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Abstract

This paper evaluates a large-scale appliance replacement program in Mexico that between 2009 and 2012 helped 1.9 million households replace their old refrigerators and air conditioners with energy-efficient models. Using household-level billing records from the universe of Mexican residential customers we find that refrigerator replacement reduces electricity consumption by 8%, about one-quarter of what was predicted by *ex ante* analyses. Moreover, we find that air conditioning replacement actually *increases* electricity consumption. Overall, we find that the program is an expensive way to reduce externalities from energy use, reducing carbon dioxide emissions at a program cost of over $500 per ton.

Key Words: Energy-Efficiency, Energy Demand, Rebound Effect
JEL: D12, H23, Q40, Q54

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Energy consumption is forecast to increase dramatically worldwide over the next several decades, raising important concerns about energy prices, geopolitics, and greenhouse gas emissions. Much of the recent energy research has focused on transportation and the demand for gasoline (Knittel 2011; Mian and Sufi, 2012; Busse, Knittel and Zettelmeyer, 2013; Allcott and Wozny, forthcoming). However, an equally important area is residential energy consumption. This category makes up 14% of total energy use worldwide, and is expected to grow by 57% through 2040 (DOE, 2013a).

Meeting this increased demand represents a severe challenge from both an economic and environmental perspective. To curtail demand use and the associated negative externalities policymakers are increasingly turning to energy-efficiency programs as a politically palatable alternative to first-best approaches. Supporters of energy-efficiency policies argue that they represent a "win-win", reducing externalities while also helping participants reduce energy expenditures. Much of the push for these programs is based on estimates from *ex ante* analyses that assume no behavioral response.[1]

In this paper, we evaluate the impact and cost-effectiveness of a large-scale appliance replacement program in Mexico. Between 2009 and 2012, "Cash for Coolers" (hereafter, "*C4C*") provided subsidies to 1.9 million households to help them replace their old refrigerators and air conditioners with newer more energy-efficient models. To participate in the program a household's old appliance had to be at least 10 years old and the household had to purchase an energy-efficient appliance of the same type. These old appliances were then transported to recycling centers to be disassembled.

We find that refrigerator replacement reduces electricity consumption by an average of 11 kilowatt hours per month, an 8% decrease. This is a substantial decrease, but is considerably less than what was predicted *ex ante* by the World Bank and McKinsey (Johnson, et. al, 2009; McKinsey and Company, 2009b). The World Bank study, for example, predicted savings for refrigerators that were about four times larger than our estimates. And while these same studies predicted even larger savings from air

[1] McKinsey and Company (2009a), for example, uses *ex ante* analyses to argue that energy-efficiency investments are a "vast, low-cost energy resource" that could reduce energy expenditures by billions of dollars per year.

conditioner replacement, we find that electricity consumption actually *increases* after households receive a new air-conditioner.

We then present ancillary evidence supporting several behavioral responses to the program which help explain why our estimated savings are so much smaller than the *ex ante* predictions. Part of the explanation is that the *ex ante* predictions were overly optimistic about the program being able to recruit households with very old, very inefficient appliances. In practice, we find that most of the retired appliances were less than 12 years old. Another important explanation, especially for air conditioners, is increased usage. More energy-efficient air conditioners cost less to use, which leads households to use them more. This pattern of usage is reflected in our estimates, with near zero changes in electricity consumption during winter months and substantial increases in the summer. Finally, we illustrate how modest increases in appliance size and added features like side-by-side doors and through-the-door ice can substantially offset improvements in energy-efficiency.

This paper helps address an urgent need for credible empirical work in this area. Allcott and Greenstone (2012) explains that, "much of the evidence on the energy cost savings from energy-efficiency comes from engineering analyses or observational studies that can suffer from a set of well-known biases." They then go on to say that, "We believe that there is great potential for a new body of credible empirical work in this area, both because the questions are so important and because there are significant unexploited opportunities for randomized control trials and quasi-experimental designs that have advanced knowledge in other domains."

Our paper is one of the first studies of an energy-efficiency program in a low or middle-income country.[2] Many low and middle-income countries are now adopting energy-efficiency policies. For example, development of energy-efficient appliances is one of the major initiatives of the *Clean Energy Ministerial*, a partnership of 20+ major

[2] The small existing literature on energy-efficiency is focused mostly on the United States. See, for example, Dubin, Miedema, and Chandran (1986), Metcalf and Hasset (1999) and Davis (2008). There is also a related literature which uses utility-level data to evaluate energy-efficiency programs, again mostly in the United States (Joskow and Marron, 1992; Loughran and Kulick, 2004; Auffhammer, Blumstein, and Fowlie, 2008; Arimura, Li, Newell, and Palmer, 2012).

economies, aimed at promoting clean energy.[3] And China recently announced a new large-scale program that will provide subsidies for energy-efficient refrigerators and air conditioners. In part, these policies reflect a widely held view that there is an abundant supply of low-cost, high-return investments in energy-efficiency, particularly in low and middle-income countries (Zhou, Levine, and Price, 2009; Johnson, et. al, 2009; McKinsey and Company, 2009b). Most global growth in energy consumption over the next several decades is expected to occur in low and middle-income countries. Between 2010 and 2040, total energy consumption is predicted to increase by 90% in non-OECD countries, compared to only 18% in OECD countries (DOE 2013a, Table 1). Many policymakers believe that energy-efficiency programs can be an effective tool for curtailing this growth in demand. But without credible empirical estimates of program impacts it is impossible to know how large a role energy-efficiency can play.

A key feature of our analysis is the use of high-quality microdata. For this analysis we were granted access to household-level electric billing records for the universe of 25+ million Mexican residential customers. The large number of households in our analysis allow us to estimate effects precisely even with highly flexible specifications. In contrast, the primary source of data used in most previous research on energy-efficiency programs in the United States comes from self-reported measures of energy savings from utilities. Economists have long argued that these self-reported measures of energy savings are overstated (Joskow and Marron, 1992).

The fact that our analysis is based on a large-scale national program gives our results an unusually high degree of intrinsic policy interest. Program evaluation, particularly with energy-efficiency policies, is typically based on small-scale interventions implemented in one particular location. In these settings a key question is external validity i.e. how well do parameter estimates generalize across sites. Utilities that choose to participate in these programs tend to be considerably different from the population of utilities, raising important issues of selection bias (Allcott and Mullainathan, 2012).

[3] See *http://www.cleanenergyministerial.org/* and *http://superefficient.org/* for details.

The format of the paper is as follows. Section I provides background information about the electricity market in Mexico and the *C4C* program. Sections II and III describe the data, empirical strategy, and main results. Section IV compares our estimates to the *ex ante* predictions, presenting ancillary evidence indicating several important explanations for the smaller than expected savings. Section V evaluates cost-effectiveness, calculating the implied cost of the program per unit of energy savings and section VI offers concluding comments.

I. Background

A. Context and Program Rationale

The Mexican Federal Electricity Commission (*Comisión Federal de Electricidad*, or "CFE") is the exclusive supplier of electricity within Mexico. CFE is responsible for most electricity generation and all electricity transmission and distribution. Electricity service in Mexico is highly reliable, with total service interruptions per household averaging just over one hour per year (CFE 2011, Table 5.14).

Residential customers are billed every two months. The standard residential tariff in Mexico is an increasing block rate with no monthly fixed fee and three tiers. Residential electricity consumption is subsidized. As of August 2011, customers on the first-tier (tariff 1), paid 0.73 Pesos (5.7 U.S. cents) per kilowatt hour. The second and third tiers are more expensive, 1.21 Pesos (9.6 cents) and 2.56 Pesos (20.2 cents) per kilowatt hour, respectively. As a point of comparison, the average retail price paid by residential customers in the United States is 11.7 cents (DOE, 2013b). The Mexican Energy Ministry estimates that residential customers face a price that is, on average, about half the average cost of providing power (SENER, 2008).

Table 1 describes demographics, electricity, and appliance saturation in Mexico. In the 2010 Census, 97.5% of households reported having electricity in their homes. Electricity consumption per capita in Mexico is 1,900 kilowatt hours annually, compared to 14,000 for the United States (World Bank, 2013). Over the next several decades, electricity consumption in Mexico is forecast to increase 3.7% per year, more than triple the increase in the United States (DOE 2013a, p.98). One of the major drivers of this increase in demand is the continued increase in residential appliance ownership, due to poverty reduction and economic growth. Figure 1 plots ownership rates for televisions, refrigerators, and vehicles by income level in Mexico. As incomes increase households first acquire televisions, then refrigerators and other appliances, and it is not until income reaches substantially higher levels that households acquire vehicles (Gertler, Shelef, Wolfram and Fuchs, 2013).

Meeting this increased energy demand will require an immense investment in generation and transmission infrastructure. The Mexican Energy Ministry has calculated that $80 billion dollars will need to be invested in new electricity generation and transmission infrastructure between 2012 and 2026 (SENER, 2012, p.157). Energy-efficiency programs are viewed by policymakers as one of the ways to potentially reduce these looming capital expenditures. Part of the broader goal of our analysis is to consider whether energy-efficiency programs like *C4C* could serve as a substitute for these capital-intensive investments.

The program was implemented, in part, because *ex ante* analyses had predicted that appliance replacements would lead to substantial decreases in electricity consumption. In independent studies of available energy-related investments in Mexico the World Bank and McKinsey concluded that replacing residential refrigerators and air conditioners would be extremely cost-effective (Johnson, et. al, 2009; McKinsey and Company, 2009b). In fact, both reports calculated a *negative* net cost of carbon abatement for these investments. That is, these were found to be investments that would pay for themselves even without accounting for carbon dioxide emissions or other externalities. At the heart of these predictions are optimistic predictions about the amount of electricity saved per replacement. We revisit these predictions later in the paper, contrasting them with the results from our empirical analysis.

B. Program Details

The *C4C* program was in place between March 2009 and December 2012. Unlike the U.S. *Cash for Clunkers* program, the program was never viewed as an economic stimulus program. The objective of the program was to reduce electricity consumption and thereby reduce carbon dioxide emissions and other negative externalities. This was a national program. The only geographic requirement was that participants in the air conditioner replacement program had to live in a warm climate zone. This excluded 75% of Mexican households, including all households living in Mexico City, Guadalajara, Puebla, and other high-elevation areas. There were no geographic restrictions for refrigerator replacement.

To participate in the program a household needed to have a working refrigerator or air conditioner that was at least 10 years old and agree to purchase a new appliance of the same type (i.e. refrigerator or air conditioner). The old appliances were transported to government-financed recycling facilities and disassembled. The new appliances were required to meet national minimum energy-efficiency standards and, in the case of refrigerators, to exceed standards by at least 5%. In addition, the new appliances had to meet certain size requirements. For example, refrigerators were supposed to be between 9 and 13 cubic feet, and with a maximum size no more than two cubic feet larger than the refrigerator which was replaced.

The program provided direct cash payments in three amounts, approximately corresponding to $30, $110 and $170 dollars. Retailers could charge $30 for delivering the new appliance and taking away the old one, reducing the net subsidy amounts to $0, $80, and $140. Eligibility for these different payment levels depended on a household's average historical electricity consumption. Households with very low levels of historic consumption were ineligible for the program. This minimum requirement was implemented in an attempt to prevent participation by households with non-working appliances. Above this threshold, households qualified for the $170 payment, while households with higher levels of historic consumption received smaller payment amounts. This structure of decreasing payments was implemented out of distributional concerns in an attempt to avoid large cash payments to high-income households. More than three-quarters of participants qualified for the most generous $170 payment. In addition to the cash payments the program offered on-bill financing at a 14% annual interest rate, repaid over four years. Households could accept the cash payment, the on-bill financing, or both. In practice, all participants choose to accept the cash payments, but many participants decided not to accept the on-bill financing.

