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Decentralized Markets for Electricity in Low-Income Countries

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Abstract

Governments in low-income countries are increasingly integrating off-grid electricity provision into national electrification strategies, creating novel, decentralized markets for electricity. This paper studies a highly decentralized product that plays an important role in energy access: pay as you go (PAYGo) solar home systems. Unlike grid electrification, PAYGo solar features low upfront costs but relatively high usage costs. To what extent do high intensive margin prices limit the adoption of solar home systems? In 2019, the Togolese government implemented a large subsidy that reduced usage costs by 17.8 to 41.7 percent, while upfront costs remained constant. This paper estimates that the subsidy dramatically increased adoption, with the largest effects occurring for the smallest systems (240 percent increase). The paper goes on to develop a theoretical framework that shows that the effects of such subsidies are uncertain due to the unique cost structure of decentralized solar electricity. The results highlight the importance of use prices in the electrification decisions of low-income households.

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Decentralized Markets for Electricity in Low-Income Countries

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1 Introduction

Extending the electrical grid to rural areas is fiscally unsustainable in many low-income countries. The costs of grid expansion are high and low-income households have low demand for electricity, making it unprofitable for utilities to serve them. As a result, governments are increasingly building decentralized electricity provision into national electrification strategies, with a strong focus on solar energy.

I study a highly decentralized product that is playing an increasingly important role in energy access: pay as you go (PAYGo) solar home systems. Consumers of PAYGo solar make a down payment to have a solar home system installed, which is often an order of magnitude smaller than the cost to become connected to the grid. The system provides basic access to electricity.[1] After installation, consumers "pay as they go" to use the electricity the system generates by purchasing access time with mobile money.[2] Households flexibly finance the solar home system through these ongoing payments for use.

Relatively low PAYGo system down payments make installation more affordable than grid connections; however, using PAYGo systems is still more expensive than traditional energy sources. In Togo, my study setting, the cost of access time for the smallest system is nearly twice median monthly spending on candles, kerosene, and batteries for non-electrified households. The structure of PAYGo contracts therefore requires a shift in the focus of energy access discussions from connection costs to intensive margin usage costs. To what extent are high intensive margin prices limiting adoption of solar home systems?

The Government of Togo rolled out a large subsidy for solar access time in 2019 following multiple public investments in supply-side efforts to develop the private market for PAYGo solar. The subsidy reduced the cost of access

[1] The appliances included in PAYGo systems typically range from light bulbs and phone chargers to rechargeable torches, radios, and televisions.

[2] The PAYGo contract is similar to on-grid prepaid electricity contracts like those in Lee, Miguel, and Wolfram (2020), Jack and Smith (2020), and Jack and Smith (2015). Lang (2021) and Bonan et al. (2023) discuss differences in greater detail.

time by 17.8%–41.7%, depending on the size of the solar home system, but the upfront costs of adoption remained unchanged. The stated goal of the policy was to increase the rural electrification rate from to 40% in 2022, electrifying 300,000 households.

I use event studies and two-way fixed effects specifications to quantify the increase in adoption in response to the policy. The Government of Togo implemented the subsidy over three phases, with priority loosely going to prefectures with lower electrification rates. The subsidy rollout creates a natural experiment to measure the impact of intensive margin prices on the extensive margin electrification decision.[3]

The policy dramatically increased adoption of solar home systems in the first few months, with the largest effects occurring for the smallest, least expensive systems. The policy increased adoption of small solar home systems by 240% and large systems by 66%. I find no statistically significant increase in adoption of medium systems. The large increase in adoption in response to the intensive margin subsidy in Togo shows that low adoption of solar home systems stems from low benefits from adoption at market prices, not from credit constraints. As such, my results highlight the importance of long-term affordability in the adoption decision for marginal households. Estimates of the carbon benefits from solar home systems are equal to one third of the cost of the subsidy. Although there may be other positive externalities associated with adoption of solar home systems, they would need to be substantial to justify the size of the subsidy.

Having established the effects of the subsidy in Togo, I develop a theoretical framework to consider under what conditions the effects of the subsidy generalize to other contexts. The model highlights two features of decentralized solar electricity that are fundamentally different from on-grid electricity: zero marginal costs of generation and distribution and contestable, potentially competitive, markets. My model illustrates the importance of the cost structure of

[3]The government was concurrently undertaking state-sponsored marketing campaigns, but the campaigns were national and did not mirror the subsidy rollout. Note that challenges with the early implementation of the subsidy in practice prevent me from estimating the effect of the subsidy on intensive margin demand.

PAYGo solar and demonstrates the large number of parameters a policymaker would need to know to predict the effects of a similar subsidy in a different context.

This paper expands our understanding of electrification policies by studying decentralized markets for electricity provision, which differ fundamentally from on-grid markets. High on-grid connection costs have necessarily concentrated attention on extensive-margin prices (Trimble et al. (2016)). Studies varying the upfront costs of grid connections document low, highly elastic demand for electrification in rural areas, clearly pointing to upfront costs as a first-order barrier to on-grid electrification (Lee, Miguel, and Wolfram (2020), Chaplin et al. (2017)).[4] Recent work by Burgess et al. (2023) highlights that high costs for on-grid electricity in Africa directly contribute to rapidly increasing demand for decentralized, solar solutions.[5] The low upfront costs associated with products like PAYGo solar raise critical questions about the relationship between electrification decisions and intensive margin prices that are less policy relevant and more difficult to study in settings with high upfront costs.

In addition to differences in the cost structure, decentralized solutions like PAYGo solar do not create natural monopolies. My paper complements studies like Blimpo, Postepska, and Xu (2020) who model optimal connection costs for on-grid utilities facing regulated prices. It also highlights the distinct issues facing policymakers pursuing electrification through decentralized markets. As Laffont and Tirole (1986) point out, information asymmetries between regulators and natural monopolies create information rents that regulators must try to minimize. The competitive market structure in place for PAYGo solar implies a different set of policy motivations. Renewable, decentralized solutions carry positive environmental externalities. Rather than addressing

[4]Work showing no significant changes in electrification as a result of factors like information further speak to the importance of extensive margin prices for on-grid electricity connections (Mahadevan, Meeks, and Yamano (2023), Alem and Dugouan (2022)).

[5]Burgess et al. (2023) develop a model where consumers choose between electrification modalities. I focus instead on rural settings where on-grid electrification is either unavailable or prohibitively expensive for most unelectrified households.

market power, policymakers dealing with decentralized solutions are likely to be concerned with achieving the socially optimal use of clean energy, or achieving social objectives around energy access. My empirical work demonstrates how well intensive margin subsidies worked in Togo to achieve such objectives while my model provides a framework for understanding how intensive margin subsidies will work in different contexts.

Beyond debates around electrification, my results speak to the relationship between use costs and purchase decisions for durable goods in low-income settings. Theory predicts that intensive margin price reductions should increase adoption of durable goods (Dubin and McFadden (1984)). However, consumers in low-income settings are often credit constrained, preventing the uptake of durable goods with lumpy upfront costs (e.g., Berkouwer and Dean (2022), Beltramo et al. (2015), Bensch, Grimm, and Peters (2015), Levine et al. (2018)). In addition, multiple studies of U.S. and European consumers find evidence consistent with inattention, myopia, and difficulty evaluating intensive margin price changes (e.g., Hausman (1979), Gallagher and Muehlegger (2011), Allcott and Wozny (2014), Allcott and Taubinsky (2015)). The effects of the subsidy in Togo show that consumers in low-income countries are highly sensitive to intensive margin cost reductions even when they apply to novel products with upfront costs. This provides important evidence on the salience of use costs for low-income consumers and establishes that credit constraints are not the only explanation for low extensive-margin demand for electrification in low-income populations.

The paper proceeds with a description of electrification in Togo and the policy I study before presenting the empirical strategy and results. I then present a model of decentralized electricity markets, discuss external validity, and consider policy implications before concluding.

2 Background and Context

In 2017, 35% of Togo's population had access to electricity: 74% of urban households and 5% of rural households. The government started a new initia-

tive called "CIZO" to increase rural electrification rates to 40% by 2022 with the goal of achieving universal access to electricity by 2030 (USAID (2017)). CIZO was a comprehensive initiative designed to address supply and demand-side barriers to decentralized electrification. On the supply side, CIZO entailed VAT exemptions and reduced tariffs along with state-sponsored solar training academies to develop the workforce needed for PAYGo solar companies to operate throughout the country (Kibala Bauer and White (2021)). On the demand side, CIZO included state-sponsored marketing and awareness campaigns and an end-user subsidy.

The government communicated about the different components of CIZO in stages. It first announced the plan to increase access to solar home systems in June, 2017 and followed it with an announcement that it was meeting with the solar company BBOXX in July. By early December, the solar company had started operations in Togo.[6] Concurrently, the government was establishing and running the solar academies, which rolled out in 2017 and ran through the first half of 2019 (African Development Bank (2017)). In March 2019, the Government of Togo announced that it would subsidize PAYGo solar to increase electrification rates, reduce the use of kerosene, and enhance economic development (Oteng (2019)). At the time, the PAYGo market was still nascent in Togo so there were only two PAYGo solar firms operating, although the market was in principle contestable.

Based on data from the Harmonized Survey on Household Living Standards, electrification rates had increased to 86% for urban households and 22% for rural households by the end of 2018 (WAEMU Commission (2018–2019)). Median monthly electricity expenditures ranged from CFA 1575–2975 (USD 2.40 to 4.50) depending on the connection type for grid-connected households.[7] Among households with no grid connection, 79.5% reported their pri-

[6]See Atcha (2017), BBOXX (2017), TogoNews (2017) for news coverage and press releases.

