence, we choose the thana level as the geographic market boundary that constitutes a uniform market for solar home systems. We aggregate our solar home system data at the thana level, which gives us a sample of 6,189 observations for 503 thanas (markets) from 2003 to 2017.[6] Table A2 in the appendix presents a summary statistics of the variables used in our analysis.

3.1 Spatio-temporal development of solar home system installations

Since the start of Bangladesh's solar home system program in 2003, there has been a significant increase in the number and the total capacity of installed solar home systems. This is shown in Table 1. In the initial years, the installations of new solar home systems increased gradually, and the program achieved its target of 50,000 cumulative installations by 2005. Thereafter, additional funding from the donors together with market liberalization and technological improvements increased the number of new solar home systems installations considerably. Rural off-grid energy markets experienced a growth phase of solar home system sales up to 2013, followed by a phase of decline in installations. Up to 2017, 4.11 million solar home systems were installed in Bangladesh, representing a cumulative capacity of 162 megawatts.

Figure 1 shows the percentage distribution of solar home system installations across thanas up to 2008 (left panel) and up to 2016 (right panel). Overall, thanas with darker colors, mainly in the North and the South as well as the South-Eastern parts of Bangladesh, to some extent, have a higher level of solar home system installations at these two points in time. These thanas are, in general, primarily rural areas, including hilly regions, relatively inaccessible, and they often have a low-level of access to the national electricity grid. In 2008, a large degree of variation can be observed for solar home system installations across thanas. In subsequent years, further

[4] Available at https://gadm.org/

[5] https://bbs.gov.bd/

[6] Overall, Bangladesh is divided into 64 districts. There are 545 thanas, and each district consists of nine thanas, on average. We exclude 42 thanas as no solar home systems were installed over the whole sample period. In general, these are thanas which constitute larger cites, e.g., around the capital city Dhaka, and, which are fully connected to the electricity grid.

Table 1: Number and total capacity of solar home system installations from 2003-2017

Year	Number	Cumul. number	Capacity	Cumul. capacity	Year	Number	Cumul. number	Capacity	Cumul. capacity
2002	226	226	12	12	*2010*	313,637	745,731	15,578	38,191
2003	16,004	16,230	765	777	*2011*	462,197	1,207,928	21,352	59,543
2004	19,347	35,577	982	1,759	*2012*	655,946	1,863,874	27,102	86,645
2005	26,585	62,162	1,382	3,140	*2013*	866,692	2,730,566	30,055	116,700
2006	37,188	99,350	2,068	5,209	*2014*	750,474	3,481,040	24,263	140,962
2007	69,135	168,485	3,842	9,050	*2015*	442,717	3,923,757	14,597	155,560
2008	96,437	264,922	5,355	14,405	*2016*	161,031	4,084,788	5,855	161,414
2009	167,172	432,094	8,208	22,613	*2017*	25,569	4,110,357	1,034	162,448

Notes: The number of new solar home system installations presents the sum over all thanas in a given year. The total capacity of installed solar home systems is given in kilowatts. The number and total capacity installed in the year 2002 are based on the pilot phase conducted by IDCOL and its partner organizations before the official commencement of the solar home system program in 2003.

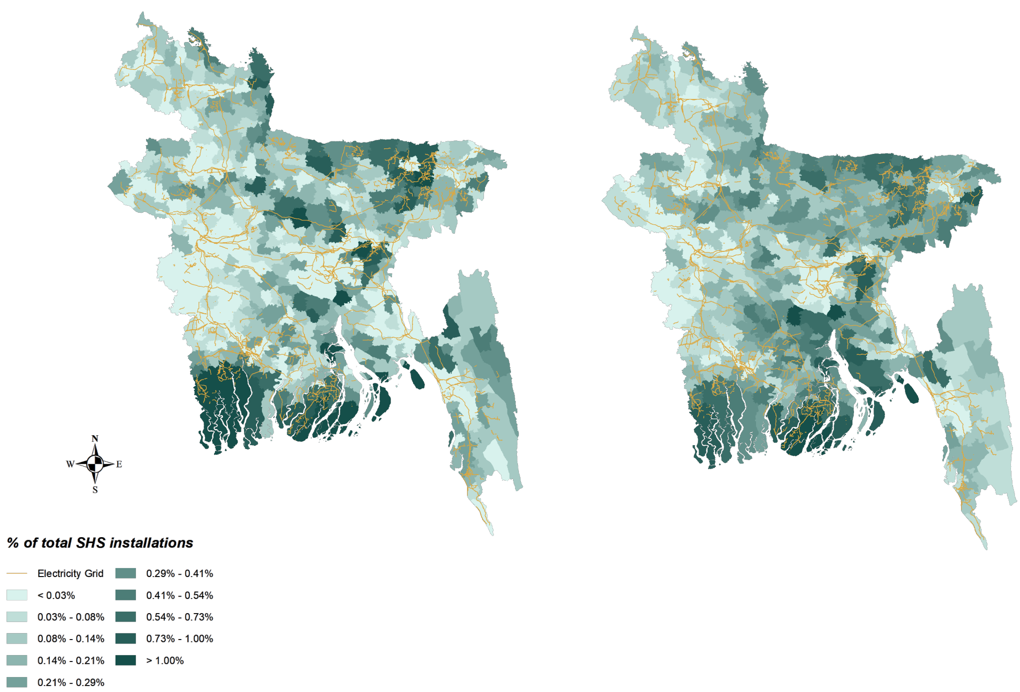

Figure 1: Solar home system installations across thanas over time. *Notes:* The left panel shows the spatial distribution of the sum of solar home system installations until 2008 and the right panel until 2016.

installations of new solar home systems led to a less pronounced spatial variation in installations by 2016.