From the households' perspective, the program represented a substantial incentive for appliance replacement. Program participants paid an average of $427 per refrigerator, and $406 per air conditioner, so the cash payments represented a large share. Another nice feature of the program from the households' perspective is that they received these subsidies immediately, with virtually no paperwork required. In order to participate, a household was required to show a recent electricity bill. The retailer then determined which subsidy a household was eligible for by entering the household's account number into a website designed for this purpose. This differs from many appliance subsidy programs elsewhere in the world which require participants to fill out and mail application forms and proofs of purchase, and then wait for a rebate check to arrive in the mail.

From the perspective of appliance manufacturers and retailers, the program represented a large increase in demand. Data is not available to directly examine the incidence of the subsidy, but several factors lead us to believe that the benefits to manufacturers and retailers would have come primarily in the form of increased sales rather than increased prices. Appliance manufacturing and retailing are highly competitive in Mexico. There are at least 10 manufacturers with a non-negligible market share and a similar number of large national retailers. Moreover, multinational appliance manufacturers like GE, LG, Samsung, and Daewoo have a significant presence in Mexico and the global manufacturing capacity to quickly adjust supply in response to demand increases.

C. Participation

Between 2009 and 2012, the program provided subsidies for 1.9 million appliance replacements. About 90% of all replacements were refrigerators. The lower level of participation in the air conditioner program reflects the geographic restrictions and the fact that air conditioning is relatively uncommon in Mexico. In the 2010 ENIGH survey ("*Encuesta Nacional de Ingresos y Gastos de los Hogares*") only 13% of households nationwide reported having air conditioners. In part, this low saturation reflects that many Mexicans live in the highland central plateau. Mexico City, for example, is located at 7,300 feet and has a mild climate year round. But even in warmer areas of Mexico, households are much more likely to own refrigerators than air conditioners, meaning that there were many more eligible participants for refrigerator replacement.

The program reached a substantial fraction of all eligible households nationwide. With refrigerators, for example, Arroyo-Cabañas, et al. (2009) estimate that as of 2009 there were approximately 23 million total refrigerators owned nationwide. Of these, they calculate that about 10 million (43%) were 10+ years old. By the end of the program, therefore, about 17% of all eligible refrigerators had been replaced. The program appears to have had had a substantial impact on refrigerator sales. During 2009, 2010, and 2011 there were 6.8 million refrigerators sold in Mexico.[4] Based on pre-2009 data from Arroyo-Cabañas, et al. (2009) we would have predicted 5.4 million sales. This yields a difference of 1.4 million refrigerators, similar to the total number of refrigerators replaced through *C4C* in those three years. This back-of-the-envelope calculation is based on a linear extrapolation and does not control for macroeconomic conditions. If anything, however, one would have expected the recession post-2008 to decrease sales relative to the trend.

II. Data and Empirical Framework

A. Data Description

The central dataset used in the analysis is a two-year panel dataset of household-level electric billing records. These data describe bimonthly electricity consumption for the universe of Mexican residential customers from May 2009 through April 2011. The *C4C* program was in place during this entire period. Each record includes the customer account number, county and state of residence, climate zone, tariff type, and other information. For confidentiality reasons these data were provided without customer names. The complete set of billing records includes data from 26,278,397 households. We dropped 15,262 households (<0.001%) for whom the records are improperly formatted

[4] This number comes from personal correspondence with the Mexican National Association of Electric Manufacturers (*Cámara Nacional de Manufacturas Eléctricas, CANAME*). Based on their own internal analysis of national-level sales data, CANAME concludes that *C4C* has generated through March 2012 a total of 900,000 additional refrigerator sales and 160,000 additional sales of air conditioners (both about 60% of total *C4C* replacements).

and 1,113 households for whom no state was indicated. We also drop 491,788 observations (1.9%) with zero reported usage in every month of the panel.

Residential customers are billed every two months using overlapping billing cycles. Half have their meters read during "odd" months (e.g., January, March, etc.) and half have their meters read during "even" months (e.g., February, April, etc.). So for most households there are six billing cycles per year, and twelve billing cycles over the two year sample period. There are also a small number of households with irregular billing cycles. The average number of months per billing cycle is 1.98 months, with 93% of all cycles representing two months. An additional 5% represent one month, with the remaining 2% representing 3+ months. These irregular billing periods arise for a variety of reasons. For example, some households in extremely rural areas have their meters read less than six times per year. We assign billing cycles to calendar months based on the month in which the cycle ends. And we normalize consumption to reflect monthly consumption by dividing by the number of months in the billing cycle. Thus, for example, a typical "July" observation reflects average monthly consumption during June and July.

Equally important for the analysis is a second dataset which describes *C4C* participants. These data describe all participants in the program between March 2009 and June 2011, a total of 1,162,775 participants. Thus our program data cover the first 28 months in which the program was in place, a period during which approximately 60% of the total replacements occurred. We dropped 51,823 participants (4.5%) for whom no installation date for the new appliance was recorded. We merged the remaining data with the billing records using customer account numbers. We were able to match 86% percent of *C4C* participants with identical account numbers in the billing records. Each record in the program data includes the exact date in which the appliance was replaced, whether the appliance replaced was a refrigerator or an air conditioner, the amount of direct cash subsidy and credit received by the participant, the reported age of the appliance that was replaced, and other program information. We drop 93 households (<.0001% of participants) who replaced more than one air conditioner, leaving us with 957,080 total treatment households.

We do not have data on other forms of energy use. This would matter much more if this were an energy-efficiency program aimed at home heating or cooking. In those cases, households are able to substitute between electricity, natural gas, bottled gas, and other energy types. With refrigerators and, in particular, air conditioners, most of the available substitutes also use electricity, and our estimates will reflect the net change in electricity consumption from all end-uses. This is not to say, however, that we are able to describe the full range of possible energy impacts of the program. For example, it could be that better refrigerators and air conditioners lead households to spend more time at home, driving less, and eating fewer meals outside the home. The estimated change in electricity consumption will reflect changes in the amount of time spent at home, but not these other impacts.

B. Empirical Strategy

This section describes the estimating equation used for our estimates of the effect of refrigerator and air conditioner replacement on household electricity consumption. The basic approach is difference-in-differences. In the preferred specification, impacts are measured by comparing electricity consumption before and after appliance replacement using a rich set of time effects that vary across locations.

Our empirical approach is described by the following regression equation,

$$y_{it} = \beta_1 1[New\ Refrigerator]_{it} + \beta_2 1[New\ Air\ Conditioner]_{it} + \gamma_{i,moy} + \omega_t + \varepsilon_{it}.$$

where the dependent variable y_{it} is electricity consumption by household i in month t measured in kilowatt hours. The covariates of interest are $1[New\ Refrigerator]_{it}$ and $1[New\ Air\ Conditioner]_{it}$, indicator variables equal to one for *C4C* participants after they have replaced their refrigerator or air conditioner. For replacements that occur in the middle of a billing cycle, we assign a value between zero and one equal to the proportion treated. Parameters β_1 and β_2 measure the mean change in electricity consumption associated with appliance replacement.

Our preferred specifications include household by month-of-year fixed effects, $\gamma_{i,moy}$. That is, for each household we include 12 separate fixed effects, one for each calendar month. This controls not only for time-invariant household characteristics such as the size of the home, but also household-specific seasonal variation in electricity demand. For example, some households have air conditioning and some do not, so electricity demand varies differentially across the year for different households.

The billing data includes identifiers for both the household and the housing unit. Consequently, we can observe when a new household moves into an existing housing unit. This is a nice feature because one might expect participation in the program to be correlated with the decision to move. In the empirical analysis we treat each household by housing unit pair as a separate "household". Thus with household by month-of-year fixed effects we are identifying the effects of C4C using only households who remain in a housing unit for at least one year.

All estimates also include month-of-sample fixed effects ω_t. This controls for month-to-month differences in weather as well as for population-wide trends in electricity consumption. Many specifications include, instead, month-of-sample by county fixed effects. This richer specification controls for county-specific variation in weather, as well as differential trends across counties. Finally, the error term ε_{it} captures unobserved differences in consumption across months. In all results we cluster standard errors at the county level to allow for arbitrary serial correlation and correlation across households within counties.

A potential concern for this empirical strategy is the possibility that participating households might have experienced other changes in their household at the same time they replaced their refrigerator or air conditioner. Participation in the program might systematically tend to coincide with, for example, other events like the arrival of a new baby, a household member receiving a new job, or the decision to purchase additional appliances. We are able to construct an event study figure and to report estimates from specifications that control flexibly for time trends, so the real concern is about changes that occur *exactly* at the same time as appliance replacement. Although it is impossible to completely rule out this concern, another test we can perform is to compare estimates by calendar month. For households who replace air conditioners, we find little change in consumption during non-Summer months, suggesting that these households did not simultaneously purchase additional appliances or make other changes that affect baseload consumption. And for households who replace refrigerators, we find similar effects across months of the year, suggesting that households did not simultaneously purchase air conditioners, fans, or other types of cooling equipment.

C. Comparison Groups

We report regression estimates based on several different comparison groups. We first report results estimated using an equal-sized random sample of non-participating households. Next we report results estimated using a sample that includes participating households only. In this specification the participating households who have not yet replaced are the comparison group, and we can continue to include time effects in these regressions because households replaced appliances at different times. Finally, we report estimates from a set of regressions that are estimated using matching.

We consider two different matched samples. The first matched sample is based purely on location. We perform this matching using account numbers. Account numbers include codes for the state and county where each household lives, as well as an internal code indicating the specific route used by meter readers. We do not have access to the route maps, and thus cannot use these codes to identify where within a county each household lives. But in selecting a comparison group, we can take advantage of the fact that households with the same meter reading route tend to live in close geographic proximity. For each *C4C* participant, we select as a comparison household the closest consecutive non-participating account number. In almost all cases this is another household on the same meter reading route. Weather is a major determinant of electricity consumption so this matching ensures, for example, that comparison households are experiencing approximately the same weather as the treatment households.

Our second matched sample is constructed based on both location and pre-treatment electricity consumption. We are somewhat limited in that we only have two years of data, and thus in many cases do not have a large number of pre-treatment observations for electricity consumption. To ensure the best possible matches given this limitation, we match on all available pre-treatment months. For example, if a household replaces in November 2010, we match using all observations between May 2009 and October 2010. When matching on both location and pre-treatment consumption level we adopt the following approach. We first select for each participating household the ten non-participating households with the closest account numbers. Then among these ten we select the non-participating household whose average monthly pre-treatment consumption is closest to that of the participating household. For a small number of households (<2%) we have zero months of pre-treatment consumption and for these households we match on location only.

Figures 2a and 2b plot electricity consumption by month of the year for households who replaced refrigerators and air conditioners and for the three comparison groups. Notice that the scale for the y-axis is not the same in both figures and that the overall level of consumption is considerably higher among households who replaced their air conditioners. For participants, consumption averages 153 kilowatt hours per month in Figure 2a and 395 kilowatt hours per month in Figure 2b. There is a great deal of variation across households and months; the standard deviation of monthly observations is 110 in Figure 2a, and 300 in Figure 2b.

