# Adaptation to Climate Change and US Residential Energy Use – Does Adaptation Reduce Greenhouse Gas Emissions?

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## Abstract

Previous literature has found that positive temperature shocks increase US residential electricity consumption because air-conditioning is used to adapt to excessive heat. This suggests that climate change adaptation could increase electricity demand. This research goes beyond previous analyses by evaluating which drivers would explain the relationship between climate change and energy use. We look at the alterations and improvements to housing associated with climate shocks – including but not limited to air-conditioning – and correlate these changes with both gas and electricity consumptions. Then resorting to a long-term simulation, we find that climate change is likely to increase residential electricity consumption. However, this surge in electricity consumption could be more than compensated by a parallel decrease in gas consumption. All in all, total energy consumption (adding gas and electricity consumptions) could decrease due to adaptation to climate change, but not necessarily greenhouse gas emissions. Electricity generation in the US is carbon-intensive so that the predicted shift from gas to electricity could sustain greenhouse gas emissions in spite of a total reduction in energy demand resulting from climate change. This puts pressure on decarbonising electricity generation.

**Keywords**: Climate change adaptation, home improvements, residential energy consumption.

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# 1. Introduction

Climate has already changed and most experts believe the global average temperature will continue to increase: the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2013) estimates that global mean surface temperature could be up to 4.8°C higher in 2081-2100 relative to 1896-2005 if greenhouse gas emissions (GHG) continue unabated. Climate change will affect human activities through many channels, including agricultural production, labour productivity, industrial output, health, energy or political stability.[1] At the aggregate level, Dell, Jones and Olken (2009, 2012) estimate that national income falls by 8.5% per degree Celsius in a world cross-section and that a 1 degree Celsius rise in temperature reduces per-capita income by 1.4% in poor countries. These authors are also able to compare the long-run consequence of temperatures on economic output with the short-run negative impact of temperature shocks. It appears that short run impacts are much sharper than long run impacts, suggesting that the negative impact of temperatures on output is compensated for by adaptation measures in the long run. More precisely, these authors find that nearly half of the negative impacts of high temperatures on income are cushioned by adaptation measures in the long run. For future global warming, this suggests that adaptation may reduce the impacts of ongoing climate change on human activities to a large extent. However, adaptation will be costly: the World Bank (2010) has estimated that the global cost of necessary adaptations to climate change could be between $ 70 billion and $ 100 billion between 2010 and 2050 for public authorities.

Whereas the climate agenda includes both the need for climate mitigation and climate adaptation, these two topics are usually considered as independent in political practice: mitigation policies focus on the decarbonisation of industry, agriculture and services, whereas adaptation measures consists in planning and carrying out necessary investments (e.g. dykes). However, climate adaptation will have an impact on GHG emissions, hence on climate mitigation. The fact is that climate adaptation will require additional investments of different types: dikes to prevent from sea level rise, changes in crop-management practices in agriculture, installation of insulation of housing to protect from heat, etc. These different types of investments have different impacts on emissions. For instance, insulation reduces energy use, and thus carbon emissions, but changes in agricultural practices have an ambiguous impact.

[1] Dell, Jones and Olken (2013) make a thorough review on the economy-climate relationship.

Consequently, whether climate adaptation leads to more or less greenhouse gas emissions depends on the mix of investments that will be undertaken. As adaptation strategies differ across sectors, climate change adaptation could reduce GHG emissions in one sector, but increase them in another.

In this paper, we focus on the US residential sector. Using dwelling-level panel data from 1985 to 2011 extracted from the American Housing Survey, we analyse the impact of temperature shocks on housing investment behaviour and its impact on residential energy consumption and carbon emissions. Our findings suggest that climate shocks increase residential electricity use, but reduce gas consumption. Globally, total energy consumption would decreases but, given the mix of energy sources currently used to generate power in the US, the predicted shift from gas to electricity would raise carbon emissions. This reinforces the need for decarbonising power generation.

These results are in line with those obtained by Deschênes and Greenstone (2011) and Auffhammer and Aroonruengsawat (2011) who have recently provided evidence that climate change would increase demand in residential electricity use by showing a positive relationship between residential electricity consumption and temperature shocks in the US.

We go however deeper into the analysis in several respects. First, we deal with both electricity and gas consumption. This extension is crucial because gas is widely used for space and water heating. In particular, one would expect that higher temperatures would reduce gas use.

A second contribution is that we explicitly consider the mechanisms that make the link between climate change and residential energy consumption. More precisely, we proceed in two steps. First we estimate how temperature shocks modify investments in dwellings. We then assess the impact of the investments made on energy consumption and GHG emissions. Deschênes and Greenstone (2011) and Auffhammer and Aroonruengsawat (2011) do not open the "black box". They directly study the relationship between the climate variables and electricity consumption.

We use micro-data from 14 biannual and national waves of the American Housing Survey (AHS, 1985-2011), which includes detailed information on the improvements performed in a large panel of US homes. The data from the AHS has been matched with climate data from the National Oceanographic Atmospheric Association Data Center gathered for 159 localities in the US. We use three climate variables: the count of heating degree days, of cooling degree days and the number of days with precipitations higher than 0.5 inches to control for precipitations and humidity. Energy price data at State level are collected from the US Energy Information Administration. The time period covered by our data is extensive, which allows us to capture the impact of changes in climate on the decisions of specific households over time.

We use the results of our econometric models of home improvement and energy consumption to perform a long run simulation of residential gas and electricity consumption. Starting on year 2000, the simulation compares a baseline scenario with no climate change to a climate change scenario corresponding to a progressive increase in inland temperatures by 3°C in the 21st century. This increase in inland temperatures is equivalent to the RCP6.0 scenario of IPCC (2013), corresponding to a medium-high level of GHG emissions rejected into the atmosphere.

Our econometric and simulation results confirm that households will adapt to climate change by purchasing more air-conditioners. This effect comes in addition to a more intensive use of already installed air conditioners and drives electricity consumption upwards (+7.7% by 2100 in the climate change scenario as compared with the baseline scenario in our simulations). However, the increase in electricity consumption could be compensated for by a reduction in gas demand (-13.4% by 2100 in our simulations), which is due both to a reduced use of gas heaters in winter and to a shift from gas to electric heaters in warmer regions. All in all, we find that energy demand decreases by 6.1% by 2100 as a result of climate change.

The impact of the cut in energy consumption on emissions depends on the energy mix of power generation. Currently, electricity produces more GHG emissions than gas in the US. Therefore, the shift from gas demand towards electricity, as predicted by our model, would lead to a slight increase (+0.7% by 2100) of GHG emissions imputable to residential energy demand if today's facilities were used to produce electricity in 2100. Our results therefore gives a new reason for US policy-makers to insist on the decarbonisation of electricity generation, considering that household level adaptation is likely to favour electricity, both for space heating and air-conditioning.

The remaining of this paper is structured as follows. In the following section, we briefly present the relevant academic literature. In section 3, we develop a home investment model to represent households' home improvement decisions, both the likelihood that investments occur and the intensity of the investments, conditioned on investments taking place. The results of the home investment model feeds into a statistical analysis of the sensitivity of energy demand to climate change in the short and the long runs. Section 4 presents the data and section 5 the estimation results. Finally in section 6, we run a long run simulation to assess the implications of our econometric results.

## 2. Previous literature

Most studies investigating the impacts of adaptation to climate change have focused on agriculture. This sector is particularly relevant since it is very dependent on climate, but also because farmers can explore several adaptation strategies. In particular, Mendelsohn, Nordhaus and Shaw (1994) explain that not taking into account this variety of adaptation measures available to farmers will lead to overestimate the impact of climate change on agriculture.

Likewise, adaptation could reduce the negative impacts associated with climate change in other sectors. For US households, current knowledge indicates that climate change could be a liability affecting living conditions. In particular, climate change is expected to have negative impacts on human health. Deschênes and Greenstone (2011) assess the effect of changes in heating degree days (HDD), cooling degree days (CDD) and extreme temperature on mortality in the US. They find that climate change could lead to a 3% increase in the age-adjusted mortality rate by the end of the 21$^{st}$ century. A relationship between mortality and heat is also corroborated by Barreca *et al.* (2013): according to these authors, days with temperatures exceeding 90°F were responsible for about 600 premature fatalities annually in the US over the 1960-2004 period.

To adapt to heat, US households might intensively resort to air conditioning. Barreca et al. (2013) find that the progressive adoption of air conditioning explains 90% of the entire decline in the temperature-mortality relationship throughout the 20$^{th}$ century. Mansur, Mendelsohn and Morrison (2008) analyse US energy demand in a setting in which fuel choice decisions are endogenous. Using a multinomial choice framework, they show that households prefer electricity when temperatures are high, in particular because electric heating appliances have lower installation costs and fit more in regions where space heating is not intensive. Additionally, Sailor and Pavlova (2003) predict that market saturation of air-conditioning could increase drastically with climate change and be more important as a driver for future energy load than the impact of temperature shocks. Focusing on 38 US cities, they forecast that a 20% increase in cooling degree days would increase residential electricity consumption by 1-9% depending on the city, mainly driven by a 20-60% increase in electricity consumption from air-conditioning.

Climate change may therefore have a strong impact on residential energy use. Using information on consumers' short run responses to higher temperatures on energy use, Deschênes and Greenstone (2011) estimate that, by the end of this century, residential energy consumption could rise by 11% in the US as a result of climate change. Similarly, Auffhammer and Aroonruengsawat (2011) examine household-level electricity consumption data in California from 2003-2006. Using a very large sample of monthly and geolocalized data, they run a model of short-run response of energy demand to shocks in temperature. In a second stage, they use their model results to run simulations of residential electricity demand under the A2 (high emissions) and B1 (low emissions) climate scenarios of the Intergovernmental Panel on Climate Change (IPCC, 2000).[2] Assuming no change in Californian population and electricity prices, these authors find that, under the A2 scenario, Californian residential electricity consumption will rise by 48% in 2080-2099 compared to 1980-2000 levels. In the B1 scenario, the rise in residential electricity consumption is 18%. If climate change is not properly mitigated, the results of Auffhammer and Aroonruengsawat (2011) show that electricity consumption could increase substantially in California. Likewise, Amato *et al.* (2005) analyse the impact of temperature shocks on residential electricity consumption, in Massachusetts. They find that residential electricity consumption increases in a series of climate change scenarios as compared with a no-climate change scenario. According to Amato *et al.* (2005), the increases in electricity consumption during summer months should outweigh the decreases in the winter months. However, they forecast that heating oil and gas consumption should decrease in Massachusetts as a result of climate change.