[7]Among the households, 41% reported experiencing at least one outage in the week before the survey with an average of 2.15 days per week with outages and 1.6 outages per day. The average duration of each outage varied, with roughly equal numbers of households reporting outages under 15 minutes, 15–30 minutes, 30–60 minutes, and 1–3 hours.

mary light source as a battery-powered lantern, 7.7% a kerosene lamp, 5.8% a solar lantern or solar panel, and the remaining 7% other sources (candles, generators, etc.). Median monthly expenditures on batteries, kerosene, and candles for these households were CFA 1192 (USD 1.80).

PAYGo solar home systems allow for rural consumers to obtain basic electricity access without the infrastructure investments required to extend the grid. Down payments are small relative to the cost of buying a solar home system outright or connecting to the grid and consumers have flexibility in the amount and timing of ongoing payments.[8] Each system includes solar panels, a battery for storing electricity generated by the solar panels, and a variety of high-efficiency appliances such as light bulbs, rechargeable radios, portable torches, phone chargers, and televisions. The consumer chooses which of these appliances to include in their solar home system (SHS), with each additional appliance increasing the value of the overall contract. Once a consumer has selected their bundle, they make a down payment and have the system installed in their home.

After installation, consumers "pay as they go." The solar company sets a daily rate, which is the price for one day of solar access time. The more appliances that are included in the SHS, the higher the daily rate. Once consumers purchase access time using mobile money, they enjoy unlimited use of their solar home system. When access time runs out, the solar company remotely locks the consumer out of their SHS, preventing them from using it until they pay for additional time. If the consumer does not purchase access for an extended period, the solar company may repossess the SHS. Contracting over prepaid access time bears a close resemblance to contracting over prepaid on-grid electricity, which is an increasingly common practice worldwide, particularly in sub-Saharan Africa (Jack and Smith (2020)). The primary difference

[8]The upfront cost for one of the solar home systems I study is USD 7–17, depending on the size of the system. Buying it outright would cost USD 250–USD 600. For comparison, Blimpo and Cosgrove-Davies (2019) estimate that the upfront cost of connecting to the grid in Togo is USD 336–428, depending on how far the household is from the existing grid. Although recent subsidies have lowered upfront connection costs for grid connections, they still remain substantially higher than those for PAYGo systems and may not be available in some remote, rural areas (see `http://www.ceet.tg` for current connection costs).

is that access time runs down continuously, while consumers who prepay for quantities of kilowatt hours on the grid can store their electricity credit.[9] In both cases, prepayment renders electricity contracts highly enforceable at a low cost to the utility or solar company.

Nearly 95% of solar adopters select one of three daily rates, the price for buying one day of system access: CFA 160 (34.16% of customers), CFA 220 (19.56% of customers), or CFA 375 (41.2% of customers). For simplicity, I refer to systems with a daily rate of CFA 160 as small, CFA 220 as medium, and CFA 375 as large. Consumers with small systems have lightbulbs, phone chargers, and either extra lightbulbs or a radio. Those with medium systems have both extra light bulbs and a radio or other additional small appliances, and those with large systems have televisions in addition to lightbulbs, phone chargers, and radios. Given the popularity of these three system sizes, I drop the remaining 5% of consumers.

The subsidy entitles each solar customer to CFA 2,000 per month; however, it is structured as a match on each qualifying purchase of a day of solar access time. It provides a constant discount on each day purchased rather than being administered as a flat subsidy at the start of the month. Regardless of the system a consumer chooses, the subsidy represents a meaningful reduction in the cost of access time. Consumers with small systems receive a discount of 41.7%, those with medium systems get a discount of 30.3%, and consumers with large systems get a discount of 17.8%.

The government phased in the subsidy over the course of five months in 2019. It introduced the subsidy in eleven prefectures on February 28, added thirteen more on April 30, and the remaining twelve prefectures started on July 4. Importantly, all state-sponsored marketing campaigns were national and did not mirror the timing of the subsidy, so while the subsidy may have benefitted from an overall expansion of available information about PAYGo solar, my effects identify the impact of the price reduction.[10] The government

[9]Lang (2022) and Lang (2021) discuss the implications of continuous rundown of PAYGo access time for consumer behavior in greater detail.

[10]Recent evidence from India speaks to the effect of information on the adoption of solar technologies. Alem and Dugouan (2022) seed information about solar lanterns and phone

announced the subsidy as a permanent policy change, so consumers could expect it to persist indefinitely. The solar company did not change prices in response to the subsidy during the period I study, effectively ensuring 100% pass-through to consumers. I leverage the phased rollout of the subsidy to empirically estimate consumer responses to reduced intensive margin prices.

3 Empirical Strategy

3.1 Data

I use administrative data from one of the largest solar companies in Togo to measure the effect of the subsidy on adoption of solar home systems. I observe the dates each customer signed a PAYGo contract and had a system installed in their home, the size of the system that they chose and the associated price for a day of access time, and the prefecture where the consumer lives. By combining information on the daily rate, the date of adoption, and the prefecture of residence, I can determine the intensive margin price each consumer expected to face at the time of adoption.

Since I lack covariates on individual consumers, I aggregate the consumer-level data to create a prefecture by day dataset. The aggregated dataset contains the total number of adopters opting into each daily rate in each prefecture on each day. Indicator variables mark when the subsidy came into effect in each prefecture and when the subsidy was first announced nationally. For ease of interpretation, I normalize counts of new adopters by the population of each prefecture, taken from the first wave of the Togo Harmonized Survey on Households Living Standards, which was collected from September–December,

chargers into social networks. Although they find that information leads to large and statistically significant increases in willingness to pay for solar lanterns, no respondent was willing to pay the market price for the solar lantern. Mahadevan, Meeks, and Yamano (2023) study an information treatment in India that used tablets to help sales agents teach potential consumers about a range of rooftop solar products. Their treatment leads to significant increases in intent to adopt, but it does not significantly increase actual adoption. Both studies suggest that information is likely second order to price in the solar adoption decision for consumers, but I cannot fully rule out information as a potential channel or as an important complementary factor amplifying the effect of the subsidy.

2018 (WAEMU Commission (2018–2019)).

The top panel of Figure 1 shows cumulative totals of solar adopters by subsidy phase, starting in July, 2018 and continuing through the end of August, 2019. Around this time, the government began implementing further measures to ensure that households were able to receive the subsidy.[11] Since it is difficult to attribute any further changes in adoption to the subsidy after this point, I end my study period in August, 2019.

3.2 Causal Identification

Two features of Figure 1 inform my identification strategies. First, within prefectures in each phase of the subsidy, growth in new adopters is close to linear in the pre-period. Second, prefectures in the first two phases trend in parallel prior to the introduction of the subsidy, and prefectures in the third phase trend in parallel starting roughly six months before the subsidy.

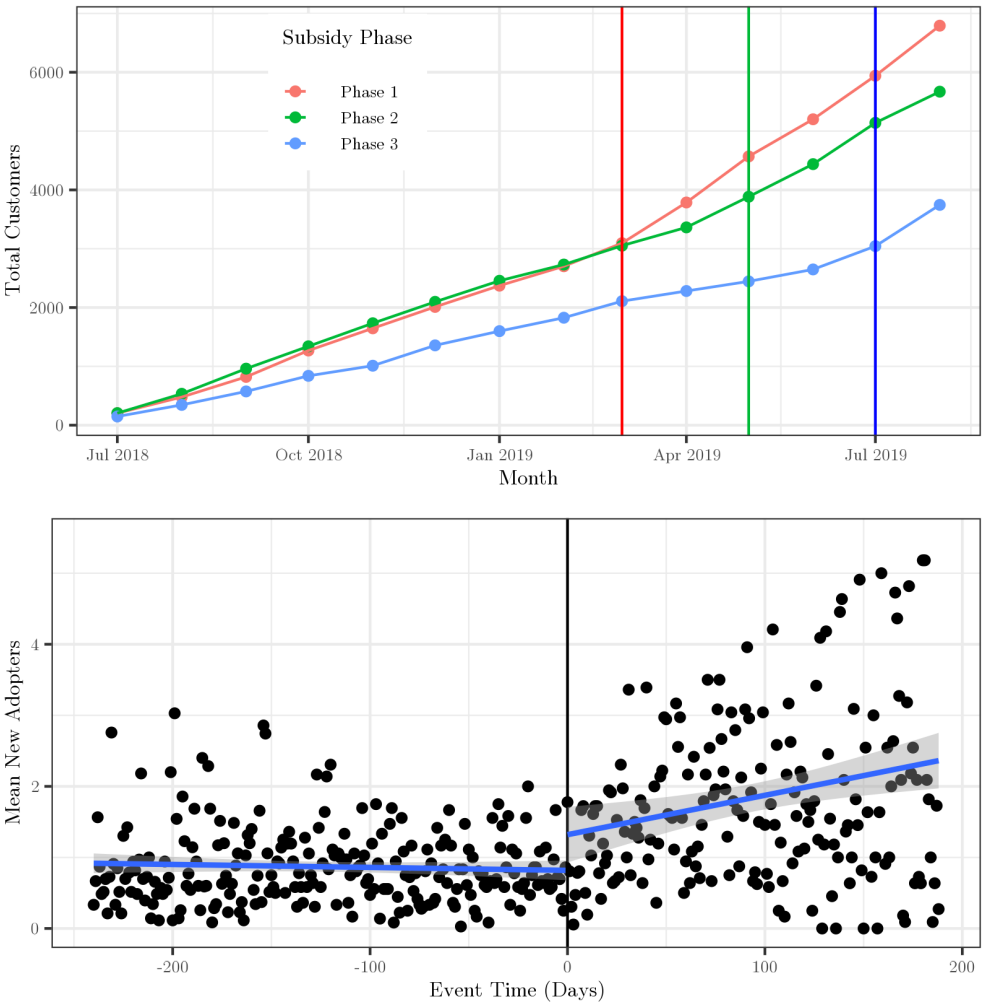
My first identification strategy is a simple event study. I estimate the impact of the policy using the specification

$$New_{lt} = \alpha + \beta_1 Sub_{lt} + \gamma_l + \delta_1 P1_t + \delta_2 P2_t + \delta_3 P3_t + \epsilon_{lt}, \tag{1}$$

where l indexes location (prefectures) and t indexes days. New_{lt} is the daily total of new customers in prefecture l on day t, normalized by population. Sub_{lt} is an indicator variable for whether the subsidy had been rolled out in prefecture l by day t, γ_l is a prefecture fixed effect. $P1_t$, $P2_t$, and $P3_t$ are phase-specific linear time trends to account for overall growth in adoption of solar home systems over time. I estimate Equation 1 pooled and then separately for small, medium, and large systems given that the proportional price reduction differs by system size. I use an 8-month pre-period, though I