These figures provide an opportunity to assess the different comparison groups. For households who replaced their refrigerators, all three comparison groups follow patterns that are reasonably similar to participating households. However, for households who replaced air conditioners, non-participants do not appear to be a particularly good comparison group, with electricity consumption levels that are much lower and less seasonal. The matched comparison groups perform better, and in particular, the pattern for the match based on both location and pre-treatment consumption is very similar on average to the treatment group. These matched samples help address potential concerns that non-participating households, as a whole, may not be a good comparison group. Households are self-selecting into the *C4C* program, and thus are likely to be different from non-participating households. Most importantly they may have fundamentally different tastes for durable goods, and thus different trajectories for electricity consumption. Although we do not observe durable good holdings explicitly, matching on pre-treatment electricity consumption is likely to be a good proxy.[5] This is particularly true because we are matching also by location, and thus the matched households experience the same climate and are living in the same neighborhoods. Nonetheless we are acutely aware that this is non-experimental data and thus pay great attention in the section which follows to possible differential trends in electricity consumption.

These figures also provide an opportunity to perform an informal inventory of the key drivers of residential electricity consumption in Mexico. For participants in the air conditioner program, electricity consumption triples during the summer, implying that about two-thirds of summer consumption (and half of annual consumption) come from air conditioners and other cooling equipment. It seems clear that most of these households indeed had operating air conditioners prior to participation; otherwise you would not expect to see such a pronounced seasonal pattern. Winter consumption averages 140 kilowatt hours per month for participants in the refrigerator program and 200 kilowatt hours per month for participants in the air conditioner program. A typical 15-year old refrigerator uses about 60 kilowatt hours per month (see Section IVA), so refrigerators represent between one-third and one-half of winter consumption. Other important sources of non-summer electricity consumption include lighting, televisions, washing machines, microwaves, and electric stoves, though none of these end-uses is as important as refrigerators (Gertler, Shelef, Wolfram, and Fuchs, 2013). The relative importance of both refrigerators and air conditioners helps explain why the program targeted these appliances.

III. Main Results

This section presents estimates of the effect of appliance replacement on electricity consumption. We present estimates from a range of different specifications. We start in Section IIIA with a graphical event study approach. Section IIIB then presents the baseline results, estimated with and without comparison households. And Section IIIC presents alternative specifications including matching estimates using our two matched samples and estimates that include polynomial time trends. Overall, the

[5] Reiss and White (2005), for example, show that electricity consumption is determined to a large degree by durable good holdings.

results are very similar across approaches.

A. Graphical Results

This subsection presents graphical results intended to motivate the regression analyses that follow. We focus in this section on refrigerators rather than air conditioners because they make up 90% of all replacements and because refrigerators lend themselves better to an event study analysis. Whereas the effect of refrigerator replacement is expected to be relatively similar across months of the year, the effect of air conditioner replacement is not. You would not expect to see, for example, much impact of air conditioner replacement on winter electricity consumption. This seasonal pattern, combined with the fact that air conditioner replacements tended to occur during warm months, makes evaluating air conditioner replacement better suited for a regression context.

Figure 3 describes graphically the effect of refrigerator replacement on household electricity consumption. The x-axis is the time in months before and after refrigerator replacement, normalized so that the month prior to replacement is equal to zero. The figure plots estimated coefficients and 95th percentile confidence intervals corresponding to the effect of appliance replacement by month, controlling for household and county by month-of-sample fixed effects. In particular, we plot the estimates of α from the following regression,

$$y_{it} = \sum_{k=-12}^{12} \alpha_k 1[\tau_{it} = k]_{it} + \gamma_i + \omega_{ct} + \varepsilon_{it}$$

where τ_{it} denotes the event month defined so that τ=0 for the exact month in which the refrigerator is delivered, $\tau = -12$ for twelve months before replacement, $\tau = 12$ for twelve months after replacement, and so on. The coefficients are measured relative to the excluded category ($\tau = -1$). Both sets of fixed effects play an important role here. Without the county by month-of-sample fixed effects (ω_{ct}), for example, the effect of replacement could be confounded with seasonal effects or slow-moving county-specific changes in residential electricity consumption. The sample used to estimate this regression includes the complete set of households who replaced their refrigerators and an equal number of non-participating households matched to the treatment households using location and pre-treatment consumption.

During the months leading up to replacement electricity consumption is flat, suggesting that the fixed effects are adequately controlling for seasonal effects and underlying trends. Beginning with replacement electricity consumption falls sharply by approximately 10 kilowatt hours per month. Consumption then continues to fall very gradually over the following year. We attribute the fact that the decrease appears to take a couple of months to the fact that the underlying billing cycles upon which this is based are bimonthly, and to a modest amount of measurement error in the replacement dates. Moreover, the gradual decline between months +2 and +12 likely reflects a modest differential time trend between the treatment and comparison households. In all periods the coefficients are estimated with enough precision to rule out small changes in consumption in either direction.

With Figure 4 we perform the same exercise but assigning event study indicators to the comparison group, rather than the treatment group. For this figure, we assigned hypothetical "replacement" dates equal to the replacement date of the participating household to which each comparison household is matched. The figure exhibits no change in consumption at time zero, indicating that the sharp change observed in the previous figure is indeed driven by changes to the treatment group. The figure exhibits a slight upward trend, consistent with modest differential time trends between the treatment and comparison groups. To address potential concerns about modest trends of this type, later in the paper we will report estimates which include parametric time trends. Overall, results are similar in those specifications indicating that our estimates are not being unduly affected.

B. Baseline Estimates

Table 2 presents baseline estimates. Least squares coefficients and standard errors are reported from five separate regressions. The regressions in columns (1)-(3) are estimated using the complete set of participating households and an equal-sized random sample of non-participating households. The specification in column (1) includes household by calendar month and month-of-sample fixed effects. In this specification, refrigerator replacement decreases electricity consumption by 12.4 kilowatt hours per month. This is similar in magnitude to the difference observed in the event study figure. Mean pre-treatment electricity consumption among households who replaced their refrigerators is 153 kilowatt hours per month so this is an 8% decrease. Whereas refrigerator replacement decreases electricity consumption, the estimates indicate that air conditioning replacement *increases* consumption by 6.6 kilowatt hours per month. Mean electricity consumption among households who replaced their air conditioners is 395 kilowatt hours per month, so this is less than a 2% increase.

Column (2) adds month-of-sample by county fixed effects to better control for differences in weather and other time-varying factors. The point estimate for refrigerator replacement decreases to -10.3 and the point estimate for air conditioner replacement increases slightly and becomes statistically significant. In column (3) we expand the specification to include an additional regressor corresponding to an interaction between air conditioning replacement and the six "summer" months (May-October). We would expect air conditioning replacement to have little effect on electricity consumption during cool months, and most meaningfully impact electricity consumption during warm months. The coefficient estimates appear to bear this out. While new air conditioners appear to have little impact during winter months, the estimates indicate an increase in summer electricity consumption of 14.3 kilowatt hours per month.

Columns (4) and (5) present results from specifications in which we drop the comparison group entirely and estimate regressions using only participating households. These regressions continue to include month-of-sample by county fixed effects and thus are identified by exploiting differential *timing* of replacement across households. The estimates in column (4) change little compared to the previous columns, suggesting that what matters most in these regressions is the within-household comparison. Column (5), in addition, drops the month during which replacement occurred and results are again similar.

Each column in Table 2 represents a single regression in which we estimate effects for both refrigerators and air conditioners. Estimates are essentially identical when we, alternatively, estimate these effects with separate regressions in each case keeping only households who replaced a certain type of appliance and the comparison households to which those households are matched. This is reassuring because it suggests that the time effects are adequately controlling for seasonal effects and underlying trends even though households who replaced air conditioners have considerably higher baseline consumption levels.

C. Additional Specifications

Table 3 reports estimates using our matched comparison groups. The estimating equations and sample of participating households are identical to Table 2, columns (1)-(3). But instead of a random sample of non-participants, these results are based on our matched comparison groups. Overall, the results are very similar to the previous table. When matching on location and pre-treatment consumption, the point estimates for the effect of refrigerator replacement are somewhat smaller, ranging from -9.2 to -9.5 kilowatt hours per month. For air conditioner replacement we continue to see a distinct seasonal pattern, with near-zero changes in electricity consumption in the winter, and an average increase of 15+ kilowatt hours per month in the summer.

These results rely on the comparison group being a reasonable counterfactual for what would have happened to participating households had they not replaced their appliances. We find it reassuring that results are similar across comparison groups, and similar even when no comparison group is used at all in Table 2, columns (4) and (5). Moreover, the sharp drop observed in electricity consumption among participating households, together with no sharp change in the comparison group, lends support to the interpretation of these changes as being *caused* by the program. Nonetheless, one could continue to be concerned about differential trends biasing our estimates. Our estimates assume that the change in electricity consumption in the comparison group is an unbiased estimate of the counterfactual. This is not testable. However, we can test whether the changes over time in the treatment group are the same as those in the comparison group in the pre-intervention period.

Table 4 reports results including time trends. Specifically, we construct a time trend variable which, for participating households, is equal to the number of months since May 2009, and for non-participating households is equal to zero for all months. And we consider specifications which include this time trend variable linearly, as well as quadratic and cubic functions of this variable. Thus in these specifications we allow average consumption by participating households to evolve according to a polynomial time trend. For these estimates the comparison group is non-participants matched on location and pre-treatment consumption. We find that the results are relatively insensitive to including a time trend. The coefficient on refrigerator replacement increases modestly from -9.2 to -11.2 once a time trend has been included and results are very similar with linear, quadratic, and cubic time trends.

IV. Mechanisms

Our estimates of savings are considerably smaller than the *ex ante* predictions that were used to motivate the program. The World Bank study, for example, considers an intervention essentially identical to *C4C*, in which refrigerators 10 years or older are replaced with refrigerators meeting current standards. The World Bank predicted that these refrigerator replacements would save 481 kilowatt hours per year, with larger savings for very old refrigerators.[6] The same study predicts that replacing air conditioners would save 1,200 kilowatt hours per year. We find that the actual savings from refrigerator replacement averaged only 135 kilowatt hours per year, about one-quarter of the savings predicted by the World Bank. And for air conditioning, we find that electricity consumption *increases* after replacement by an average of 91 kilowatt hours per year.

This section considers the key mechanisms that led actual savings to fall short of the *ex ante* predictions. We begin in Section IVA by examining the age of the appliances that were replaced. We show that while the World Bank predictions hinged on the program effectively targeting very old appliances, that most of the appliances that were replaced were close to the 10-year cutoff. Section IVB examines the seasonal pattern of

[6] See Johnson, et. al. (2009), Appendix C "Intervention Assumptions" pages 123-124 (air conditioners) and page 125 (refrigerators). Another point of comparison is Arroyo-Cabañas, et al. (2009) which predicted that replacing a pre-2001 refrigerator in Mexico would reduce electricity consumption by an average of 315 kilowatt hours per year.

treatment effects, finding that it points towards increases in air conditioning usage during summer months. In Section IVC we discuss increases in appliance size and features, showing, for example, that side-by-side doors and through-the-door ice increase electricity consumption substantially. Then in Section IVD we consider the possibility that some of the appliances may have been non-working at the time of replacement. Finally, Section IVE presents complementary evidence from comparing estimated savings across different subsets of households. We find that the mechanisms explored in this section, taken together, can easily reconcile our results with the *ex ante* predictions.