Household response to higher temperatures in terms of higher electricity consumption is not specific to the US. Eskeland and Mideksa (2010) assess the evolution of residential electricity consumption in about 30 countries over ten years. They find that a one unit increase in CDD (i.e. a warmer weather) amplifies residential electricity consumption by about 4 times as much as a one unit increase in HDD (i.e. a cooler weather). The net effect of climate change on global energy consumption is however very uncertain, as changes in consumption patterns depend both on local climatic conditions and on the diffusion of adaptations, such as the use of air conditioning. Morna and van Vuuren (2009) have tried to model global residential sector energy demand for heating and air conditioning in the context of climate change. Their results point to a sharp decrease in energy consumption from space heating resulting from climate change (minus 30% by 2100) compensated for by a sharp increase in energy consumption from air conditioning (plus 70% by 2100). The net forecasted effect of climate change would be a small decrease in energy use. However, because the carbon emission factor of the electricity used by air-conditioners could be higher than the one of the secondary fuels used for heating, this might lead to a worldwide increase in GHG emissions.

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[2] The B1 scenario is a "sustainability" scenario with relatively low GHG emissions. IPCC (2001) predicts that the B1 scenario should lead to a 1.9°C temperature increase between 2000 and 2100. On the other hand, under the A2 scenario, GHG emissions are substantially larger and IPCC (2001) predicts a 3.6°C temperature change over the 21st century.

To our knowledge, Auffhammer and Aroonruengsawat (2011) are the only ones to resort to household level panel data to estimate residential energy consumption. They provide clear evidence that electricity demand will rise in California as a result of climate change. However, these authors focus on electricity consumption between 2003 and 2006. Their time span is relatively short and their results specific to electricity demand and the Californian climate. Furthermore, these authors use monthly shifts in temperatures to assess climate change impacts. This is a limitation as the use of variables covering longer time periods is preferable to study climate change, as explained by Deschênes and Greenstone (2011).

Furthermore, studies looking at the relationship between changes in temperatures and energy consumptions (e.g. Auffhammer and Aroonruengsawat, 2011; Deschênes and Greenstone, 2011; Atamo et al., 2005) captures correlations between climate variables and energy use but do not analyse the reasons that could explain such correlations. On the other hand, Mansur, Mendelsohn and Morrison (2008) and Sailor and Pavlova (2003) argue that long run adaptation measures could play an important role. The limitations of these two studies are that they focus on one specific aspect of adaptation (fuel choice for Mansur, Mendelsohn and Morrison, 2008; air-conditioning for Sailor and Pavlova, 2003) and use US-wide cross-sectional data. From a methodological perspective, they cannot properly account for unobservables.

To account for the largest panel of potential adaptations and explain the drivers behind the relationship between climate and energy use, we look at the likely adaptation of the housing stock to climate change. It should be noted that outside economics, looking at the nature of the building stock and its fitness to climate is not particularly original: there are many historical examples of human settlements that adapted to their climate. In fact, a large share of past adaptations to climate can be found in vernacular architecture, i.e. the architecture that grew out of "the needs of the inhabitants of a place and the constraints of site and climate" (Oktay, 2002). For instance, dwellings are usually oriented to the south and placed below a hill to protect from winds in cold countries.

Within economics, the determinants of home improvements have been studied by a series of empirical papers at least since the 1970s. Apart from a few regional-level examples (e.g. Mendelsohn, 1977; Mayer, 1981; Melchert and Naroff, 1987; or Helms, 2003), the empirical analysis of US home renovation has principally relied on the data from the American Housing Survey (AHS), examined at different time periods and for different geographical areas (Shear, 1983; Reschovsky, 1992; Bogdon, 1996; Montgomery, 1996; Baker and Kaul, 2002; Gyourko and Saiz, 2004; Plaut and Plaut, 2010). However, previous empirical research on home improvements has focused on the socioeconomic characteristics of households and homes that undergo renovation. To the best of our knowledge, no research on US home improvements has ever looked at the impact of climate change on household decisions.

## 3. Model

### *Home improvements*

Scholars using the AHS data on home improvements have principally relied on probit and tobit models in the past. The probit and tobit models are run on a cross-section of residential units and the data from the previous years is used to construct independent variables. In fact, home improvements can be interpreted as a left-censored variable because investments are only observed with a positive value. Actually, Helms (2003) provides a very simple model to link household utility and household capital investment, which finally takes the form of a latent variable that can be estimated with a tobit model.

Even though these types of econometric models appear attractive at first sight, they proved to be insufficient to understand renovation efforts. For example, the predictive power of the models of Helms (2003) is very low. Additionally, cross-sectional probit and tobit models may be biased if the independent variables are correlated with the unobservables. Furthermore, tobit models tend to overlook the “lumpy” nature of the investments in home improvements: long periods with no or low investments are usually preceded by more active investment periods.

Various reasons can make home improvements lumpy. In particular, it is unlikely that households will perform similar investments twice over a short time period, because the utility of making an investment depends on the state of decay of the part of the home that is renovated or improved. Additionally, households may prefer to make all the necessary improvements at one point in time, and not to delay them over a longer time period because of the hidden fixed costs associated with home improvements. For example, home improvements may limit the possibility to live in the house while it is being renovated.

This is why the econometric model below tries to consider the lumpy nature of investments in home improvements by referring to a framework developed by the investment literature. Furthermore we use the longest panel available with the AHS and cover the entire US, from 1985 to 2011 and exploit the panel nature of the data by using fixed effects. The long time span also allows us to look both at the short run and the long run impacts of climate change on home improvements.

## An empirical application of the (S,s) framework

Our econometric specification is a reduced-form model inspired by the literature on private investments. We consider that the decision of improving a home is similar to firms' decisions to invest in capital to increase production capacity. By analogy to firms' investments in additional production capacity, the optimal level of output corresponds to an optimal level of housing services and the level of investment in extra capital to the level of investment in home: whereas firms are interested in the level of capital that will be necessary to reach a target level of final output, households are interested in a given amount of investment in housing that will provide them with the desired level of housing services. We are first assuming that a home is a uniform good, which is an assumption that we relax later on.

In the investment literature, it is well known that capital investments by industries are lumpy (e.g. Doms and Dunne, 1998). Dixit and Pyndick (1994) provide the theoretical foundations: in a context in which the optimal level of firm output is stochastic and the decision to invest is costly, firms are better off investing once and for all in new production capacities when the gap between the current and the optimal level of output is sufficiently high to motivate new investments. Likewise, when the level of optimal output reaches a bottom threshold, much lower than the current level of output, disinvestment is the optimal decision. Within an upper bound and a lower bound, the difference between the current and the optimal level of output is too small to motivate an investment or a disinvestment. In this case, the cost of adjustment is higher than the expected utility derived from it.

A family of investment models with adjustment costs is constituted by the (S, s) models, the two "s" corresponding to the upper and the lower bounds of inaction. This "range for inaction" makes any analysis of investment decisions at the micro-level relatively complex: the investment decisions are dependent on past investments and appear in a lumpy fashion, which makes any single investment difficult to predict. This complexity is well represented by the (S, s) setting of Caballero and Engel (1999). Their model, developed for firm decisions, assumes that the profitability of investing evolves stochastically and entails random adjustment costs proportional to the amounts that have already been invested. Making the analogy with home improvements is straightforward: shocks on the utility for specific housing services and house depreciation can lead to disequilibria between the level of housing services provided by a house and the desired level of homeowners. On the other hand, home improvements usually affect the possibility of using one's house at the same time. Consequently, changes to the current level of stock are likely to entail adjustment costs proportional to the total amounts already invested in housing, but these adjustment costs (if investments are undertaken) may change from one year to the other for reasons unobserved by the econometrician.

Based on Caballero and Engel (1999), we denote the utility $U$ of household i at time t as:

$$U\left(K_{i,t},\theta_{i,t}\right)=K_{i,t}{}^{\beta}\theta_{i,t}-(r+\delta)K_{i,t}$$

Where $K_{i,t}$ represents the total amount of invested capital in housing by household i at time t, $\theta_{i,t}$ is a stochastic parameter that follows a random walk, $r$ and $\delta$ are the discount and the depreciation rates and $\beta$ is a parameter that is less to one. In the absence of any adjustment cost, the frictionless stock of capital invested in housing, $K_{i,t}^{*}$, would be achieved by the household after maximizing Eq. (1) with respect to K so that:

$$\theta_{i,t}=\frac{r+\delta}{\beta}K_{i,t}^{*}{}^{1-\beta}$$

However, like Caballero and Engel (1999), we consider that households undergo an adjustment cost proportional to the housing services that are foregone when home improvements are made:

$$C\left(K_{i,t},\theta_{i,t}\right)=\omega_{i,t}\left(\pi\left(K_{i,t},\theta_{i,t}\right)+(r+\delta)K_{i,t}\right)=\omega K_{i,t}^{\beta}\theta_{i,t}$$

Where $\omega_{i,t}$ corresponds to the adjustment cost factor. This parameter is stochastic, changes at each time period and follows the distribution function G(.). With adjustment costs, the utility function of the household can be rewritten as a function of the frictionless stock of embedded capital in housing:

$$\pi\left(K_{i,t}^{*},z_{i,t}\right)=\frac{r+\delta}{\beta}K_{i,t}^{*}\left(e^{\beta z_{i,t}}-e^{z_{i,t}}\right)$$

With:

$$z_{i,t}\equiv\ln\left(\frac{K_{i,t}}{K_{i,t}^{*}}\right)$$

The decision of adjusting or not adjusting becomes dynamic and is computable according to the value function of adjusting capital at time t for a given level of pre-adjustment disequilibrium $z_{i,t}$, frictionless capital stock $K_{i,t}^{*}$ and adjustment cost $\omega_{i,t}$. If we denote $V\left(z_{i,t},K_{i,t}^{*},\omega_{i,t}\right)$ the household's bellman value function, with $V\left(z_{i,t},K_{i,t}^{*}\right)$ its realization with no adjustment and $V\left(c_{i,t},K_{i,t}^{*}\right)$ its value if the firm adjusts, we can write:

$$V\left(z_{i,t},K_{i,t}^{*},\omega_{i,t}\right)=\max\left\{V\left(z_{i,t},K_{i,t}^{*}\right),V\left(c_{i,t},K_{i,t}^{*}\right)-\omega_{i,t}\frac{r+\delta}{\beta}K_{i,t}^{*}e^{\beta z_{i,t}}\right\}$$

Here, $c_{i,t}$ is the optimally determined return point after investment: it corresponds to the desired level of capital if the investment/disinvestment decision is made. Similarly, we can define $x_{i,t} \equiv z_{i,t} - c_{i,t}$ as household's imbalance with respect to its target point. Caballero and Engel (1999) show that the solution can be derived from the policy $\Omega(z_{i,t})$, defined as the largest adjustment cost factor $\omega_{i,t}$ for which an agent would still adjust[3], so that the adjustment hazard $\Lambda$ according to imbalance $x_{i,t}$ is given by the policy $\Omega(.)$ and the cumulative distribution function G(.) of the adjustment factor $\omega_{i,t}$:

$$\Lambda(x_{i,t}) = G\left(\Omega(x_{i,t} + c_{i,t})\right) \tag{1}$$

Furthermore, and by definition, the amount $I$ invested by households once they have decided to invest corresponds to the difference in capital necessary to reach the target point c from current imbalance point x:

$$I(x_{i,t}) = (e^{c_{i,t}} - e^{z_{i,t}})K^*_{i,t} = (e^{-x_{i,t}} - 1)e^{z_{i,t}}K^*_{i,t} = (e^{-x_{i,t}} - 1)K(x_{i,t}) \tag{2}$$

### Econometric specification

We make a sequential interpretation of the model of Caballero and Engel (1999). In our reduced-form setting, consumers first decide whether they invest or not and then opt for an amount proportional to their capital imbalance. Importantly though, equation (1) and (2) suggest that the probability of investing and the amounts that are invested depend on the same latent variable $x_{i,t}$. In our setting, we use a set of independent variables and fixed effects to proxy $x_{i,t}$.