[11] In practice, many households did not initially receive the subsidy because it required paying for access time using the same mobile phone number that the household used to register the system. Since many consumers asked relatives or mobile money agents to send the payments for them, the subsidy went under-claimed for the first few months. Such implementation issues are unlikely to have affected adoption because households get a full month of free access time when they have a system installed, and then take time to learn about the process of purchasing access time.

Figure 1: Trends in Adoption over Time



Note: The top panel shows total numbers of customers who have adopted by prefectures in each phase of the subsidy, with each dot representing the cumulative monthly total. The vertical red line shows the date the subsidy started in the first phase of prefectures, the vertical green line shows the date the subsidy started for the second phase, and the vertical blue line shows the date the subsidy started for the third phase. The bottom panel collapses the three phases into event time. Each dot represents a daily mean of new customers per prefecture. The solid black line denotes the subsidy start date. Blue lines are linear regressions for the pre- versus post-period, with grey shading showing 95% confidence intervals.

also show robustness to using shorter pre-periods.

The identifying assumption for the event study is that the growth in adop-

tion of solar home systems would have followed a linear trend within prefectures in each phase absent the introduction of the policy. The linear trends in adoption in the top panel of Figure 1 within each phase support this assumption. The bottom panel of Figure 1 shows mean adoption in each prefecture collapsed into event time. Doing so shows low, stable adoption rates prior to the policy going into effect and a subsequent jump in adoption, further supporting the identifying assumptions for the event study. Using Equation 1, β_1 is the average increase in daily adopters of all systems per 100,000 people in each prefecture where the policy was rolled out, or when I estimate by system size the average increase in daily adopters of a specific size of system.

My second identification strategy leverages the phased rollout of the subsidy to estimate a two-way fixed effects model. I estimate

$$New_{lt} = \alpha + \sum_m \beta_m P1_l \times Month_m + \sum_m \delta_m P2_l \times Month_m + \gamma_l + \gamma_m + \epsilon_{lt}. \quad (2)$$

Here, $P1$ is an indicator variable equal to one if prefecture l is in the first phase of the rollout and $P2$ is an indicator variable equal to one if prefecture l is in the second phase, leaving the third group of prefectures to act as the control group. γ_m is a month fixed effect. I interact phase indicators with month indicators to estimate impacts of the policy separately for each group of prefectures in each treated month (Wooldridge (2021)). Averaging across all of these estimated effects yields a single, average increase in adoption attributable to the policy. Estimating the subsidy impacts in this way avoids the weighting concerns with two-way fixed effects highlighted in Goodman-Bacon (2021) because I explicitly calculate the average effect from estimates for each group of prefectures and each treated month rather than relying on a two-way fixed effects specification to compute a weighted average. This also allows me to avoid assuming homogeneity of the β and δ coefficients (Callaway and Sant'Anna (2021), De Chaisemartin and d'Haultfoeuille (2020)). I estimate Equation 2 pooling system sizes and separately for small, medium, and large systems.

The identifying assumption for the two-way fixed effects approach is that

prefectures in each phase of the subsidy would have continued to trend in parallel absent the introduction of the subsidy. I provide supporting evidence of parallel trends by regressing the number of new customers in the pre-period on phase-specific linear time trends and prefecture fixed effects, then testing for significant differences in slopes between phases. I find no significant differences (see Table A1).

4 Results

Table 1 shows that under the event study specification, the policy increases overall adoption by just under 3 adopters per day per 100,000 households. While small in absolute terms, this is a 122% increase over the average in the month prior to the subsidy rolling out. The pooled effect is primarily driven by small systems, which see adoption increase by 2.1 adopters per day per 100,000 households, a 240% increase. Medium systems exhibit no significant change in adoption. Adoption of large systems increases significantly by 0.8 adopters per 100,000 households per day (66% increase).

I normalize all estimates by the size of the subsidy to facilitate comparison between effects for different system sizes. The large increase in adoption of small and large systems translates into large elasticities of adoption with respect to the intensive margin price of electricity. The bottom panel of Table 1 shows the elasticities implied by the estimated effects of the subsidy given the intensive margin price reduction for each system size. Adoption of small systems responds strongly to reductions in the intensive margin price with an elasticity of -5.8. While the estimate is imprecise, I can reject unit elasticity. In line with small impacts on adoption of medium systems, I cannot reject perfectly inelastic demand. Large systems exhibit less elastic demand than small systems at -3.5, although I cannot reject that the elasticities for small and large systems are the same.

Table 1: Adoption Impacts of CIZO

	(1) Event Study	(2) TWFE	(3) ES, No Phase 3
Daily New Adopters per 100,000 Households			
Pooled	2.963	3.373	3.769
	(1.081)	(1.087)	(1.649)
Small	2.142	2.047	2.552
	(0.746)	(0.715)	(0.982)
Medium	0.043	0.199	0.174
	(0.227)	(0.265)	(0.38)
Large	0.778	1.127	1.043
	(0.28)	(0.321)	(0.421)
Implied Elasticities			
Small	-5.77	-5.52	-5.06
	(2.01)	(1.93)	(1.95)
Medium	-0.38	-1.74	-1.17
	(1.99)	(2.32)	(2.56)
Large	-3.46	-5.02	-4.09
	(1.25)	(1.43)	(1.65)
% Electrified 2018	42.79%	42.787%	33.255%
Pre-period Adoption	2.433	2.433	3.075
Pre-period Adoption: Small	0.894	0.894	1.234
Pre-period Adoption: Medium	0.366	0.366	0.478
Pre-period Adoption: Large	1.173	1.173	1.363
N	14972	14972	9912

Notes: The top panel shows the change in new adopters each day per 100,000 households as a result of the CIZO subsidy. Column (1) shows results from the event study, my preferred specification. Column (2) shows results from manually averaging monthly estimates from a twoway fixed effects specification and column (3) shows results from the event study using only prefectures in the first two phases. The middle panel shows the estimated effects transformed into elasticities of adoption with respect to the intensive margin price. I do so by dividing the estimated effect by the mean number of new adopters in the month prior to the subsidy going into effect in each prefecture to obtain the percentage change in quantity, then dividing by the subsidy size (41.7% for small systems, 30.3% for medium systems, and 17.8% for large systems). The bottom panel shows electrification rates as of 2018 based on the Togo Harmonized Survey on Household Living Standards and average daily adopters per 100,000 households in the month prior to the subsidy starting based on administrative data from the solar company. I show show standard errors clustered at the prefecture level in parentheses.

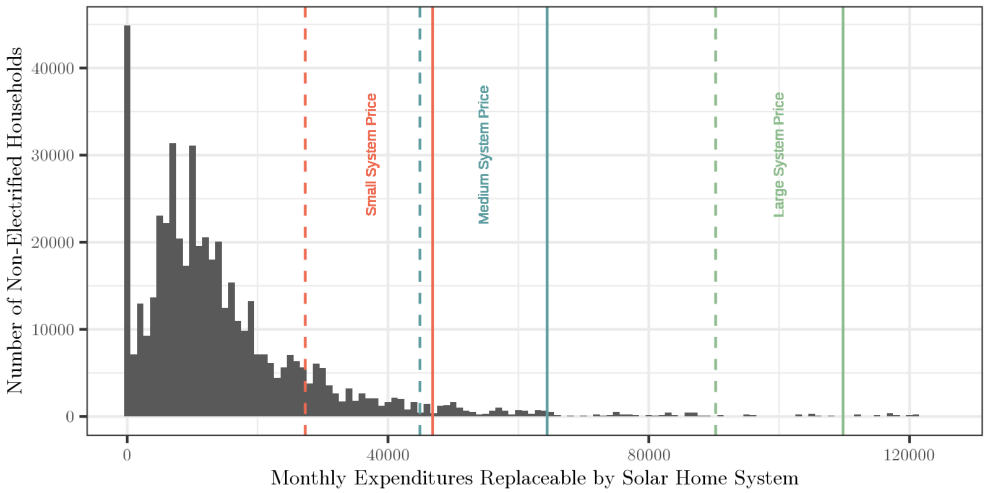
Small and statistically insignificant increases in sales of medium systems may be due to overlap in the market segment served by small, unsubsidized systems and medium, subsidized systems. Figure 2 shows that the subsidized price for a medium system falls just below the unsubsidized price for a small system. There are two reasons that this may have limited the increase in adoption of medium systems. First, consumers may prefer to pay a lower price for a small system rather than upgrading to a medium system. The structure of PAYGo contracts necessitates that each day of access time is more expensive for a medium system. Unlike on-grid contracts, where consumers can choose not to use an appliance to lower use costs, PAYGo contracts uniformly increase the intensive margin price when there are more appliances included in the system. Second, new consumers can easily upgrade from small to medium systems, as it only involves adding a small appliance to the system. Larger systems require installing extra solar panels. As such, new customers may prefer to learn about the quality and reliability of the system before opting for a more expensive contract.