3.2 Market concentration in solar home system markets

The Herfindahl-Hirschman Index is a widely used concentration measure to assess the competition between firms in a market and serves as a proxy indicator for capturing the degree of market

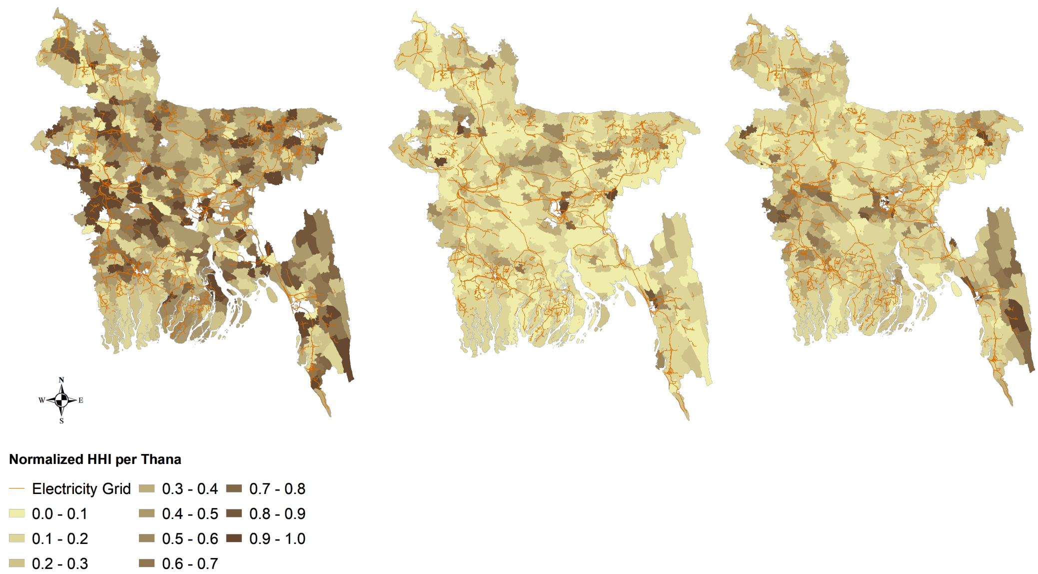

Figure 2: Market concentration across thanas over time. *Notes:* The left panel shows the spatial distribution of market concentration in 2008, the middle panel in 2012, and the right panel in 2016.

power or monopoly power of firms in a market. It is a summary measure that takes the complete market share distribution of all individual firms in a market and assigns each firm a weight equal to its market share, giving higher weights to those firms with larger market shares. The value of the index increases as the market is divided up among fewer firms, and decreases as the number of firms in the market rises.

However, the value of the Herfindahl-Hirschman Index remains problematic when the number of partner organizations differs widely across markets (Brezina, Pekár, Čičková & Reiff 2016). In our sample, the number of partner organizations is right-skewed ranging on average between 1 and 30 active partner organizations in one thana. Following Khurshid, Singh & Singh (2009), we apply a normalized Herfindahl-Hirschman Index as specified in equation 1, which is not affected by the number of partner organizations in a market, but by their relative size distribution.

$$MC_{it} = \frac{\left(\sum_{p=1}^{N} s_{pit}^2\right) - \frac{1}{N}}{1 - \frac{1}{N}} \tag{1}$$

In each thana, i, and year, t, the market share, s, of each PO, p, ranges between $0 \leq s_p \leq 1$. The market share of each PO, s_p, is indexed in a non-increasing order $s_1 \geq s_2 \geq \cdots \geq s_n$. The maximum value of MC_{it} equals 1, when a single PO holds the entire market, indicating a highly concentrated and less competitive market. With a given number of equally distributed firms $s_p = \frac{1}{N}$, the minimum value of MC_{it} equals 0 indicating a non-concentrated and highly competitive market.

In our setting, partner organizations with higher market power are able to drive prices and profits above the price level prevailing in perfect competition. In a market-based program, the profit margin is not necessarily only determined by the market price of the solar home system, but also by other pricing components, such as loan interest rate, as mentioned in section 2.[7]

Figure 2 shows the spatial distribution of market concentration per thana for the years 2008 (left panel), 2012 (middle panel), and 2016 (right panel). Overall, we observe a large spatial and temporal heterogeneity in the degree of market concentration across thanas in a year and within a thana over time. Thanas with darker colors are more concentrated and represent less competitive markets. The year 2008 represents an initial development phase of solar home system markets in Bangladesh. Only a few partner organizations provided solar electricity to the off-grid population. Later, several new partner organizations, including commercial firms, entered rural off-grid energy markets. With an increasing number of partner organizations in a thana, the degree of market concentration decreased considerably, which led to a situation in 2012 whereby only a few thanas were still characterized by highly concentrated solar home system markets. After a peak in solar home system installations in 2014, several partner organizations started to leave some rural markets, leading to a slight increase in the degree of market concentration in 2016. This was particularly true for several thanas in the South-Western and South-Eastern regions. These formed a cluster of concentrated markets at that time. One possible explanation for this is that several partner organizations exited the IDCOL program and participated in the government-initiated free distribution program, which started operating in 2014-2015.

3.3 Other independent variables

The installation of solar home systems in a thana is affected by various demand-side and supply-side factors. To account for market size and income effects, we use measures of population size and GDP, respectively. Our yearly measure of population size per thana stems from the WorldPop - Global High Resolution Population Denominators Project.[8] The WorldPop project combines different datasets, such as census data, mobile phone data and satellite imaginary, with a random forest regression tree-based mapping approach as laid out in Stevens, Gaughan, Linard & Tatem (2015), to generate an annual gridded prediction of population density at 100m resolution. We combine this variable with geo-referenced information on subnational boundaries at the thana level to create a yearly thana level population measure.

As yearly observations on income are not available at thana level for Bangladesh, we rely on the intensity of nighttime light as a proxy measure of economic activity, which is increasingly used in the relevant scientific literature.[9] Like GDP, nighttime light is a proxy of economic activity.

[7] However, the price information, including the cost breakdown of a solar home system, on the market-level, is, owing to confidentiality issues, not publicly available (Mainali & Silveira 2011, Brunet, Savadogo, Baptiste & Bouchard 2018). Following Donsimoni, Geroski & Jacquemin (1984) and Kamien (1989), we therefore assume that differences in market concentration between thanas reflect differences in the price of a solar home system.