We estimate $\Lambda_{i,t}$ in a first stage. We denote $D_{i,t}$ the decision of making an investment, such that $D_{i,t} = 1$ if an investment is performed by household i at time t, or zero otherwise. As we observe $D_{i,t}$, we can implement a fixed-effect logit model[4]. Thus, we assume that there is a latent variable $D^*_{i,t}$ such that:

$$D^*_{i,t} = Z'_{i,t}B + \sum_f P'_{f,t}\tau_f + \sigma(1-\delta)K_{i,t-1} + u_i + \varepsilon_{i;t}$$

and:

[3] The value of $\Omega(z)$is such that the following equation holds: $V(c, K^*) - \Omega(z)\frac{r+\delta}{\beta}K^* e^{\beta z} = V(z, K^*)$

[4] To study the time dependency of $D_{i,t}$, we could alternatively use a dynamic fixed effect logit model. This possibility, which is not presented in this working paper, will be explored in future research.

$$D_{i,t} = \begin{cases} 1 \ if \ D^*_{i,t} > 0 \\ 0 \ otherwise \end{cases}$$

Above, $Z_{i,t}$ is a vector of independent variables including climate variables, B a vector of parameters, $u_i$ an individual-specific fixed effect and $\varepsilon_{i;t}$ an error term following an extreme value distribution. Moreover, $P_{f,t}$ is the price of fuel f and $\tau_f$ a parameter associated with fuel f (e.g. gas or electricity). Furthermore, we expect that the decision D depends on the total amounts of investments that have already been capitalized in the house, i.e. $(1-\delta)K_{i,t-1}$ where $\delta$ is the depreciation rate. Finally, $\sigma$ is a parameter such that $\sigma < 0$: the more improvements that have been performed previously, the less a household will be prone to perform additional home improvements.

The estimation of such a model allows recovering the probability that individual i decides to make an investment. We can apply the formula of the logit model to recover the probabilities of investing, assuming that the fixed effect is equal to zero[5]:

$$\Lambda_{i,t} = \frac{\exp\left(Z'_{i,t}B + \sum_f P'_{f,t}\tau_f + \sigma(1-\delta)K_{i,t-1}\right)}{1 + \exp\left(Z'_{i,t}B + \sum_f P'_{f,t}\tau_f + \sigma(1-\delta)K_{i,t-1}\right)} \tag{3}$$

In a second stage, we estimate $I_{i,t}$ with a fixed effect linear regression model such that:

$$I_{i,t} = X'_{i,t}A + \sum_f P'_{f,t}S_f + \rho(1-\delta)K_{i,t-1} + \mu_i + \epsilon_{i,t} \ \ if \ I_{i,t} > 0$$

In the equation above, $X_{i,t}$ is a set of independent variables, A is a vector of parameters, $S_f$ a parameter associated with fuel f, $\rho$ a parameter capturing the influence of past investments on new ones, $\mu_i$ is a fixed effect and $\epsilon_{i,t}$ an error component.

Note that we estimate $\Lambda_{i,t}$ and $I_{i,t}$ independently. The limitation of doing so is that there could be a selection bias on $I_{i,t}$ if time-varying unobservables affect the choice of investing or not (i.e. $\Lambda_{i,t}$). However, we reduce this risk by controlling for the main drivers affecting decisions to invest. The first one is the current state of the house, which is captured by $K_{i,t}$, and the second one is household specific tendency to make home improvements, which is to a very large extent controlled for thanks to the use of fixed effects at household level: both the time constant features of housing units and households are controlled for in our setting. Additionally, our base specification controls for income shocks.

[5] It is not possible to recover the fixed effects of a fixed effect logit model once it has been estimated.

### Accounting for different types of home improvements

The estimation process above can be applied even when we relax the assumption that housing services constitutes a homogeneous good. If we consider that there are H types of housing services and therefore H types of potential home improvements, we can write as many systems of equations ($\Lambda_{i,h,t}; I_{i,h,t}$) as there are types of housing services. In this case though, the investments performed in type h become dependent on the investments performed in any other type $j$. This is why we consider that all the $K_{j,i,t-1}$ affect $D^*_{i,h,t}$:

$$D^*_{i,h,t} = Z'_{i,h,t}B_h + \sum_f P'_{f,t}\tau_{f,h} + \sum_{j=1}^{H} \sigma_{j,h}(1-\delta)K_{i,j,t-1} + u_{i,h} + \varepsilon_{i,h,t}$$

The amounts to be invested in h depend on the amounts that have been capitalized in all the other types j and in h previous to the investment that is considered. Because the $K_{i,j,t-1}$ are good predictors of $\Lambda_{i,j,t}$ and $I_{i,j,t}$, they allow controlling for the likeliness that investments in other categories occur simultaneously to $I_{i,h,t}$. Furthermore, they are also good indicators about consumers' expectations regarding future home improvements, i.e. the fact that a household can forecast that, within a few years, he/she will have to perform works in his/her home.[6]

Likewise, we consider that the amounts invested in one category at time t depends on the amounts that have been capitalized in other categories of housing services:

$$I_{i,h,t} = X'_{i,h,t}A_h + \sum_f P'_{f,t}S_{f,h} + \sum_{j=1}^{H} \rho_{j,h}(1-\delta)K_{i,j,t-1} + \mu_{i,h} + \epsilon_{i,h,t}$$

## *Model of residential energy consumption*

The model of home improvements presented previously allows capturing household decisions to invest in their homes. This model therefore allows us to assess in which proportions climate change could trigger new home improvements. However, the model of home improvements does not say much about the impact of the adoption of specific adaptations on GHG emissions. To look at this aspect, which is of primary interest to this research, we need to make the link between the home improvement model and a model of residential energy consumption and GHG emissions.

[6] Note that including the values of $I_{i,j,t}$ as independent variables to explain $D_{i,h,t}$ is not only difficult because these variables would be endogenous, but also because they are censored: we do not always observe at least one investment in all H categories.

As already explained, there are two main sources f of energy consumed by US households: electricity (e) and gas (g). Therefore we need to model both sources of energy. Electricity is consumed by every household and we therefore observe electricity consumption for every household in our sample. On the other hand, gas is not consumed by every household in our sample and therefore, gas consumption is not observed for every household in every year. To circumvent this problem, we adopt different estimation strategies to estimate the energy consumption of both fuels. We first describe the model used for electricity and then the model used for gas.

### Model of electricity consumption

To model residential electricity consumption, we use a linear econometric equation where the dependent variable is the annual energy consumption of household i at time t, denoted $q_{i,t}$. Like Auffhammer and Aroonruengsawat (2011), we consider that the dependent variable varies with temperature, energy prices and a series of household and unit specific features:

$$q_{i,e,t} = M'_{i,t}\phi_{M,e} + \psi_{i,e} + \tau_{t,e} + \varsigma_{i,e,t}$$

$M_{i,t}$ is a vector of independent variables, which includes heating degree days, cooling degree days, days with precipitations, the prices of electricity and gas ($P_{f,t}$ with $f \in \{e, g\}$), and income. $\psi_{i,e}$ is a household-specific fixed effect capturing household-level specificities, $\tau_{t,e}$ a time dummy and $\varsigma_{i,e,t}$ is an error term. $\phi_{M,e}$ is a vector of parameters to be estimated.

Moreover, the originality of our approach is that we introduce the expected amount of capital in the housing units into the model, as an explanatory variable of energy use. This expected amount of capital, noted $\widehat{K}_{i,j,t}$, corresponds to the previously accumulated capital plus the expected amount of investment:

$$q_{i,e,t} = \sum_{j=1}^{H} \phi_{j,e}\widehat{K}_{i,j,t} + M'_{i,t}\phi_{M,e} + \psi_{i,e} + \tau_{t,e} + \varsigma_{i,e,t} \tag{4}$$

With:

$$\widehat{K}_{i,j,t} = (1-\delta)K_{i,j,t-1} + \hat{I}_{i,j,t}\hat{\Lambda}_{i,j,t}$$

Above, $\hat{I}_{i,j,t}$ and $\hat{\Lambda}_{i,j,t}$ are the predicted values of $I_{i,j,t}$ and $\Lambda_{i,j,t}$ as estimated with our home improvement model. These predicted values exclude fixed effects, which are assumed to be zero. This is because they cannot be recovered for $\hat{\Lambda}_{i,j,t}$ and this allows enlarging the sample of predictions for $\hat{I}_{i,j,t}$. This could create a bias in the estimation of $\phi_{j,e}$, which we limit as we are estimating $\phi_{j,e}$ not only on $\hat{I}_{i,j,t}\hat{\Lambda}_{i,j,t}$, but on $\widehat{K}_{i,j,t}$ which includes $K_{i,j,t-1}$ and therefore the past realizations of $I_{i,j,t}$. In equation (4), two vectors of parameters provide relevant information about the relationship between climate and energy use: $\phi_{M,e}$, the vector of parameters that, once estimated, describes household response to climate shocks with the available capital stock; and $\phi_{j,e}$ which provides information on the impact of home improvements on residential energy consumption.

### Model of gas consumption

Ideally, we would like to use equation (4) to model gas consumption as we have done for electricity consumption. However, gas is not consumed by every household and, consequently, gas consumption is a left-censored variable.