Columns (2) and (3) of Table 1 speak to the robustness of the results. Column (2) shows effects using the two-way fixed effects specification from Equation 2. Column (3) repeats the event study but omits phase three prefectures. Omitting phase three prefectures serves two purposes. First, the specification from Equation 2 uses phase three prefectures as a control group and therefore only estimated effects for the first two prefectures relative to the third, making column (3) a more appropriate comparison for column (2). Second, the choice of prefectures for each phase was not random, despite evidence of parallel trends: 2018 electrification rates were 31% in phase one prefectures, 38% in phase two prefectures, and 62% in phase three prefectures (WAEMU Commission (2018–2019)).[12] Showing consistent results between the specifications in columns (2) and (3) builds confidence that using phase three prefectures as the control group in column (2) is not biasing results.

Results are stable under all three specifications in Table 1. Although point estimates vary for medium systems, I continue to find no significant changes

[12]Figure A1 shows 2018 electrification rates by prefecture.

Figure 2: PAYGo Solar Price Points Relative to Distribution of Replaceable Expenditures



Note: Nationally representative distribution of annual expenditures that a solar home system could replace, based on the 2018–2019 Togo HSHLS survey (WAEMU Commission (2018–2019)). I include kerosene, candles, batteries, lightbulbs, electric lamps/torches in the measure of replaceable expenditures. Solid lines show unsubsidized prices for different sizes of solar home systems. Dotted lines show subsidized prices. We consider the price should a household purchase access time 80% of the time, based on data from existing customers.

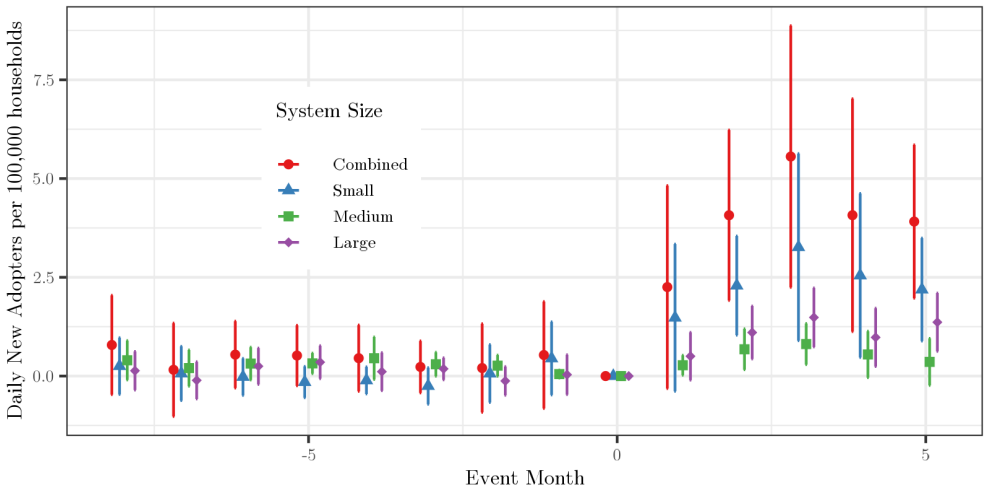
in adoption. Estimates vary somewhat for small and large systems but are a similar order of magnitude and maintain statistical significance. I further show that my results are robust to using shorter pre-period lengths for the event study (see Table A3), and to alternative specifications of the phase-specific time trend in the event studies (Table A2).[13] Given these results, I continue to use the event study as my preferred specification.

A critical question is whether changes in adoption persist over time. Figure 3 shows estimated impacts of the policy month by month using the event study specification. In the months prior to the introduction of the subsidy, trends are flat. The increase in adoption after the introduction of the sub-

[13]Removing the phase-specific linear time trend slightly inflates all of my estimated effects, suggesting that estimates are biased upward when I fail to account for the approximately linear growth in adoption that would have occurred absent the introduction of the subsidy. Quadratic time-trends give results that closely align with the linear trends in my primary specification.

sidy persists for small and large systems, although the much smaller increase in adoption of medium systems becomes statistically insignificant after three months. There is some variation in the magnitude of effects month to month, but I cannot reject that effects are equal within each size category. The persistence of the effects suggests that the policy created sustained growth in adoption at least during the period of my study.

Figure 3: Monthly Subsidy Impacts



Note: Increase in the number of new daily adopters due to the subsidy, per 100,000 households, plotted by event month. Red circles show effects combining all system sizes, blue triangles show effects for small systems, green squares show effects for medium systems, and purple diamonds show effects for large systems. Bars show 95% confidence intervals calculated using standard errors clustered at the prefecture level.

Although my study period is limited, my results imply that the subsidy led to an additional 2,060 households gaining access to electricity each month through the solar company with which I partnered.[14] Examining heterogeneous effects by above- versus below-median electrification rates in 2018 shows that effects are largest for prefectures with low electrification rates, consistent with most systems going to previously unelectrified households (see Figure A2).

[14]The population of Togo in 2018 was 8.047 million, with an average rural household size of 3.53 for roughly 2.28 million households. This implies roughly an additional 67.5 households adopt solar home systems each day and 2060 adopt solar each month as a result of the subsidy.

Electrifying 2,060 households per month is relatively small, representing only around 0.2% of Togo's unelectrified rural households at the time (or 2.3% over the course of a year). As previously discussed, Togo had two major PAYGo providers at the time of the subsidy. If both saw similar impacts from the subsidy, it implies that the subsidy may reduce the unelectrified population in Togo by around 4.6% in one year.

Another way to contextualize the size of these effects is to benchmark against the stated policy goal. The government's goal with CIZO was to increase the rural electrification rate to 40% in 2022, deploying 300,000 solar home systems over four years. Assuming that all PAYGo systems go to unelectrified rural households, that the two PAYGo providers have equal market share, and that the effects I observe from the first few months of the subsidy continue over time, counterfactual adoption of solar home systems would electrify 40,608 households per year and more than 162,000 over four years. Thus, counterfactual adoption alone would meet over half of the CIZO electrification target. The additional adoption induced by the subsidy would add 49,440 households per year for a total of nearly 200,000 households over four years. Even if adoption were to slow somewhat over the four year period, initial indications show that CIZO was on track to meet its stated goals. However, implementation challenges led to significantly lower adoption after the study period. As such, my results likely represent an upper bound.

My results indicate that the policy significantly increased adoption of small and large solar home systems. However, there are two threats to identification that could generate upward bias in estimates of the policy's short-term impact: anticipation effects and differential trends between prefectures in different phases.

4.1 Threats to Identification

Both the event studies and two-way fixed effects estimates leave reason to be concerned about anticipation effects for consumers living in second- and third-phase prefectures. Consumers in second- and third-phase prefectures may increase adoption prior to the subsidy if they anticipate future savings.

Such anticipatory increases in adoption would bias my estimates downward. Conversely, delayed adoption in anticipation of the subsidy will cause me to overstate its impact.

Negative anticipation effects should lead to a drop in adoption in the period between the initial announcement and the subsidy start date. Examining daily adoption totals shows no such reduction for consumers in second- or third-phase prefectures: trends in adoption remain flat after the subsidy announcement at levels that are not significantly different from pre-announcement levels (see Figure A3). Alternatively, smooth trends around the initial subsidy announcement could mask growth in adoption that would have happened had the subsidy not been announced. Bunching around initial subsidy implementation would indicate pent-up demand, but I find no jump in adoption immediately after the subsidy rollout in second- or third-phase prefectures.

Finally, I use an event study to estimate effects of the subsidy announcement for prefectures in the second and third phases. Negative effects indicate anticipation biasing estimates of the policy's impact upward. Table 2 shows no statistically significant evidence of negative anticipation effects for small systems. If anything, consumers adopting small systems positively anticipate the subsidy, though effects are not statistically significant. There is some evidence of anticipation effects for consumers choosing medium systems, driven by consumers living in prefectures included in phase two of the subsidy. However, even with these anticipation effects I find no significant effect of the subsidy on the adoption of medium systems. Consumers choosing large systems in the second phase exhibit no statistically significant anticipation effects but those in the third phase do, although the effects are only significant at the 10% level. My results are robust to excluding third phase prefectures, so such anticipation effects do not appear to substantially bias my estimates.

Table 2: Test for Anticipation Effects

	Dependent variable: Daily New Adopters per 100,000 Households		
	(1)	(2)	(3)
	Phases 2 and 3	Phase 2	Phase 3
Pooled	-0.0986	0.2003	-0.3984
	(0.8374)	(0.4329)	(0.255)
Small	0.3161	0.776	0.0167
	(0.2572)	(0.6124)	(0.1644)
Medium	-0.2143	-0.468253	-0.1263
	(0.0853)	(0.1559)	(0.0733)
Large	-0.2004	-0.1074	-0.2888
	(0.1793)	(0.3367)	(0.1446)
N	8002	3698	4304

Notes: Test for anticipatory effects of the subsidy. Column (1) estimates changes in adoption around the initial subsidy announcement for second and third phase prefectures, pooled between system sizes and then separately for small, medium, and large systems. Columns (2) and (3) do analogous tests for second and third phase prefectures separately. I show standard errors clustered at the prefecture level in parentheses.

