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HOW EFFECTIVE IS ENERGY-EFFICIENT HOUSING? EVIDENCE FROM A FIELD EXPERIMENT IN MEXICO

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ABSTRACT

Despite growing enthusiasm, there is little empirical evidence on how well energy efficiency investments work. Evidence is particularly lacking from low- and middle-income countries, despite a widespread view that these countries have many of the best opportunities. This paper evaluates a field experiment in Mexico in which a quasi-experimental sample of new homes was provided with insulation and other energy-efficient upgrades. A novel feature of our study is that we deploy large numbers of data loggers which allow us to measure temperature and humidity at high frequency inside homes. We find that the upgrades had no detectable impact on electricity use or thermal comfort, with essentially identical temperature and humidity levels in upgraded and non-upgraded homes. These results stand in sharp contrast to the engineering estimates that predicted up to a 26% decrease in electricity use. Part of the explanation is that air conditioner ownership is lower than expected, thus reducing the potential for reductions in energy use. In addition, we document that most households have their windows open on hot days, nullifying the thermal benefits of roof and wall insulation. Overall, we conclude that the benefits from these investments are unlikely to exceed the costs, which added $400-$500 USD to the cost of each home. Our results underscore the urgent need to fully incorporate socioeconomic conditions and human behavior into engineering models of energy use.

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A randomized controlled trials registry entry is available at https://osf.io/vbrc3/

1 Introduction

Global energy consumption is expected to increase dramatically over the next several decades, particularly in low- and middle- income countries. According to the U.S. Energy Information Administration, energy consumption in non-OECD countries is expected to grow by 71% by 2040, while growing only 18% in non-OECD countries over the same period.[1] Some economists have argued that energy consumption could grow even more rapidly, driven by increased adoption of air conditioners and other energy-using assets (Wolfram et al., 2012; Davis and Gertler, 2015).

Meeting this increased demand for energy will be an enormous challenge, particularly because most of the world's energy continues to come from fossil fuels. Carbon dioxide emissions from fossil fuels is the largest contributor to global greenhouse gas emissions, with 30+ gigatons in annual emissions (IPCC, 2014). Emissions are forecast to increase steadily through 2040, with 90%+ of the growth in emissions coming from non-OECD countries (DOE, 2016).

Faced with this daunting challenge, policymakers around the world are turning to energy efficiency as a way of potentially curtailing energy demand growth. Supporters argue that energy efficiency is a "win-win", paying for itself in the form of reduced energy expenditures while also reducing negative externalities.[2] Many environmental groups and international organizations envision energy efficiency playing a large role in mitigating climate change.[3]

But despite this growing enthusiasm for energy efficiency, there is little empirical evidence on how well energy efficiency investments actually work (Allcott and Greenstone, 2012). Evidence is particularly lacking from low- and middle-income countries, despite

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[1] DOE, 2016, Table 1-1, "World Energy Consumption By Country Grouping" predicts energy consumption for members and non-members of the *Organization for Economic Cooperation and Development*, a group of 35 mostly higher-income countries.

[2] Energy efficiency proponent Amory Lovins famously remarked about energy efficiency that, "It's better than a free lunch – it's a lunch you are paid to eat." (Lovins and Browning, 1992). McKinsey and Company (2009) argues that energy efficiency is a "vast, low-cost energy resource" that could reduce U.S. energy expenditures by billions of dollars per year, and similar analyses have identified billions of dollars in negative net cost energy efficiency investments for Mexico (USAID, 2013).

[3] For example, the International Energy Agency has predicted that half of all carbon dioxide abatement by 2030 will come from energy efficiency (IEA, 2015). Energy efficiency also features prominently in the Paris climate agreement, with 143 out of 162 countries mentioning energy efficiency in their nationally determined contributions (IEA, 2016).

a widespread view that these countries have many of the best opportunities (see, e.g. USAID, 2013; IEA, 2015). Without credible empirical estimates, it is impossible to know how large a role energy efficiency can play, or to know where investments should be best targeted.

This paper evaluates a field experiment in Mexico in which a quasi-random sample of new homes was provided with insulation and other energy efficiency upgrades. The area in Northeast Mexico where the field experiment took place is hot and semi-dry during the summer, so this is an ideal setting for studying energy-efficient housing. Based on an energy-efficiency simulation model, the investments were expected to reduce electricity demand by up to 26%, thus reducing carbon dioxide emissions, as well as to improve thermal comfort.[4]

In contrast to the engineering predictions, we find that the upgrades had no detectable impact on electricity use or thermal comfort. Across specifications there is no evidence of decreased electricity use, and this is true for both homes with and without air conditioning. Moreover, we find no differences in thermal comfort between upgraded and non-upgraded homes, with essentially identical levels of temperature and humidity across all hours of the day. Overall, we conclude that the benefits from these investments are unlikely to exceed the costs, which add $400-$500 USD to the cost of each home (Sadasi, 2017).

The lack of evidence of impacts is not because of a lack of statistical precision. The thermal comfort impacts, in particular, are extremely precisely estimated. With hourly data on temperature and humidity from over 450 homes, we can rule out 1% improvements in average temperature and humidity, even after adjusting our standard errors to account for serial correlation. This statistical precision reflects the large sample size as well as the relative homogeneity of the housing units in this housing development, with long rows of nearly identical homes all constructed and sold at the same time.

Part of the explanation is that most households do not have air conditioners. Only 13% of homes in the study sample have air conditioners, and we find the same rate of air conditioner ownership in upgraded and non-upgraded homes. Without air conditioning, the upgrades have much less potential to reduce energy use. In addition, we document that most households have their windows open on hot days. We find, for example, that 96% of households had at least one window open on a hot day in June 2017 and that

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[4] See Section 2.2 for further details.

households report having windows open for an average of 16.7 hours per day. An open window provides air flow on hot and humid days, but it also largely nullifies the thermal benefits of building insulation and the other energy-efficiency upgrades.

The field experiment takes place in a large housing development with a quasi-random sample of new homes receiving upgrades. Despite not using explicit randomization, the upgrades were distributed across sections of the housing development without any systematic pattern. In addition, home buyers were not aware of the upgrades when they purchased their homes. Upgraded and non-upgraded homes were built and sold by the same developer at the same time and at the same price. These features of the experiment mitigate concerns about selection bias, and we show that household characteristics are very similar in homes with and without upgrades.

Our study is the first that we are aware of to deploy large numbers of high-frequency data loggers to measure interior temperature and humidity. We placed loggers in the living areas of upgraded and non-upgraded homes and recorded hourly measures over 16+ months. This information provides highly-accurate, granular information about thermal comfort, allowing us to observe the performance of the upgrades across hours of the day, months of the year, and in a variety of different climatological conditions. In contrast, most previous studies of thermal comfort use engineering analyses which rely on strong assumptions about the performance of the building shell and household behavior.[5] We see broad potential for deploying data logger technology like this in evaluating similar programs.

Our focus on a middle-income country differentiates this paper from the existing literature on energy efficiency which has focused overwhelmingly on the United States (see, e.g. Joskow and Marron, 1992; Metcalf and Hassett, 1999; Davis, 2008; Allcott and Taubinsky, 2015; Fowlie et al., forthcoming; Houde and Aldy, forthcoming) and Western Europe (see, e.g. Brounen and Kok, 2011; Brounen et al., 2012; Aydin et al., 2017). Economists have long argued that credit constraints play a large role in energy-investment decisions (Hausman, 1979; Dubin and McFadden, 1984; Gertler et al., 2016; Ryan, 2017), making studies from low- and middle- income countries particularly interesting.

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[5] The paper is also related to a substantial existing literature on adaptive thermal comfort and sustainable buildings. See, e.g., Givoni (1992); Baker and Standeven (1996); Nicol and Humphreys (2002); Nikolopoulou and Steemers (2003).

Another novel feature of our analysis is the focus on new homes. There is a large gap between projected demand and supply of affordable housing in low- and middle-income countries, and new home construction is a major focus of governments and development agencies.[6] Installing energy efficiency technologies at the time of construction also has certain advantages compared to retrofitting existing homes. With large-scale social housing programs, the installation of energy-efficient upgrades at the time of construction by the developer takes advantage of economies of scale in the procurement and installation of materials.

Our analysis is thus also germane to a recent literature on the effectiveness of building codes (Aroonruengsawat et al., 2012; Jacobsen and Kotchen, 2013; Levinson, 2016; Novan et al., 2017; Kotchen, 2017). This is another literature that has focused, up until now, almost entirely on the United States and other high-income countries. In our field experiment homes standing right next to each other were built to two different standards, making this a particularly lucid illustration of the potential effectiveness (or ineffectiveness) of building codes. Indeed, one of the policy implications of our study is that a building code aimed at the type of energy-efficiency upgrades studied here would be unlikely to pass a cost-benefit test.

The paper proceeds as follows. Section 2 provides background about the housing development and the field experiment, including details about the energy efficiency upgrades. Section 3 presents results, first in graphical form and then regression estimates. Section 4 discusses possible mechanisms including open windows and evaluates cost effectiveness. Section 5 concludes with a short summary and policy implications.

2 Background

2.1 The Housing Development

The field experiment we evaluate in this paper took place in a large housing development in Northeast Mexico in the state of Nuevo Leon. The development is located west of

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[6] United Nations (2016) reports a shortfall of 980 million urban households lacking decent housing and a billion new homes needed by 2025 at a cost of \$9-11 trillion USD. Rojas and Medellin (2011) projects a demand for 3 million new housing units per year in Latin America and Bouillon et al. (2012) shows a 34% deficit nationally for Mexico, with higher rates in lower income quintiles.

Monterrey in the municipality of Garcia. Most of the homes were sold during 2013 or the beginning of 2014, at prices ranging from $18,000 to $24,000 USD. Buyers in this housing development tend to have relatively low incomes by Mexican standards.

In the ideal experiment, we would have assigned energy efficiency upgrades to homes randomly. The developer was unwilling to use explicit randomization, however, because of logistical impracticalities. These homes were constructed quickly and sequentially and the additional materials and personnel necessary for the upgrades were not always available. Instead, the developer distributed the upgrades in a “quasi-random” pattern as widely as possible throughout the development.

Figure 1 is a map of the northwest corner of the housing development where many of the upgrades were installed. Despite not using explicit randomization, the upgrades were quite widely distributed without any systematic pattern. Along most streets there is a mix of homes with and without upgrades, and the type of upgrades do not appear to follow any regular sequence. The buildings in this part of the development have two stories, with one owner on the first floor and a different owner on the second floor, and the figure shows that there is a mix of units with upgrades on the first floor only, second floor only, and both.

Throughout the building development homes are constructed in long rows of identical units. The housing development includes one- and two-story buildings.[7] Along any given street, however, the homes are identical with exactly the same size and layout. Moreover, as we show later, all of the homes were constructed and sold at approximately the same time. This homogeneity is valuable from an empirical design perspective because it reduces scope for omitted variables to influence the results.