[8] A combined project of the School of Geography and Environmental Science, University of Southampton; Department of Geography and Geosciences, University of Louisville; Departement de Geographie, Universite de Namur and the Center for International Earth Science Information Network (CIESIN), Columbia University (2018). The Global High Resolution Population Denominators Project is funded by The Bill and Melinda Gates Foundation (OPP1134076) and is available at www.worldpop.org.

[9] Chen & Nordhaus (2011) and Henderson, Storeygard & Weil (2012), for example, emphasize the applicability of nighttime light data for data-poor countries. Michalopoulos & Papaioannou (2013) use nighttime light data as proxy of economic activity in Africa. They cross-validated the data using micro-level data from the Demographic and Health Surveys and find a significant correlation of around 70 percent.

Most forms of consumption and production in the evening require light, and public infrastructure is often lit at night. The advantage of nighttime light data is that it is available at high quality at a local level (Storeygard 2016), which makes it well suited to our locally disaggregated study on solar home system installations at a local level.

Information on the level of nighttime light stems from satellite imagery provided by the National Oceanic and Atmospheric Administration's (NOAA) National Geophysical Data Center (NGDC).[10] In particular, we use two different products. For the period from 2002 to 2011 our data stems from the Defense Meteorological Satellite Program's Operational Line-scan System (DMSP-OLS) datasets. For the period from 2012 to 2016, we use data stemming from the Visible Infrared Imaging Radiometer Suite (VIIRS) dataset. Again, we combine this data with geo-referenced information on subnational boundaries and aggregate the 1km^2 raster values at thana level. Finally, we divide this by the total raster value for the whole of Bangladesh.[11] This results in our final proxy measure of GDP, which is the relative nighttime light intensity per thana and year.

Following Graziano & Gillingham (2015), we account for differences in the overall demand for solar home systems by controlling for the number of households and access to grid electricity. Both variables stem from the national census, which collects data at thana level and is available for two years: 2001 and 2011. Census data is obtained from the Bangladesh Bureau of Statistics upon official request.[12] After retrieval, we performed several pre-processing tasks in order to align the census data with our main solar home system dataset. Finally, we prepared electricity access and household data for all 503 thanas. This means, that these variables capture overall trends in these two factors. More temporally disaggregated information at the thana level is unfortunately not available.

Apart from our market concentration measure we also control for other supply-side differences by using the number of partner organizations within a thana, and the average market experience of the active partner organizations within a thana. In particular, the latter variable is calculated as the mean cumulative years of experience for each active partner organization in a thana in a year. Partner organization-level information stems from our solar home system dataset. Finally, we use the number of solar home systems installed by the government's free distribution program, KABITA, to control for the potentially confounding impact of this program. The KABITA program is a non-commercial solar home system program initiated as part of social safety nets. It involves the free distribution of solar home systems to the poorest segment of the society across thanas, i.e. to those who don't have access to electricity and cannot afford to buy solar home systems. IDCOL's partner organizations were officially assigned to this program in 2015-2016. Data is retrieved from IDCOL upon official request and covers the two years (2016-2017) since the program has started.

[10] https://www.ngdc.noaa.gov/eog/download.html

[11] The procedure for measuring nighttime light changed between the DMSP-OLS and the VIRRS datasets, which results in different nighttime light values per raster. Using relative values for the country totals enables us to use a consistent nighttime measure over the whole time period of our sample.

[12] Census reports are available at http://bbs.gov.bd/.

4 Empirical implementation

To answer our research question, we specify a generic model that accounts for the impact of market concentration on a market's solar home system installations. Our model is given by the following specification,

$$Y_{idt} = exp(\lambda + \beta_1 MC_{it-1} + \beta_2 X_{it} + \kappa T_{it} + \gamma_i + \theta_{dt}) + \varepsilon_{idt}, \tag{2}$$

where Y_{idt} is either the number or the total capacity of installed solar home systems in thana, i, district, d, and year, t. X_{it}, is a vector of all thana characteristics which affect the number as well as the total capacity of installed solar home systems in a thana and which vary over time, e.g., demand-side factors as measured by income, population, and access to the electricity grid, and supply-side factors, e.g., the number of partner organizations in a market, or the participating organization's capability to serve a specific market.

MC_{it}, is our parameter of interest, the normalized Herfindahl-Hirschman Index, which serves as a measure of market concentration in thana, i, and year, t. Market concentration is considered to be a proxy measure of market power. Hence, price effects due to market concentration should manifest themselves in a statistically significant estimate of β_1. A nonzero coefficient estimate implies that a thana's level of solar home system installations is determined by the intensity of competition between the participating partner organizations. In line with our discussion in section 1, a less competitive market would lead partner organizations to charge higher prices or interest rates and deliver poor service quality. Therefore, we expect β_1 to be negative, meaning that the degree of market concentration reduces both the number and the total capacity of installed solar home systems.

T_{it} is a thana specific parametric year trend, which captures, for instance, technological change in a thana over time (Kim & Heshmati 2019). γ_i is a thana dummy, which covers all factors that are thana specific but invariant over time, e.g., topography and accessibility, as well as the distance to markets, district headquarters or larger cities. θ_{dt} is a district-year dummy, which controls for all district specific factors which vary over time, e.g., country or region-wide support policies, the extension of the electricity grid and political election cycles. Based on this dummy set, our identifying variation comes from differences in the market concentration within a single thana over time, or across thanas in the same district and year. Through our empirical set-up, we should be able to disentangle the impact of a change in the market concentration from other confounding factors that affect the number and the total capacity of installed solar home systems in a thana. Finally, the error term, ε_{idt}, contains unobserved market-level demand and cost characteristics and is clustered at the thana level.