The second threat to identification is differential post-period trends between prefectures in different phases of the subsidy. The ordering of prefectures was not random. If first- or second-phase prefectures happened to also be those with the largest overall economic growth during the policy rollout, or if they benefitted from other concurrent policies that increased demand for energy, then my estimates may be misattributing the effects of the subsidy.

To provide further reassurance that the assumptions for causal identification hold, I examine two placebo outcomes using the Togo Harmonized Survey on Household Living Standards (HSHLS). The first is monthly household spending on food and the second is monthly spending on all non-food, non-energy goods and services. The survey implemented two waves: one in fall, 2018 and the second in spring, 2019. Intuitively, the CIZO subsidy should not have had a large effect on either category of spending, so I should not see effects on either outcome unless a concurrent policy or other factors were driving differential trends between prefectures in different phases of the subsidy.

I interact indicators for subsidy phases with indicators for survey waves to test for differential trends in these two expenditure categories between phases (see Appendix B for full details). Estimates are noisy given limited data, but there are no significant differential trends for either category (see Table A4). If anything, trends are more negative for prefectures in the first two phases than they are for prefectures in the third phase, suggesting that economic conditions were slightly worsening in prefectures in the first two phases. This should bias the analysis away from finding positive effects from the subsidy.

Taken together, my results demonstrate that the subsidy included in Togo's CIZO policy was effective at expanding the number of electrified households. Would the same policy have similar effects in other settings? In this section, I present a general framework of decentralized energy markets which shows that the effects of the subsidy in Togo are not guaranteed to materialize in other settings.

5 A general framework of decentralized markets

I adapt the model from Littlechild (1975), which considers two-part tariffs with a continuum of consumers. I take as given that firms will use a two-part tariff to help consumers finance a solar home system. Consumers, indexed by i, are heterogeneous in income but otherwise identical. They face price p for each day of solar consumed and a down payment d to adopt a solar home system. A consumer considering whether to adopt a solar home system first determines optimal intensive margin demand (access time) at the current price, denoted $q_i(p, y_i)$, with $\frac{\partial q_i}{\partial p} < 0$ and $\frac{\partial q_i}{\partial y} > 0$. They adopt a solar home system at a given d and p if their consumer surplus from adopting is weakly positive.

For any (d, p) combination, there is a marginal adopter who is indifferent between adopting and not. I denote the income of the marginal consumer $\underline{y}$ and their optimal intensive margin demand $q^*(p, \underline{y})$. Intensive margin consumer surplus for the marginal consumer, not accounting for the down payment is

$$s(p, \underline{y}) = \int_p^\infty q^*(p', \underline{y}) dp'.$$

Since the marginal consumer has total consumer surplus equal to zero, it follows that the down payment d must be equal to this intensive margin consumer surplus. Consumers have identical preferences, so all consumers with income above $\underline{y}$ adopt. I denote the number of adopters as $M(\underline{y})$.

I assume the firm has no information on consumers, so it must set a single p and d. It incurs fixed costs $f(y_i)$, where I assume $\frac{df}{dy_i} < 0$ due to the higher risk of default among lower-income consumers. I assume zero marginal costs because systems run on solar energy. Ordering consumers by income and denoting the highest income level as $\overline{y}$, the firm's problem is

$$\max_{p,\underline{y}} \Pi(p, \underline{y}) = \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[(pq_i(p, y_i) - f(y_i) \right] + d(p, \underline{y}) M(\underline{y}). \tag{3}$$

I consider the firm's problem with and without a subsidy on the intensive margin price. I remain agnostic about the motivation for the subsidy: the government may be addressing positive externalities or pursuing social objectives. The model illustrates the effects of the subsidy and highlights the parameters the social planner would need to know to predict the effects of the subsidy. Since there were only two PAYGo solar firms operating in Togo during my study period, I model a monopolist and a perfectly competitive market. Studying these two extremes of market power allow me to understand the role of market power along with the cost structure of PAYGo solar contracts.

5.1 Monopolist

The monopolist chooses p and d to maximize profits. Taking first order conditions of Equation 3 with respect to $\underline{y}$ and simplifying yields

$$d = f(\underline{y}) - pq^* - \frac{\partial d / \partial \underline{y}}{\partial M / \partial \underline{y}} M(\underline{y}).^{15}$$

[15] For brevity, I omit the solution of the optimal price. See appendix section C for the full solution to the model.

The optimal down payment is equal to the firm's fixed costs from the marginal adopter minus the intensive margin profits from the marginal adopter, plus the total down payment revenue lost from admitting the marginal customer.[16]

Now consider the response of a monopolistic firm when the government imposes a subsidy on p such that the consumer pays some price p_s for each day of solar and the firm receives $p_s + s$. The firm's problem is now

$$\max_{p,\underline{y_s}} \Pi(p_s, \underline{y_s}) = \sum_{i=i_{\underline{y_s}}}^{i_{\overline{y}}} \left[(p_s + s)q_i(p_s, y_i) - f(y_i)\right] + d_s(p_s, \underline{y_s})M_s(\underline{y_s}),$$

and the optimal down payment is

$$d_s = f(\underline{y_s}) - (p_s + s)q_s^* - \frac{\frac{\partial d_s}{\partial \underline{y_s}}}{\frac{\partial M_s}{\partial \underline{y_s}}} M_s.$$

Adoption is higher under the subsidy if and only if $M_s \geq M$, or if

$$\frac{[d_s - f(\underline{y_s}) + (p_s + s)q_s^*]\frac{\partial M_s}{\partial \underline{y_s}}}{-\partial d_s/\partial \underline{y_s}} \geq \frac{[d - f(\underline{y}) + pq^*]\frac{\partial M}{\partial \underline{y}}}{-\partial d/\partial \underline{y}}. \tag{4}$$

It is not clear that the price subsidy will increase adoption. The numerators in Equation 4 are the total profits earned from marginal consumers. The denominators are the change in the down payment amount required to admit the marginal consumers. Thus, the ratio of profits to the amount the down payment has to change to admit the marginal consumers must be higher with versus without the subsidy for the subsidy to increase access.[17] Determining whether Equation 4 holds requires information about the income elasticity of

[16] The final term is positive because $\frac{\partial d}{\partial \underline{y}} > 0$ and $\frac{\partial M}{\partial \underline{y}} < 0$. Lowering the down payment to admit the marginal consumer lowers down payment revenue from all adopters because the firm must set a single d.

[17] Even assuming that $\frac{\partial d_s}{\partial \underline{y_s}} = \frac{\partial d}{\partial \underline{y}}$, it is not guaranteed that the subsidy increases adoption. If $M_s \geq M$ then costs are higher for the marginal consumer: $f(\underline{y_s}) > f(\underline{y})$. Although $p_s + s \geq p$ depending on the degree of pass-through, it is not clear whether the marginal consumer under the subsidy will consume more or less than the marginal consumer absent the subsidy since the two consumers have different incomes and face different prices.

demand on both the extensive and intensive margins, the price elasticity of demand on the extensive and intensive margins with respect to both prices, the shape of the income distribution, and the shape of the cost function.

In practice, the solar company did not change either d or p in response to the subsidies in Togo, although it is not clear whether this was mandated or reflects optimal pricing. If the subsidy is fully passed through, then firm profits are higher under the subsidy if and only if

$$\sum_{i=i_{\underline{y_s}}}^{i=i_{\underline{y}}} \left[pq_i(p-s,y_i)-f(y_i)\right]+\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} p(q_i(p-s,y_i)-q_i(p,y_i))+d(M(\underline{y_s})-M(\underline{y})) \geq 0. \tag{5}$$

The first and third terms are net profits from marginal adopters under the subsidy. The second term is the change in net, intensive margin profits from inframarginal consumers, who purchase more access time under the subsidy. The only uncertainty comes from the first term. Depending on how quickly marginal costs rise and demand falls in the income distribution between $\underline{y}$ and $\underline{y_s}$, the first term could be either negative or positive.

With a continuum of consumers and costs that are decreasing in income, a subsidy is not guaranteed to increase the profits of the monopolist. The large, positive effects observed in Togo with no change in p or d suggest that costs among consumers induced to adopt by the subsidy do not outweigh revenues from those consumers and increased demand from inframarginal consumers.

5.2 Competitive firm

Now suppose that there are homogenous solar firms operating in a perfectly competitive market, so profits for each firm are zero. In line with Hayes (1987), firms can choose multiple possible combinations of d and p that satisfy the zero profit condition, trading off higher down payment amounts with lower intensive margin prices. Under the price subsidy, the firm picks p_s and d_s to satisfy

$$\Pi_s = \sum_{i=i_{\underline{y_s}}}^{i=i_{\overline{y}}} \left[(p_s+s)q_i(p,y_i) - f(y_i)\right] + d_s M_s(\underline{y_s}) = 0.$$

As such, adoption will be higher under the price subsidy than without it if and only if $M(\underline{y_s}) > M(\underline{y})$, or

$$\frac{\sum_{i=i_{\underline{y_s}}}^{i=i_{\underline{y}}} \left[(p_s+s)q_i(p_s,y_i) - f(y_i)\right] + \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[(p_s+s-p)(q_i(p_s,y_i) - q_i(p,y_i))\right]}{\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[pq_i(p,y_i) - f(y_i)\right]} + 1 \geq \frac{d_s}{d}.$$

The left-hand side is the ratio of net profits on the intensive margin with versus without the subsidy. The right-hand side is the ratio of down payments with versus without the subsidy. The proportional change in intensive margin net profits has to be at least as large as the change in the down payment amount for the subsidy to increase adoption. As with the monopolist, determining whether the subsidy will expand energy access depends on extensive and intensive margin income elasticities and price elasticities, the shape of the cost function, and the shape of the income distribution.