To properly account for the fact that consumers may choose to consume or not to consume gas, we use a random effect tobit model. For gas consumption, we therefore assume that:

$$q^*_{i,g,t} = \sum_{j=1}^{H} \phi_{j,g}\widehat{K}_{i,j,t} + W'_{i,t}\phi_{W,g} + \psi_{i,g} + \tau_{t,g} + \varsigma_{i,g,t}$$

And:

$$q_{i,g,t} = \begin{cases} q^*_{i,g,t} \; if \; q^*_{i,g,t} > 0 \\ 0 \; otherwise \end{cases}$$

$q^*_{i,g,t}$ is a latent variable that determines gas consumption $q_{i,g,t}$ and $W_{i,t}$ is a set of independent variables including all the variables in $M_{i,t}$ used in equation (4). Importantly, $\psi_{i,g}$ is not a fixed effect, but a random effect following a normal distribution[7]. The random effect tobit model that we use requires that unobservables in the error term are uncorrelated with independent variables. To ensure that this is the case, we need to control for the main time-constant household and unit features. This is why $W_{i,t}$ includes all the variables in $M_{i,t}$ plus an additional set of control variables described in the data section.

### Heterogeneity of the impact of home improvements on energy consumptions

Either in the electricity or the gas consumption model, the capital invested in the various categories of home improvements may not have a constant marginal impact, $\phi_{j,g}$, on energy consumption. There can be non-linearities of the impact of one category of home improvements on energy

[7] Honoré (1992) has developed a consistent estimator for fixed effect tobit models. The use of this estimator, which has not been applied in this working paper, will be explored in future research.

consumption and interactions with other categories. For example, the impact of a better insulation on energy consumption is likely to depend on the size of the home, captured by the amount of capital accumulated in all other indoor amenities. Therefore, we have complemented our base specifications for the models of electricity and gas consumption with interaction parameters between the categories of housing services.

Furthermore, the type of investment that is made within one category may differ depending on climate constraints. For example, the investments in major equipment performed when temperatures are high are likely to consist in air-conditioners, whereas they are more likely to consist in gas heaters when temperatures are low. Likewise, this creates an interaction between the marginal impact of additional investments in major equipment and temperatures which we need to take into account. We have modified our base specification accordingly.

### Energy price exogeneity

We consider that gas and electricity prices are exogenous in our base specifications of residential energy demand: no unobservables affect both individual household consumption and State level energy prices. There is however a small risk that price variables are weakly endogenous because it is possible that patterns of individual decision and prices at State level are both influenced by unobserved policies and media.

To check that our model with exogenous energy prices is accurate, we make the assumption that prices are endogenous in an additional model of electricity consumption and apply a two-stage least square (2SLS) setting.[8]

In this 2SLS regression, we adopt two sets of instruments: the average prices paid in the industrial sector; and the prices paid in the residential sector of the neighbouring States. Industrial energy prices are likely to be correlated to residential energy prices, but should have no impact on residential energy demand. Likewise, the price of energy in neighbouring States will be correlated with the price of energy in the State in which household i lives. However, changes in the price of energy in neighbouring States should have no impact on the demand for energy of household i. These instruments are available at State level and for each year.

[8] We have reproduced this test in a linear model for gas and the results proved to be very similar assuming either endogenous or exogenous energy prices. We do not reproduce the test in the model of gas consumption that is used because we have adopted a non-linear model to control for household choice to consume gas or not.

In the 2SLS regression, the predicted values for the expected amounts of home improvements performed by each household i at time t become endogenous. This is because they are expressed as a function of energy prices. To avoid having as many additional endogenous variables as types of housing services, we generate predictions of $I_{i,h,t}$ and $\Lambda_{i,h,t}$ corresponding to the hypothetical scenario in which energy would be free, which we denote $\tilde{I}_{i,h,t}$ and $\tilde{\Lambda}_{i,h,t}$:

$$\tilde{I}_{i,h,t} = \hat{I}_{i,h,t}\big|_{P_{f,t}=0\ \forall f} = \hat{I}_{i,h,t} - \sum_f P'_{f,t}\hat{S}_{f,h}$$

$$\tilde{\Lambda}_{i,h,t} = \hat{\Lambda}_{i,h,t}\big|_{P_{f,t}=0\ \forall f} = \frac{\exp\left(Z'_{i,h,t}\hat{B}_h + \sum_{j=1}^{H}\hat{\sigma}_{j,h}(1-\delta)K_{i,j,t-1}\right)}{1+\exp\left(Z'_{i,h,t}\hat{B}_h + \sum_{j=1}^{H}\hat{\sigma}_{j,h}(1-\delta)K_{i,j,t-1}\right)}$$

Estimated variables from the home improvement model are presented with a hat (^). In fact, $\tilde{I}_{i,h,t}$ and $\tilde{\Lambda}_{i,h,t}$ present the advantage of being strictly exogenous whereas $\hat{I}_{i,h,t}$ and $\hat{\Lambda}_{i,h,t}$ are endogenous due to the alleged endogeneity of the energy prices used to compute them. $\tilde{I}_{i,h,t}$ and $\tilde{\Lambda}_{i,h,t}$ are therefore preferred in the 2SLS setting to reduce the amount of endogenous variables. In this case, the impact of electricity prices on energy consumption though home improvements is captured by the energy price parameters (along with the other impacts of energy prices on energy consumptions).

# 4. Data

This paper relies on three data sources to estimate the model of home improvement and the model of residential energy consumption. Firstly, the American Housing Survey is used to gather data on housing units, home improvements, energy consumptions and households. Moreover, meteorological data has been extracted from the National Oceanic and Atmospheric Administration's (NOAA) Data Center. Finally, energy price data for the study period has been obtained from the State Energy Data System (SEDS) monitored by the U.S. Energy Information Administration (EIA).

### *American Housing Survey (AHS)*

The first wave of American Housing Survey was conducted in 1973 under the name of Annual Housing Survey. The survey was conducted again on an annual basis until 1981. Due to budget constraints, it became biennial, changed its name to the American Housing Survey and is conducted every odd-numbered year ever since. The American Housing Survey includes two samples of US retail estate: a metropolitan sample and a national sample. The metropolitan sample covers a set of 21 metropolitan areas and each metropolitan area is surveyed once every six years. The national sample is a nationally representative survey of the housing stock of the United States. It is a longitudinal survey: the same housing units are surveyed each time. However, it underwent a redesign in 1985 and the units of 1985 and after are different from the units surveyed during the previous years. The sample size of the national AHS since 1985 is approximately 47,000 housing units.

For this study, we have extracted data on households and housing conditions from the national waves of the AHS since its redesign in 1985. We have therefore gathered longitudinal data from 14 waves of the national AHS, from 1985 to 2011. We are not using all the observations of the AHS from 1985 to 2011 though, firstly because the localization of the housing units is confidential for about half of the sample[9] and also because the information on home improvements has been collected for owner-occupied units only. The sample of geolocalised, owner-occupied units between 1985 and 2011 is composed of 262,872 observations.

In the AHS, the geographical information is displayed at the level of the Metropolitan Statistical Areas (MSAs). A MSA is an area which contains a core urban area of at least 50,000 inhabitants and can consist of one or more counties. The AHS waves between 1985 and 2011 include housing units from 144 MSAs, spread all over the United States.[10]

The AHS includes information on different types of home improvements.[11] For this research, we distinguish three types of housing services, corresponding to three types of home improvements. The first category covers the installation of major (energy-consuming) equipment, including principally space heating appliances and air conditioners (either room or central air conditioners). The second category covers all the types of improvements that we expect to be directly or indirectly related to *energy integrity*, including direct works to insulate the home (i.e. addition/replacement of foam, weather stripping and caulking), the addition or replacement of storm doors and windows

[9] Principally, the public use files of the AHS do not provide information on the location of the units that are situated in areas with less than 100,000 inhabitants to ensure that the public use files are entirely anonymous. In the end, about half of the owner-occupied units of the AHS are not geolocalised in the public use files.

[10] In 2013, there was a total of 387 MSAs in the US according to the Census Bureau: http://www.census.gov/population/metro/files/metro_micro_Feb2013.pdf

[11] Before 1997, owners were asked about the amount they had invested in 9 different types of home improvements: roofing; insulation; siding; storm doors and windows; installation of major equipment; changes to the bathroom; changes to the kitchen; home extensions; and any other major improvement costing $ 500 or more. In 1997, the typology was refined but we had to stick to the previous typology to be able to use the entire study sample from 1985. Among the nine types of home improvements that were available to us, we decided to follow in detail the two that were the more obviously related to climate adaptation. For the others, we just decided to aggregate them and analyse them as one type of home improvements by its own. On the other hand, please note that we cannot control for the home improvements realized outside the home, because the information is not recoded before 1997 and we need to use the entire panel to consider climate change adaptation.

(double or triple glass), roofing jobs and improvements on siding. We expect that works related to energy integrity reduce energy bills, whereas the installation or replacement of major equipment could either increase energy bills with the installation of new equipment or reduce energy bills if old, energy inefficient appliances are replaced with energy efficient ones. On the other hand, the third category consists in all the other indoor amenities[12] which we have considered as not directly related to energy use: changes to the bathroom; changes to the kitchen; home extensions; and any other major indoor improvement. For this last category, we may expect however that climate has an impact on the decision to perform some investments.

We use the survey identifiers of each housing unit to compute the total amounts of a type of housing services capitalized by each household at a specific time, i.e. $K_{h,i,t}$. We can only compute $K_{h,i,t}$ for the subset of houses for which we have information on the purchase price or the construction cost of the home at specific periods of time. This is because we use this information to calculate the amount of capital embodied in the house before home improvements are made.

We note $k_{i,t}$ the amount of capital embodied in a home net of any home improvement from the householder. For the years in which the housing units are neither sold nor built, $k_{i,t}$ is unobserved. We can however input the value of $k_{i,t}$ for the years following the sale/construction of the house by applying the depreciation rate of capital:

$$k_{i,t} \approx (1-\delta)^{\tau_i} k_{i,t-\tau_i}$$

$\tau_i$ represents the observed date of construction or sale. We take 2% for the value of the depreciation rate of past investments (i.e. $\delta = 2\%$). This value corresponds to the depreciation rate of real estate as estimated by Harding *et al.* (2007) on AHS data. Additionally, for the years that precede a sale and for which we have no previous information on the initial capitalized investments net of home improvements, we infer it from the sales price of the home at a later date:

$$k_{i,\tau_i - s} \approx \frac{k_{i,\tau_i}}{(1-\delta)^s}$$

s represents the lag between the observed purchase and the time of interest for the calculation of $k$. This technique allows us to proxy the total amount of capitalized investments in a home provided that we observe at least one sale or the construction cost of the unit.