A. Appliance Age

Figure 5 plots sales-weighted electricity consumption for refrigerators and room air conditioners sold in the United States between 1980 and 2009. Similar data are not available for Mexico but the U.S. experience is informative because the two countries have had identical energy efficiency standards since the mid-1990s for both appliances. U.S. minimum energy-efficiency standards for refrigerators were first enacted in 1990, and then updated in 1993 and 2001. The second two changes are clearly visible in the figure with large, discontinuous decreases in consumption in 1993 and 2001. Mexico adopted the same standards in 1994 (NOM-072-SCFI-1994) and 2002 (NOM-015-ENER-2002). U.S. minimum standards for room air conditioners started in 1990, and were updated in 2000. Neither change resulted in an immediate, visible, change in average energy consumption. Mexico adopted the same standards in 1994 (NOM-073-SCFI-1994) and 2000 (NOM-021-ENER-2000).

Over these three decades there was a dramatic decrease in electricity consumption for both appliances. Refrigerator electricity consumption decreased 67% while air conditioner consumption decreased 30%. For both appliances, however, most of this decrease occurred during the 1980s and early 1990s. These data imply that, on average, replacing a twenty year old refrigerator would save about 530 kilowatt hours per year, while replacing a ten year old refrigerator would save only about 250 kilowatt hours per year. Although the World Bank is not explicit about where its estimate came from, implicitly in predicting savings of 481 kilowatt hours per year, the analysts seem to have been assuming that the program was going to tend to draw a large fraction of refrigerators that were 20+ years old.

For air conditioners it is harder to make sense of the World Bank estimate. In constructing Figure 5 we assumed 750 hours of annual usage. This is the number of hours used by the U.S. Federal Trade Commission in reporting estimated yearly operating costs in the yellow *EnergyGuide* labels, and is the baseline level of usage for statistics reported by the Association of Home Appliance Manufacturers (AHAM, 2010). Although a reasonable starting point, this is probably too low of a level of usage for Mexico. In Figure 2b, households with air conditioners have about 2,200 kilowatt hours of "excess" consumption during summer months. Before replacement a typical air conditioner used about 1,000 watts, so assuming this entire excess is air conditioning this is 2,200 hours of annual usage. With this level of usage the implied savings of replacing a 25+ year old air conditioner is about 900 kilowatt hours per year. To reach the World Bank's prediction of 1,200 kilowatt hours one would need to assume a somewhat higher level of usage and to continue to assume that the program was effective at targeting very old units.

Thus, the World Bank predictions hinged on the program being successful at recruiting households with very old, very inefficient appliances. There is an economic argument for this. After all, these households do have the most to gain from replacement. However, it also depends on the number of old appliances in circulation. According to Arroyo-Cabañas, et al. (2009), when the program started there were approximately 10 million refrigerators in Mexico over ten years old, but only about 15% of which were 20+ years old. Similar analysis of room air conditioners is not available but most analysts assume that room air conditioners have a shorter average lifetime than refrigerators. See, for example, the U.S. Department of Energy's Modeling System (NEMS).

In practice, the program does not appear to have been particularly effective at targeting households with very old appliances. The average reported age of the refrigerators that were replaced is 13.2 years. Almost 70% were reported to be 10-14 years old, 20% were 15-19, and only 10% were 20 years or older. The average reported age for air conditioners is 10.9 years and only 5% were reported to be more than 15 years old. There is likely to be significant measurement error in these self-reported ages. It can be difficult to determine an appliance's age just by looking at it, and there was no particular incentive for participants to report this age correctly (aside from reporting it was 10+ years old). Nevertheless, this apparent lack of success at targeting very old appliances is striking, and can provide part of the explanation as to why our results differ from the *ex ante* predictions.

B. Appliance Usage

Another explanation for the differences is that the *ex ante* analyses did not account for possible increases in appliance usage. Although changes in usage are likely to be modest or even non-existent for refrigerators, one would expect the new air conditioners to be used more because they cost less to operate. Increases in usage can mean leaving the unit on more hours per day or adjusting the settings to achieve additional thermal comfort. Changes in air conditioner usage also reflect substitution between alternative cooling technologies (electric fans, evaporative coolers, natural ventilation, etc.). Air conditioners use much more electricity than these alternative cooling technologies. For example, a typical room air conditioner uses 500-1000 watts while a fan uses less than 50 watts. So just about any form of substitution would have led to increased electricity consumption.

Figures 6A and 6B plot the effect of appliance replacement by month of year. To create these graphs we estimate 12 separate regressions, one for each calendar month. In each regression we keep only observations from a single calendar month. For example, for "May" we keep only electricity consumption that was billed in May 2009 or May 2010. Thus the estimated coefficient reflects the changes in electricity consumption from May to May, identified using households who replaced their appliances during any of the months between. All regressions include household fixed effects so the estimates should be interpreted as the change in consumption before and after appliance replacement.

For refrigerators the estimates are similar across calendar months. The estimates are precisely estimated so we reject the null hypothesis that all twelve estimates are equal, but the range is fairly narrow. The air conditioner estimates, however, follow a distinct seasonal pattern. The effect of replacement on electricity consumption is close to zero during winter months, but large and positive during summer months. The largest coefficient corresponds to September. Because the billing data is bimonthly, this reflects change in consumption during August and September, two of the warmest months in Mexico. The value of air conditioning is highest during hot months, and the evidence is consistent with an increase in usage during these months.

For households that replaced air conditioners, the estimates imply a total increase of about 90 kilowatt hours annually. This could be explained by a modest increase in usage. Before replacement, households with air conditioners use on average about 400 kilowatt hours more per month during the summer than the winter (see Figure 2b). This is mostly air conditioning. Based on the analysis in Section IVB, replacing a 10-15 year old air conditioner would be expected to reduce consumption from air conditioning by about 10%, i.e. 40 kilowatt hours per month. Instead, we are finding an increase of 20-30 kilowatt hours per month during the warmest months. This would have required only about a 20% increase in usage.

One would expect air conditioner usage in Mexico to be particularly price elastic. In high-income countries, many households choose to maintain near ideal levels of thermal comfort at most hours of the day regardless of energy costs. In middle-income countries, however, most households operate their air conditioners only on hot days, or during particular hours of the day, so there is more scope for changes in usage. Still, the implied increase in usage is higher than one would have expected based on the pure price response. Estimates in the literature of the short-run price elasticity of air conditioner usage tend to be considerably smaller than one (see, e.g., Rapson, 2013). Thus it seems likely that the increase in consumption is a result of not only the lower cost of operation, but also increased capacity and features.

C. Appliance Size and Features

Another reason the *ex ante* predictions were too optimistic is that they failed to incorporate increases in appliance size and features. Under the program's rules, refrigerators and air conditioners were supposed to meet specific size requirements. New refrigerators were supposed to be between 9 and 13 cubic feet, and have a maximum size no more than two cubic feet larger than the refrigerator which is replaced. Similar requirements were imposed for air conditioners. Many of the appliances for sale in Mexico during this period exceeded these requirements. For example, in a July 2009 report, the Mexican Consumer Protection Office tested 27 refrigerators for sale in Mexico (PROFECO, 2009). The average size among refrigerators that were tested was 13.5 cubic feet, and 17 out of 27 were larger than 13 cubic feet. Each additional cubic foot of refrigerator capacity adds about 10 kilowatt hours of electricity consumption per year.[7]

Perhaps more important than the size increases is the fact that new appliances tend to have more advanced features that increase electricity consumption. Most new refrigerators have ice-makers, and many also have side-by-side doors and through-the-door ice and water. These features are valued by households but they are also energy-intensive. Side-by-side doors, for example, increase electricity consumption by 100+ kilowatt hours per year.[8] And through-the-door ice increases electricity consumption by about 80 kilowatt hours per year.[9] Air conditioners have also added features. They have become much quieter, and many new models have lower cycle speeds for operating at night, thermostats, and remote control operation. These features make air conditioners

[7] Current energy-efficiency standards in the United States and Mexico specify that refrigerators with top-mounted freezers and automatic defrost without through-the-door ice have a maximum annual electricity use of 9.80AV+276.0 where AV is the total adjusted volume in cubic feet. Under C4C new refrigerators were supposed to be between 9 and 13 cubic feet, implying a range of minimum consumption from 364 to 403 kilowatt hours per year, with each cubic foot adding 9.8 kilowatt hours per year.

[8] Current energy-efficiency standards in the United States and Mexico specify that refrigerators with top-mounted freezers and automatic defrost without through-the-door ice have a maximum annual electricity use of $9.80AV+276.0$ where AV is the total adjusted volume in cubic feet. Refrigerators with side-mounted freezers without through-the-door ice have a maximum annual electricity use of $4.91AV+507.5$. Side-by-side doors are typically only available at larger sizes. For a 20 cubic foot refrigerator, for example, the difference in maximum electricity consumption is 133.7 kilowatt hours per year.

[9] Current energy-efficiency standards in the United States and Mexico provide separate requirements for refrigerators with and without through-the-door ice. Refrigerators without through-the-door ice have a maximum energy use of $9.80AV+276.0$ where AV is the total adjusted volume in cubic feet. The equivalent formula for refrigerators with through-the-door ice is $10.20AV+356.0$.

easier and more convenient to use, contributing to increased usage.

D. Possible Non-Working Appliances

Another potential mechanism that has been raised is non-working appliances. Appliances were supposed to be in working order to be eligible for replacement. But if households were somehow able to replace non-working appliances (or appliances that did not work well), this would provide an additional explanation for the gap between our estimates and the *ex ante* predictions. Although we think this may have occurred in some cases, we do not think this was widespread.

First, the retailer was supposed to verify that the old appliance was in working order. Typically this was performed at the same time the old appliance was picked up. While it is true that the retailer had an incentive to see the transaction completed, it also would have been risky for a retailer to grossly violate the program requirements. Appliances were tested again upon arrival at the recycling centers, and although occasionally one might expect an appliance to be damaged in transit, it would have been suspicious if a large fraction of appliances from a particular retailer showed up defective.

Second, as we mentioned in Section IB, households with very low levels of historic average electricity consumption were ineligible for the program. This requirement was implemented explicitly to prevent households from replacing non-working appliances. The minimum consumption level was 75 kilowatt hours per month for refrigerator replacement, and 250 kilowatt hours per month for air conditioner replacement. Although of course no simple rule like this is going to work perfectly, these minimums were set at reasonable levels such that households without working appliances in these categories would have likely been below the cutoffs.

Finally, the pre-treatment pattern of consumption (Figure 2) provides additional evidence that most appliances were working at the time of replacement. Households who replaced their refrigerators have winter consumption of 130-140 kilowatt hours per month. It would be unusual to reach this level of baseload consumption without a working refrigerator. And households who replaced their air conditioners exhibit a pronounced seasonal pattern. This is not to say that every single air conditioner that was turned in was in perfect working condition, but you would not expect to see this three-fold increase between winter and summer months if a large fraction of participants were replacing non-working air conditioners.