Consider again a case of full pass-through from Equation 5. As with the monopolist, the subsidy only increases adoption if the added profits from inframarginal consumers plus intensive margin net profits from marginal consumers are positive. This condition is not guaranteed to hold. The zero-profit condition implies that

$$-dM = \sum_i \left[pq_i(p,y_i) - f(y_i)\right].$$

In a competitive market, firms using two-part tariffs lose money on consumers with high f and low q. Marginal adopters under the subsidy with full pass-through will cause competitive firms to lose money, but if the gains in demand from inframarginal consumers are large enough then firms will remain open. Although the market in Togo was not perfectly competitive when the subsidy started, my model illustrates that the cost structure of PAYGo solar presents similar challenges regardless of market structure.

5.3 Extensions

The likelihood of default, captured in the fixed cost term, may increase in the intensive margin price p. With a lower p, consumers are more likely to continue

purchasing access time, thereby avoiding default. If so, the firm will internalize the effect of any price change on the likelihood of default. The conditions for the subsidy to expand access will be more likely to hold because there will be two countervailing effects on costs: higher costs from serving lower-income consumers and lower costs from lower prices reducing the likelihood of default. If the reduction in the likelihood of default dominates, then subsidies are guaranteed to expand access. This points to the importance of yet another parameter: changes in default with respect to prices at different income levels.

The government could alternatively subsidize down payments, which may be logistically more feasible.[18] The major difference in the firm's problem with an extensive- rather than an intensive margin price subsidy is that there will be no increase in demand among inframarginal consumers on the intensive margin. Therefore, down payment subsidies are less likely to satisfy the participation constraints in both monopolistic and competitive settings.

My framework illustrates the potential challenges of using subsidies to expand energy access in decentralized markets. The fundamental issue is that firms use down payments and intensive margin prices to screen out low demand, high cost consumers. Subsidies weaken the screening power of prices. These issues are present in both monopolistic and competitive markets, as both feature the same cost structures. However, markets like Togo where firms have market power but which are, in principle, contestable may be uniquely situated to benefit from subsidies. If firms anticipate competition in the future, their participation constraint may be more flexible than that of a typical monopoly, allowing governments to encourage firms with market power to pass through most or all of the subsidy to consumers.

6 Conclusion

A large, intensive margin subsidy for PAYGo solar in Togo significantly increased adoption of solar home systems. However, my theoretical framework

[18] If intensive margin demand is relatively price inelastic then inducing more adoption may be an equally effective strategy for addressing any positive externality.

shows that the effects of the subsidy in Togo may not generalize to other decentralized energy markets. Increasing costs of default and lower demand among lower-income consumers mean that subsidies designed to expand access to PAYGo may have adverse effects. Mandating full pass-through of such subsidies may violate firms' participation constraints, regardless of market structure.

My empirical results combined with my framework speak to the importance of better understanding demand fundamentals in decentralized electricity markets. Such markets are increasingly important in the push for universal electrification. As Burgess et al. (2023) show, high costs for on-grid electrification have made decentralized solutions like solar hugely popular across many African countries. The World Bank announced a multi-billion dollar push for distributed renewable energy in Africa in 2022 (The World Bank (2022)), followed by a 2023 announcement of a USD 750 million loan to Nigeria for distributed renewable energy (The World Bank (2023)). Rigorously estimating extensive- and intensive margin price and income elasticities and developing a better understanding of costs in these markets will be central to designing policies that allow decentralized markets to develop alongside government efforts to achieve universal access to electricity.

Was Togo's policy cost effective? My estimates imply that the Government of Togo spent around USD4.30 per additional watt of installed solar capacity induced by the subsidy.[19] USD 4.30 per watt is high compared to subsidy and incentive schemes for solar in high-income countries, where estimates range from USD 0.13 to 1.68 (Hughes and Podolefsky (2015), Crago and Chernyakhovskiy (2017), Best, Burke, and Nishitateno (2019), Mastioff and Johnson (2017)). However, the magnitude of the positive externalities from solar in a setting like Togo fundamentally differ from those in high-income

[19]The solar home systems subsidized by CIZO are, on average, 50W. My estimates imply that the subsidy induced adoption of approximately 67.5 solar home systems per day: 3,375 watts of installed solar capacity. Inframarginal adoption is around 55.5 systems per day. The government pays CFA 2,000 to each household that adopts for 36 months, for a total cost of CFA 72,000 per system. This implies that the government pays a total of CFA 8.9 million to gain 3,375 additional watts of installed solar capacity under CIZO, around USD 4.30 per watt.

countries. Solar home systems are a first step toward electrification. As such, the systems displace fuels like kerosene or disposable batteries rather than electricity produced with dirtier fuels.

The subsidy is welfare-improving if the costs are less than the total positive externalities captured as a result of subsidizing solar. Using estimates from Fetter and Phillips (2019), reductions in carbon emissions alone are equal to one third of the cost of the subsidy.[20] My estimate of the subsidy's cost assumes that the full amount going to inframarginal adopters is a pure cost. In reality, even if a household is an inframarginal adopter, the subsidy encourages increased use of the solar home system, potentially yielding additional social benefits. There are further positive externalities from solar that I cannot quantify: reductions in local pollution (e.g., Grimm et al. (2017), Stojanovski et al. (2017)), shared benefits with non-electrified neighbors, improved information dissemination, etc. From a longer-run perspective, demand stimulation policies may also bring down future costs (Gillingham and Stock (2018)). However, given the inframarginal costs of the subsidy, such externalities and long-run benefits would need to be substantial.

To design optimal policies, it is necessary to identify and quantify the positive externalities that electrification generates in addition to measuring demand fundamentals. As Berkouwer and Dean (2022) point out, in contexts where Pigouvian taxes are infeasible, subsidies for cleaner and more energy efficient technologies are a second-best solution. Optimally setting such subsidies requires valuing the averted negative externalities from alternative energy sources at different levels of intensive margin use, then combining such valuations with intensive and extensive margin price and income elasticities.

[20] Fetter and Phillips (2019) estimate that the yearly benefits of climate-affecting emissions for each household with a solar home system in East Africa is USD 13.70. Assuming systems are 50W and have a lifespan of five years, this implies that the reduction in climate-affecting emissions alone is roughly USD 1.40 per watt.

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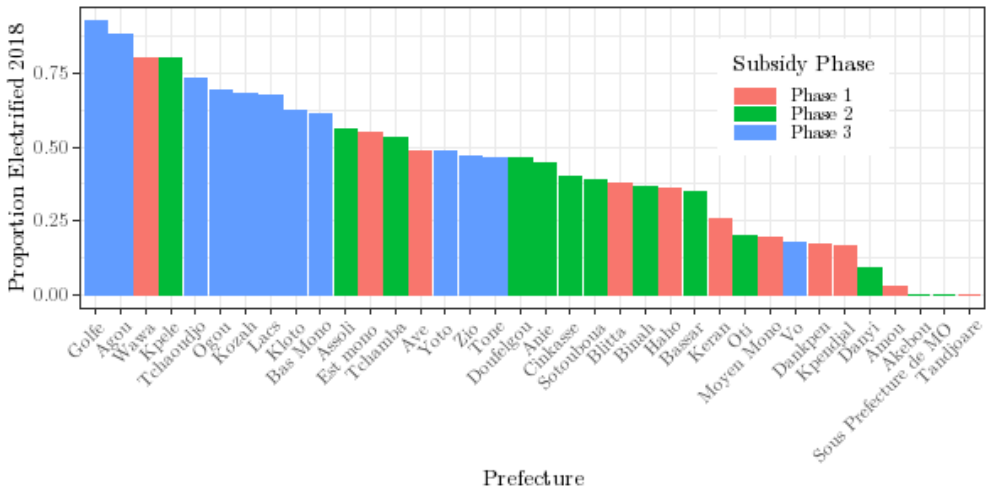
A Appendix A - supporting tables and figures

Figure A1: Pre-Subsidy Electrification Rates by Prefecture



Note: Proportion of the population with access to electricity (either formally or informally) in 2018, by prefecture. I calculate electrification rates using the 2018 wave of the Togo Harmonized Survey on Household Living Standards. Colors denote the timing of the prefecture's access to the solar subsidy.

Table A1: Test of Parallel Trends in the Pre-Period

	Daily New Adopters per 100,000 Households
Linear time	0.00731
	(0.00416)
Linear time × Phase 2	-0.00769
	(0.00612)
Linear time × Phase 3	-0.00406
	(0.0043)
Phase 2 = Phase 3 (p-value)	0.433
Prefecture Fixed Effect	Y
N	8276

Notes: Test of parallel trends in the pre-period. Linear time is a linear time trend, making the coefficient in the first row the slope of the trend in new adopters in the pre-period for prefectures in the first phase. Interacting the linear time trend with indicators for being in the second and third phase show differences in slope for second and third phase prefectures relative to first phase prefectures. I show standard errors clustered at the prefecture level in parentheses.