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[7] Overall, the sample is composed of 55% homes in one-story buildings and 45% homes in two-story buildings. There are a total of four different prototypes in the sample, ranging in size from 39 to 58 square meters. The specific models are “Roble” units of 39 square meters built in one-story buildings , “Ebano” units of 55 square meters built on the first floor of two-story buidings, “Ebano” units of 45 square meters built on the second floor of two-story buildings, and “Caoba” units of 58 square meters built on either floor of two-story buildings. In our sample 55.3% of homes are Roble, 38.4% Ebano and 6.3% Caoba. Our full regression specification controls for housing unit type. In addition, one might have been interested in testing for interaction effects between first- and second-story homes but less than 5% of homes are in two-story homes for which treatment status differs between the two floors.

2.2 The Field Experiment

As is the case in many new housing developments, buyers in this housing development selected their homes before they were built. Potential buyers visited a furnished model home that was identical in size, layout, and materials to the actual homes. Then if they decided to buy a home, buyers selected a specific unit by looking at a map of the housing development. At this point of purchase, buyers were not told which homes would have energy efficiency upgrades. In fact, at this point of purchase, nobody including the sales people knew which homes were going to be upgraded.

This "double blind" field experiment design greatly reduces the scope for selection bias. If buyers had known in advance which homes were going to be upgraded this would have raised serious concerns about self-selection. For example, home buyers might have first selected the homes with upgrades. Moreover, if the developer had this information at the point of sale there would potentially be concerns about more subtle forms of selection bias, even if the salespersons were instructed not to share this information with potential buyers.

This may seem like a subtle point, but mitigating selection bias is of paramount importance in this type of study. Households influence energy use, temperature, and humidity in their homes based on the number of household members, whether or not they are home during the day, and through behaviors like closing blinds during the day, cooking patterns, as well as the number and type of appliances. Were there systematic differences between the households in homes with and without upgrades, it would be difficult to make any credible inference about the causal impact of upgrades.

2.3 The Upgrades

In the field experiment, there were two different types of energy efficiency upgrades. Upgrade 1 consisted of additional thermal insulation installed outside the house. All homes have thermal insulation in the south-facing wall, but homes with upgrade 1 received additional 1.5" EPS (Expanded Polystyrene) foam insulation on the east- and west-facing walls, as well as 1" EPS foam on the roof. Upgrade 2 consisted of 1" EPS foam on the roof, window shading on the south-facing windows, and a passive cooling system. The window shading was built with concrete and installed above the windows, reducing the amount of solar radiation entering the home during the middle of the day. The passive cooling system was a thermal chimney, running vertically from the kitchen to the roof with a metal top which spins in the wind, lifting hot air up and out of the kitchen. The upgrades are immobile, permanent features of the home that cannot be easily removed or adjusted.

Our comparison group is homes that did not receive upgrades. It is worth noting that this "base model" home already includes several energy-efficient features. Mexican government housing policy has long encouraged energy efficiency and Mexico's standard "green mortgage" program requires homes to have LED lighting and other energy-efficient features. Based on an energy efficiency simulation model, upgrades 1 and 2 were expected to reduce electricity use and, thus, carbon dioxide emissions from electricity use, by 26% and 8%, respectively.[8]

2.4 Data Collection

The evaluation sample was initially designed to include all the units in the housing development that had energy-efficient upgrades and were sold between 2013 and 2014. An equal number of units without upgrades, but located in the same blocks with the same construction characteristics and sold at the same time, was included in the sample as comparison homes. Homes located in corners and with different sizes, or located along the main access roads of the development were excluded upfront.

During fieldwork nearly 50% of the initial sample had to be dropped from the analysis because the units were temporarily or permanently uninhabited. These are homes that

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[8] These predictions come from the DEEVI model, an energy efficiency simulation model adapted for Mexico (Passive House Institute, 2012). Upgrade 1 was expected to reduce annual electricity use from 89.5 to 66.34 kilowatt hours per square meter (26%) (DEEVI, 2014a) while upgrade 2 was expected to reduce annual electricity use from 87.36 to 80.10 kilowatt hours per square meter (8.3%) (DEEVI, 2014b). These predictions are for electricity only (not all energy) for the standard single story "Roble" home prototype. The primary source of energy reduction in the DEEVI model is from lower consumption of air conditioning when temperature surpasses $25°\mathrm{C}$. These DEEVI predictions were calculated in 2014 after many of the homes were already constructed and sold. In the absence of air conditioning, the model predicted no improvement in comfort for upgrade 1 (house above 25 degrees Celsius 56.6% of time with and without the upgrades), and a 13.8% improvement in comfort for upgrade 2 (from 51.9% to 44.7% of time during which the house is above 25 degrees Celsius).

were sold, but not yet occupied or used too infrequently for the residents to be located even after multiple repeat visits by our enumerators. This attrition was very similar for upgraded (44%) and non-upgraded homes (44%) and thus is unlikely to bias our results. In interpreting our cost-effectiveness results, however, it is important to take into account that many homes are used less than was forecast.

The initial household survey took place between June and August 2016 and was carried out by trained enumerators from an independent survey firm. The questionnaire included modules on basic demographic characteristics, education, health and income of household members, self-reported perceptions of comfort, appliance ownership, and subjective well-being. The application of the survey lasted 45 minutes on average.

Information on electricity use was captured in several ways. First, electricity consumption was recorded from the electricity meters outside the homes. Meters record cumulative electricity use and surveyors photographed and recorded this information during several visits. Second, households were asked to recall the amount in pesos of their last electricity bill. Third, households were asked to describe all the lightbulbs and appliances in the home and the frequency with which they were used.

Finally, interior temperature and humidity were measured using the LogTag HAXO-8 logger.[9] Data loggers were installed by trained technicians from the same firm after the application of the survey in each home. The data loggers were installed 1.8 meters above the floor on an inner wall of the home facing the primary living quarters (living and dining room area). Instructions were given to household members to not tamper with the data loggers. Information from the loggers was then downloaded every three to four months over a 16+ month period. We also have data on outdoor temperature from a meteorological station that we installed on the roof of one of the homes in the development.

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[9] The LogTag HAXO-8 logger can measure and record up to 8,000 readings, up to 167 days of dry bulb air temperature and relative humidity if measured every 30 minutes. The meter is highly accurate, plus or minus up to $1^{\circ}\mathrm{C}$ and up to 3% relative humidity. The LogTag logger works over a large range, -40° to 85° for temperature and 0% to 100% for relative humidity. Downloading logged data is performed using special LogTag software included with the product and a small base which connects to the logger.

2.5 Covariate Balance

Table 1 reports mean characteristics for homes with and without upgrades. Mean household characteristics are very similar. For example, there are an average of 3.73 household members in homes with upgrades, compared to 3.76 members in homes without upgrades. Number of children, proportion owner occupied, monthly income, as well as the age, education, marital status, and employment status of the household head are all very similar in the two groups.

The date the homes were sold is also very similar for homes with and without upgrades. All of the homes were constructed and sold by the same developer during the same time period. This is important because it mitigates potential concerns about changes over time in materials or construction methods as well as about temporal or seasonal patterns in the composition of buyers.

Appliance saturation is balanced too. Most homes own televisions, fans, and refrigerators, and saturation is similar between homes with and without upgrades, albeit with a somewhat higher refrigerator ownership rate in homes with upgrades (*p*-value .03). Air conditioner ownership is 13% in upgraded homes and 12% in non-upgraded homes, so essentially identical in the two groups, and well below the 36% which was assumed in the engineering calculations (DEEVI, 2014a,b).

For all characteristics the table reports *p*-values for the null hypothesis of equal means between homes with and without upgrades. Only for refrigerator ownership do we reject the null hypothesis of equality at the 5% level. This balance provides reassurance that the comparisons which follow will not be unduly biased by compositional differences between the two groups. Although not derived from a true randomized experiment, the households living in homes with upgrades are highly comparable to households living in homes without upgrades.

3 Results

In this section we now turn to measuring the effect of upgrades on energy use and thermal comfort. Section 3.1 introduces the data with a simple comparison of means. Section 3.2

then compares mean daily outcomes over our time period. Sections 3.3 and 3.4 compare outcomes by hour-of-the-day and for different levels of outdoor temperature, looking for evidence of how the upgrades perform under different conditions. Finally, Section 3.5 reports regression estimates, allowing us to perform formal statistical tests with a range of different control variables, and Section 3.6 tests for a potential rebound effect by performing additional analyses on homes with air conditioning.

3.1 Comparison of Means

Table 2 compares mean outcomes for homes with and without upgrades. Overall, outcomes are almost identical in the two groups. The last column in the table reports *p*-values for the null hypothesis of equal means, and in almost all cases we cannot reject the null hypothesis at the 5% level.

The table first describes thermal comfort. Across all hours in our sample, mean temperature is almost identical in homes with and without upgrades, $27.0°\mathrm{C}$ compared to $26.9°\mathrm{C}$. Temperature varies widely during the year so later in the paper we examine summer and winter separately. Relative humidity is, surprisingly, somewhat *higher* in homes with upgrades, 56.8% compared to 56.1%. The difference is statistically significant, but small in magnitude. The table also reports the proportion of hours with temperature above $25°\mathrm{C}$. Again there is no evidence of improved thermal comfort in homes with upgrades, with about 70% of hours above $25°\mathrm{C}$ in both upgraded- and non-upgraded homes.

The table next reports cumulative electricity consumption as of October 2016 and November 2017 as recorded from the electricity meters outside the homes. The table also reports the difference in electricity consumption between October 2016 and November 2017. Contrary to what was expected, all three measures indicate somewhat *higher* electricity consumption in homes with upgrades, although the differences are not statistically significant. No evidence of electricity savings also implies no evidence of reductions in carbon dioxide emissions which was one of the major objectives of the upgrades.

The next set of outcomes are self-reported measures of thermal comfort.[10] Most house-

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[10] This emphasis on self-reported measures is germane to a growing literature in development economics which uses self-reported measures of happiness and other “softer” measures to get at household well-being. See, e.g. Cattaneo et al. (2009); Devoto et al. (2012); Galiani et al. (2015). Sometimes these broader measures pick up other, perhaps unexpected impacts of investments as in the case of water connections

holds report their homes being “hot” or “very hot” in the summer, and this is similar in homes with and without upgrades. About half of households also report their homes being “cold” or “very cold” in the winter, though this is somewhat lower in homes with upgrades (*p*-value .05). Outcomes are also similar with regard to whether households report their homes having an “agreeable” temperature during different parts of the day during the summer. So, although most of the differences are not statistically significant, these self-reported measures provide some suggestive evidence of greater thermal comfort in upgraded homes in winter.