E. Heterogeneous Effects

Table 5 reports estimates from three separate regressions, one per panel. We report estimates corresponding to interactions between indicator variables for appliance replacement and indicator variables for whether a participant belongs to a particular subset as indicated in the row headings. The sample used in these regressions includes all participants, along with our matched sample of non-participating households in which matching is performed using both location and pre-treatment consumption. All regressions include household by calendar month and county by month-of-sample fixed effects and thus can be compared to the estimates in Table 3, column (5).

Panel (A) describes how the effect of appliance replacement varies by the mean household income in the county where the participant lives. For refrigerators, the estimates are negative and statistically significant for all three income terciles. The largest decreases are observed in high-income counties. This could reflect that households in these counties already tended to have larger and more feature-rich refrigerators pre-substitution, so there was less scope for increases along these dimensions to offset the efficiency gains. It might also be that in higher-income municipalities there was more of a tendency for households to turn in well-functioning refrigerators. For air conditioners, the estimates are positive for all three income terciles, but not statistically different from one another.

Panel (B) presents estimates by the self-reported age of the old appliance. For both appliance types the estimates are very similar across age groups. Somewhat surprisingly, there is no evidence of larger savings for households who replace older appliances. We have already mentioned that these self-reported ages are likely observed with considerable measurement error, and this could explain the lack of a consistent pattern. It could also be that there are systematic differences in appliance size and features that tend to work in the other direction. For example, older appliances tend to be smaller with less features, tending to offset the pure age effect.

Lastly, panel (C) reports estimates by the year of replacement. The program was launched in 2009 and we have in our analysis replacements made during each of the first three years. Savings tend to decrease over time. Refrigerators replaced during 2011 are associated with savings of only 3.2 kilowatt hours per month. And although the differences are not statistically significant, the point estimates for air conditioners have the same pattern, showing larger increases in later years. One might expect to see this pattern if households who participated early in the program had the most to gain. For example, households with very old or very energy-inefficient appliances would have likely wanted to participate in *C4C* as soon as possible. As time goes on, however, an increasing proportion of the participating households are close to indifferent between replacing and not replacing. These newly eligible households tend to have less to gain on average from replacement, and the estimates appear to bear this out.

Overall, the estimates are remarkably similar across subsets. Across groups, we find modest savings for households who replaced refrigerators, and modest increases in consumption for households who replaced air-conditioners. These estimates provide further corroboration of our main findings, indicating that the results are not driven by the experience of any particular subgroup.

V. Cost-Effectiveness

A. Baseline Estimates

Table 6, Panel (A) reports the mean annual impacts implied by our estimates. Based on the estimates in Table 4, column (4), refrigerator replacement reduces electricity consumption by 135 kilowatt hours annually, while air conditioner replacement increases electricity consumption by 91 kilowatt hours per year. At average residential electricity prices, refrigerator replacement saves households $13 annually, while air conditioner replacement costs households an additional $9 annually.

Panel (B) describes the total impact of *C4C* between May 2009 and April 2011. In our sample there are close to 850,000 refrigerator replacements and 100,000 air conditioner replacements so our estimates imply a total reduction in electricity consumption of 106.7 gigawatt hours annually (858,962 * 135 + 98,604 * -91 = 106,700,000 kilowatt hours). At average residential electricity prices this is a reduction in household expenditures of $10 million annually.

This panel also reports estimates of the total change in carbon dioxide emissions. One of the central goals of *C4C* was to reduce carbon dioxide emissions so these estimates are an important measure of the effectiveness of the program. Multiplying the change in electricity consumption by the average carbon intensity of electricity generation in Mexico yields a decrease of 57,400 tons of carbon dioxide emissions annually. Using an estimate for the social cost of carbon dioxide of $34 per ton these emissions reductions provide $2.0 million in benefits annually.[10]

Electricity generation also emits sulfur dioxide and other criteria pollutants. According to CEC (2011), Mexican plants emit 2.4 times as much sulfur dioxide, 1.7 times as much nitrogen oxide, and 2.2 times as much particulates (PM_{10}) per kilowatt hour as U.S. plants. Muller, Mendelsohn, and Nordhaus (2011) estimate the external damages from these pollutants for different forms of U.S. power generation. Coal-fired power plants are the most damaging (2.8 cents per kilowatt hour), while oil (2.0 cents) and, in particular, natural gas (0.2 cents) are less damaging. Using the mix of electricity generation in Mexico and scaling damages by 2.4 to reflect higher emissions levels yields additional benefits of $2.9 million annually.

These calculations reflect the changes in energy consumption from appliance operation but not changes in energy consumption from other parts of the appliance "life-cycle". The program accelerated appliance production and recycling; both of which are energy-intensive. Incorporating these sources of energy consumption would offset the estimated reductions, but only modestly. Taking into account materials production and processing, assembly, transportation, dismantling, recycling, shredding, and

[10] Greenstone, Kopits, and Wolverton (2013) presents a range of values for the social cost of carbon dioxide according to different discount rates and for different time periods that is intended to capture changes in net agricultural productivity, human health, property damages from increased flood risk, and other factors. These estimates were then updated by U.S. IAWG (2013). With a 3% discount rate (their "central value") for 2010 they find a social cost of carbon dioxide of $34 per ton.

recovery of refrigerant, Kim, Keoleian, and Horie (2006) find that energy usage during operation accounts for 90% of total refrigerator life-cycle energy use. We are not aware of a similar "life-cycle" analysis of air conditioners but their energy consumption is also heavily driven by operation.

Panel (C) reports baseline estimates of cost-effectiveness. Based on the total number of participants and the subsidies that they received we calculate that direct program costs were $129 million for refrigerators, and $13 million for air conditioners. This includes the cash subsidies received by households, but not costs incurred in program design, administration, advertising, or other indirect costs. Dividing by the estimated change in electricity consumption provides a measure of the direct program cost per kilowatt hour reduction. The relevant change here is the total discounted *lifetime* change in electricity consumption. For this calculation we adopt a 5% annual discount rate and assume that the program accelerated appliance replacement by 5 years. Under these assumptions the program cost per kilowatt hour is $.25 for refrigerators and $.29 overall. We do not report program cost per kilowatt hour separately for air conditioners because the program led to an increase in consumption. The program cost per ton of carbon dioxide emissions can be calculated similarly. For both refrigerators-only and for the entire program this exceeds $450 per ton.

These estimates of program cost per kilowatt hour are high compared to most available estimates from energy-efficiency programs in the United States. For example, U.S. electric utilities reported in 2011 spending $4.0 billion in energy-efficiency programs leading to 121 terawatt hours of energy savings, implying an average direct program cost per kilowatt hour of 3.3 cents.[11] Economists have long argued that these self-reported measures likely overstate the cost-effectiveness of these programs (Joskow and Marron, 1992). Nonetheless, it is striking that our estimate for *C4C* is about 9 times larger. With regard to carbon dioxide abatement, Knittel (2009) finds that the direct program cost for *Cash for Clunkers* exceeded $450 per ton, similar in magnitude to our estimates.

Our estimates of program cost per kilowatt hour remain high under more

[11] DOE (2013b), Tables 10.1 and 10.5. As another point of comparison, Allcott (2011) reports a program cost per kilowatt hour for peer-comparison reports from OPOWER ranging from 2-5 cents.

generous assumptions. With a 0% discount rate the program cost per cost per kilowatt hour is $0.27, and the program cost per ton of carbon dioxide is $497. If one assumes that the program accelerated appliance retirement program by 10 years, then the program cost per kilowatt hour is $0.17, and the program cost per ton of carbon dioxide is $307. Alternative program designs might have modestly improved cost-effectiveness. Some have argued, for example, that *C4C* would have been more cost-effective if participants had been required to purchase appliances that greatly *exceed* energy-efficiency standards.[12] Had the new refrigerators been forced to meet U.S. 2014 standards, we calculate that the refrigerator program would have had a program cost per kilowatt hour of $0.20, and a program cost per ton of carbon dioxide of $363.

B. Welfare

These measures of cost-effectiveness provide some but not all of the pieces of information necessary to evaluate whether or not the program is welfare-improving. In considering welfare, it is important to distinguish between "marginal" households who are induced to replace their appliance because of the program and "inframarginal" households who are getting paid to do what they would have done otherwise. The cost-effectiveness measures above assume that all households are marginal, potentially substantially overstating the environmental benefits of the program.

Distinguishing between marginal and inframarginal participants is also important for evaluating the economic costs of the program. Inframarginal participants value each $1 in subsidy at exactly $1, so for them the subsidy should be viewed as a pure transfer from taxpayers to program participants. Marginal households, however, value each $1 in subsidy by at most $1. These households otherwise would have stayed with their old, energy-inefficient durable good, but are induced by the subsidy to replace. For these participants the program is shifting income away from taxpayers who

[12] The United States, for example, will have new energy-efficiency standards for refrigerators in 2014 that require a 25% decrease in consumption compared to previous standards. A typical refrigerator meeting these more stringent standards uses 63 fewer kilowatt hours annually. The old standard both in the United States and Mexico requires that refrigerators with top-mounted freezers and automatic defrost without through-the-door ice have a maximum annual electricity use of $9.80AV$+276.0 where AV is the total adjusted volume in cubic feet. The new U.S. standard for this refrigerator type adopts a formula $8.07AV+233.7$ so a 12 cubic foot refrigerator uses 63 fewer kilowatt hours per year.

value it 1:1, toward participants who value it at less than 1:1. If demand is linear, for example, then there is a welfare loss of $.50 per $1 of subsidy.

In addition to this welfare loss, collecting tax revenues distorts labor and other markets. This social cost of public funds is above and beyond the welfare loss from recipient households valuing the subsidies less than 1:1. That is, even for households who value these subsidies at close to 1:1, there still is welfare loss because the subsidies must be financed. These distortions are particularly unfortunate when the funds go toward households who are inframarginal because welfare losses are being incurred to transfer income to households who would have purchased the energy-efficient durable good even in the absence of the subsidy.

These welfare losses must be compared to welfare gains from decreased externalities. The total change in externalities depends on the total number of households induced to adopt the energy-efficient durable good, and the reduction in externalities per adoption. With this first component, it is important to avoid counting inframarginal households. This is often challenging empirically because while one can observe the number of adoptions, it is difficult to construct a credible counterfactual to describe what would have occurred in the absence of the policy. Typically even more difficult to measure is this second component. Accordingly, this is where we focused our attention in the previous sections.

We find that the program incurred direct costs of about $140 million in exchange for carbon dioxide abatement worth $2.0 million per year and criteria pollutant abatement worth $2.9 million per year. Whether or not this is a welfare-improving tradeoff depends on how much the households value the subsidy per $1 and on the social cost of public funds. With linear demand, participants value the $140 million in subsidies at $70 million, with $70 million in welfare loss. Added to this, one would want to multiply $140 million by the social cost of public funds. Even for low values of the social cost of public funds, this would add tens of millions in additional welfare loss. Thus, overall, it appears that the costs of the program greatly exceeded the benefits.

VI. Conclusion

Meeting the increase in energy demand over the next several decades will be an immense challenge and in most countries it seems unlikely in the short term that there will be the political will to implement Pigouvian-style taxes on the externalities associated with the production and consumption of energy. Thus it is perhaps not surprising that policymakers are increasingly turning to energy-efficiency programs. Proponents argue that these programs represent a "win-win", reducing energy expenditures while also decreasing greenhouse gas emissions and other externalities. In countries where energy prices are subsidized, there is even a potential third "win" as governments reduce the amount they spend on subsidies. Moreover, among available energy-efficiency programs, appliance replacement subsidies would appear to have a great deal of potential. Residential appliances have experienced dramatic gains in energy efficiency, so there would seem to be scope for these programs to substantially decrease energy consumption.