To account for the count data characteristics of our dependent variables, i.e., non-negative data with zeros, we estimate model 2 using a Poisson pseudo maximum likelihood estimator, as proposed by Silva & Tenreyro (2006). The advantage of the Poisson pseudo maximum likelihood estimator is its flexible application. It does not rely on the data being Poisson distributed, which allows us to use it for the number as well as the total capacity of installed solar home systems. It is also consistent in the presence of fixed effects, and it allows for both over- and under-dispersion.

In our empirical setting, the main identification concern is reverse causality. In case where the current number of installed solar home systems influence the current degree of competition in a specific market, we cannot claim that equation 2 is causal. It could be possible that market concentration may affect firm performance through changes either in the efficiency due to increases in sales or in the market power of the firm (Evans, Froeb & Werden 1993). The second source of endogeneity arises due to unobserved shocks, which influence both the degree of market concentration and our dependent variables. Lower demand for solar home systems in a market could be associated with inadequate housing facilities or low electricity demand, which in turn affects the solar home system demand. The households, for instance, which experience substantial uncertainty in getting grid electricity, may prefer to adopt solar home systems regardless of the market concentration level. At the same time, partner organisations may also plan their investments according to the extent of the electricity grid irrespective of concentration levels.

To account for the potential endogeneity of market concentration and solar home system installations, we combine a thorough fixed effects structure with temporally lagged information on market concentration. The temporally lagged information on the level of market concentration in a thana accounts for potential reverse causality as it is unlikely that future market developments affect current market concentration in a thana. However, in the case that partner organizations systematically make strategic investment decisions based on expected solar home system demand trends, reverse causality would still be an issue. Therefore, in a robustness exercise, we construct an alternative instrument for the degree of market concentration in a thana, using the average market concentration in the eight spatially nearest markets. These instruments are valid under the assumption that supply shocks are correlated across markets (e.g., Nevo 2001). Finally, thana specific parametric time trends, thana fixed effects and district-year fixed effects are used to control for correlated unobservables. These may be thana specific characteristics, such as accessibility and population structure and time-varying district specific factors, such as policy-support campaigns or general policy decision on the extensions of the electricity grid. Based on this identification strategy, we are confident that our parameter estimate of market structure can be interpreted causally.

5 Results and discussion

Table 2 presents the results, which are based on specification 2. Columns (1) to (3) depict the results for the number of installed solar home systems, and columns (4) and (5) present the results for the total capacity of installed solar home systems. In column (1), a baseline model is shown. This includes the number of partner organizations as a measure of the size of the market supply as well as additional covariates, such as the degree of economic activity, population size, partner organization experience, and the existence of the KABITA program. The outcomes in columns (2) and (4) present our preferred model for the number and the total capacity of installed solar home systems, respectively. Finally, columns (3) and (5) in table 2 additionally include a trend in electricity access and the number of households in order to ensure that our estimate on market concentration is not biased due to the omission of variables related to the number and the total capacity of installed solar home systems. In all models in table 2, the results are based on the full fixed effects structure, including thana fixed effects, and district-year fixed effects, as well as a thana-year trend.

Table 2: The impact of market concentration on solar home system installations

	Number			*Total capacity*	
	(1)	**(2)**	**(3)**	**(4)**	**(5)**
Partner organizations$_{t-1}$	0.024^{***}	0.021^{***}	0.019^{***}	0.021^{***}	0.018^{**}
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Market concentration$_{t-1}$		-0.371^{***}	-0.353^{***}	-0.309^{***}	-0.286^{***}
		(0.064)	(0.065)	(0.062)	(0.063)
Economic activity$_{t-1}$	-0.981^{***}	-0.937^{***}	-1.035^{***}	-0.787^{***}	-0.869^{***}
	(0.182)	(0.178)	(0.181)	(0.183)	(0.183)
(ln) Population	0.205	0.308	−0.145	0.339	0.021
	(1.107)	(1.119)	(1.056)	(1.140)	(1.058)
Experience	-0.028^{*}	-0.035^{**}	-0.028^{**}	−0.020	−0.009
	(0.015)	(0.014)	(0.014)	(0.013)	(0.013)
KABITA	−0.000	−0.000	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Electricity access			-0.020^{***}		-0.020^{***}
			(0.004)		(0.004)
Household number			0.389^{*}		0.395^{*}
			(0.205)		(0.202)
Thana-Year Trend	Yes	Yes	Yes	Yes	Yes
Thana FX	Yes	Yes	Yes	Yes	Yes
District-Year FX	Yes	Yes	Yes	Yes	Yes
Observations	6,189	6,189	5,892	6,189	5,892
pseudo R^2	0.961	0.961	0.962	0.959	0.960

Notes: Dependent variables are stated in the column header. Market concentration is given by the temporal lag of the normalized Herfindahl-Hirschmann index. *, **, *** indicate 10, 5, and 1 % significance levels, respectively. Robust standard errors in parentheses, clustered at the thana level. Estimates are based on a Poisson fixed effect model estimated by a Poisson pseudo maximum likelihood estimator (PPMLHDFE, Correia, Guimarães & Zylkin 2019). Constant is included but not reported. Column (1) is the baseline model including the number of partner organizations in a thana; Columns (2) and (4) present the final model additionally including market concentration. In columns (3) and (5), additional controls for electricity access and the number of households are included.

Across all specifications the size of the market supply, which is measured by the number of partner organizations within a thana, increases both the number and the total capacity of installed solar home systems in a thana. Concerning our parameter of interest - the the degree of market concentration in a thana - our results provide a robust evidence supporting a negative and highly statistically significant effect of market concentration on both the number and the total capacity of installed solar home systems. A one percentage point increase in the degree of market concentration in a thana reduces the average number of solar home system installations by 0.37 percent in column (2) and total installed capacity by 0.31 percent in column (4). To put it differently, a one standard deviation increase in the degree of market concentration reduces the average number of installed solar home systems by 11.9 percent, and the total installed capacity by 9.9 percent, respectively.