[12] As explained in the previous footnote, we have no information on outdoor improvements for the entire survey period.

We expect our approximation of $k_{i,t}$ to be representative of the value of all the services delivered by the housing unit net of any future home improvement after $\tau_i$. We furthermore want to distinguish the capitalized investments associated with major equipment and the capitalized investments associated with energy integrity from the rest. To do so, we use the information provided by the National Association of Home Builders (NAHB, 2010) on construction costs. According to the NAHB, 20.3% of the construction cost of a single-family unit is due to the lot price. Furthermore, the NAHB also provides a breakdown of the construction cost of a home according to the part of the unit that is considered. In particular, heating, ventilation and air-conditioning systems represent 4.0% of the construction cost, and appliances 1.6% in average. We therefore proxy the amount of capitalized investments in major equipment, net of any home improvement after $\tau_i$, by evaluating the share of $k_{i,t}$ that is most likely to have been allocated to major equipment at the time of construction based on NAHB (2010). This leads us to apply the following formula:

$$k_{1,i,t} = k_{i,t} * (1 - 20.3\%) * (4\% + 1.6\%)$$

In the equation above, $k_{1,i,t}$ is the capitalized investments in type 1 (major equipment) at time t for household i, net of any improvement performed to the home after $\tau_i$. We can likewise assess the capitalized investments net of home improvements for insulation and storm doors and windows, and all the other home improvements covered with our data.[13]

Once the capitalized investments net of home improvements after $\tau_i$ have been calculated for all the three types of homes improvements, we add the value of all the home improvements performed in the house since the last purchase ($\tau_i$) or withdraw the sum of all the home improvements done between time t and the upcoming purchase (in $\tau_i$) to proxy the value of capitalized investments in a specific type h of housing services at time t:

$$K_{h,i,t} = \begin{cases} k_{h,i,t} + \sum_{s=\tau_i}^{t} I_{h,i,s}(1-\delta)^{t-s} \ \ if\ t \geq \tau_i \\ k_{h,i,t} - \sum_{s=t}^{\tau_i} I_{h,i,s}(1-\delta)^{\tau_i - s} \ if\ \ t < \tau_i \end{cases}$$

On the other hand, the AHS provides household level information, in particular household total income which we use as a control variable in all the equations. Furthermore, we use additional

[13] According to NAHB (2010), Insulation is 1.5% of construction costs, windows represent 2.8%, exterior doors 0.9%, framing and trusses 15.6%, roof shingles 3.8% and siding 5.8%. To assess the initial capital for all the other homes improvements, we consider that it correspond to the remaining share, excluding outdoor features and fees, i.e. lanscaping and sodding (3.2%), wood decks or patios (0.9%), asphalt driveways (1.4%), building fees (1.9%) and impact fees (1.4%).

control variables for the gas consumption model: the age and gender of the householder, the year of construction of the housing unit, the type of housing (one-building housing unit, detached or attached; or a building with two or more apartment), whether the neighbourhood has access to pipe gas and the census region of the unit[14]. Furthermore, we have information on the time since the household moved in. The latter allows us to identify the moment when a household left and was replaced by a new one in a given housing unit. We can therefore construct household-specific fixed effects.

Additionally, we also extract information on the energy bills paid by households from the AHS. This allows us to calculate the quantities of energy consumed by each household, which constitutes the dependent variable of the second step of our econometric exercise. To do so, we divide the energy bills for electricity and gas by the average price of these fuels in the State in which the housing unit is located. The price data is taken from the Energy Information Administration and is presented just after the climate data.

Finally, for the households who perform home improvements, we know if they have benefitted a low interest loan or grant from a government program to help pay for making any of the alterations to their home. We use this element as a control variable for the amounts that are invested in home improvements by a household.

### *NOAA Climate Data*

The climate data has been extracted from the Climate Data Online (CDO) service of the National Climatic Data Center (NCDC), which is monitored by the National Oceanographic and Atmospheric Administration (NOAA).

We have extracted three measures to proxy climatic conditions: heating degree days, cooling degree days, and the annual number of days with precipitations over 0.5 inches. We use heating and cooling degree days instead of temperature because it provides a more precise measure of heating and cooling needs. We are using the total number of days with precipitations above 0.5 inches to control for the impact of precipitations on home improvements. This is because precipitations can be correlated with temperatures and not accounting for changes in precipitation levels could bias our results. Furthermore, precipitations are a good proxy for humidity, which is known to increase the perceived sensation of heat and cold.

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[14] Four census regions are coded in the AHS: Northeast, Midwest, South and West. The exact definition of each region is provided in the AHS codebooks.

Our data corresponds to land-based (*in situ*) historical observations recorded by meteorological stations in the US from 1985 to 2011. We use the information from about 2,200 meteorological stations situated in 159 locations that match the Metropolitan Statistical Areas covered with the AHS data. The records are available for different time spans depending on the opening and closure of the meteorological stations. We have extracted the monthly data and then calculated the yearly averages and sums with the meteorological stations that were active during the entire year. For each metropolitan statistical area, we averaged the values recorded in all the nearby active stations to get variables that could be matched with the AHS data.

### *Energy Price data from the SEDS*

The energy price data is taken from the State Energy Data System administered by the U.S. Energy Information Administration. The data includes information on residential and industrial energy prices for each US State from 1985 to 2011. The prices are provided for coal, natural gas, liquefied petroleum gas, electricity, fuel oil, kerosene and wood in dollars per million btu but we are only using the information on gas and electricity prices, as these two fuels are the ones that are principally used by households.

We combine the energy price data with the AHS data by matching the metropolitan statistical areas of the AHS with the State-level information of the SEDS. Each time at MSA is situated on more than one State, average price values are obtained by calculating the average energy price corresponding to the different States on which a metropolitan statistical area is overlapping.

Furthermore, we construct instruments for energy prices by using the energy price data from the SEDS. We can easily recover the price of neighbouring States and we also have information on energy prices in the industrial sector. As explained before, these two sets of prices are used to account for the endogeneity of energy prices in an alternative specification of the energy consumption model.

### *Summary of statistics*

Table 1 provides the list of the descriptive statistics from all the three data sources that are used for the home improvement model estimation. These statistics are reported for the 21,889 observations that were directly used in the model estimations.

This amount may appear as relatively small as compared with the sample of 262,872 observations of geolocalised, owner-occupied units. The reduction in sample size is principally due to the fact that we only have about 55,000 units for which we have either information on the purchase price or the construction cost, matching with our energy and temperature data. Additionally, some observations have missing information on the variables used in the econometric estimations and we have excluded outliers.[15]

Finally, please note that the observations which have been used to make descriptive statistics are not used in all the equations estimated in our setting. This is because some equations focus on the observations for which one investment is recorded.

[15] The 5% of units with very high or very low values for heating degree days, cooling degree days, electricity and gas prices has been excluded. This is because there could be differences in the response of the households that live in very hot/very cold regions or in regions in which energy is either very cheap or very expensive (as these households could already be very well equipped or on the contrary underequipped in terms of energy conservation). Furthermore, among the observations that perform an investment in one investment category, we have dropped the 5% of observations that invested the highest amounts, considering that the investments performed by these households are likely to be structural and to have occurred anyway. Likewise, our data registers many small amounts of investment in any of the three categories, corresponding to small maintenance efforts. To distinguish these small maintenance works from home improvements, we have considered that the 10% cheapest alterations recorded in our data should be disregarded. They enter in the calculation of the total embodied capital in the home but are not used in the fixed effect logit models and the linear models. Finally, for the energy consumption models, we have excluded the 5% observations with smallest and the 5% observations with largest predicted amounts of investment in the three categories of housing services.

**Table 1: Descriptive statistics of the data used**

| Variable | Unit | Mean | Std deviation |
|---|---|---|---|
| Capitalized investments in main equipment, $K_{1,i,t}$ | $ | 9,876 | 7,844 |
| Share of households making an investment in main equipment | % | 0.07 | 0.26 |
| Expenditure in main equipment for those who perform an investment | $ | 3,710 | 2,227 |
| Capitalized investments in energy integrity, $K_{2,i,t}$ | $ | 52,502 | 41,669 |
| Share of households making an investment in insulation | % | 0.2 | 0.4 |
| Expenditure in energy integrity for those who perform an investment | $ | 3,668 | 3,519 |
| Capitalized investments in all the other home improvements, $K_{3,i,t}$ | $ | 100,802 | 78,295 |
| Share of households making an investment in a least one of all the other home improvements | % | 0.34 | 0.47 |
| Expenditure in other home improvements for those who perform an investment | $ | 4,446 | 5199 |
| Logarithm of total household income | $ | 11.08 | 0.88 |
| Percentage of units with at least one air conditioner | % | 0.89 | - |
| Share of households that have benefitted from a government grant or loan to perform home improvements | % | 0.0092 | - |
| *Climate variables and energy prices* | | | |
| Heating Degree Days | # | 4,038 | 1,761 |
| Cooling Degree Days | # | 1,433 | 688 |
| Days with precipitation over 0.5 inches | # of days | 24.3 | 10.7 |
| Residential electricity consumption | MM.btu/year | 37.24 | 23.93 |
| Residential gas consumption | MM.btu/year | 70.70 | 68.15 |
| Residential price of electricity | $/MM.btu | 39.94 | 8.33 |
| Residential price of gas | $/MM.btu | 11.92 | 2.28 |
| *Additional variables used in the random effect tobit model of gas consumption* | | | |
| Percentage of units whose neighbourhood is connected to pipe gas | % | 0.83 | - |
| Age of householder | Years | 47.21 | 15.63 |
| Gender of household (share of males) | | 0.64 | - |
| Year of construction of unit | | 1,961 | 22 |
| Share of one-building, detached units | % | 0.84 | - |
| Share of one-building, attached units | % | 0.08 | - |
| Share of buildings with two or more apartments | % | 0.09 | - |
| Share of units which census region is Northeast | % | 0.21 | - |
| Share of units which census region is Midwest | % | 0.26 | - |
| Share of units which census region is South | % | 0.33 | - |
| Share of units which census region is West | % | 0.20 | - |

Notes. Source: AHS, CDO and SEDS. Survey years: 1985-2011. Number of observations: 21,889 (21,651 for census regions, except for electricity consumption – 21,714; and for the amounts invested in the three home improvement categories). Comments: all the variables in dollars are expressed in 2011 real dollars. The correction of nominal values has been made using the U.S. Consumer Price Index of the Bureau of Statistics of the U.S. Department of Labour.

## 5. Model results

The section below presents the model results. They are first provided for the home improvement model and then for residential energy consumption. For home improvements, the results are separately displayed for the probability of making an investment and then for the amounts that are invested, for the three types of home improvements considered.