Thus it is hard to not be somewhat disappointed by the estimated savings. We found that households who replace their refrigerators with energy-efficient models indeed decrease their energy consumption, but by an amount considerably smaller than was predicted by *ex ante* analyses. Even larger decreases were predicted for air conditioners, but we find that households who replace their air conditioners actually end up *increasing* their energy consumption. Overall, we find that the program is an expensive way to reduce energy use, reducing electricity consumption at a program cost of $.29 per kilowatt hour, and reducing carbon dioxide emissions at a program cost of over $500 per ton.

These results underscore the urgent need for careful modeling of household behavior in the evaluation of energy-efficiency programs. Households receive utility from using appliances, so they can and should increase usage in response to increases in energy efficiency. This "rebound" is a good thing – it means that households are increasing their utility. It does, however, complicate the design of energy-efficiency policy and *ceteris paribus*, in pursuing environmental goals it will make sense for policymakers to target technologies for which demand for usage is inelastic.

Our results also point to several additional lessons for the design and evaluation of energy-efficiency programs. Over time cars, appliances, and houses have become more energy efficient, but also bigger and better. These size and quality increases are another form of the demand for increased usage, and it makes sense to take them into account when designing policy. There is also a tendency for energy-efficiency programs to lose effectiveness over time. While initially a program tends to attract participants with the most to gain, as time goes on the pool will be made up increasingly by participants who just barely meet the eligibility requirements.

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FIGURE 1
Durable Good Ownership Rates by Income Level in Mexico

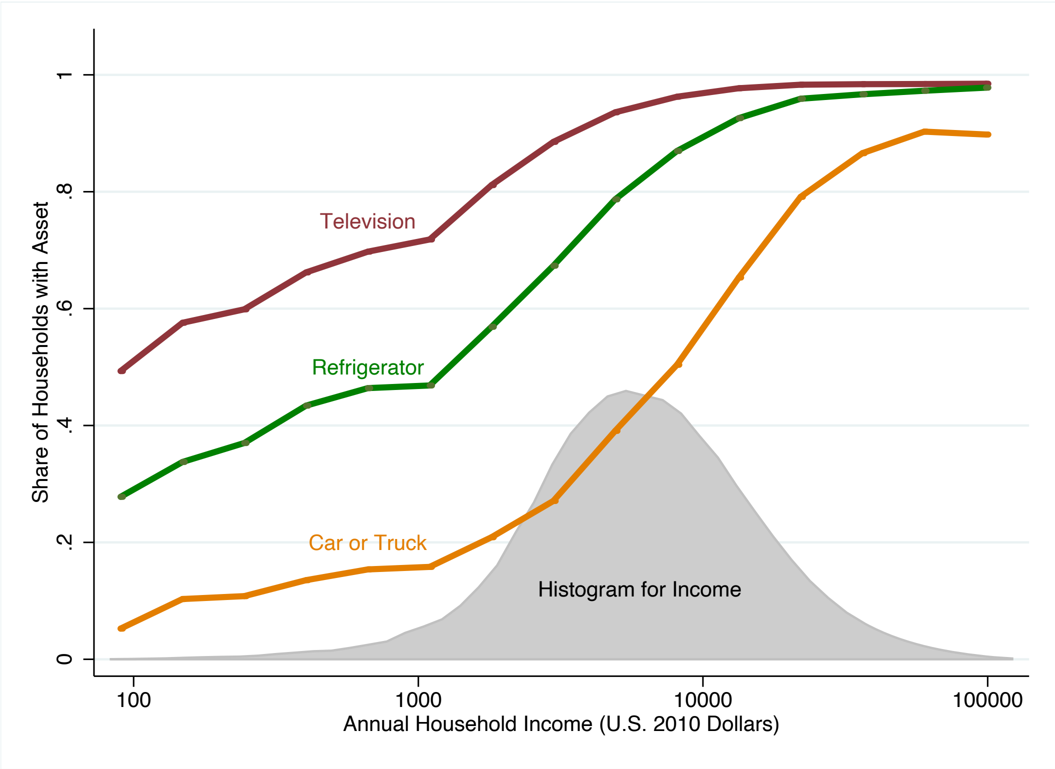


FIGURE 2a
Comparing Participants to Non-Participants: Refrigerators

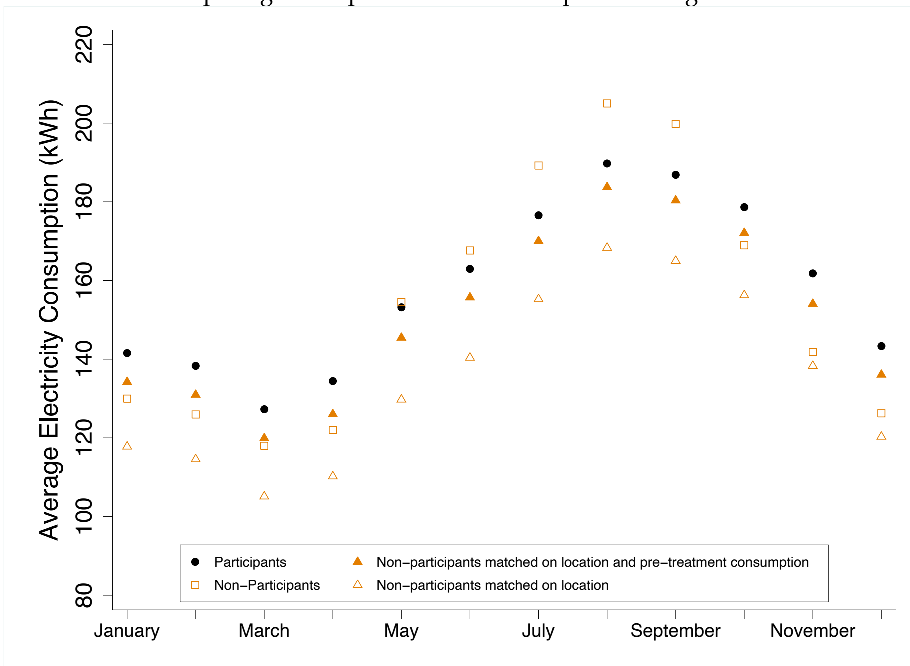
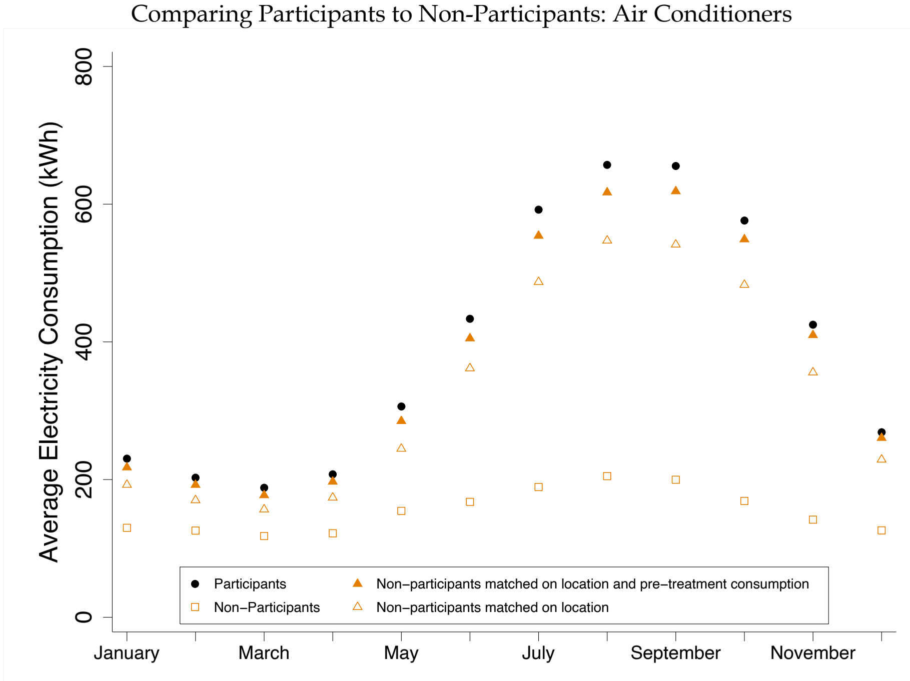
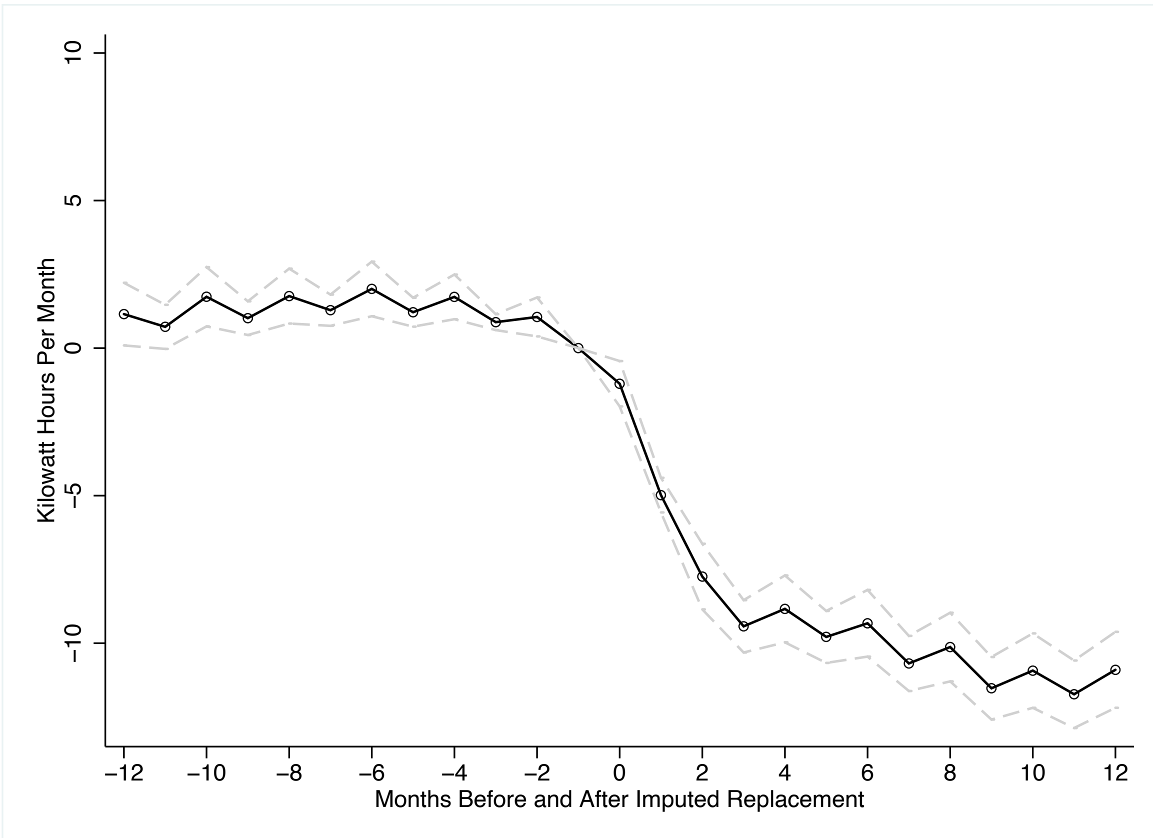