Besides our main results, the outcomes for the other supply and demand-side factors provide a deeper understanding of what contributes to the extension of solar home system installations in general. Based on our preferred model specification, as shown in columns (2) and (4) in table 2, economic activity in a thana negatively influences the number and the total capacity of installed solar home systems. This makes sense, as the solar home program was designed to reach out to poor households in remote rural areas. These are areas with an inadequate grid infrastructure and a lack of access to reliable electricity supply.

The coefficient estimate of a partner organization's capability to serve a specific market, which is measured by the average market experience of the actively operating partner organizations in a thana, is negative and statistically significant for the number of installed solar home systems in column (2). In general, more experienced partner organizations often operate in many thanas and can serve the market more economic efficiently by spreading the fixed costs over a larger number of installations (Gillingham et al. 2016, O'Shaughnessy 2018*b*). Interestingly, we find that a higher level of experience of the partner organizations decreases the number of installed solar home systems. This can be explained in the context of the IDCOL program. IDCOL aims to transform partially subsidy-driven solar home system markets into self-sustained markets, in which partner organizations source commercial loans at the market interest rate. Therefore, partner organizations with outstanding soft loans exceeding US$2.5 million - these are mainly experienced partner organizations - have to pay a higher interest rate or get a lower percentage of the total investment as refinance (World Bank 2012, World Bank 2018). As the IDCOL program policy does not affect the type of installations a partner organization is providing, we don't find a statistically significant effect of average experience of the partner organisations on the total capacity of installed solar home systems in column (4).

Columns (3) and (5) in table 2 depict the results, after including a trend in electricity access and the number of households. As expected, access to the electricity grid is negative and highly statistically significant. The negative coefficient estimate suggests that solar home systems serve as a bridge technology and with increasing access to grid electricity the demand for solar home system decreases. Finally, the number of households is significant within the 10% significance level and positive. This is true for the number as well as the total capacity of installed solar home systems. Our other control variables, the population size in a thana and the KABITA program, have no significant influence on the number and the total capacity of installed solar home systems.

In a recent study, O'Shaughnessy (2019) report non-linear effects of market concentration on the on-grid solar photovoltaic price in the United States, i.e. an additional increase in market power in an already concentrated market has a significantly stronger effect on the market price. To gain a deeper understanding, we augment specification 2 to allow for a nonlinear relationship

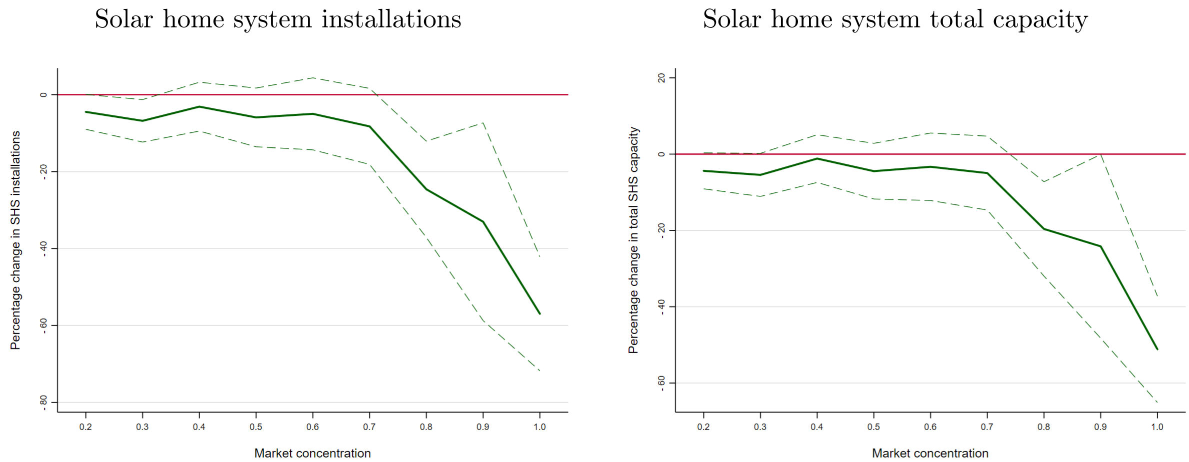

Figure 3: Effects of market concentration on the number and the total capacity of installed solar home systems. *Notes:* The solid line represents point estimates and the dashed lines show the associated 95% confidence intervals. Each panel is separately estimated based on specification 3 and includes thana fixed effects, district-year fixed effects and a parametric thana specific year trend. Standard errors are clustered at the thana level.

between the degree of market concentration and the number and the total capacity of installed solar home systems. Thereby, we estimate the following econometric model:

$$Y_{idt} = exp(\lambda + \sum_{k=1}^{K} \beta_1^k MC_{it-1}^k + \beta_2 X_{it} + \kappa T_{it} + \gamma_i + \theta_{dt}) + \varepsilon_{idt}, \tag{3}$$

where the variable MC_{it-1}^k is an indicator variable for 0.1 value increments, k, in the degree of market concentration, which allows for differential shifts in solar home system installations for each market concentration bin. The 0 - 0.1 indicator bin is omitted as the reference category. The coefficient estimates of β_1^k can be interpreted as the marginal change in the number and the total capacity of installed solar home systems relative to the lowest degree of market concentration. Figure 3 plots the response function between the degree of market concentration and solar home system installations. The solid line represents the point estimates, and the dashed lines present the 95% confidence intervals for β_1^k in equation 3.

We find a negative non-linear relationship between market concentration and solar home system installations. The adverse affect of market concentration on the number and the total capacity of installed solar home systems increases, the higher the degree of market concentration is in a thana. This means that it is particularly the highly concentrated markets, which drive this negative relationship.

5.1 Solar home system installation size and customer group

The IDCOL program offers different solar home systems with a capacity ranging between 10-130 watts. These are designed to serve rural households' energy demand for lighting, charging facilities, and communication services. The installation sizes serve various customer groups.