Table A2: Adoption Impacts of CIZO Using Alternative Time Trends

	(1) Event Study	(2) ES No Phase 3	(3) Event Study	(4) ES No Phase 3
	Daily New Adopters per 100,000 Households			
Pooled	3.552	2.679	4.076	3.076
	(0.97)	(1)	(1.234)	(1.384)
Small	2.338	2.047	2.655	2.322
	(0.713)	(0.707)	(0.851)	(0.88)
Medium	0.239	-0.052	0.276	-0.057
	(0.177)	(0.236)	(0.243)	(0.339)
Large	0.974	0.683	1.145	0.812
	(0.267)	(0.273)	(0.325)	(0.361)
N	14972	14972	9912	9912

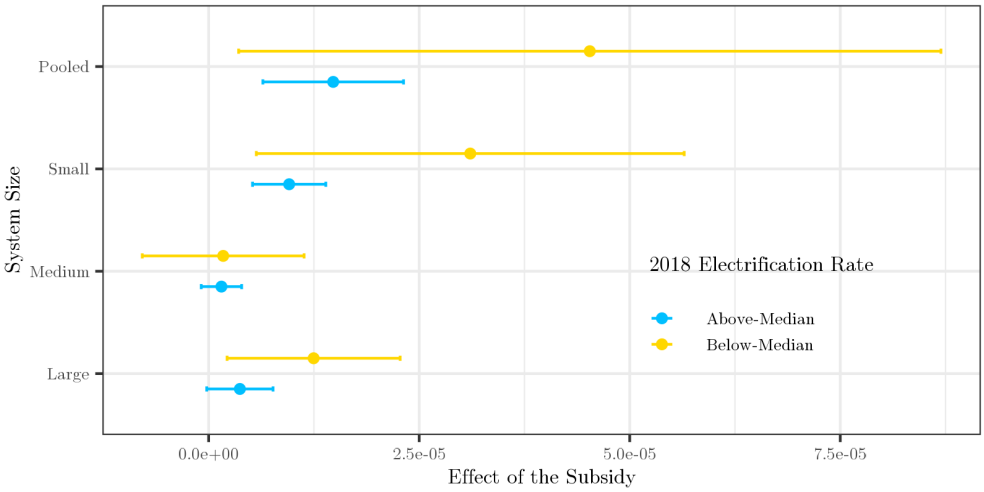
Notes: Change in new adopters each day per 100,000 households as a result of CIZO demand-side policies. Columns (1) and (3) show estimates using event studies that do not include phase-specific linear time trends. Columns (2) and (4) show estimates using event studies that use quadratic time trends. Columns (1) and (2) shows results from the event study and columns (3) and (4) shows results from the event study using only prefectures in the first two phases. I show standard errors clustered at the prefecture level in parentheses.

Table A3: Adoption Impacts: Robustness to Different Pre-Periods

	(1) Eight Month	(2) Four Month	(3) Two Month
	Daily New Adopters per 100,000 Households		
Pooled	2.963	2.556	2.37
	(1.081)	(0.829)	(0.806)
Small	2.142	1.96	1.79
	(0.746)	(0.631)	(0.601)
Medium	0.043	-0.01	-0.018
	(0.227)	(0.214)	(0.187)
Large	0.778	0.606	0.599
	(0.28)	(0.229)	(0.207)
N	14972	11016	8820

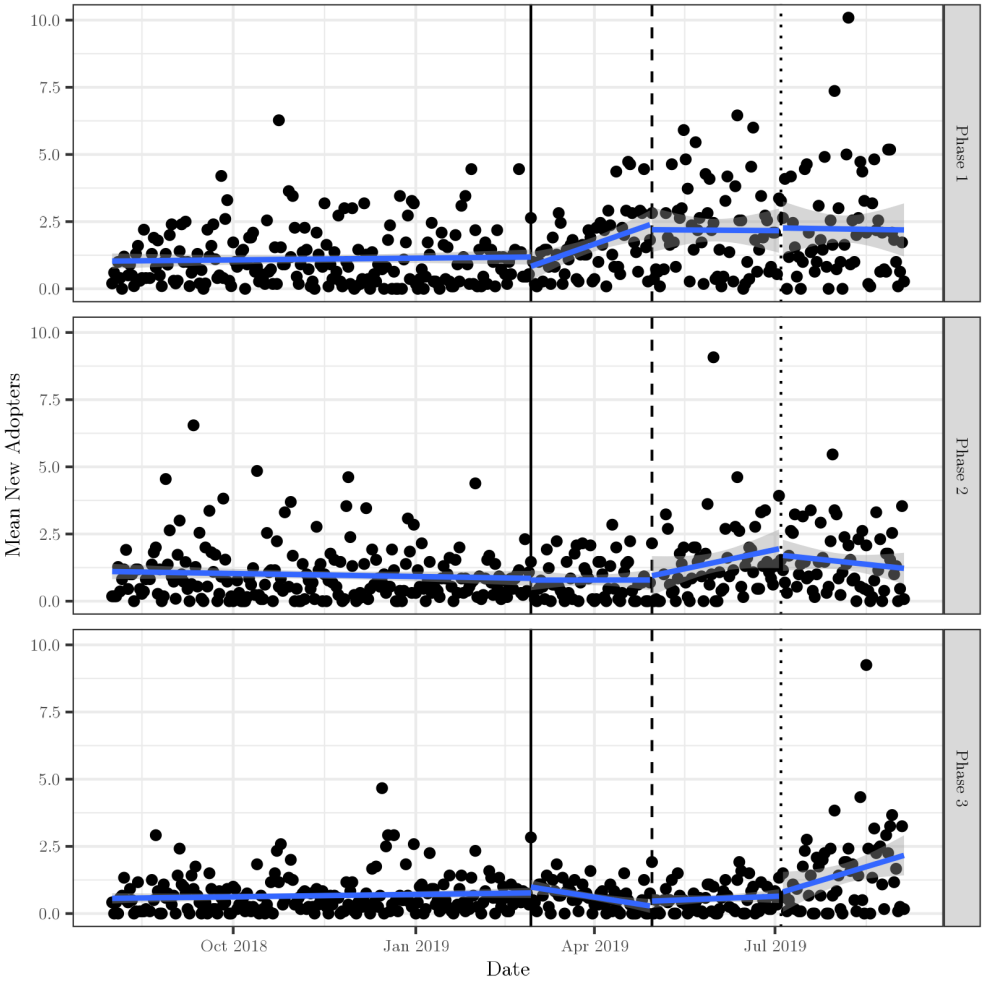
Notes: Change in new adopters each day per 100,000 households as a result of the policy. All columns show results from the event study specification. Column (1) shows results using an 8-month pre-period, my preferred specification. Columns (2) and (3) show estimates using a 4-month and 2-month pre-period. The panel becomes slightly unbalanced with the 8-month pre-period because the solar company did not start operating in certain prefectures until October, 2018. I show standard errors clustered at the prefecture level in parentheses.

Figure A2: Heterogeneity by Pre-Subsidy Electrification Rates



Note: Effects of the subsidy estimated heterogeneously for prefectures with above- versus below-median electrification rates in 2018, prior to the introduction of the subsidy. The median electrification rate in 2018 is 54%. Bars show 95% confidence intervals calculated using standard errors clustered at the prefecture level.

Figure A3: Daily Adoption by Subsidy Phase



Note: Daily means of new adopters per prefecture, broken out by the three phases of the subsidy. The solid vertical line marks the date the subsidy went into effect for prefectures in the first phase of the subsidy. The dashed and dotted vertical lines mark the dates the subsidy went into effect for prefectures in the second and third phases of the subsidy. Blue lines are linear regressions through each time period for prefectures in each phase with grey shading showing 95% confidence intervals.

B Appendix B - Placebo outcomes

I examine a range of placebo outcomes using the Togo Harmonized Survey on Household Living Standards (WAEMU Commission (2018–2019)). The HSHLS contains data from a repeated cross section with two waves: September–December, 2018 and April–June, 2019. I use the HSHLS to compute monthly expenditures on food and non-food items excluding energy. Intuitively, large changes in any of these measures between 2018 and 2019 that happen differentially between prefectures in different phases of the subsidy would suggest that there were concurrent policy changes or other factors that could be driving the results I observe. If so, I may be misattributing changes in demand for solar home systems to CIZO.

Concretely, for each category of expenditure for household h, exp_h, I estimate

$$exp_h = \beta_1 Wave2_h + \beta_2 Phase1_h \times Wave2_h + \beta_3 Phase2_h \times Wave2_h + \gamma_p + \epsilon_h.$$

$Wave2_h$ is an indicator equal to one if household h is in the second wave of the HSHLS, $Phase1_h$ is an indicator equal to one if household h lives in a phase 1 prefecture, $Phase2_h$ is an indicator equal to one if household h lives in a phase 2 prefecture, and γ_p is a prefecture fixed effect. Rejecting $\beta_2 = 0$ or $\beta_3 = 0$ is evidence that prefectures in the first two phases of the subsidy may have been trending differently than those in the third phase for reasons unrelated to the price of PAYGo solar. Rejecting $\beta_2 = \beta_3$ would suggest that prefectures in the first two phases of the subsidy were trending differently for reasons unrelated to the price of PAYGo solar.

Table A4: Effects on Household Expenditure Categories

	(1) Food	(2) Non-food non-energy
	Dependent variable: Expenditures (CFA)	
2019	-316.16	-1453.04
	(1145.82)	(383.61)
Phase 1 ×2019	-4098.06	-8.93
	(3054.58)	(912.71)
Phase 2 ×2019	-1474.53	80.37
	(2868.32)	(750.79)
Prefecture FE	Y	Y
2018 Mean	23682.1	8610.19
Phase 1 = Phase 2 (p-val.)	0.497	0.932
N	6171	6171

Notes: Changes in expenditures between the two waves of the 2018–2019 Togo Harmonized Survey on Household Living Standards over time and by phase of the subsidy for solar home systems. The first wave took place between September and December, 2018 and the second wave took place between April and June, 2019. 2019 is an indicator variable for the 2019 wave of the survey. Phase 1 and Phase 2 are indicator variables for whether a given household lives in a prefecture included in one of the first two phases of the solar subsidy. All estimates include a prefecture fixed effect. I convert all expenditures to a monthly basis. I show standard errors clustered at the prefecture level in parentheses.