Finally, the table reports a variety of additional self-reported outcomes. Television, fan, and air conditioner usage are all similar between homes with and without upgrades. The upgrades were intended to reduce energy consumption from air conditioning and other appliances, but this does not appear to be the case. Nor are there differences in how much people report having spent on their last electricity bill. Finally, had the upgrades resulted in energy savings or other benefits, we would expect this to be capitalized into the value of the property. Our measure of monthly rent is self-reported for renters and, for homeowners, is a hypothetical question about how much the home would rent for. This rental value is statistically indistinguishable for homes with and without upgrades, providing no evidence of capitalized benefits.

3.2 Mean Daily Outcomes

We now turn to more detailed comparisons of thermal comfort using the information from the data loggers. Figure 2 plots mean daily temperature and relative humidity for homes with and without upgrades. Overall, temperature and humidity are very similar in the two groups. Mean daily temperature, in particular, is essentially identical in homes with and without upgrades. Mean daily humidity is also very similar, particularly during both summers when humidity is of biggest concern. During the one winter for which we have data, humidity tends to be higher in upgraded homes, though the differences are relatively small. Thus, overall, Figure 2 provides no evidence that the upgrades have increased thermal comfort. In the appendix we also plot daily measures for the proportion of hours above $25°\mathrm{C}$ and there is again no evidence of increased thermal comfort in upgraded

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increasing the time available for leisure and reducing household conflicts on water matters (Devoto et al., 2012).

homes.

In addition to the comparison between upgraded and non-upgraded homes, Figure 2 shows how thermal comfort changes over the course of the year. As we mentioned earlier, this kind of high-frequency measurement of interior temperature and humidity made possible by our data loggers is novel and of significant independent interest. Strikingly, there is wide variation in both temperature and humidity across days. Daily mean temperatures range from about $14°\mathrm{C}$ in the winter to $33°\mathrm{C}$ in the summer, a very wide range. Daily mean humidity ranges from 20% to 80%. Generally 40% to 60% relative humidity is considered comfortable, so this range for humidity is also very wide.

3.3 Mean Hourly Outcomes

Figure 3 plots mean temperature and humidity by hour-of-day during the summer months. Along the x-axis hours run from 1AM to midnight, so the figure shows mean outcomes starting in the morning, then afternoon, and finally evening hours. Again, we plot means separately for homes with and without upgrades. These figures include 95% confidence intervals, calculated using standard errors that are clustered by household to account for serial correlation. The hourly pattern for temperature and humidity is very similar in the two groups. In both cases, the point estimates line up almost exactly on top of one another. Temperature reaches its nadir in the morning, and then peaks around 6PM. Humidity peaks much earlier, around 10AM, then reaches its nadir at 7PM.

Figure 4 provides additional detail, breaking the results up into upgrade 1 and upgrade 2. Recall that upgrade 1 is wall and roof insulation, while upgrade 2 is roof insulation, shading and ventilation, so the two potentially have different impacts on thermal comfort. There is no evidence, however, that either upgrade type outperforms homes without upgrades. If anything, homes with upgrade 1 have somewhat higher average temperatures, while homes with upgrade 2 have higher humidity. In the appendix, we provide additional evidence, including mean hourly measures for the proportion of observations above $25°\mathrm{C}$, as well as a complete set of results for non-summer months. Across all outcomes, there is no evidence of increased thermal comfort in upgraded homes.

3.4 Outdoor Temperature

Figure 5 plots mean indoor temperature as a function of mean outdoor temperature, in three-degree temperature bins. As expected, there is a strong positive relationship between indoor and outdoor temperature. The thermal mass of the homes protects households from the most extreme temperatures, so indoor temperature varies somewhat less overall than outdoor temperature. However, indoor temperatures still get very warm, for example, above $32°\mathrm{C}$ during hours in which the outdoor temperature exceeds $36°$.

Indoor temperature is essentially identical in homes with and without upgrades for all levels of outdoor temperature. The markers for the two groups are right on top of one another, and very precisely estimated. The figure includes 95% confidence intervals for the sample means, calculated using standard errors that are clustered by household to account for serial correlation, and the confidence intervals are extremely narrow. Figure 6 plots estimates separately by upgrade type. Consistent with the other results, there is no evidence that either type of upgrade improves thermal comfort. There is no evidence that upgraded homes are cooler in the summer, nor warmer in the winter.

3.5 Regression Estimates

Table 3 presents regression estimates for mean temperature. We report estimates from fifteen separate least squares regressions, all variations of the following regression equation,

$$y_{it} = \beta 1(Upgrade)_i + \omega_t + \epsilon_{it}. \tag{1}$$

The dependent variable y_{it} in all regressions is temperature in logs. The covariate of interest is an indicator variable equal to one for homes with upgrades. For all regressions we report estimates of the parameter of interest β, which measures the difference in mean temperature between homes with and without upgrades. Panel (A) reports estimates for the entire sample, while Panel (B) restricts the sample to May to October, and Panel (C) restricts the sample to November to April.

We add controls across columns. Column (1) has no controls, and thus simply reports the difference in means. Column (2) adds fixed effects for all hours in the sample. We have more than sixteen months of data, so this is more than 11,000 total fixed effects in Panel

(A). These fixed effects control for outdoor temperature, sun, and other climatological factors common to all homes. Columns (3), (4), and (5) add household characteristics, housing unit fixed effects, and date of sale, respectively.

Across specifications there is no evidence that the upgrades improve thermal comfort. In the full specification, upgrades are associated with a 0.002 decrease in mean temperature, in logs. This effect is negligible, equivalent to only two-tenths of one percent, and not statistically significant. Nor is there any evidence that the upgrades improved thermal comfort during summer or winter. Mean temperature in upgraded homes is not lower during the summer, nor is it higher during the winter. Point estimates vary across specifications but in all cases are quite small in magnitude, much smaller than 1% in absolute value. None of the fifteen regression estimates are statistically significant. Our standard errors are clustered at the household level to allow for arbitrary serial correlation within housing-unit observations, but are nonetheless quite small in magnitude. Across specifications the estimates are precise enough to easily rule out a 1% change in temperature.

Table 4 reports regression estimates for electricity consumption. In all regressions the dependent variable is cumulative electricity consumption as of November 2017, in logs. Across specifications there is no evidence of a decrease in electricity consumption. In Panel (A) with the complete set of homes all four estimates are positive. Although none of the estimates are statistically significant, in three out of four cases they are estimated with enough precision to rule out the 8% to 26% reductions predicted by the engineering model. For homes with air conditioning in Panel (B), point estimates are negative in three out of four specifications, but the standard errors are large. Finally, for homes without air conditioning in Panel (C), all four point estimates are again positive. While the estimates are again not statistically significant, in two out of the four cases they are estimated with enough precision to rule out the reductions predicted by the engineering model. This is using 95% confidence intervals; with 90% confidence intervals we can reject the engineering predictions in eight of eight cases in Panels (A) and (C).

3.6 Rebound Effect

Economists have long pointed out that energy efficiency lowers the cost of household services, potentially leading households to consume more (see, e.g., Hausman, 1979; Dubin and McFadden, 1984; Dubin et al., 1986; Borenstein, 2015; Gillingham et al., 2016). In our field experiment, upgraded homes are better insulated, so air conditioning potentially delivers more cooling for a given level of energy input. If households in upgraded homes respond to this decreased "price" by consuming more cooling, this would be a form of the rebound effect.

To further evaluate the potential for a rebound effect, we performed additional analyses on homes with air conditioning. As we showed earlier, the rate of air conditioner ownership is almost exactly the same in upgraded homes (13%) and non-upgraded homes (12%), so there is no evidence that the upgrades induced adoption. Instead, the additional analyses are aimed at using our thermal comfort data to test whether households in upgraded homes are using the air conditioners more intensively. As we describe in a simple conceptual framework in the appendix, if there is a rebound effect we would expect it to take the form of improved thermal comfort in upgraded homes.

Figures 7 and 8 plot mean hourly outcomes and outdoor temperature impacts for homes with air conditioning. For these figures, both the upgraded and non-upgraded homes are restricted to include only homes with air conditioning. There is no evidence of increased thermal comfort in upgraded homes and, thus, no evidence of a rebound effect. Table 5 reports analogous regression estimates for homes with and without air conditioning. There is no evidence of an improvement in thermal comfort in either group. Point estimates are negative in all ten specifications, but small in magnitude and not statistically significant.

4 Discussion

Thus across a wide variety of graphical and regression analyses, there is no evidence that upgraded homes have resulted in reduced energy consumption or improved thermal comfort. Particularly relevant is the lack of any discernible improvement in thermal comfort, across all hours of the day, all seasons of the year, and all levels of outdoor temperature. In this section we explore potential mechanisms and perform a cost-benefit analysis.

4.1 Mechanisms

Part of the explanation for the lack of energy savings is that the percentage of homes with air conditioners (13% of homes in the study) is smaller than the percentage assumed by the engineering model (36% for low-income homes in Monterrey). The energy savings in the engineering model come from reduced air conditioner usage (Passive House Institute, 2012; DEEVI, 2014a,b). Specifically, the engineering model assumes that air conditioning is used whenever the interior temperature of the home exceeds $25.0°\mathrm{C}$, adjusted by the percentage of houses in the region and income segment that have air conditioners. Furthermore, in the small fraction of homes with air conditioners, the way households buy and use these devices may differ from the assumptions of the engineering model, including the size of the air conditioner, hours of operation, or setting of the thermostat.

Without air conditioning there is less scope for improvements in thermal comfort. Insulation and the other upgrades are valuable, in part, because they help keep cool air inside the house. When homes use passive cooling, however, there is less cool air to keep inside, so insulation is less valuable. Another part of the explanation for the lack of improvements in comfort is that most households have their windows open on hot days, presumably in order to increase air flow when the indoor temperature is hot. The purpose of insulation and many other energy-efficiency investments is to help maintain the interior temperature, even when the exterior temperature is very different. In cold climates, this means keeping a home warm in the winter and, in the context of Northeast Mexico, this primarily means keeping a home cool during hot summer days. These thermal benefits are largely nullified, however, if a household has a window or door open.

Table 6 shows that on a typical summer day, 96% of households had at least one window open. These data come from observations made by our surveyors in the field in late June 2017. We also asked households about their window behavior, and 86% of households reported generally having their windows open in the summer during the day. Moreover, 77% of households reported opening windows “every day” with an additional 10% reporting having their windows open “almost every day”. This pattern of open windows in the summer holds even for households with air conditioners. Among households with an air conditioner, 92% had at least one window open when we visited their homes in June 2017, and 60% report opening windows “every day” with an additional 8% reporting “almost every day”. Households with air conditioning report having windows open an average of

13.3 hours per day, compared to 16.7 hours per day for all households.[11]

4.2 Cost-Effectiveness

We conclude that the benefits from the investments studied here are unlikely to exceed the costs, which added \$400-\$500 USD to the cost of each home. We find no evidence of energy savings or thermal comfort benefits, so it is difficult to justify this added expense which, although not large compared to some types of energy-efficiency investments (see, e.g. Fowlie et al., forthcoming), raise the total cost of these homes by a non-negligible 2-4 percent.