A small solar home system, with a capacity of ⩽50 watts, is specifically designed for those who have a low energy demand or a limited payment capacity. In contrast, a large system provides higher-end energy services to financially solvent customers. Following Shrieves (1978) and O'Shaughnessy (2018*a*), we assume that the level of market power a partner organization can exert depends on the type of solar home system sold and the characteristics of the market segments served by the partner organizations. We estimate the effect of market concentration across solar home system size and ownership category based on specification 2.[13]

Table 3: The impact of market concentration on small and large system installations

	Small installation size		*Large installation size*	
	Number	**Total capacity**	**Number**	**Total capacity**
	(1)	**(2)**	**(3)**	**(4)**
Partner organizations$_{t-1}$	0.020***	0.022***	0.014*	0.012
	(0.006)	(0.007)	(0.008)	(0.008)
Market concentration$_{t-1}$	−0.433***	−0.424***	−0.130*	−0.121*
	(0.070)	(0.067)	(0.066)	(0.068)
Economic activity$_{t-1}$	−1.025***	−0.935***	−0.621***	−0.604**
	(0.187)	(0.186)	(0.239)	(0.236)
(ln) Population	−0.026	−0.128	0.003	0.128
	(1.136)	(1.106)	(1.495)	(1.514)
Experience	−0.047***	−0.038**	0.004	0.006
	(0.016)	(0.015)	(0.014)	(0.015)
KABITA	−0.000	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Thana-Year Trend	Yes	Yes	Yes	Yes
Thana FX	Yes	Yes	Yes	Yes
District-Year FX	Yes	Yes	Yes	Yes
Observations	6,187	6,187	6,134	6,134
pseudo R^2	0.964	0.963	0.920	0.941

Notes: Dependent variable stated in the column header. Market concentration is given by the temporal lag of the normalized Herfindahl-Hirschmann index. *, **, *** indicate 10, 5, 1 % significance levels. Robust standard errors in parentheses, clustered at the thana level. Estimates are based on a Poisson fixed effect model estimated by a Poisson pseudo maximum likelihood estimator (PPMLHDFE, Correia et al. 2019). Constant included but not reported. Columns (1) and (2) present estimates for the number and the total capacity of installed small solar home systems (⩽50 watts), respectively. Columns (3) and (4) include estimates of the number and the total capacity of installed large solar home systems (>50 watts).

The estimation results for small systems in columns (1) and (2) and for large systems in columns (3) and (4) are presented in table 3. We find for both product types that a higher degree of market concentration significantly reduces solar home system installations. However, our results additionally show that market concentration affects small solar home system installations much more strongly than large systems. A one percentage point increase in the degree of market

[13] Over our sample period, 1,870,015 small and 543,216 large solar home systems were sold.

concentration reduces the number as well as the total capacity of installed small solar home systems by 0.43 percent and 0.42 percent, respectively. For large solar home systems, a one percentage point increase in the degree of market concentration decreases the number of installed solar home systems by 0.13 percent and the total capacity of installed solar home systems by 0.12 percent.

Based on these findings, in an additional empirical exercise presented in table 4, we differentiate between households and non-household owners to see if the ability of the partner organizations to exert market power differs among customer groups. We consider non-household owners as being offices, restaurants, and shops.[14] We only find a significant effect of market concentration on solar home system installation for the household customer group. A one percentage point increase in the degree of market concentration reduces the number and the total capacity of installed solar home systems of the household in a thana by 0.37 percent and 0.32 percent, respectively.

Overall, our results show that it is particularly rural households buying small solar home systems, such as farmers, fishermen, day laborers, and hawkers, who are adversely affected by an increase in market concentration and by a subsequent increase in market power of the partner organizations. This customer group is rather price-sensitive and has a limited ability to pay the full market price (Grimm et al. 2020). They often compromise their energy consumption in order to prioritize other basic needs when in financial difficulty (Baurzhan & Jenkins 2016).

5.2 Robustness

Although, we apply thana fixed effects as well as district-year fixed effects in our main model specification, factors may still change over time, which are thana specific and, therefore, are not covered by the district-year fixed effects. For instance, the extension of the electricity grid due to national energy policy may differ between thanas. Therefore, in a first set of robustness exercises, shown in columns (1) and (2) in table 5, we use thana-period fixed effects and district-year fixed effects. The thana-period fixed effect covers all thana specific factors, which are generally time-invariant within four years, e.g., topography and accessibility, but are allowed to change between periods. We find robust evidence of the negative and statistically significant impact of market concentration on the number and the total capacity of installed solar home systems.

As discussed in section 4, it is possible that partner organizations systematically make strategic investment decisions based on expected solar home system demand trends. This would invalidate the use of a temporally lagged measure of market concentration to identify the causal relationship between market concentration and solar home system installations. Therefore, in a robustness exercise, we construct an alternative instrument for the degree of market concentration in a thana using the average market concentration in the eight spatially nearest markets. These instruments are valid under the assumption that supply shocks are correlated across markets (e.g., Nevo 2001). In columns (3) and (4) in table 5, we present the outcomes of this robustness

[14] We exclude social institutions, such as educational establishments and mosques, as these are often not considered as commercial sales. It has to be noted that the group of non-household owners is rather small (15,522) compared to the household group (2,277,673).

Table 4: The impact of market concentration on solar home system installations across customer groups

	Household ownership		*Non-household ownership*	
	Number	**Total capacity**	**Number**	**Total capacity**
	(1)	**(2)**	**(3)**	**(4)**
Partner organizations$_{t-1}$	0.025***	0.025***	−0.042	−0.024
	(0.007)	(0.007)	(0.045)	(0.045)
Market concentration$_{t-1}$	−0.373***	−0.325***	0.125	0.131
	(0.064)	(0.061)	(0.081)	(0.083)
Economic activity$_{t-1}$	−0.809***	−0.645***	0.612	0.349
	(0.176)	(0.173)	(0.790)	(0.940)
(ln) Population	0.383	0.379	3.624	4.901
	(1.084)	(1.085)	(5.052)	(5.593)
Experience	−0.050***	−0.036***	−0.111**	−0.104*
	(0.015)	(0.013)	(0.054)	(0.061)
KABITA	−0.000	−0.000	0.000	0.001**
	(0.000)	(0.000)	(0.000)	(0.000)
Thana-Year Trend	Yes	Yes	Yes	Yes
Thana FX	Yes	Yes	Yes	Yes
Distict-Year FX	Yes	Yes	Yes	Yes
Observations	6,170	6,170	1,696	1,696
pseudo R^2	0.964	0.962	0.671	0.832