### *Results of the model of home improvements*

#### Results for the decisions to invest in specific types of home improvements

Table 2 below clearly shows that the probability of making a home improvement depends on the total amounts that have already been capitalized in the category that is considered: the more investments have already been capitalized in one category, the fewer households are likely to invest again in this category. This is consistent with the fact that household will not invest twice in similar home improvements.

On the other hand, the probability of investing in one category increases if the investments capitalized in the other categories are high. This is logical as the investments in one category are complementary to the investments in the other categories.

Furthermore, the probabilities to invest in major equipment and energy integrity are positively correlated with more heating or more cooling degree days. We find statistically significant effects at 10% for heating degree days, and at 1% for cooling degree days on the decisions to invest in energy related home improvements. Moreover, a one-unit increase in cooling degree days appears to have a stronger impact on the probability to invest in major equipment than a one-unit increase in heating degree days. This same trend is found for the investments in energy integrity.

On the other hand, investments in other amenities appear to be more frequent with hotter temperatures and with higher precipitations. The correlation with hotter temperatures and other indoor home improvements might be due to changes in lifestyle but we do not have a clear-cut explanation for it. On the other hand, depreciation is likely occur at a higher pace with humidity, explaining that other indoor home improvements are more frequent when precipitations are higher.

Interestingly, we find statistically significant correlations between energy prices and the probabilities of investing either in major equipment or in energy integrity. Higher energy prices may therefore encourage consumers to purchase energy efficient appliances for heating and cooling, and to improve home insulation.

Finally and with no surprise, income has a statistically significant impact on the probability of performing home improvements in any of the three categories followed with our model.

**Table 2: Fixed effect logit model on the decision to perform investments according to the type of investments**

| Independent variables | Major Equipment | Energy integrity[$] | All other indoor improvements |
|---|---|---|---|
| Capitalised investments in major equipment, $\widehat{K}_{1,i,t}$ | -0.001022*** (-21.75) | 0.000028* (1.78) | -0.000004 (-0.29) |
| Capitalised investments in energy integrity[$], $\widehat{K}_{2,i,t}$ | 0.000043*** (3.55) | -0.000124*** (-16.56) | 0.000022*** (4.28) |
| Capitalised investments in other indoor improvements, $\widehat{K}_{3,i,t}$ | 0.000002 (0.74) | 0.000012*** (4.41) | -0.00002*** (-7.78) |
| Heating degree days | 0.000369* (1.73) | 0.000231* (1.9) | 0.000053 (0.53) |
| Cooling degree days | 0.000739*** (2.58) | 0.000469*** (2.78) | 0.000234* (1.74) |
| Number of days with precipitations over 0.5 inches | 0.001649 (0.21) | 0.001795 (0.39) | 0.007079* (1.85) |
| Price of electricity | 0.0478** (2.19) | -0.0162 (-1.32) | 0.0085 (0.83) |
| Price of gas | 0.1609** (2.34) | 0.1374*** (3.81) | 0.0632** (2.14) |
| Household income | 0.1081* (1.67) | 0.1349*** (3.46) | 0.098*** (3.04) |
| Household fixed effects | Yes | Yes | Yes |
| Year dummies | Yes | Yes | Yes |
| Observations | 5,084 | 10,097 | 12,719 |

Notes. T-statistics in brackets. Results marked with one to three stars are statistically significant at 10%, 5% and 1% respectively. $: Energy integrity corresponds to insulation, storm doors and windows, roofing and siding.

### Results for the amounts that are invested

As explained in the model section, a fixed effect linear regression model is run on the amounts invested in each of the three types of home improvements. The results, presented in Table 3, corroborate some of the findings obtained with the fixed effect logit models.

In particular, we similarly find that the amounts already capitalized in one category are lower when high amounts have already been capitalized in this category. On the other hand, high amounts capitalized in other categories are a good indication that household investments may be higher.

**Table 3: Fixed effect linear regression model on the amounts that are invested according to the type of investments**

| Independent variables | Major Equipment | Energy integrity[$] | All other indoor improvements |
|---|---|---|---|
| Capitalised investments in major equipment, $\widehat{K}_{1,i,t}$ | -0.2994*** (-5.36) | 0.1649** (2.38) | 0.0614 (0.87) |
| Capitalised investments in energy integrity[$], $\widehat{K}_{2,i,t}$ | 0.0188 (0.49) | -0.3205*** (-9.04) | 0.1079*** (3.07) |
| Capitalised investments in other indoor improvements, $\widehat{K}_{3,i,t}$ | 0.002 (0.24) | 0.036** (2.23) | -0.0494*** (-2.88) |
| Heating degree days | 0.63 (1.19) | -0.65 (-1.48) | -0.25 (-0.53) |
| Cooling degree days | 1.85** (2.12) | -0.57 (-0.78) | 0.43 (0.69) |
| Number of days with precipitations over 0.5 inches | 39* (1.82) | 26.6 (1.47) | 18.9 (1.03) |
| Price of electricity | 155.6** (2.21) | 52.6 (0.88) | -11 (-0.24) |
| Price of gas | -323.6 (-1.19) | -246 (-1.61) | -25 (-0.18) |
| Household income | -444.6 (-1.59) | -231.6 (-1.41) | -25 (-0.18) |
| Benefitted from government loan or grant for making home improvements | -429.6 (-1.15) | 973.3 (1.39) | 2046.1** (2.44) |
| Constant | -1358 (-0.22) | 20928*** (3.99) | 2202 (0.54) |
| Household fixed effects | Yes | Yes | Yes |
| Year dummies | Yes | Yes | Yes |
| Observations | 1,617 | 4,558 | 7,828 |
| R2 | 0.287 | 0.157 | 0.046 |

Notes. T-statistics in brackets. The sample includes only observations for which an investment is recorded. Standard errors are clustered on households. Results marked with one to three stars are statistically significant at 10%, 5% and 1% respectively. $: Energy integrity corresponds to insulation, storm doors and windows, roofing and siding.

In the case of major equipment, we find that expenditures are higher when temperatures are higher (i.e. with more cooling degree days) or when electricity prices are important. Unfortunately, the model of expenditure for energy integrity has low statistical significance, which may be due to the heterogeneity of the investments covered with this category or because the impacts that we want to assess are small. Finally, for the other indoor improvements, we find a statistically significant impact of government loans or grants on the amounts invested by households. It appears that the benefiters of these subsidies or loans have invested more money in home improvements than non-benefiters.

### *Results of the model of residential energy consumption*

#### Electricity consumption

The predictions of the home improvement model are used as explanatory variables in fixed effect models of electricity consumption. Table 4 displays the results of our base specification, with exogenous energy prices. This specification includes the squared $\widehat{K}_{h,i,t}$ and interaction parameters that proved to be statistically significant and are therefore likely to influence electricity consumption. For the sake of comparison, the results without interaction parameters are also provided. Additionally, the results of the alternative 2SLS specification with endogenous prices are also displayed. To ease interpretation, the specification with endogenous electricity prices does not include interactions and squared parameters.

In our base specification, we find that the capitalized investments in major equipment, energy integrity and other indoor amenities have statistically significant and non-linear effects on electricity consumption. When accounting for all the interactions, one can find that investments in major equipment and other indoor amenities tend to increase energy consumption, whereas the investments in energy integrity tend to decrease them. However, the magnitude of these effects depends on the total amounts that have been invested in the different types of housing services. For example, when the amounts accumulated in major equipment and energy integrity are high, the additional investments in these categories are more likely to correspond to energy conservation investments, as captured by the negative coefficient associated with the interaction between $\widehat{K}_{1,i,t}$ and $\widehat{K}_{2,i,t}$.

Our model also captures statistically significant responses to temperature shocks. As we have included an interaction parameter between investments in major equipment and heating degree days in our base specification, the net effects of a change in heating and cooling degree days is not easy to read in the base specification, but appears much clearer in the linear cases. In fact, a one-unit increase in heating degree days increases electricity consumption, but less than a one-unit increase in cooling degree days.

**Table 4: Linear models of residential electricity consumption**

| Independent variables | Exogenous energy prices (base specification) | Exogenous energy prices (no interaction parameter) | Endogenous energy prices (2SLS) |
|---|---|---|---|
| Capitalised investments in major equipment, $\widehat{K}_{1,i,t}$ | 0.000181<br>(0.38) | 0.000054<br>(0.25) | -0.000059<br>(-0.33) |
| *Squared* | 4.48E-8**<br>(2.47) | | |
| Capitalised investments in energy integrity[$], $\widehat{K}_{2,i,t}$ | -0.000267**<br>(-2.07) | -0.000225***<br>(-2.9) | -0.000227***<br>(-2.94) |
| *Squared* | 3.03E-9***<br>(2.7) | | |
| Capitalised investments in other indoor improvements, $\widehat{K}_{3,i,t}$ | 0.000195***<br>(3.03) | 0.000125***<br>(3.2) | 0.000129***<br>(3.22) |
| Interaction parameters: | | | |
| $\widehat{K}_{1,i,t}$ x $\widehat{K}_{2,i,t}$ | -1.40E-8***<br>(-2.66) | | |
| $\widehat{K}_{2,i,t}$ x $\widehat{K}_{3,i,t}$ | -1.11E-9*<br>(-1.75) | | |
| $\widehat{K}_{1,i,t}$ and heating degree days | -1.54E-7**<br>(-2.55) | | |
| Heating degree days | 0.004284***<br>(4.11) | 0.002356***<br>(3.05) | 0.001266<br>(1.45) |
| Cooling degree days | 0.003756***<br>(3.06) | 0.003832***<br>(3.18) | 0.005118***<br>(3.05) |
| Number of days with precipitations over 0.5 inches | 0.008216<br>(0.25) | 0.003253<br>(0.1) | -0.005669<br>(-0.17) |
| Price of electricity | -0.272799***<br>(-2.7) | -0.288399***<br>(-2.91) | -1.63615***<br>(-4.17) |
| Price of gas | 0.169272<br>(0.65) | 0.187329<br>(0.73) | 1.294374<br>(0.85) |
| Household income | 0.844967***<br>(3.02) | 0.851453***<br>(3.08) | 0.964012***<br>(3.47) |
| Constant | 15.62005*<br>(1.76) | 23.24609***<br>(2.98) | |
| Household fixed effects | Yes | Yes | Yes |
| Year dummies | Yes | Yes | Yes |
| Observations | 18,870 | 18,870 | 14,372 |
| R2 | 0.042 | 0.041 | 0.017 |

Notes. T-statistics in brackets. Results marked with one to three stars are statistically significant at 10%, 5% and 1% respectively. Standard errors are clustered on households. $: Energy integrity corresponds to insulation and storm doors and windows. In the specification at the right, 2SLS are used to instrument electricity and gas prices. The instruments are: the industrial price of gas in the State, the residential price of electricity in neighbouring States and the residential price of gas in neighbouring States. The instruments pass the tests of underidentification, overidentification and weak identification, which ensure their validity. The Kleibergen-Paap rk Wald F statistic is 72.3 suggesting that the IV size biais is inferior to 10% and the Hansen J Statistic is 0.12. The p-value of the overidentification test is 0.73.