It is worthwhile to ask, however, how large the benefits would have needed to be to justify this upfront cost. We focus on energy savings as they are the most easily monetized.[12] Households in this housing development consume an average of 1,500 kilowatt hours annually.[13] Mexican households pay an average of \$.05 (5 U.S. cents) per kilowatt hour, and thus average annual electricity expenditures are \$75.[14]

We find no evidence of energy savings. However, suppose these investments had reduced electricity use by 5%. This would yield energy savings of about \$4 annually. In addition, these savings would yield external benefits in the form of reduced emissions of carbon dioxide and local pollutants. With a social cost of carbon dioxide of \$34 per ton, these external costs are worth an additional \$.04 per kilowatt hour.[15] Thus a 5% reduction in electricity use (75 kilowatt hours annually) would yield external benefits worth \$3 annually

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[11] We do not observe whether households tend to leave the window open or not while concurrently running the air conditioner.

[12] This analysis takes into account only the benefits from energy savings, however public investments in thermal comfort, while difficult to monetize, may also be justified.

[13] As a point of comparison, the average U.S. household uses 10,800 kilowatt hours annually, according to the U.S. Energy Information Administration.

[14] For Mexican residential electricity rates see `cfe.gob.mx`. Mexican residential rates are increasing block rates that vary by climate zone with longer steps in hotter areas. In Monterrey the relevant rate is the 1C tariff, which in July 2017 was 0.70 pesos/kWh for the first 150 kilowatt hours per month, 0.82 pesos/kWh for the next 150 kilowatt hours, then 1.05 pesos/kWh for the next 150 kilowatt hours. Most households in this housing development are on the first or second tier, and thus paying the equivalent of \$.04 or \$.05/kWh, a rate which is quite low by U.S. standards. There is a minimum monthly consumption level of 25 kilowatt hours which is usually not binding and no monthly fixed charge.

[15] This \$0.04 per kilowatt hour includes damages from both carbon dioxide and local pollutants, and is calculated using the average emissions intensity of electricity generation in Mexico. See Davis et al. (2014) and Boomhower and Davis (2014) for details.

in addition to the private benefits of $4 annually.

Thus a 5% reduction in electricity use would yield $7 annually in benefits. The rate-of-return for a $400 investment that pays back $7 annually over twenty years is negative 8%. Air conditioning penetration is expected to increase over time, so energy savings could increase in future years. However, even for a 10% reduction in electricity use, the rate-of-return is still negative (-3%). Thus, overall, the benefits from these investments do not seem to be large enough to justify the upfront costs.

Morover, it is worth emphasizing that this calculation is conservative along two dimensions. First, we have assumed a 20-year time horizon, but that may be overly optimistic given recent evidence from the United States which suggests energy-efficiency investments tend to become considerably less effective over time (Kotchen, 2017). Second, we've used the bottom of the range for upfront costs. If one uses $500 rather than $400 for upfront cost, the implied rate-of-return is even lower.

5 Conclusion

An estimated one billion new homes will be built worldwide over the next decade (United Nations, 2016). With good reason, policymakers are enthusiastic about incorporating energy-efficiency into this construction. Energy-efficiency offers a potential "win-win", delivering both private savings and reduced externalities from energy use. Moreover, economies of scale, both in construction and verification, mean that energy-efficient technologies can be incorporated into new buildings at lower cost than retrofitting older units.

The energy-efficient investments considered in this paper are aimed right at this sweet spot. Insulation, window shading, and passive cooling systems were selected because they were thought to be well-suited for Northeast Mexico's hot climate. Indeed, these technologies were expected to generate large energy savings based on an engineering model. In sharp contrast to the engineering estimates, however, we find that the upgrades had no detectable impact on energy use or thermal comfort. Particularly striking is the lack of improvement in thermal comfort, in both summer and winter, and for both homes with and without air conditioning. Overall, the benefits from these investments are almost certainly smaller than the costs, which added $400-$500 USD per home.

A novel feature of our analysis was the use of data loggers to record high-frequency measures of temperature and humidity. With three billion people living in the tropics, understanding how to build homes to improve thermal comfort is of large independent interest, and we show how this technology can be used to test policy interventions. We show how comparisons across hours of the day, months of the year, and across climatological conditions can be used to perform a rigorous evaluation which is highly complementary to analyses of energy demand.

Our results add to a growing number of analyses that find *ex post* energy savings well below engineering estimates. See, e.g., Davis et al. (2014); Levinson (2016); Fowlie et al. (forthcoming). In our case, the differences stem from low penetration of air conditioning, one of the key sources of energy savings in the engineering estimates. In addition, we document that most households have windows open during the summer, making building insulation and the other energy-efficiency investments less effective than predicted by the model.

Thus our results point to the urgent need to fully incorporate socioeconomic conditions and human behavior into engineering models. Adjusting engineering estimates to account for air conditioner ownership is relatively easy and can and should be done. Modeling household window behavior is more challenging, and will require a better understanding and more detailed data on how households use their windows.

This learning has great social value. Finding out what doesn't work, and then pivoting quickly to test promising alternatives, is a proven path to success and these findings will motivate the search for alternative, more-effective technologies. If energy efficiency investments are going to play a significant role in improving thermal comfort, reducing energy consumption and lowering carbon dioxide emissions then we need to start optimizing these investments as soon as possible.

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Figure 1: Quasi-Random Assignment of Home Upgrades

Note: This is a map of the northwest corner of the housing development where the field experiment occurred. Although explicit randomization was not possible, the developer distributed the upgrades widely throughout the development, resulting in this quasi-random pattern. The buildings in this part of the development have two stories, with one owner on the first floor and a different owner on the second floor. In the map white indicates no upgrade. Blue is an upgrade on the first floor only. Red is an upgrade on the second floor only. Green is upgrades on both floors.

Figure 2: Mean Daily Outcomes

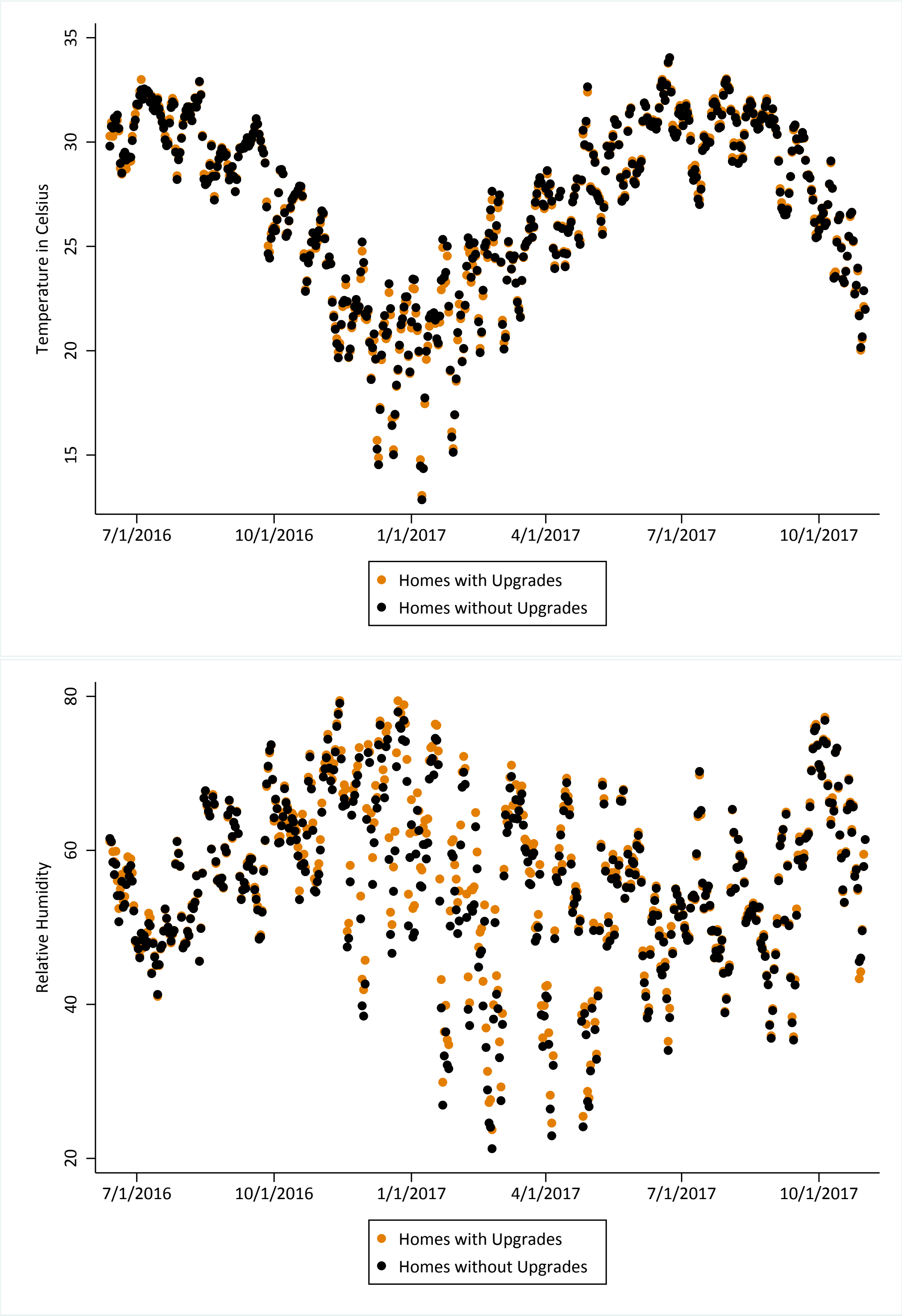
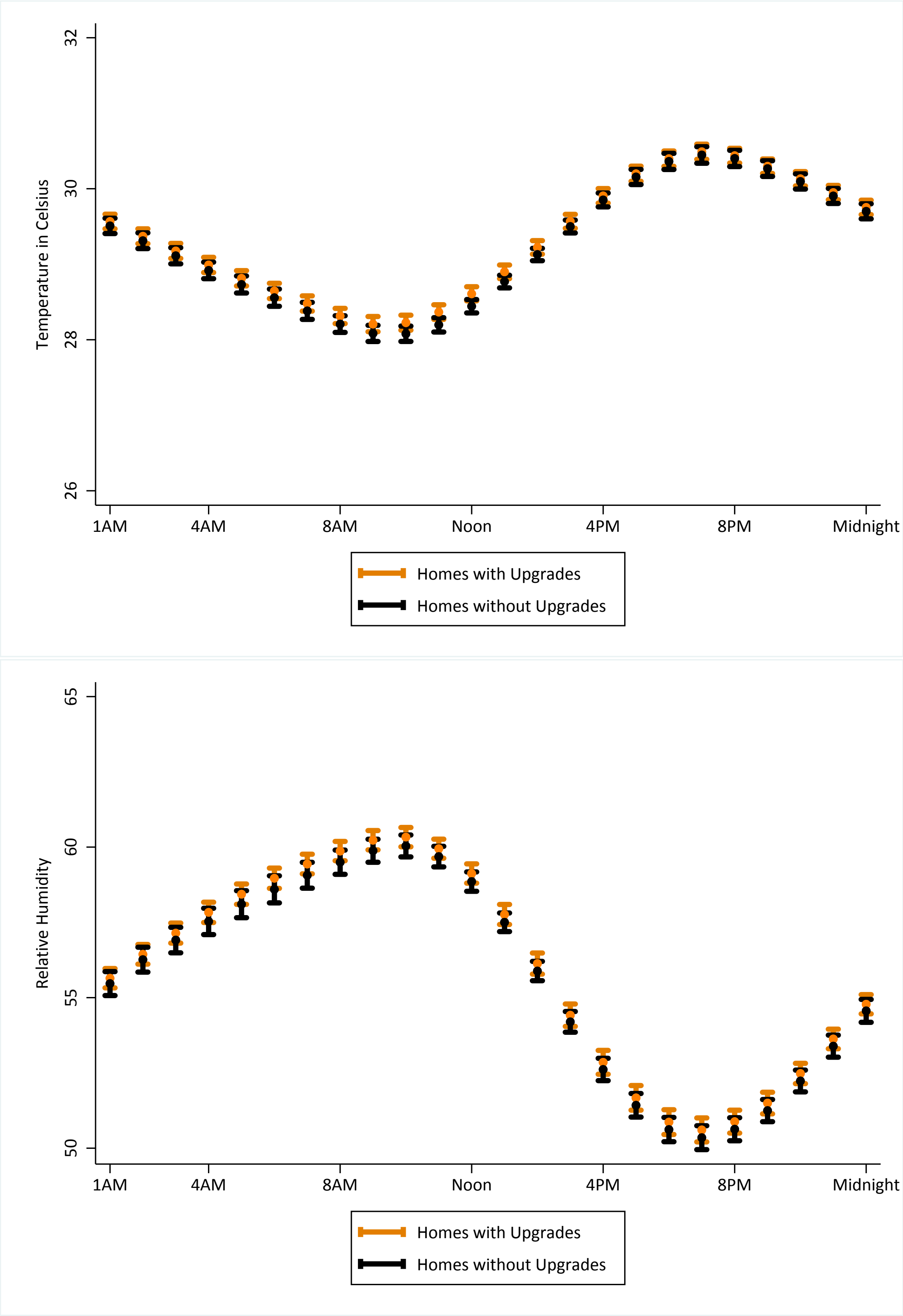