FIGURE 2b
Comparing Participants to Non-Participants: Air Conditioners



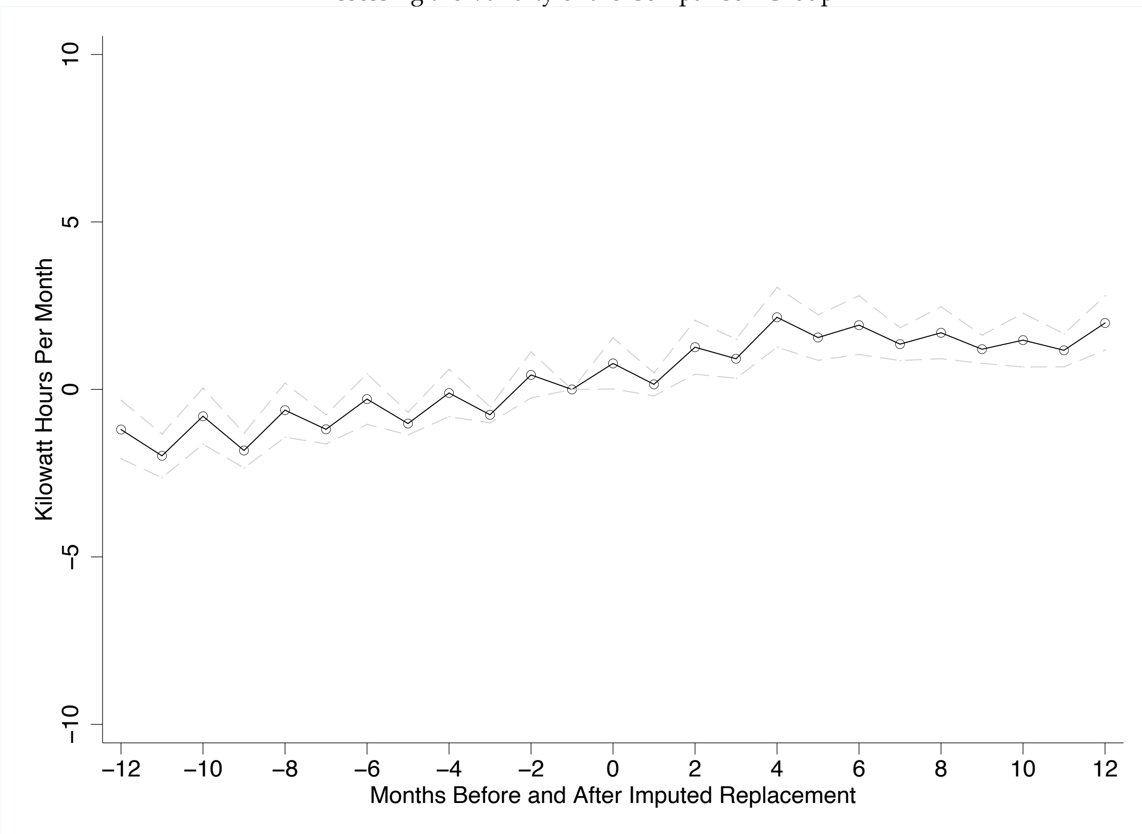
Note: These figures plot average electricity consumption by calendar month for households who replaced their refrigerators and air conditioners through the *C4C* program ("participants"), households who didn't participate in the program ("non-participants"), and for two matched samples of non-participants. For all households the sample is restricted to observations from the first year of the program (May 2009-April 2010). Additionally, for participants the sample is limited to those who participated during the second year of the program (May 2010-April 2011). This restriction ensures that the means for participating households are from before replacement.

FIGURE 3
The Effect of Refrigerator Replacement on Household Electricity Consumption



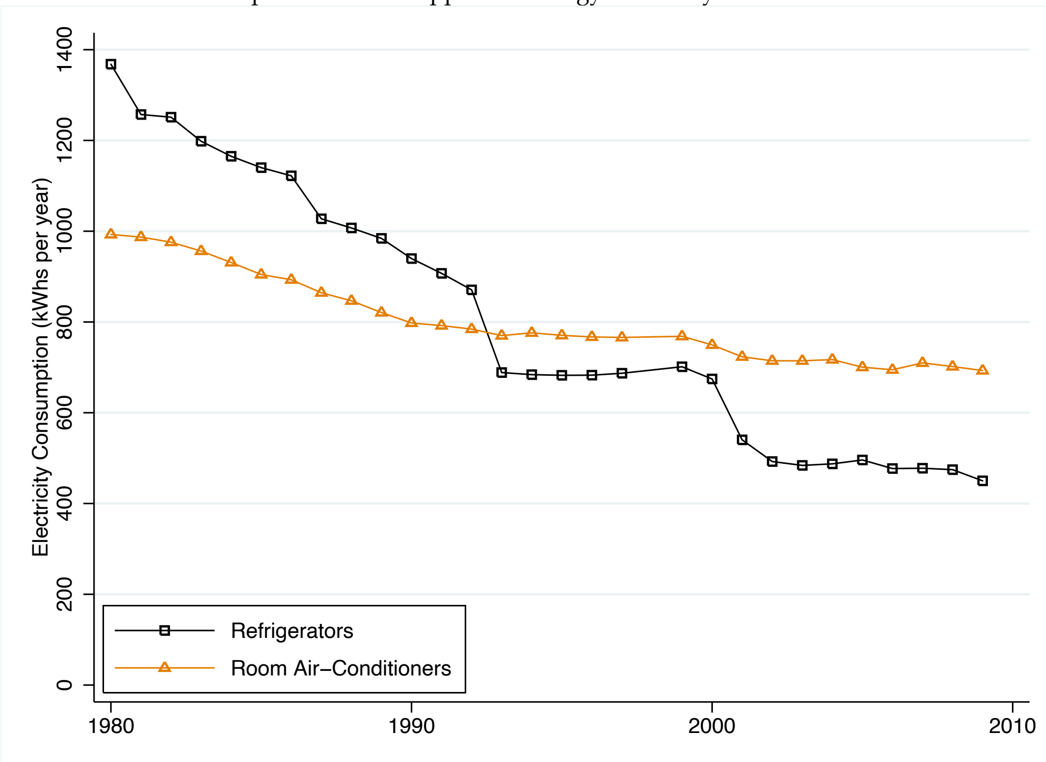
Note: This figure plots estimated coefficients and 95th percentile confidence intervals describing monthly electricity consumption before and after refrigerator replacement. Time is normalized relative to the delivery month of the appliance (t=0) and the excluded category is t=-1. Observations from before t=-12 and after t=12 are dropped. The sample includes 858,962 households who received new refrigerators through *C4C* between March 2009 and May 2011 and an equal number of non-participating comparison households matched to treatment households using location and pre-treatment consumption. The regression includes household and county by month-of-sample fixed effects. Standard errors are clustered by county.

FIGURE 4
Assessing the Validity of the Comparison Group



Note: This figure is constructed in the same way as Figure 3 but for the comparison group rather than the treatment group. Non-participating households are assigned hypothetical replacement dates equal to the replacement dates of the participating household to which they are matched.

FIGURE 5
Improvements in Appliance Energy-Efficiency Over Time



Note: This figure was constructed by the authors using data from AHAM (2010). See Nadel (2002) and Rosenfeld and Poskanzer (2009) for similar figures. These series have been normalized to reflect average 2009 appliance sizes. Refrigerators experienced a modest increase in average size over this time period so the non-normalized series shows a somewhat smaller change in electricity consumption. Room air conditioners, meanwhile, have experienced a modest decrease in average capacity so the non-normalized series shows a somewhat larger change in electricity consumption. Data from 1998 are not available.

FIGURE 6A
The Effect of Refrigerator Replacement by Month of Year

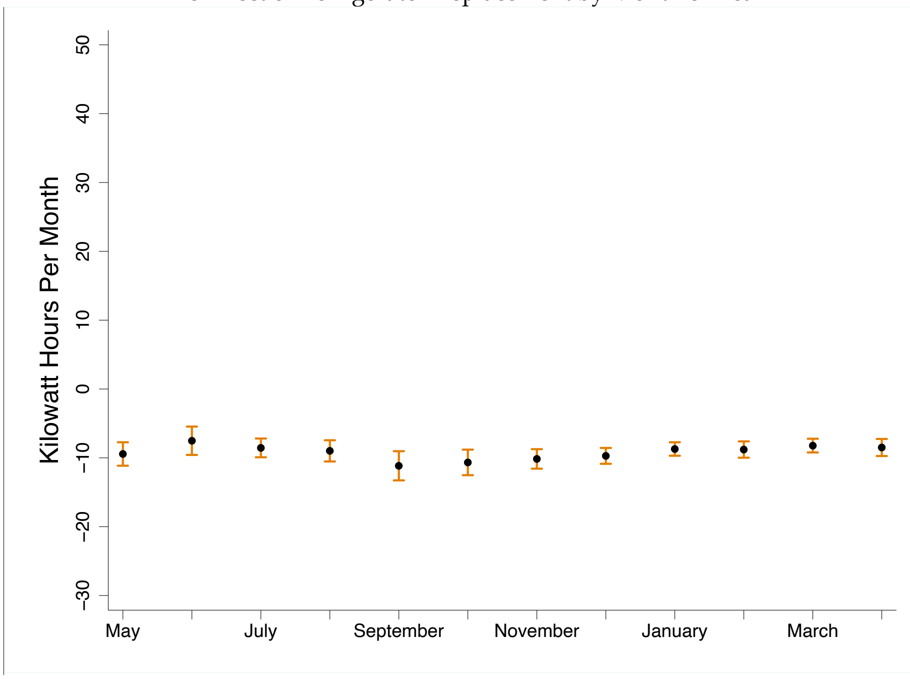
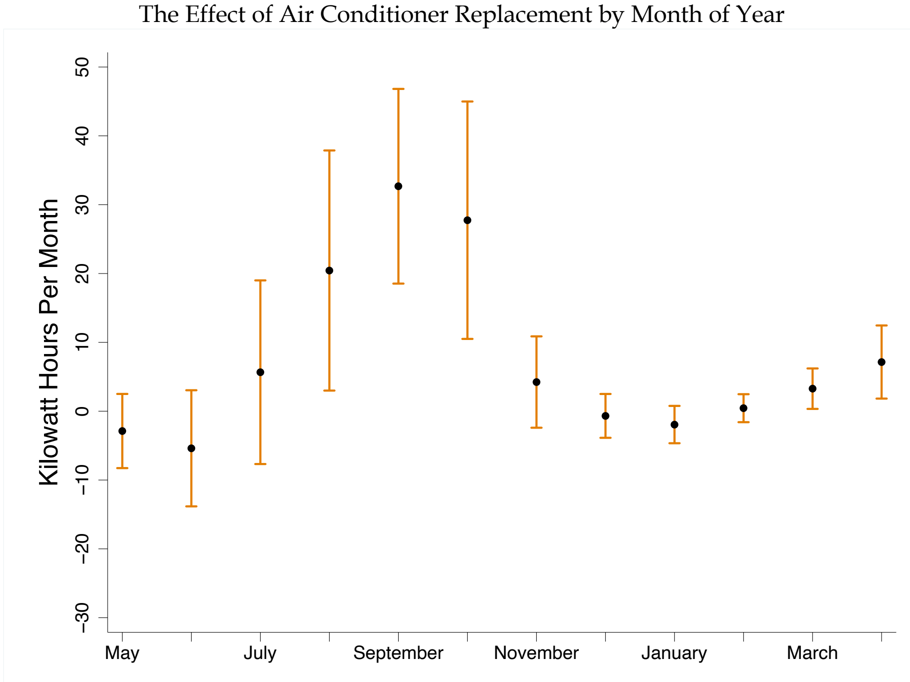


FIGURE 6B
The Effect of Air Conditioner Replacement by Month of Year



Note: Each figure plots estimated coefficients and 95th percentile confidence intervals corresponding to an indicator variable for households that have replaced their appliance from 12 separate regressions, one for each calendar month. The dependent variable in all regressions is monthly electricity consumption in kilowatt hours and the regressions include, in addition household by calendar month fixed effects and month-of-sample by county fixed effects. The sample includes billing records from May 2009 through April 2011. The 1,914,160 households in the complete sample include 957,080 households who participated in *C4C* and an equal number of non-participating households matched on location and pre-treatment consumption. Standard errors are clustered by county.