Notes: Dependent variables are stated in column header. Market concentration is given by the normalized Hirschmann-Herfindahl index. *, **, *** indicate 10, 5, and 1 % significance levels. Robust standard errors in parentheses, clustered at the thana level. Estimates are based on a Poisson fixed effect model estimated by a Poisson pseudo maximum likelihood estimator (PPMLHDFE, Correia et al. 2019). Constant is included but not reported. Columns (1) and (2) present estimates for households. Columns (3) and (4) include estimates for non-household customers, i.e., offices, restaurants, and shops.

exercise. The impact of market concentration remains robust with respect to both, the size of the coefficient as well as to statistical significance.

Hellmer & Wårell (2009) report that increasing sales from many small partner organizations do not increase market competition. Melnik, Shy & Stenbacka (2008) suggest that market competitiveness depends on the relative size difference between the two largest firms in a market and propose an alternative market competitiveness measure, which takes this into account. Following the authors, we specify a market dominance indicator as laid out in equation 4.

$$MC^{*}_{it} = \frac{1}{2}\left[1 - (s_{1it} - s_{2it})\,(1 - \sum_{i=3}^{n} s_{pit})\right] \tag{4}$$

The market dominance indicator decreases as the difference in the relative market shares of the two largest partner organizations increases. And, the higher their joint market share the lower the significance of other (small) partner organizations in the competition process and,

Table 5: Robustness: Thana-period fixed effects and spatially weighted market concentration

	Thana-period FE		*Spatial lag*	
	Number	**Total capacity**	**Number**	**Total capacity**
	(1)	**(2)**	**(3)**	**(4)**
Partner organizations$_{t-1}$	0.012**	0.011*	0.023***	0.023***
	(0.006)	(0.006)	(0.007)	(0.007)
Market concentration$_{t-1}$	−0.302***	−0.255***	−0.463**	−0.336*
	(0.074)	(0.072)	(0.206)	(0.198)
Economic activity$_{t-1}$	−0.810***	−0.693***	−0.978***	−0.819***
	(0.170)	(0.172)	(0.180)	(0.185)
(ln) Population	0.591	0.455	0.045	0.115
	(0.963)	(0.902)	(1.089)	(1.121)
Experience	−0.045***	−0.031**	−0.027*	−0.014
	(0.013)	(0.012)	(0.015)	(0.014)
KABITA	−0.000*	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Thana-Year Trend	No	No	Yes	Yes
Thana FX	No	No	Yes	Yes
Thana-Period FX	Yes	Yes	No	No
Distict-Year FX	Yes	Yes	Yes	Yes
Observations	6,072	6,072	6,189	6,189
pseudo R^2	0.976	0.978	0.961	0.959

Notes: Dependent variables are in column heading. Market concentration is given by the normalized Hirschmann-Herfindahl index. *, **, *** indicate 10, 5, and 1 % significance levels. Robust standard errors in parentheses, clustered at the thana level. Estimates are based on a Poisson fixed effect model estimated by a Poisson pseudo maximum likelihood estimator (PPMLHDFE, Correia et al. 2019). Constant is included but not reported. Columns (1) and (2) include thana period fixed effects. In columns (3) and (4), a spatial lag as market concentration measure is used.

therefore, the lower the market dominance indicator. The market dominance measure ranges from 0 and 0.5, whereby a value of 0.5 indicates a highly competitive market.

Columns (1) and (2) in table 6 show the results based on the use of the market dominance measure as an alternative way of determining the degree of competitiveness in a market. Our findings remain robust for both the number and the total capacity of installed solar home systems. The higher the degree of competition between the two largest partner organizations, as indicated by a larger market dominance measure, the larger the level of solar home system installations in a thana.

In a final robustness exercise, we redefine our sampling strategy and include observations following the program's first milestone - the sale of 50,000 solar home systems - achieved in 2005 (World Bank 2013). In the initial three years, only a few partner organizations participated in the program. Again, the impact of market concentration on solar home system installations is found to be robust, as shown in columns (3) and (4) in table 6.

Table 6: Robustness: Market dominance and reduced sample period

	Market dominance		*Year > 2005*	
	Number	**Total capacity**	**Number**	**Total capacity**
	(1)	**(2)**	**(3)**	**(4)**
Partner organizations$_{t-1}$	0.021***	0.020***	0.021***	0.020***
	(0.007)	(0.007)	(0.007)	(0.007)
Market concentration$_{t-1}$	0.634***	0.544***	−0.371***	−0.307***
	(0.121)	(0.116)	(0.069)	(0.066)
Economic activity$_{t-1}$	−0.949***	−0.797***	−0.869***	−0.709***
	(0.178)	(0.184)	(0.174)	(0.176)
(ln) Population	0.202	0.240	0.205	0.254
	(1.109)	(1.133)	(1.130)	(1.154)
Experience	−0.034***	−0.0019	−0.034**	−0.018
	(0.015)	(0.013)	(0.014)	(0.013)
KABITA	−0.000	−0.000	−0.000	−0.000
	(0.000)	(0.000)	(0.000)	(0.000)
Thana-Year Trend	Yes	Yes	Yes	Yes
Thana FX	Yes	Yes	Yes	Yes
Distict-Year FX	Yes	Yes	Yes	Yes
Observations	6,189	6,189	5,397	5,397
pseudo R^2	0.961	0.959	0.960	0.958

Notes: Dependent variables are stated in column header. Market concentration is given by the normalized Hirschmann-Herfindahl index. *, **, *** indicate 10, 5, and 1 % significance levels. Robust standard errors in parentheses, clustered at the thana level. Estimates are based on a Poisson fixed effect model estimated by a Poisson pseudo maximum likelihood estimator (PPMLHDFE, Correia et al. 2019). Constant is included but not reported. Columns (1) and (2) include a market dominance measure used as an alternative measure for market concentration. Columns (3) and (4) are based on a reduced sample including observations after 2005.