Figure 3: Mean Hourly Outcomes, May to October



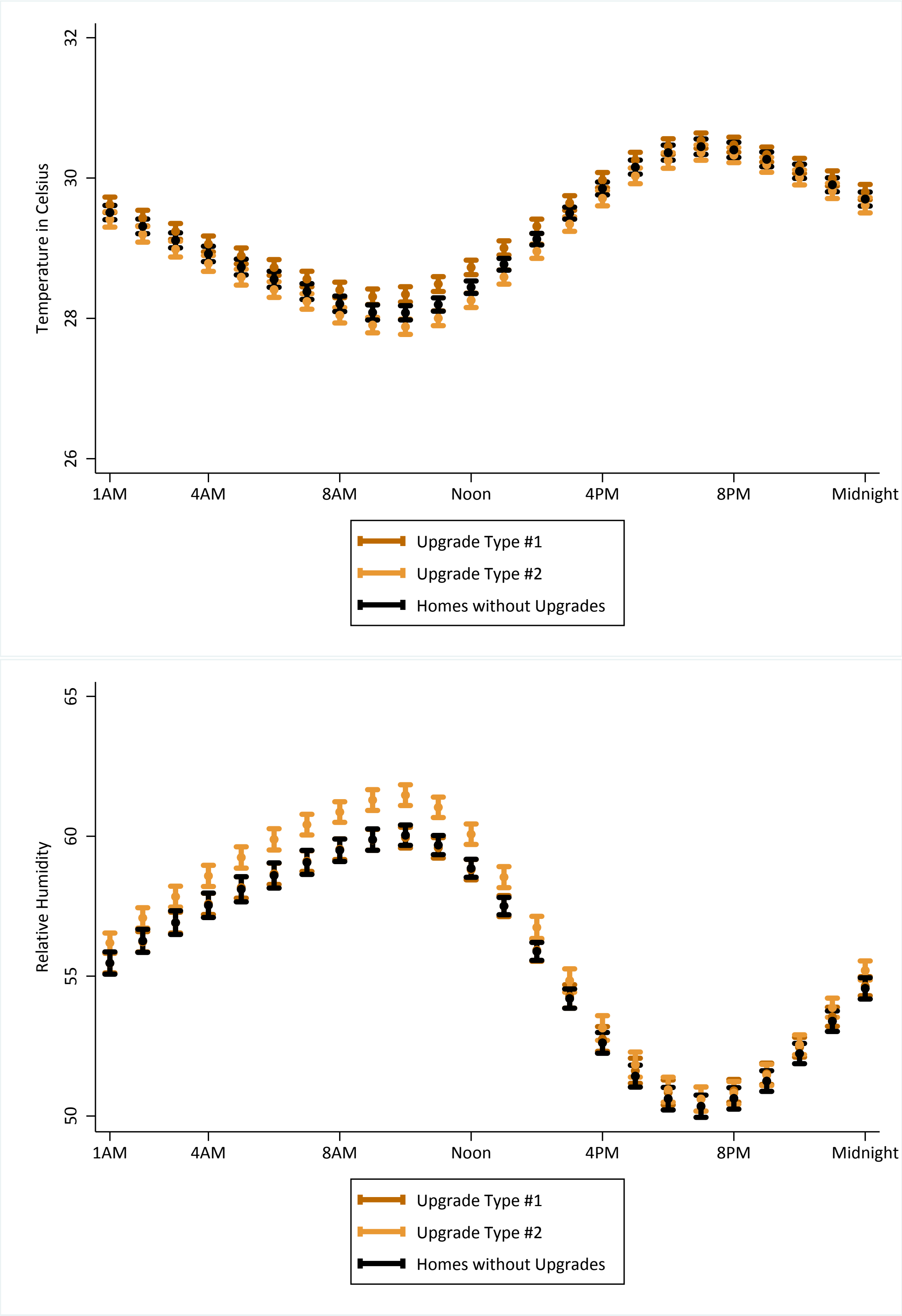


Figure 4: Mean Hourly Outcomes, May to October by Upgrade Type

Figure 5: Indoor vs. Outdoor Temperature

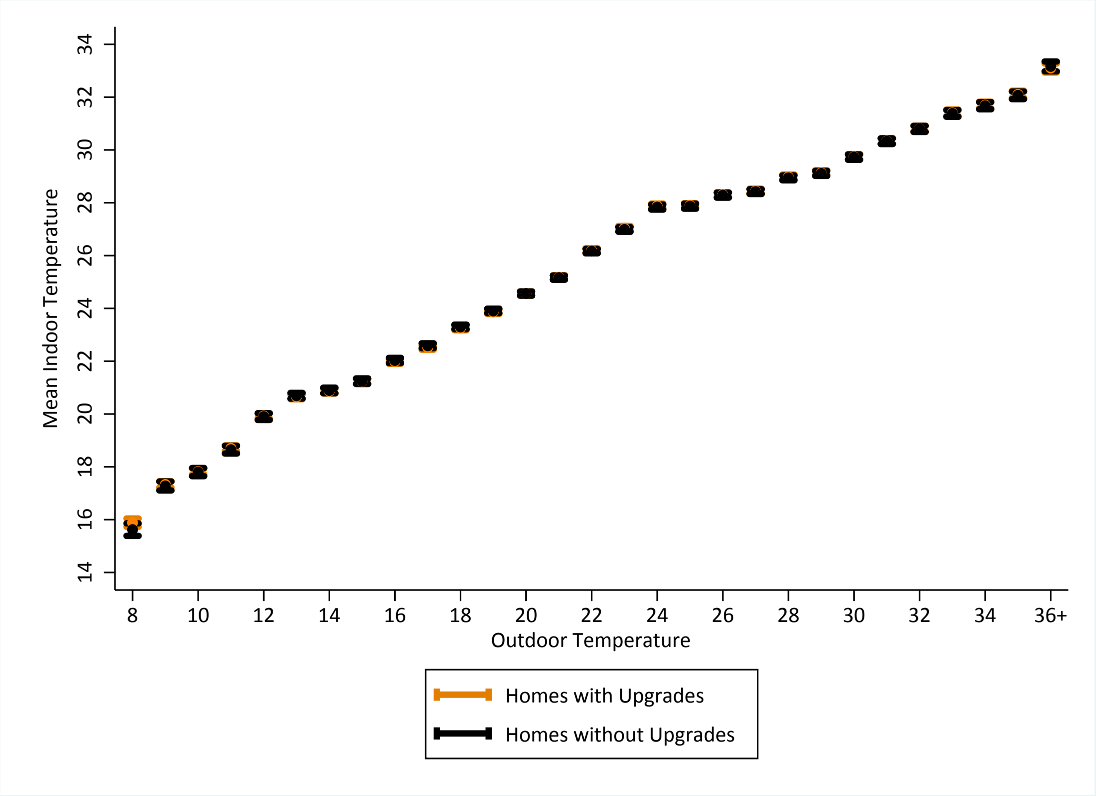


Figure 6: Indoor vs. Outdoor Temperature, By Upgrade Type

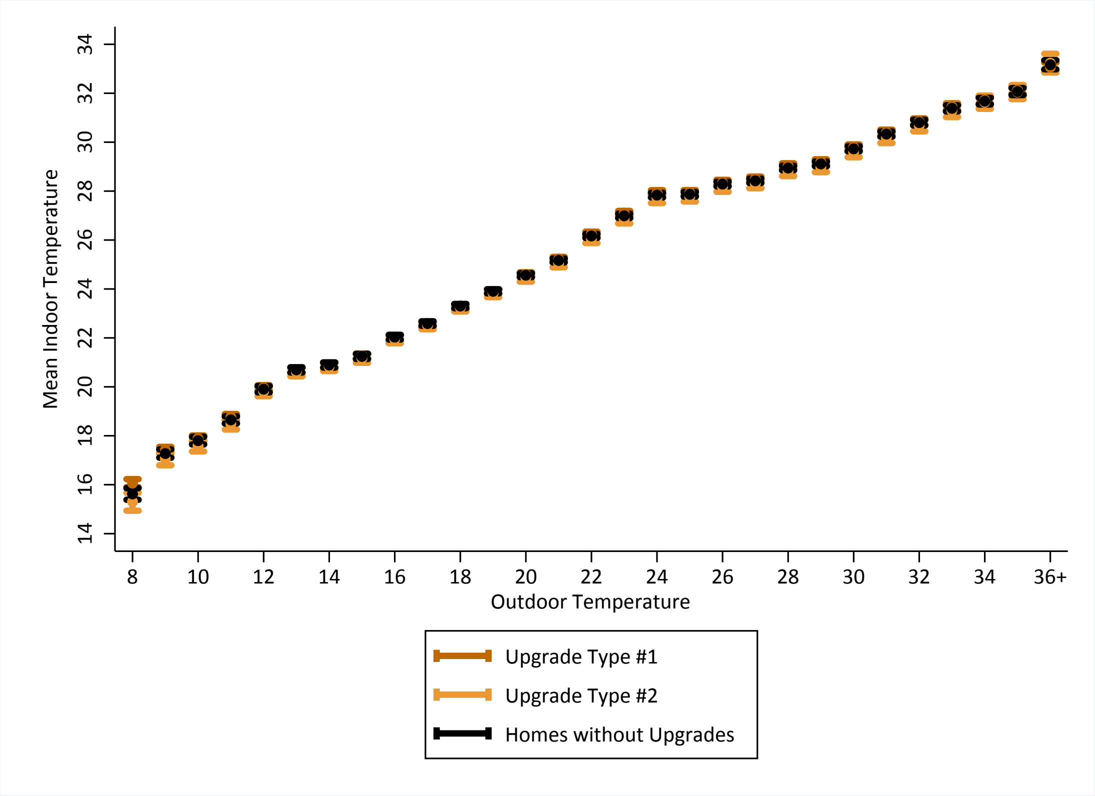


Figure 7: Mean Hourly Temperature, May to October, Homes with Air Conditioning

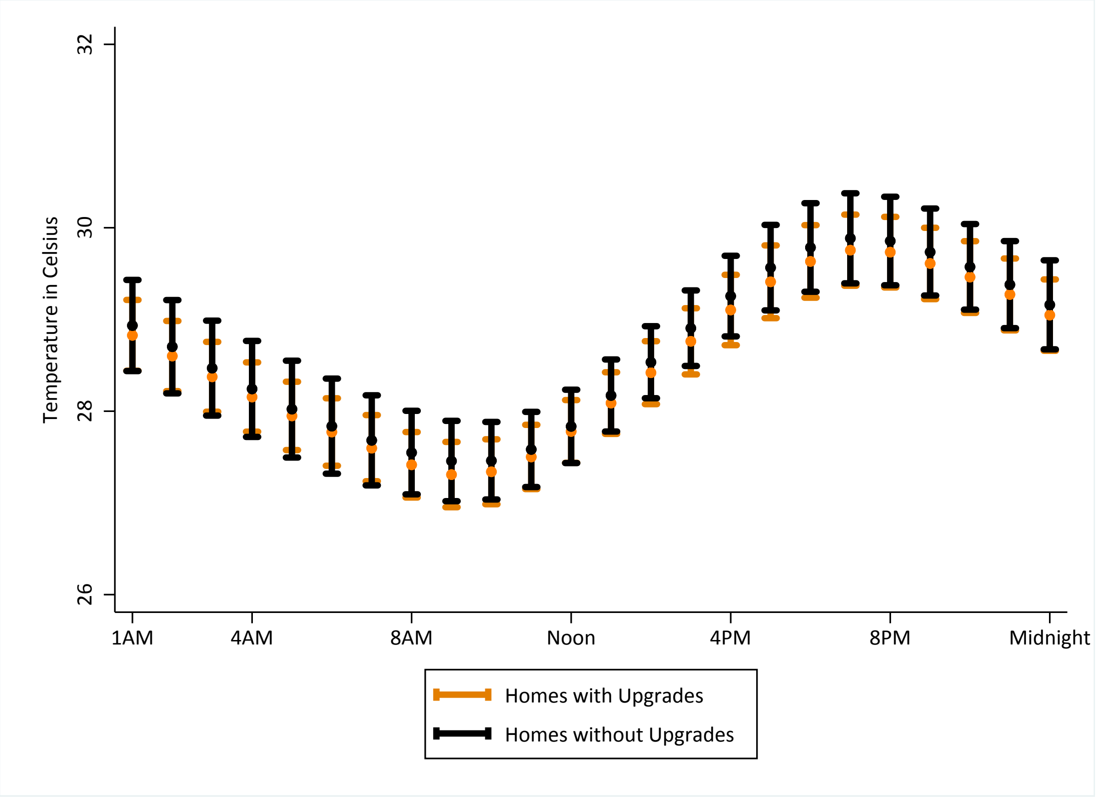


Figure 8: Indoor vs. Outdoor Temperature, Homes with Air Conditioning

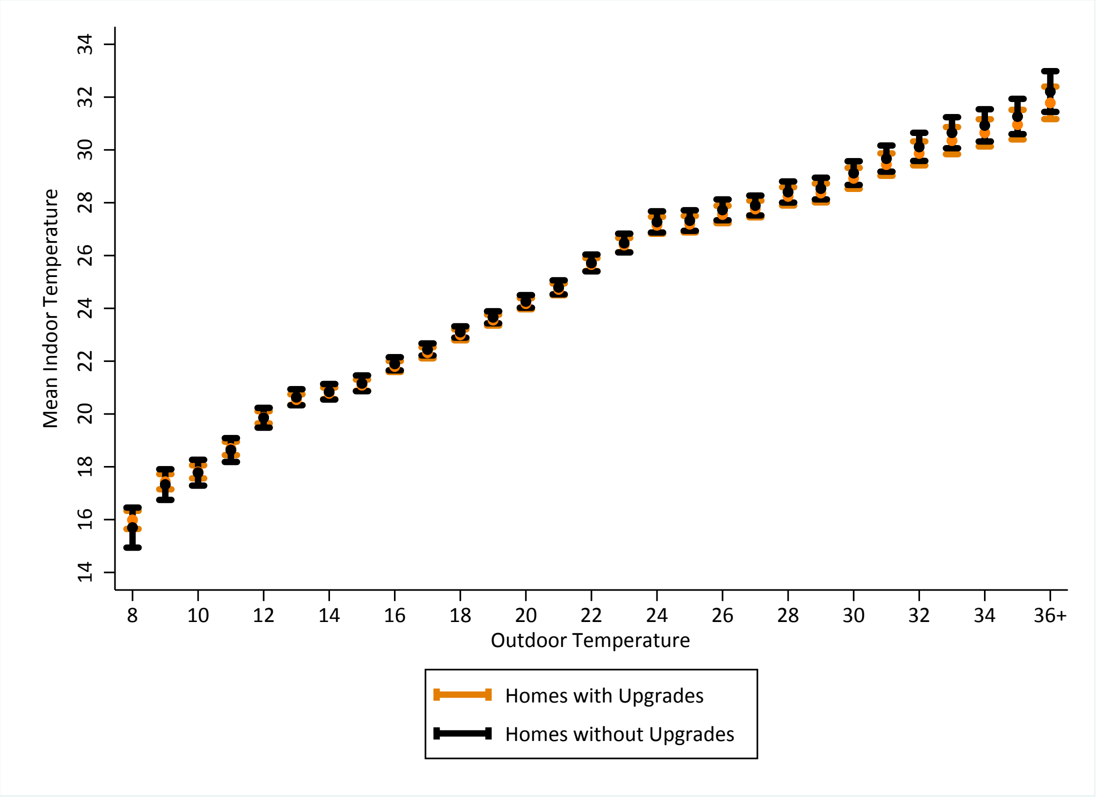


Table 1: Covariate Balance

	(1) Homes with Upgrades	(2) Homes without Upgrades	(3) *p*-value (1) vs (2)
Household Characteristics			
Number of Household Members	3.73	3.76	0.81
Number of Children Under 18	1.59	1.58	0.90
Proportion Owner Occupied	0.86	0.84	0.39
Monthly Household Income, (Pesos, 1000s)	10.1	10.4	0.85
Household Head Characteristics			
Age, Years	34.2	34.7	0.55
Education, Years	8.97	9.02	0.82
Proportion Married	0.88	0.84	0.24
Proportion Employed	0.93	0.93	0.94
Date Home was Sold			
Date Sold, Contract Signed	2013.85	2013.85	0.91
Date Sold, Keys Received	2013.96	2013.93	0.70
Appliance Saturation			
Television	0.96	0.93	0.18
Electric Fan	0.91	0.89	0.52
Refrigerator	0.92	0.86	0.03
Air Conditioner	0.13	0.12	0.88
Electric Heater	0.12	0.13	0.90

Note: This table compares mean characteristics of households living in homes with and without upgrades. The last column reports *p*-values from tests that the means in the two subsamples are equal. There are 229 homes with upgrades and 238 homes without upgrades.