Unsurprisingly, the price of electricity reduces electricity demand and income has a positive and statistically significant impact on electricity consumptions. We find no impact of precipitations on electricity consumptions.

The results of the linear model without interaction parameters are very similar to the results of our base specification. However, the model fails to capture a statistically significant impact of the additions in major equipment on energy consumption, and also fails to account for a differentiated effect of the three types of home improvements depending on the climatic context. Besides, the 2SLS results are very similar to the results of the fixed effect linear model. This corroborates our assumption that electricity and gas prices can be considered as exogenous.

### Gas consumption

Table 5 displays the results of our random effect tobit model for residential gas consumption. It also includes interaction parameters and squared variables. Like for the residential electricity consumption model, we furthermore provide the results of a random effect tobit model with no interaction parameters.

We can properly account for the decision to use gas or not because we know if the household can easily be connected to a gas pipe present in the neighbourhood. The coefficient for this variable is both strong and particularly statistically significant.

On the other hand, the impacts of the home improvement variables on gas consumption are very similar to the impacts on electricity consumption. In average, investment in major equipment would increase gas consumption, investments in energy integrity would reduce it and investments in all other indoor amenities would increase it. However, the magnitude of these effects depends on the initial stock of capital in the three types of housing services.

The major difference in the gas consumption model relates to the sensitiveness of gas consumption to temperatures: a one-unit increase in heating degree days has a significant and stronger impact on gas consumption than a one-unit increase in cooling degree days. This is the exact opposite as for electricity, and this can interact with the investments that are performed in insulation and major equipment. At sufficiently high temperatures, the investments in major equipment are negatively correlated with gas consumption. Our interpretation is that, at sufficiently high temperatures, the installation of major equipment consists in air conditioners and electric heaters instead of gas heaters.

**Table 5: Random effect tobit models of residential gas consumption**

| Independent variables | Base specification | No interaction parameters |
|---|---|---|
| Capitalised investments in major equipment, $\widehat{K}_{1,i,t}$ | 0.00614***<br>(3.76) | 0.000221<br>(0.62) |
| *Squared* | 6.27E-8***<br>(2.58) | |
| Capitalised investments in energy integrity[$], $\widehat{K}_{2,i,t}$ | -0.001275***<br>(-4.2) | -0.000322***<br>(-2.69) |
| *Squared* | 5.41E-9**<br>(2.41) | |
| Capitalised investments in other indoor improvements, $\widehat{K}_{3,i,t}$ | 0.000284***<br>(2.87) | 0.000248***<br>(4.19) |
| Interaction parameters: | | |
| $\widehat{K}_{1,i,t}$ x $\widehat{K}_{2,i,t}$ | -2.24E-8**<br>(-2.11) | |
| $\widehat{K}_{2,i,t}$ x $\widehat{K}_{3,i,t}$ | -2.37E-9**<br>(-2.03) | |
| $\widehat{K}_{1,i,t}$ and heating degree days | -7.65E-7***<br>(-3.58) | |
| $\widehat{K}_{1,i,t}$ and cooling degree days | -2.19E-6***<br>(-3.97) | |
| $\widehat{K}_{2,i,t}$ and heating degree days | 1.53E-7***<br>(4.3) | |
| $\widehat{K}_{2,i,t}$ and cooling degree days | 3.96E-7***<br>(4.26) | |
| Heating degree days | 0.006336***<br>(4.13) | 0.005531***<br>(6.03) |
| Cooling degree days | 0.007614**<br>(2.02) | 0.001608<br>(0.88) |
| Number of days with precipitations over 0.5 inches | -0.108852<br>(-1.24) | -0.06881<br>(-0.8) |
| Price of electricity | 0.002602<br>(0.02) | 0.081719<br>(0.58) |
| Price of gas | -4.100268***<br>(-9.09) | -4.203105***<br>(-9.53) |
| Household income | 1.942543***<br>(2.8) | 1.884413***<br>(2.74) |
| Age of householder | 0.075173*<br>(1.89) | 0.08229**<br>(2.06) |
| Gender of householder (male is reference) | -1.31169<br>(-1.04) | -1.516946<br>(-1.2) |
| Year when unit was built | -0.205853***<br>(-6.81) | -0.190006***<br>(-6.35) |
| Type of housing unit (reference is detached): | | |
| Attached, one-building unit | -22.04899***<br>(-9.32) | -22.00561***<br>(-9.29) |
| Building with 2 appartments or more | -48.18212***<br>(-22.94) | -48.00599***<br>(-22.84) |
| Census region (reference is Northeast): | | |
| Midwest | 6.961227**<br>(2.5) | 4.876998*<br>(1.77) |
| South | -13.82028***<br>(-3.83) | -14.74702***<br>(-4.11) |

| Independent variables | Base specification | No interaction parameters |
|---|---|---|
| West | -32.75207***<br>(-8.06) | -32.48167***<br>(-8) |
| Neighborhood is connected to gas pipes | 158.8539***<br>(64.01) | 158.8942***<br>(63.95) |
| Constant | 326.7075***<br>(5.31) | 313.7656***<br>(5.25) |
| Year dummies | Yes | Yes |
| Observations | 18,846 | 18,846 |

Notes. T-statistics in brackets. Results marked with one to three stars are statistically significant at 10%, 5% and 1% respectively. $: Energy integrity corresponds to insulation and storm doors and windows. 4529 left-censored observations and 15 right-censored (top coded) observations.

## 6. Implications and long-run simulation

### *Expected impacts from climate change*

In the energy consumption models, a one unit increase in cooling degree days has a larger impact on electricity consumptions than a one unit increase in heating degree days, whereas the opposite has been found for gas consumption. Increases in average temperatures should therefore raise the electricity bills of US households, but lower their gas bills. This result has already been obtained at national level by Deschênes and Greenstone (2011) for electricity. At regional level, similar analyses have been made by Auffhammer and Aroonruengsawat (2011) and Amato *et al.* (2005).

Additionally, the results of our home improvement model lead to the conclusion that US homeowner may increase the total amounts that they invest in their homes as a result of climate change, to perform both adaptations that will increase energy consumption, and adaptations that will reduce it.

For major appliances, the model predicts that increases in temperatures should lead to more frequent alterations along with an increase in the average expenditure made for each investment. In parallel, the model of energy consumption pinpoints that an increase in the capital invested in this category tend to increase electricity consumption. Our model results are therefore broadly consistent with the idea that consumers may equip more their homes with air-conditioners under climate change. Furthermore, the adoption of air-conditioners may not be compensated by the use of more energy efficient electric appliances.

Additionally, we find that works in insulation, storm doors and windows, roofing and siding will become more frequent with higher temperatures, even though our model could not predict the average amounts invested in a satisfactory way. Under climate change, we can therefore expect consumers to equip themselves with air-conditioners but also to improve the energy integrity of their homes.

On the other hand, households seem to adapt to temperature changes by performing additional home improvements to their homes, even though this effect was only statistically significant at 10%. Our model predicts that temperature increases lead to slight increases in the capital stock invested in other aspects of the home, not directly related to energy use (as major equipment or insulation) but which may, in average, increase energy consumption.

Based on these results, we can provide a quantitative assessment of the net impact of all these adaptations on energy use, from short run responses to long run adjustments of capital stock. To assess long-run changes in electricity and gas consumption under climate change, we simulate the year-on-year capital adjustments in housing services likely to occur under climate change, caused by progressive temperature shocks affecting us housing and residential energy use.

### *Simulation*

Our simulation is based on the coefficients of the home improvement model and the energy consumption model as estimated with the AHS, NOAA and SEDS data. Please note beforehand that the results must be interpreted carefully: they directly depend on the accuracy of the coefficients as we have estimated them. Furthermore, we are interested in long run trends and we are extrapolating the validity of these coefficients to a very long time frame. This simulation exercise is therefore bound by the fact that our home improvement and energy consumption models only provide limited knowledge, and with statistical uncertainty, on capital accumulation in housing services and energy consumption by households. Besides, our simulation does not take into account many factors that will affect energy demand, in particular economic and population growth. Importantly too, it does not take into account the likely changes in the technologies used for space heating and air-conditioning, in particular in terms of energy efficiency but also the fact that gas could be more frequently used for air-conditioning in the coming decades. This is why our simulation does not aim to provide an estimate of energy demand within 20 or 50 years, but is above all interested in the likely magnitude of temperatures and climate change adaptation as a driver for residential energy demand. We want to assess if, based on the model results, we should expect that adaptation of the housing stock increases or reduces energy demand.

Our simulation is run for a representative household whose initial capital stock in each type of housing services is equal to the average of our data sample. Likewise, we assume that this representative household consumes an amount of electricity and an amount of gas equal to our data average and is subject to heating and cooling needs corresponding to the mean heating degree days and cooling degree days of our sample. Similarly, his probability to perform an investment in one category and the amount that he would invest are equal to the average predicted probability and predicted amount obtained with our sample.

To assess the impact of climate change on electricity while allowing for capital adjustments in housing services, we construct a baseline scenario in which there is no climate change and then compare it with a climate change scenario. For the baseline scenario, we recurrently compute, from one year to the other, the evolution of the capital stock of the representative household assuming no change in heating or cooling degree days. The change in capital stock is then simply driven by the fact that we have predicted an average amount of investments to be performed each year (equal to the expected probability of investing times the predicted amount that is invested at each time period), which evolution depends on the capital already accumulated in major equipment, energy integrity and other indoor home improvements. From one year to the other, we can therefore define baseline values for the amount of capital embodied in each category of housing services. Additionally, we create baseline electricity and gas consumption values. They correspond to the average electricity and gas consumption of our sample, which are adjusted to take into account the predicted changes in capital likely to occur from one year to the other.

In parallel, we construct a climate change scenario close to IPCC (2013) scenario RCP6.0. This scenario corresponds to a 3°C (5.4° F) temperature increase between 2000 and 2100. To generate this scenario, we make the simplifying assumption that the temperature increase over the century is steady over time; the same over the US; that a 1°F increase corresponds to 182.5 cooling degree days more and 182.5 heating degree days less[16]; and does not affect precipitations. In the climate change scenario, the representative household responds to the temperature shock by increasing immediately his electricity and gas use, and also adapts through home improvements which have persistent effects on energy consumption: the steady increase in temperature modifies the amounts of capital that are invested each year in the three categories of housing services. The changes in invested capital are calibrated based on the probabilities to invest and the predicted amounts that are invested according to the econometric model of home improvements. The simulated values for the accumulated capital in the three types of housing services are reported in Annex C for the baseline and the climate change scenarios.