C Appendix C - Detailed Model

C.1 Monopolist

Taking first order conditions of Equation 3 with respect to $\underline{y}$ gives

$$\frac{\partial \Pi}{\partial \underline{y}} = \frac{\partial M}{\partial \underline{y}}\big[(pq^*(p,\underline{y}) - f(\underline{y})\big] + \frac{\partial d}{\partial \underline{y}}M(\underline{y}) + \frac{\partial M}{\partial \underline{y}}d(p,\underline{y}) = 0, \text{ implying that}$$

$$d = f(\underline{y}) - pq^* - \frac{\frac{\partial d}{\partial \underline{y}}}{\frac{\partial M}{\partial \underline{y}}}M(\underline{y}). \tag{6}$$

The optimal downpayment is equal to the firm's fixed costs from the marginal adopter less the profits earned from the marginal adopter on the intensive margin plus the total downpayment revenue lost from admitting the marginal customer (note that the final term is positive because $\frac{\partial d}{\partial \underline{y}} > 0$ and $\frac{\partial M}{\partial \underline{y}} < 0$). Lowering the downpayment to admit the marginal consumer lowers downpayment revenue from all adopters because the firm must set a single d.

Taking first order conditions of Equation 3 with respect to p gives

$$\frac{\partial \Pi}{\partial p} = \sum_i \Big[\frac{\partial q_i}{\partial p}p + q_i\Big] + \frac{\partial d}{\partial p}M(\underline{y}) = 0.$$

Let $Q(p,\underline{y})$ denote total demand among all adopters so that

$$0 = Q + \frac{\partial d}{\partial p}M(\underline{y}) + \sum_i p\frac{\partial q_i}{\partial p}.$$

As shown above, the downpayment is equal to intensive margin consumer surplus for the marginal consumer. It follows that $\frac{\partial d}{\partial p} = -q^*(p,\underline{y})$. Therefore,

$$p = \frac{q^*M - Q}{\frac{\partial Q}{\partial p}}.$$

Now consider the response of a monopolistic firm when the government imposes a subsidy on p such that the consumer pays some price p_s for each

day of solar and the firm receives $p_s + s$. The firm's problem is now

$$\max_{p,\underline{y_s}} \Pi(p_s, \underline{y_s}) = \sum_{i=i_{\underline{y_s}}}^{i_{\overline{y}}} \left[(p_s + s)q_i(p_s, y_i) - f(y_i)\right] + d_s(p_s, \underline{y_s})M_s(\underline{y_s}).$$

It follows that the optimal downpayment is now

$$d_s = f(\underline{y_s}) - (p_s + s)q_s^* - \frac{\frac{\partial d_s}{\partial \underline{y_s}}}{\frac{\partial M_s}{\partial \underline{y_s}}} M_s. \tag{7}$$

If $M_s \geq M$ then adoption is higher under the subsidy. Solving Equation 6 and Equation 7 for M and M_s, $M_s \geq M$ if and only if

$$\frac{[d_s - f(\underline{y_s}) + (p_s + s)q_s^*]\frac{\partial M_s}{\partial \underline{y_s}}}{-\partial d_s/\partial \underline{y_s}} \geq \frac{[d - f(\underline{y}) + pq^*]\frac{\partial M}{\partial \underline{y}}}{-\partial d/\partial \underline{y}}. \tag{8}$$

Equation 8 shows that it is not clear that the price subsidy will increase adoption. The numerators are the total profits earned from marginal consumers, while the denominators are the change in the downpayment amount required to admit the marginal consumers. Thus, the ratio of profits from marginal consumers over the amount the downpayment has to change to admit the marginal consumers must be higher under the subsidy than without the subsidy for the subsidy to increase access. Even assuming that $\frac{\partial d_s}{\partial \underline{y_s}} = \frac{\partial d}{\partial \underline{y}}$, it is not guaranteed that the subsidy increases adoption. If $M_s \geq M$ then costs are higher for the marginal consumer: $f(\underline{y_s}) > f(\underline{y})$. Although $p_s + s \geq p$ depending on the degree of pass-through, it is not clear whether the marginal consumer under the subsidy will consume more or less than the marginal consumer absent the subsidy since the two consumers have different incomes and face different prices. Determining whether Equation 7 holds requires information about the income elasticity of demand on both the extensive and intensive margins, the price elasticity of demand on the extensive and intensive margin with respect to both price parameters, the shape of the income distribution, and the shape of the cost function.

In practice, the solar company did not change either d or p in response to the subsidies in Togo, although it is not clear whether this was mandated by the government or reflects optimal pricing. If the subsidy is fully passed through in the sense that d remains the same and consumers face price $p_s = p - s$, then firm profits are higher under the subsidy than without the subsidy if and only if

$$\sum_{i=i_{\underline{y_s}}}^{i=i_{\overline{y}}} \left[pq_i(p-s, y_i) - f(y_i)\right] + dM(\underline{y_s}) \geq \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[pq_i(p, y_i) - f(y_i)\right] + (d)M(\underline{y}), \text{ or}$$

$$\sum_{i=i_{\underline{y_s}}}^{i=i_{\underline{y}}} \left[pq_i(p-s, y_i) - f(y_i)\right] + \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} p(q_i(p-s, y_i) - q_i(p, y_i)) + d(M(\underline{y_s}) - M(\underline{y})) \geq 0.$$

The first and third terms on the lefthand side are net profits from marginal adopters under the subsidy. The second term is the change in net, intensive margin profits from inframarginal consumers, who purchase more access time under the subsidy. The only uncertainty comes from the first term. Depending on how quickly marginal costs rise in the income distribution between $\underline{y}$ and $\underline{y_s}$, the first term could be either negative or positive. In short, with a continuum of consumers and costs that are decreasing in income, a subsidy is not guaranteed to increase the profits of the monopolist. If the monopolist's participation constraint is earning profits at least as great as they would without a subsidy, it is not clear that mandating full pass-through satisfies the firm's participation constraint.

C.2 Competitive firm

Suppose that there are homogenous solar firms operating in a perfectly competitive market, so profits for each firm are zero. In line with Hayes (1987), firms can choose multiple possible combinations of d and p that satisfy the

zero profit condition:

$$\Pi(p, \underline{y}) = \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[pq_i(p, y_i) - f(y_i) \right] + dM(\underline{y}) = 0$$

Under the price subsidy, the firm instead picks p_s and d_s to satisfy

$$\Pi_s = \sum_{i=i_{\underline{y_s}}}^{i=i_{\overline{y}}} \left[(p_s + s)q_i(p, y_i) - f(y_i) \right] + d_s M_s(\underline{y_s}) = 0.$$

As such, adoption will be higher under the price subsidy than without it if and only if $M(\underline{y_s}) > M(\underline{y})$, or if

$$\frac{-\sum_{i=i_{\underline{y_s}}}^{i=i_{\overline{y}}} \left[(p_s + s)q_i(p_s, y_i) - f(y_i) \right]}{d_s} \geq \frac{\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[pq_i(p, y_i) - f(y_i) \right]}{d}.$$

Simplifying:

$$\frac{\sum_{i=i_{\underline{y_s}}}^{i=i_{\underline{y}}} \left[(p_s + s)q_i(p_s, y_i) - f(y_i) \right] + \sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[(p_s + s - p)(q_i(p_s, y_i) - q_i(p, y_i)) \right]}{\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}} \left[pq_i(p, y_i) - f(y_i) \right]} + 1 \geq \frac{d_s}{d}.$$

The lefthand side is the ratio of net profits on the intensive margin (i.e., not including downpayment revenue) under the subsidy versus without the subsidy. The righthand side is the ratio of downpayments with versus without the subsidy. The proportional change in intensive margin net profits has to be at least as large as the change in the downpayment amount for the subsidy to increase adoption. As with the monopolist, determining whether the subsidy will expand energy access depends on extensive and intensive margin income elasticities and price elasticities, the shape of the cost function, and the shape of the income distribution.

Consider again a case of full pass-through, potentially mandated by the

government. Then the number of adopters will be higher as long as

$$\frac{\sum_{i=i_{\underline{ys}}}^{i=i_{\underline{y}}}\left[pq_i(p-s,y_i)-f(y_i)\right]+\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}}\left[p(q_i(p-s,y_i)-q_i(p,y_i))\right]}{\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}}\left[pq_i(p,y_i)-f(y_i)\right]}+1 \geq \frac{d}{d}=1, \text{ or}$$

$$\sum_{i=i_{\underline{ys}}}^{i=i_{\underline{y}}}\left[pq_i(p-s,y_i)-f(y_i)\right]+\sum_{i=i_{\underline{y}}}^{i=i_{\overline{y}}}\left[p(q_i(p-s,y_i)-q_i(p,y_i))\right]\geq 0.$$

Thus even with full pass-through, the subsidy only increases adoption if the added profits from inframarginal consumers plus intensive margin net profits from marginal consumers are positive. If this condition does not hold, then profits under the subsidy are negative and the firm exits.

It is important to note that this condition is not guaranteed to hold. The zero-profit condition implies that

$$-dM=\sum_i\left[pq_i(p,y_i)-f(y_i)\right].$$

In a competitive market, firms using two-part tariffs lose money on some consumers, in this case consumers with higher f and lower q. Marginal adopters under the subsidy with full pass-through will cause competitive firms to lose money, but if the gains in demand from inframarginal consumers are large enough then firms will remain open.