Table 2: The Effect of Upgrades on Thermal Comfort and Electricity Consumption

	(1) Homes with Upgrades	(2) Homes without Upgrades	(3) *p*-value (1) vs (2)
Thermal Comfort			
Temperature (in Celsius)	27.0	26.9	0.24
Relative Humidity (in percent)	56.8	56.1	0.01
Proportion of Hours Above 25°C	0.70	0.69	0.35
Electricity Consumption (kWh)			
Cumulative as of October 2016	3332	3030	0.21
Cumulative as of November 2017	5018	4581	0.27
Difference October 2016 to November 2017	2193	1994	0.46
Self-Reported Thermal Comfort			
Home is Hot or Very Hot in Summer	0.75	0.79	0.32
Home is Cold or Very Cold in Winter	0.48	0.57	0.05
Home is Agreeable on Summer Mornings	0.86	0.82	0.28
Home is Agreeable on Summer Afternoons	0.45	0.41	0.41
Home is Agreeable on Summer Nights	0.59	0.60	0.88
Other Self-Reported Outcomes			
Television Usage (Hours per Day)	8.1	7.6	0.31
Electric Fan Usage (Hours per Day)	11.1	11.1	0.96
Air Conditioner Usage (Hours per Day)	10.7	9.5	0.50
Expenditure on Last Electricity Bill (Pesos)	280	246	0.29
Monthly Rent (Pesos)	1082	1070	0.58

Note: This table reports mean outcomes for homes with and without upgrades. The last column reports *p*-values from tests that the means in the two subsamples are equal. There are 229 homes with upgrades and 238 homes without upgrades. For self-reported appliance usage we report conditional means for homes with that appliance.