6 Conclusions

To achieve the SDG 7.1.1 target, governments in developing countries need to provide electricity access to the millions of energy-poor people residing in off-grid remote rural areas. Market-based energy programs in off-grid areas, which mainly focus on the provision of solar home systems, have been adopted across many electricity deficit countries to alleviate energy poverty. In consequence, the number of solar home system users has gradually increased in the last 15 years and accounted for 47 million people in 2018 (Rysankova, Peters & Sturm 2020).[15]

The government of Bangladesh envisions universal electrification being achieved by 2021. The IDCOL solar home system program was implemented to create rural off-grid energy markets by engaging local partner organizations in order to provide affordable electricity to the non-electrified population in rural areas. As a part of a sustainable market development policy, IDCOL is increasing the number of partner organizations, which distribute solar home systems,

[15]The access to small-scale off-grid solar devices, e.g., pico-solar and solar lanterns, by 373 million people, is not reported here.

while also providing market-based incentives to increase sales. The increasing number of partner organizations fosters market competition and drives the prices of solar home systems down. As a result, the market price, around US$6 - US$8 per watt, is one of the world's lowest (World Bank 2012).

However, market competition, which depends on the relative size distribution of the partner organizations, largely remains heterogeneous within markets over time. These heterogeneous supply structures tend to impact the diffusion of solar home systems in rural off-grid energy markets. Our study provides empirical evidence on the impact of market competition on the extent of solar home system installations within a thana. It shows that a one standard deviation increase in the degree of market concentration reduces both the number and the total capacity of installed solar home systems in a market by 11.9 percent and 9.9 percent, respectively. Further, it is particularly the highly concentrated markets, which drive this negative relationship. The policy concern, therefore, is not only to scale up the installations of solar home systems, but also to focus on the development of the market structure in rural off-grid energy markets. To establish a sustainable market for solar home systems, program implementing authorities and development donors must continue their efforts to support the growth of small partner organizations and ensure the financial sustainability of large partner organizations.

A lack of competition does not affect everybody in rural off-grid energy markets in the same way. Our results indicate that it is rural households buying small solar home systems, e.g., farmers, fishermen, day laborers, and hawkers, who are particularly affected by a change in a thana's market concentration. This customer group is found to be quite price-sensitive, having only a limited ability to pay for solar home systems, even in the presence of consumer financing. Grimm et al. (2020) recently show that the amount a household is willing to dedicate to electricity expenditures does not cover the market price of solar home systems. They conclude that a purely market-based approach without direct consumer subsidies is unlikely to reach the broader population in off-grid rural areas. When designing rural electrification policies and off-grid energy programs, it is important to provide subsidies to rural households alongside developing commercial markets for solar home systems.

To conclude, off-grid solar home systems remain an important instrument in achieving universal electrification in rural areas in developing countries by 2030. Although our study is based on Bangladesh, we are confident that our findings are relevant for other market-based solar home system programs in Kenya, Nigeria, and Rwanda, to name just a few. Knowledge of the implications of supply-side competition will give a better understanding of how rural off-grid energy markets evolve and how this affects the diffusion path of renewable energy technologies. As our study mainly focuses on one type of off-grid solar energy technology, we see one potential future research avenue in evaluating the impact of market competition in other renewable energy programs, including solar irrigation and village-level mini-grid services, which are increasingly being established in electricity access deficit countries.

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Appendix

Table A1: Variable description and sources

Variable	Description	Source
Dependent Variables		
Y_{idt}	Number of new solar home systems installed in thana i and district d in year t. Total capacity in watts of installed solar home systems in thana i and district d in year t.	IDCOL solar home system program
Independent Variables		
Partner organization $number_{t-1}$	Indicator variable, which represents the number of active partner organization in thana i and year t. We use the temporal lag of the variable.	Calculated based on IDCOL program data
Market concentration$_{t-1}$	Indicator variable, which represents the normalized Herfindahl-Hirschman Index based on the total capacity of installed solar home systems, in thana i and year t. We use the temporal lag of the variable.	Calculated based on IDCOL program data
Economic activity$_{t-1}$	Indicator variable, which captures the intensity of night-time light as as a proxy measure of economic activity in thana i and year t. A temporal lag is used.	NOAA and NGDC (source: https://www.ngdc.noaa.gov/eog/download.html)
(ln) Population	Indicator variable, which measures population size, based on predicted population density at 100m resolution, in thana i and year t. We use log transformation for this variable.	Worldpop (source: www.worldpop.org)
Partner organization experience	Indicator variable, which captures the mean cumulative years of experience of all active partner organizations in thana i and in year t.	Calculated based on IDCOL program data
KABITA	Indicator variable, which presents the number of solar home systems installed under the government's free distribution program in thana i and in year t.	KABITA program data
Electricity access	Indicator variable, which presents the rate of grid electrification in thana i and year t.	Census data, Bangladesh Bureau of Statistics
Household number	Indicator variable, which shows how many households are in thana i and year t.	Census data, Bangladesh Bureau of Statistics

Table A2: Summary statistics

	Obs.	Mean	St.dev	Min	Max
Dependent variables					
Number of installed solar home systems	6,189	637.81	1126.08	0	9,932
Total capacity of installed solar home systems	6,189	25,077.89	42,104.04	0	456,518
Independent variables					
Partner organizations	6,189	6.71	5.65	0	30
Market concentration	6,189	0.34	0.29	0.00	1.00
Economic activity (in %)	6,189	0.19	0.22	0.00	3.06
(ln) Population	6,189	12.37	0.58	9.88	14.90
Experience	6,189	4.00	1.87	0	15
Electricity access	5,892	37.35	23.03	2.03	99.62
Number of households	6,178	10.79	0.59	7.96	13.02
KABITA installation	6,189	59.06	240.32	0	3,224