TABLE 1
Demographics and Appliance Saturation in Mexico, Census 2000-2010

	2000 Census	2005 Census	2010 Census
Demographics:			
Total Population (in millions)	97.0	102.8	112.0
Total Number of Households (in millions)	22.6	24.7	28.7
Household Size (persons)	4.3	4.2	3.9
Household Head Completed High School	26.8%	29.6%	32.1%
Number of Rooms in Home	4.32	4.19	4.58
Improved Flooring	86.0%	89.2%	93.9%
Electricity and Appliance Saturation:			
Electricity in the Home	94.7%	96.4%	97.5%
Refrigerator	68.2%	79.1%	82.5%
Washing Machine	51.6%	63.0%	67.0%
Television	85.6%	90.9%	92.6%
Computer	9.2%	19.9%	30.0%

Notes: This table describes data from the Mexican National Census *Censo de Poblacion y Vivienda* from the years indicated in the column headings. These statistics were compiled by the authors using microdata from the long-form survey which is completed by a 10% representative sample of all Mexican households. All statistics are calculated using sampling weights. We have cross-checked total population, number of households, and appliance saturation at the national and state level against published summary statistics and the measures correspond closely. Improved flooring includes any type of home flooring except for dirt floors.

TABLE 2
The Effect of Appliance Replacement on Household Electricity Consumption, Main Results

	(1)	(2)	(3)	(4)	(5)
$1[\text{New Refrigerator}]_{it}$	-12.4**	-10.3**	-10.3**	-11.4**	-11.9**
	(1.4)	(0.6)	(0.6)	(0.7)	(0.75)
$1[\text{New Air Conditioner}]_{it}$	6.6	7.2*	1.4	1.4	1.2
	(5.6)	(3.2)	(1.1)	(1.2)	(1.3)
$1[\text{New Air Conditioner}]_{it}$ x $1[\text{Summer Months}]_{it}$			14.3*	12.1*	13.6*
			(6.0)	(5.9)	(6.2)
Household By Calendar Month Fixed Effects	Yes	Yes	Yes	Yes	Yes
Month-of-Sample Fixed Effects	Yes	Yes	Yes	Yes	Yes
Month-of-Sample By County Fixed Effects	No	Yes	Yes	Yes	Yes
Including Treatment Households Only	No	No	No	Yes	Yes
Dropping Month of Replacement	No	No	No	No	Yes
Number of Households	1,914,160	1,914,160	1,914,160	957,080	957,080
R^2	.91	.91	.91	.93	.93

Notes: This table reports coefficient estimates and standard errors from five separate regressions. In all regressions the dependent variable is monthly electricity consumption in kilowatt hours and the coefficients of interest correspond to indicator variables for households who have replaced their refrigerator or air conditioner through *C4C*. The sample includes billing records from May 2009 through April 2011 from the complete set of households that participated in the program and an equal-sized random sample of non-participating households. Mean pre-treatment electricity use is 153 and 395 kilowatt hours per month for households who replaced refrigerators and air conditioners, respectively. Standard errors are clustered by county. Double asterisks denote statistical significance at the 1% level; single asterisks at the 5% level.

TABLE 3

The Effect of Appliance Replacement on Household Electricity Consumption, Matching Estimates

	Matching on Location			Matching on Location and Pre-Treatment Consumption		
	(1)	(2)	(3)	(4)	(5)	(6)
$1[\text{New Refrigerator}]_{it}$	-11.0**	-10.9**	-10.9**	-9.5**	-9.2**	-9.2**
	(0.7)	(0.5)	(0.5)	(0.7)	(0.5)	(0.5)
$1[\text{New Air Conditioner}]_{it}$	8.0	6.5*	0.1	9.5	8.3**	2.1*
	(5.3)	(3.2)	(1.2)	(5.2)	(3.0)	(1.0)
$1[\text{New Air Conditioner}]_{it}$ x $1[\text{Summer Months}]_{it}$			15.5*			15.2*
			(6.3)			(6.1)
Household By Calendar Month Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-Sample Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-Sample By County Fixed Effects	No	Yes	Yes	No	Yes	Yes
Number of Households	1,914,160	1,914,160	1,914,160	1,914,160	1,914,160	1,914,160
R^2	.93	.93	.93	.92	.92	.92

Notes: This table reports coefficient estimates and standard errors from six separate regressions. In all regressions the dependent variable is monthly electricity consumption in kilowatt hours and the coefficients of interest correspond to indicator variables for households who have replaced their refrigerator or air conditioner through *C4C*. The sample includes billing records from May 2009 through April 2011 from the complete set of households that participated in the program and an equal-sized matched sample of non-participating households. Matching is performed using location only in columns 1-3 and using both location and pre-treatment electricity consumption levels in columns 4-6. Standard errors are clustered by county. Double asterisks denote statistical significance at the 1% level; single asterisks at the 5% level.

TABLE 4
The Effect of Appliance Replacement on Household Electricity Consumption, Including Time Trends

	(1) No Time Trend	(2) Linear Time Trend	(3) Quadratic Time Trend	(4) Cubic Time Trend
1[New Refrigerator]$_{it}$	-9.2**	-11.2**	-11.2**	-11.2**
	(0.5)	(0.7)	(0.7)	(0.7)
1[New Air Conditioner]$_{it}$	2.1*	0.1	0.3	0.2
	(1.0)	(1.0)	(1.0)	(1.0)
1[New Air Conditioner]$_{it}$ x 1[Summer Months]$_{it}$	15.2*	15.3*	15.0*	15.0*
	(6.1)	(6.1)	(6.1)	(6.1)
Household By Calendar Month Fixed Effects	Yes	Yes	Yes	Yes
Month-of-Sample By County Fixed Effects	Yes	Yes	Yes	Yes
Number of Households	1,914,160	1,914,160	1,914,160	1,914,160
R^2	0.92	0.92	0.92	0.92

Notes: This table reports coefficient estimates and standard errors from four separate regressions aimed at assessing the robustness of the results with regard to including a parametric time trend for participants. In all regressions the dependent variable is monthly electricity consumption in kilowatt hours and the coefficients of interest correspond to indicator variables for households who have replaced their refrigerator or air conditioner through *C4C*. The sample includes billing records from May 2009 through April 2011 from the complete set of households that participated in the program and an equal-sized matched sample of non-participating households selected using location and pre-treatment electricity consumption. Standard errors are clustered by county to allow for arbitrary serial correlation and correlation across households within municipalities. Double asterisks denote statistical significance at the 1% level; single asterisks at the 5% level.

TABLE 5
Heterogeneous Effects

	Refrigerators	Air Conditioners
A. By Mean Household Income in County (2010 Census)		
First Tercile (Less than $5,000/year)	-6.7** (0.3) N=305,669	5.4* (2.9) N=13,202
Second Tercile ($5,000 - $7,637/year)	-10.0** (1.1) N=275,941	7.6** (1.8) N=42,176
Third Tercile (More than $7,637/year)	-11.0** (0.9) N=277,352	9.5 (6.5) N=43,226
B. By Age of Old Appliance (Self-Reported)		
Old Appliance Exactly 10 Years Old	-9.2** (0.6) N=380,803	8.9* (3.5) N=66,964
Old Appliance 11 – 14 Years Old	-9.1** (0.7) N=214,940	6.8** (2.7) N=23,753
Old Appliance 15+ Years Old	-9.3** (0.5) N=263,219	7.3* (3.1) N=7,887
C. By Year of Replacement		
Appliance Replaced in 2009	-9.7** (0.7) N=180,507	6.4 (5.0) N=15,267
Appliance Replaced in 2010	-9.5** (0.6) N=497,148	8.3** (3.1) N=59,499
Appliance Replaced in 2011	-3.2** (0.4) N=181,307	11.7** (2.5) N=23,838

Notes: This table reports coefficient estimates and standard errors from three separate regressions, one per panel. In all regressions the dependent variable is monthly electricity consumption in kilowatt hours. We report estimates corresponding to interactions between indicator variables for appliance replacement and indicator variables for whether a participant belongs to a particular subset as indicated in the row headings. The sample used in these regressions includes all participants, along with a matched sample of non-participating households in which matching is performed using both location and pre-treatment consumption. All regressions include household by calendar month and county by month-of-sample fixed effects. Standard errors are clustered by county. Double asterisks denote statistical significance at the 1% level; single asterisk denotes 5% level. The sample sizes indicated above are the number of treatment households in each category. The implied total number of participants differs slightly from the sample size in other tables because 486 households replaced both a refrigerator and an air conditioner.

TABLE 6
Electricity Expenditures, Carbon Dioxide Emissions, and Cost-Effectiveness

	Refrigerators (1)	Air Conditioners (2)	Both Appliances Combined (3)
A. Mean Per Replacement			
Mean Annual Change in Electricity Consumption Per Replacement (Kilowatt Hours)	-135	91	--
Mean Annual Change in Household Expenditure Per Replacement (U.S. 2010 dollars)	-$13	$9	--
B. Totals			
Total Replacements Nationwide (Between May 2009 and April 2011)	858,962	98,604	957,566
Total Annual Change in Electricity Consumption (Gigawatt Hours)	-115.7	9.0	-106.7
Total Annual Change in Household Expenditures (U.S. 2010 dollars, millions)	-$11.1	$0.9	-$10.2
Total Annual Change in Carbon Dioxide Emissions (Thousands of Tons)	-62.2	4.8	-57.4
C. Cost-Effectiveness			
Total Direct Program Cost (U.S. 2010 dollars, millions)	$129.4	$13.4	$142.7
Program Cost Per Kilowatt Hour (U.S. 2010 dollars)	$0.25	--	$0.29
Program Cost Per Ton of Carbon Dioxide (U.S. 2010 dollars)	$457	--	$547

Notes: Mean annual change in electricity consumption per replacement comes from Table 4, Column (4). Change in expenditures is calculated using an average price of $.096 per kilowatt hour. Carbon dioxide emissions are calculated using 0.538 tons of carbon dioxide per megawatt hour (538 tons per gigawatt hour) following Johnson, et. al. (2009). Direct program cost is the dollar value of the cash subsidies and excludes administrative costs. In calculating the program cost per kilowatt hour and program cost per ton of carbon dioxide we assumed that the program accelerated replacement by 5 years and use a 5% annual discount rate.