Table 3: The Effect of Upgrades on Mean Temperature, Regression Evidence

	(1)	(2)	(3)	(4)	(5)
			A. All Days		
1(Upgrade)	0.002	0.000	0.000	-0.003	-0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Observations	4,975,775	4,975,775	4,975,775	4,975,775	4,975,775
R-squared	0.00	0.94	0.94	0.94	0.94
			B. May to October		
1(Upgrade)	0.003	0.002	0.002	-0.003	-0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Observations	3,124,038	3,124,038	3,124,038	3,124,038	3,124,038
R-squared	0.00	0.85	0.85	0.85	0.85
			C. November to April		
1(Upgrade)	-0.002	-0.003	-0.003	-0.003	-0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	1,851,737	1,851,737	1,851,737	1,851,737	1,851,737
R-squared	0.00	0.91	0.91	0.91	0.91
Date by Hour-of-Sample FEs	no	yes	yes	yes	yes
Household Characteristics	no	no	yes	yes	yes
Housing Unit Type FEs	no	no	no	yes	yes
Date of Sale	no	no	no	no	yes

Note: This table reports coefficient estimates and standard errors from fifteen separate least squares regressions. All regressions include hourly data from 467 households. The dependent variable in all regressions is the natural log of interior temperature in degrees Celsius. Date by hour-of-sample fixed effects are indicator variables for each hour of each day throughout the entire sample period. Household characteristics are household size, number of children under 18, whether the home is owned, and, for the household head, age, number of years of education, marital status, and employment status. Housing unit type fixed effects are indicator variables for six different housing unit types (e.g. layout and number of bedrooms). Date of sale includes separate controls for when the contract was signed and when they keys were received. Standard errors are clustered by household. None of the estimates are statistically significant at the 5% level.

Table 4: The Effect of Upgrades on Electricity Consumption

	(1)	(2)	(3)	(4)
		A. All Homes		
1(Upgrade)	0.17	0.18	0.16	0.15
	(0.12)	(0.12)	(0.11)	(0.13)
Observations	388	388	388	388
R-squared	0.00	0.05	0.09	0.10
		B. Homes with Air Conditioning		
1(Upgrade)	0.12	-0.17	-0.28	-0.14
	(0.36)	(0.41)	(0.38)	(0.46)
Observations	44	44	44	44
R-squared	0.00	0.18	0.27	0.32
		C. Homes without Air Conditioning		
1(Upgrade)	0.17	0.20	0.18	0.19
	(0.13)	(0.13)	(0.12)	(0.14)
Observations	344	344	344	344
R-squared	0.01	0.06	0.09	0.11
Household Characteristics	no	yes	yes	yes
Date of Sale	no	no	yes	yes
Housing Unit Type FEs	no	no	no	yes

Note: This table reports coefficient estimates and standard errors from twelve separate least squares regressions. The dependent variable in all regressions is cumulative electricity use as of November 2017, in logs. Robust standard errors are reported. None of these estimates are statistically significance at the 5% level.

Table 5: The Effect of Upgrades on Temperature, By Air Conditioning Status

	(1)	(2)	(3)	(4)	(5)
			A. Homes with Air Conditioning		
1(Upgrade)	-0.003	-0.004	-0.004	-0.017	-0.002
	(0.010)	(0.010)	(0.011)	(0.011)	(0.011)
Observations	377,863	377,863	377,863	377,863	377,863
R-squared	0.00	0.72	0.73	0.74	0.75
			B. Homes without Air Conditioning		
1(Upgrade)	-0.001	-0.003	-0.002	-0.002	-0.002
	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)
Observations	1,617,959	1,617,959	1,617,959	1,617,959	1,617,959
R-squared	0.00	0.91	0.91	0.91	0.91
Date by Hour-of-Sample FEs	no	yes	yes	yes	yes
Household Characteristics	no	no	yes	yes	yes
Housing Unit Type FEs	no	no	no	yes	yes
Date of Sale	no	no	no	no	yes

Note: This table describes the effect of upgrades on interior temperature during summer months. The table reports coefficient estimates and standard errors from ten separate least squares regressions. The dependent variable in all regressions is the natural log of interior temperature in degrees Celsius. Standard errors are clustered by household. None of these estimates are statistically significance at the 5% level.

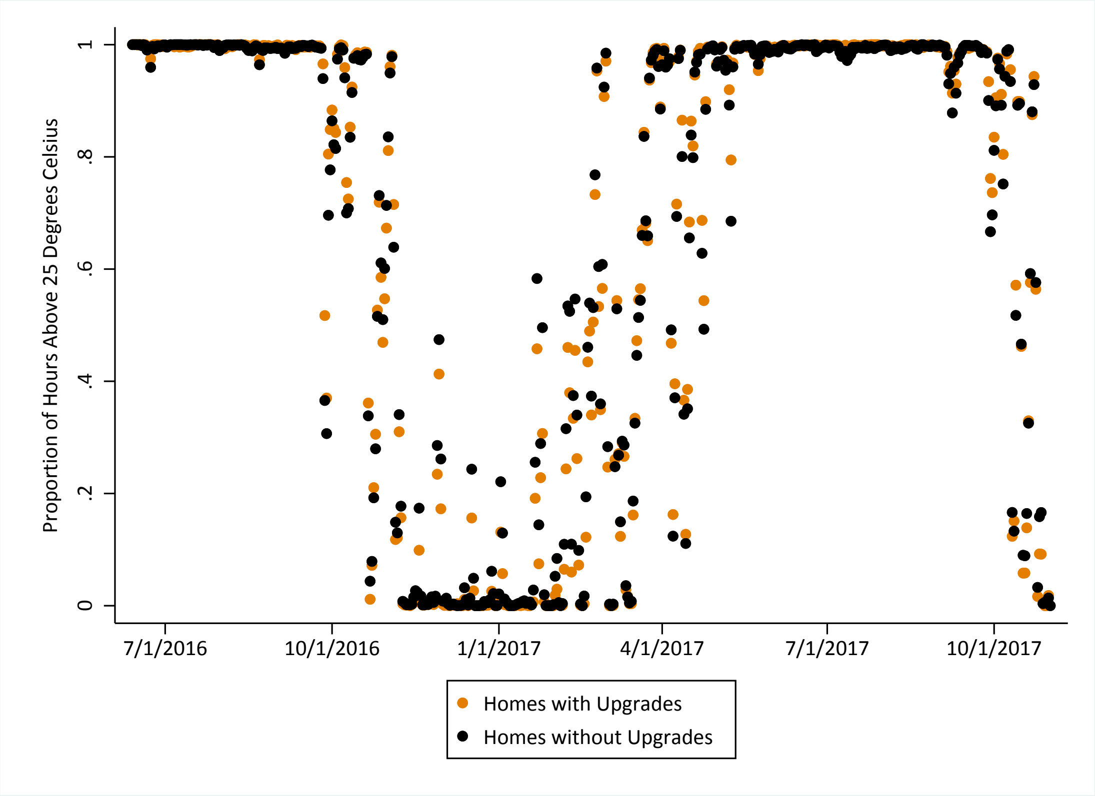
Table 6: Do Households Open Their Windows?

	All Households	Households with Air Conditioning
At Least One Open Window at Time of Interview	96%	92%
Household Reports Opening Windows During Summer	95%	81%
Windows Generally Open Summer Days	86%	81%
Windows Generally Open Summer Nights	80%	56%
How Many Days Per Week Do You Open Windows?		
Every Day	77%	60%
Almost Every Day	10%	8%
Sometimes	8%	13%
Almost Never	6%	19%
Hours Per Day With Window Open	16.7	13.3

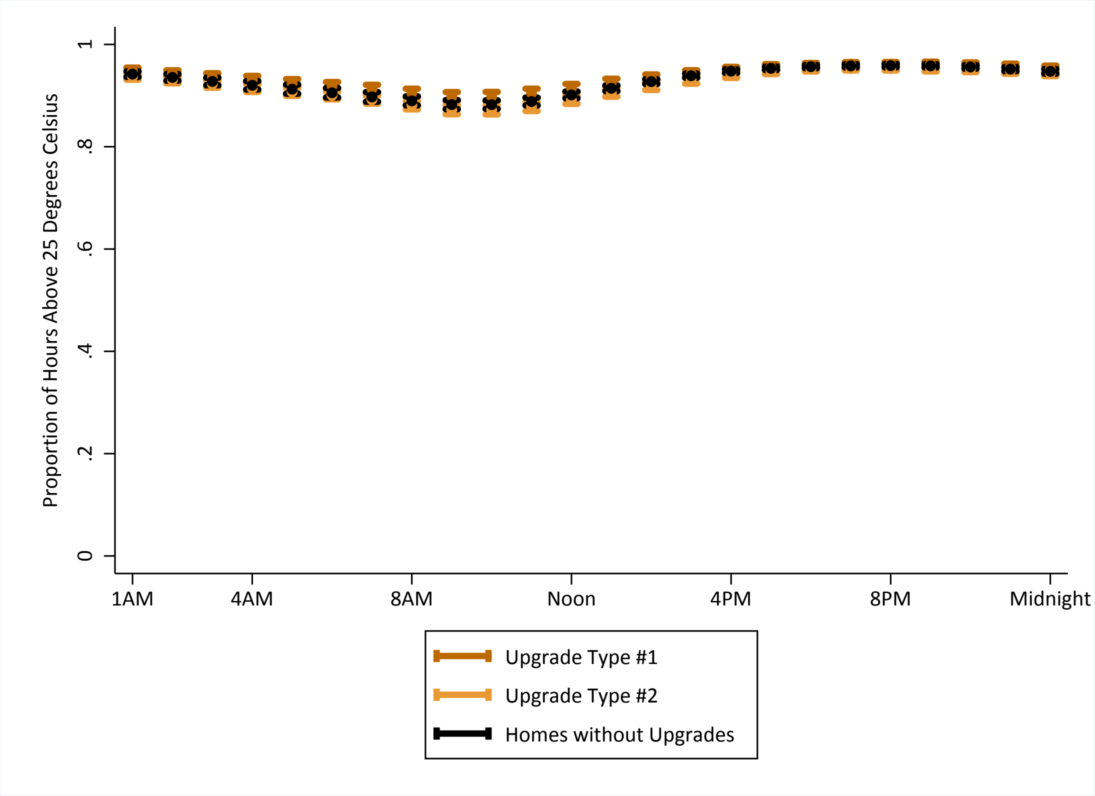
Note: This table reports summary information about window opening behavior for all households and households with air conditioning. This information comes from a survey administered June 2017. The first measure was recorded by the surveyor at the time of the survey. All other measures were reported by the household.

Appendix

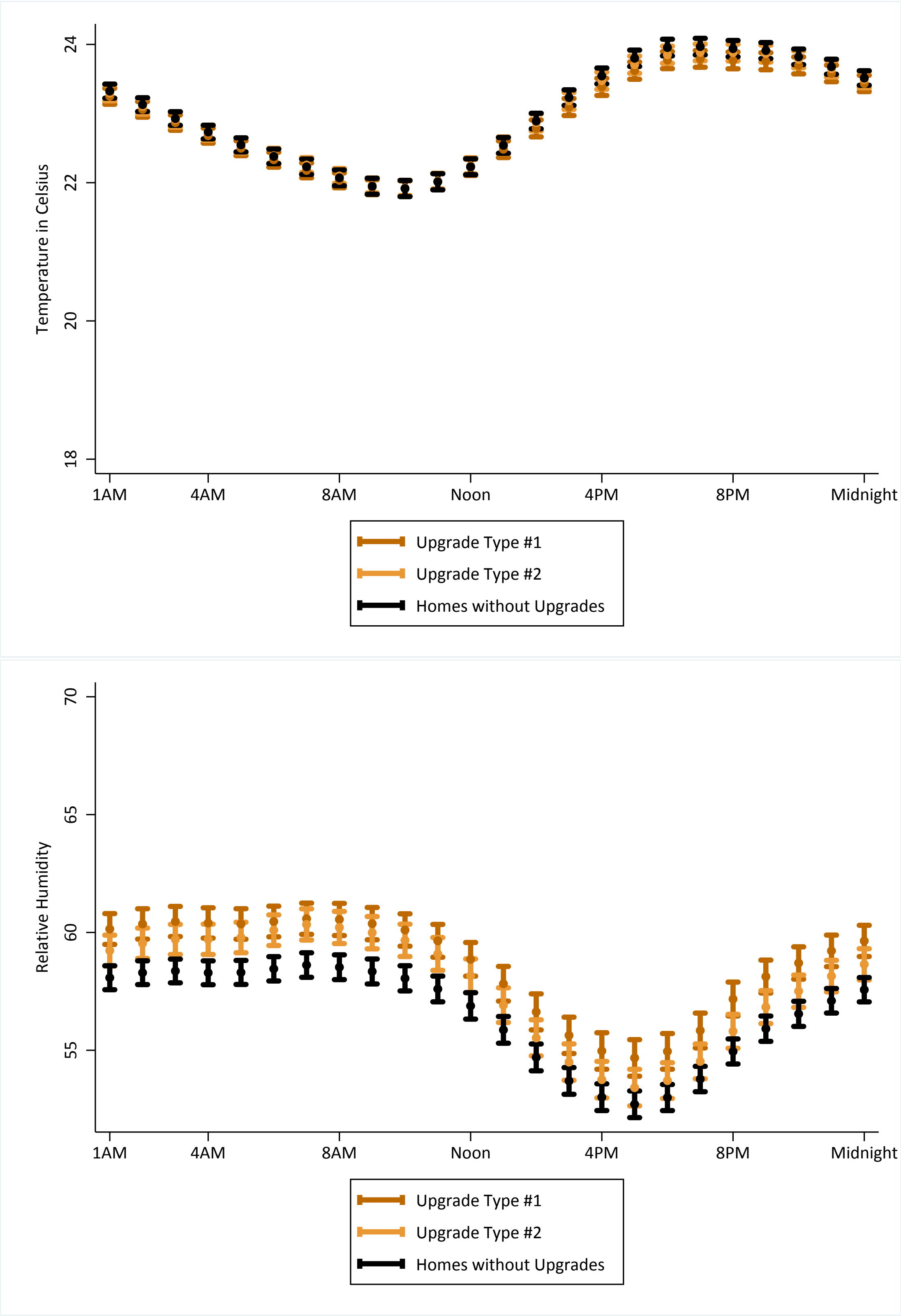
Appendix Figure 1: Mean Daily Outcomes, Additional Measure



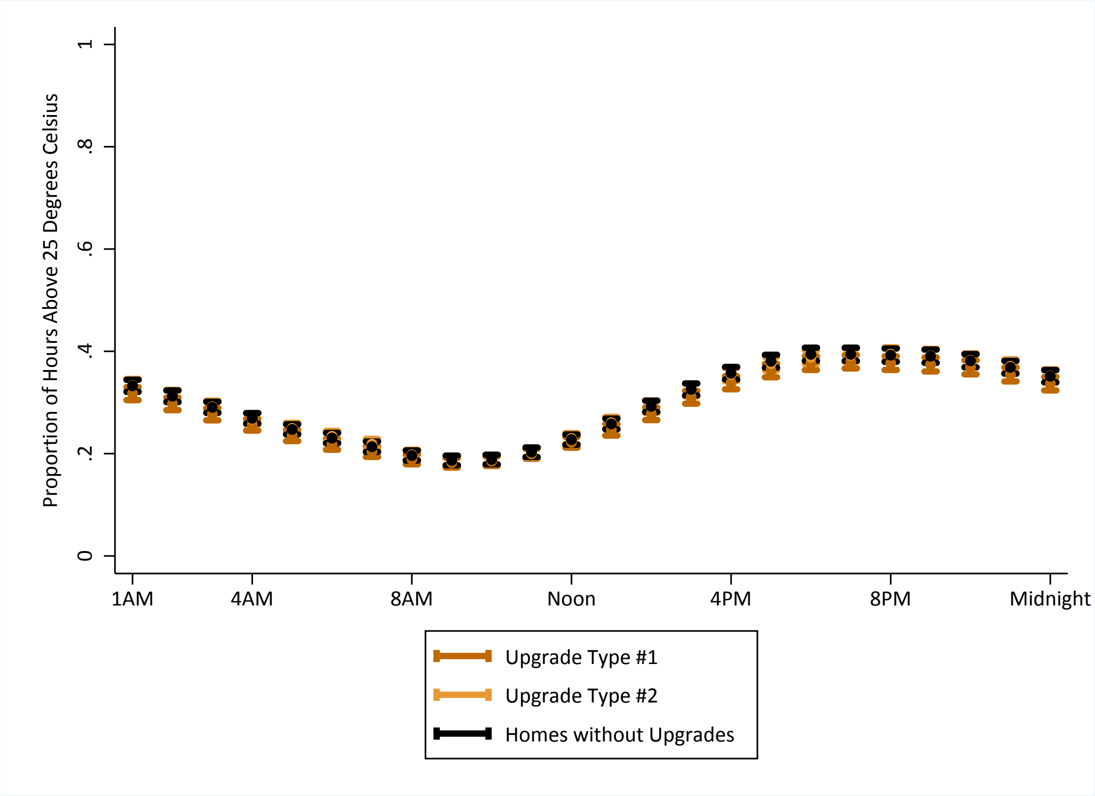
Appendix Figure 2: Mean Hourly Outcomes, May to October



Appendix Figure 3: Mean Hourly Outcomes, November to April



Appendix Figure 4: Mean Hourly Outcomes, November to April



Appendix Table 1: The Effect of Upgrades on Mean Temperature, By Upgrade Type

	(1)	(2)	(3)	(4)	(5)
			A. All Days		
1(Upgrade Type #1)	0.003	0.002	0.002	-0.001	0.000
	(0.003)	(0.002)	(0.002)	(0.002)	(0.003)
1(Upgrade Type #2)	0.001	-0.005	-0.006	-0.006	-0.005
	(0.004)	(0.003)	(0.003)	(0.004)	(0.004)
Observations	4,975,775	4,975,775	4,975,775	4,975,775	4,975,775
R-squared	0.00	0.94	0.94	0.94	0.94
			B. May to October		
1(Upgrade Type #1)	0.005*	0.005*	0.005*	-0.000	0.002
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
1(Upgrade Type #2)	-0.005	-0.006	-0.007	-0.007	-0.006
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Observations	3,124,038	3,124,038	3,124,038	3,124,038	3,124,038
R-squared	0.00	0.85	0.85	0.85	0.85
			C. November to April		
1(Upgrade Type #1)	-0.002	-0.003	-0.003	-0.002	-0.003
	(0.004)	(0.003)	(0.003)	(0.003)	(0.004)
1(Upgrade Type #2)	-0.001	-0.003	-0.003	-0.004	-0.002
	(0.005)	(0.004)	(0.004)	(0.004)	(0.004)
Observations	1,851,737	1,851,737	1,851,737	1,851,737	1,851,737
R-squared	0.00	0.91	0.91	0.91	0.91
Date by Hour-of-Sample FEs	no	yes	yes	yes	yes
Household Characteristics	no	no	yes	yes	yes
Housing Unit Type FEs	no	no	no	yes	yes
Date of Sale	no	no	no	no	yes

Note: This table reports coefficient estimates and standard errors from fifteen separate least squares regressions identical to the regressions in Table 3 except these regressions include separate indicator variable for the two types of upgrades. A single asterisk indicates statistical significance at the 5% level; none of these estimates are statistically significance at the 1% level.

Conceptual Model of the Rebound Effect

Suppose households derive utility from cooling z and all other consumption,

$$U = (z, y - xp_x) \tag{2}$$

where all other consumption is household income y minus what households spend on energy for cooling x, which costs p_x per unit. Cooling z is produced in the home according to the following production technology:

$$z = \begin{cases} \alpha_1 * x & \text{if home is upgraded} \\ \alpha_2 * x & \text{if home is not upgraded.} \end{cases} \tag{3}$$

That is, upgraded homes produce α_1 units of cooling per unit of energy input x, whereas non-upgraded homes produce α_2 units of cooling per unit of energy input. The presumption is that upgraded homes are more energy-efficient so $\alpha_1 > \alpha_2$.

Households maximize utility by equating the marginal rate of substitution with the price ratio, where the "price" of cooling depends on the price of energy p_x and on the energy efficiency of the home α. Households living in upgraded homes face a lower price of cooling, and thus will tend to consume more,

$$z^*(\alpha_1) > z^*(\alpha_2) \tag{4}$$

Here we have omitted income y and energy prices p_x as they are assumed to be the same in both upgraded and non-upgraded homes.

The engineering estimates of energy savings for our field experiment ignored the rebound effect, assuming that both upgraded and non-upgraded homes would be maintained at the same level of thermal comfort. Under this assumption, z is the same in both sets of homes, so the energy savings from the upgrades can be calculated,

$$\frac{z}{\alpha_2} - \frac{z}{\alpha_1}. \tag{5}$$

Energy savings thus depend on the relative magnitudes of α_1 and α_2. If, for example, α_1 is twice as large as α_2 then the new homes will use half as much energy. In contrast, what we observe in the data is the energy savings *net* of any behavioral response,

$$\frac{z^*(\alpha_2)}{\alpha_2} - \frac{z^*(\alpha_1)}{\alpha_1}. \tag{6}$$

If there is a behavioral response, then $z^*(\alpha_1) > z^*(\alpha_2)$, so observed energy savings will be smaller than the engineering calculation. This may mean, for example, that upgrades lead to smaller reductions in externalities than was predicted. However, this behavioral response is a positive phenomenon from the household's perspective. When z goes up this is the household consuming more cooling, which increases their utility. It would be naive to believe that households would not want to reoptimize their choice about how much cooling to consume, and incorrect to exclude these utility benefits in valuing the upgrades.

That said, our empirical results provide clear evidence against this type of behavioral response. In our field experiment we observe thermal comfort, so we are able to show that $z^*(\alpha_1)$ and $z^*(\alpha_2)$ are essentially identical. Thus while in theory the energy efficiency upgrades might have led to increased consumption of thermal comfort, in practice, we find no empirical evidence. Consequently, when we find that energy consumption x is not significantly different in upgraded and non-upgraded homes, this is very unlikely to be driven by the rebound effect.