[16] This corresponds to a schematic case in which temperatures homogenous increase by the same amount of degrees all year round, assuming 6 months (182.5 days) in which days have an average temperature under 65 Fahrenheit degrees and 6 months in which days have an average temperature over 65 Fahrenheit degrees.

### *Impacts in terms of energy consumption*

Figure 1 and Figure 2 present the evolution of electricity and gas consumptions as simulated for our representative household between 2000 and 2100. In each Figure 4, the grey line corresponds to the scenario without climate change whereas the black line corresponds to the climate change scenario. The difference between the two lines corresponds to the impact of climate change, including both immediate shocks from higher temperatures and capital adjustments. The model predicts a shift from gas (-13.4% by 2100 in the policy scenario as compared to the baseline) to electricity (+7.7%). Interestingly, this shift from gas to electricity consumption reduces total energy demand by 6.1%, estimated at 122.7 MM.btu for the representative household in 2100 in the baseline scenario, versus 115.1 MM.btu in the climate change scenario.

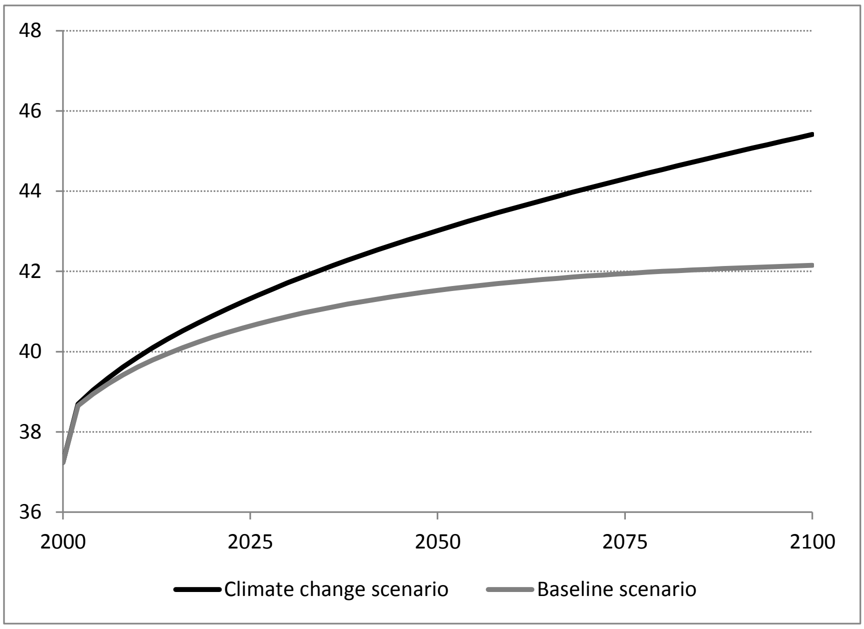


**Figure 1: Electricity consumption under the baseline and climate change scenarios (million btu for the representative household)**

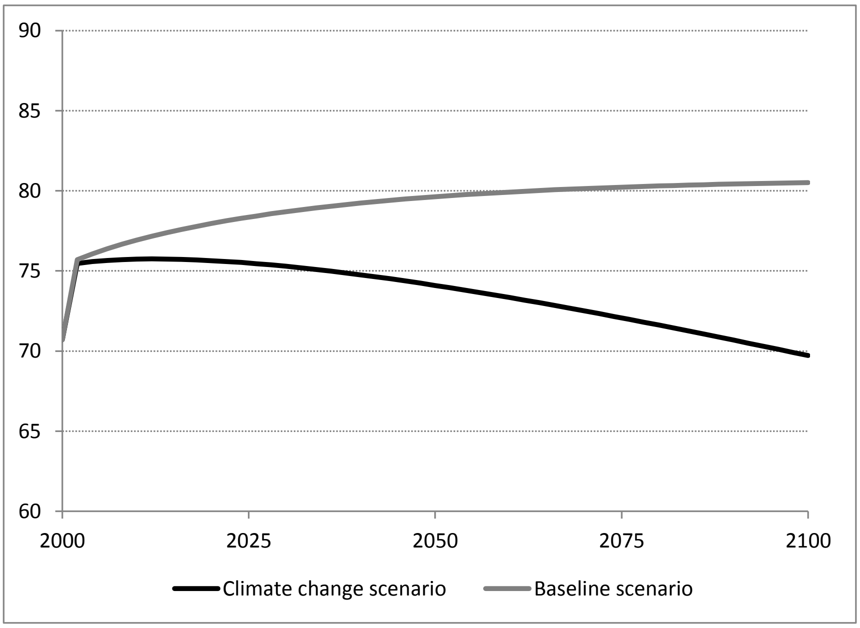


**Figure 2: Gas consumption under the baseline and climate change scenarios (million btu for the representative household)**

To analyse the contribution of immediate temperature shocks on energy consumption levels, we run additional simulations in which we assume no change in the stock of capital. Likewise, to analyse the contribution of major equipment and energy integrity altogether, we run a simulation in which we assume no change in the accumulated capital in other indoor amenities. To finally understand the role of major equipment alone as a driver of energy consumption, we run a last simulation in which we assume no adjustment of the stock of capital in energy integrity and other indoor improvements. Figure 3 and Figure 4 compare the results on electricity and gas consumption obtained with our reference simulation and these additional simulations. The comparison of all these simulations allows us to analyse the relative contribution of each type of capital on electricity and gas consumption.

For electricity consumption, direct changes in consumption resulting from higher temperatures explain 28%.1 of the increase in consumption by 2100, whereas 46.7% are explained by major equipment and 25.2% by other indoor amenities. On the other hand, improvements in insulation reduce the total increase in electricity consumption resulting from climate change by 6.2%.

At the same time, direct changes in consumption resulting from higher temperatures explain only 0.3% of the decrease in gas consumption by 2100. This is based on the model estimates even though we may coherently assume that this model may be underestimating the role of higher temperature on the reduction of gas consumptions. The remaining is explained by the substitution of major equipment in favour of electrical appliances (98.3%) and a small share by energy integrity improvements (1.4%). On the other hand, other amenities reduce the gas savings resulting from climate change by 13.8% as compared with total potential savings.

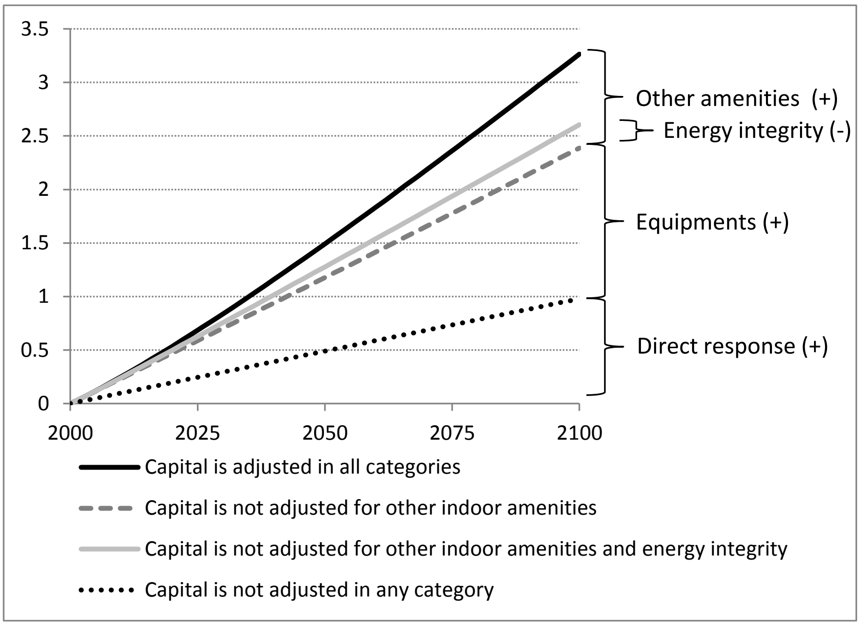


**Figure 3: Impact of climate change on electricity consumption (MM.btu/year) when allowing for household level capital adjustments or not**

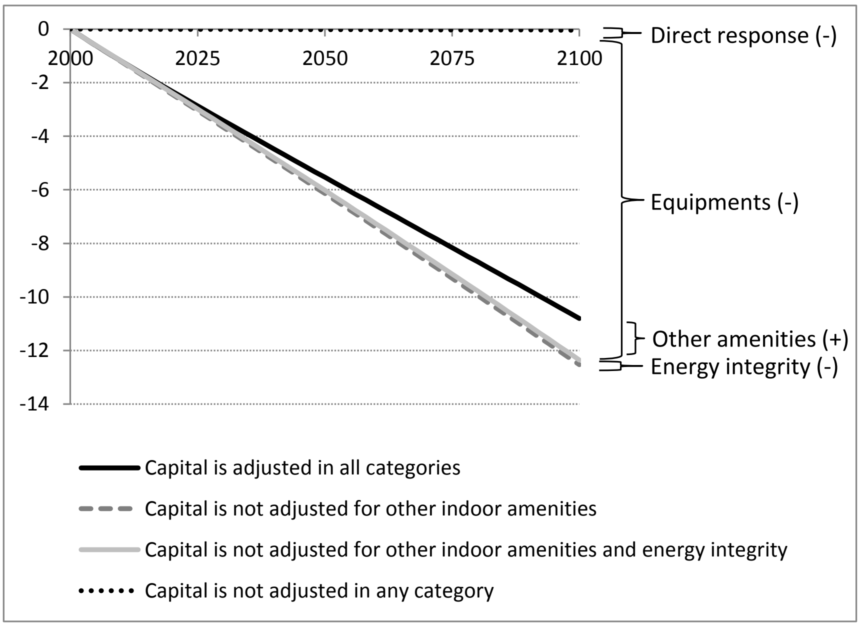


**Figure 4: Impact of climate change on gas consumption (MM.btu/year) when allowing for household level capital adjustments or not**

We therefore find that a higher use of the air conditioners already installed will increase electricity demand, whereas the installation of new electric heaters and air-conditioners will accentuate this phenomenon. Furthermore, we understand that the adjustment in major equipment in favour of electric appliances could have a strong effect in reducing residential demand for gas.

Besides, our econometric model of home improvements predicts that additional indoor home improvements (including kitchens, bathroom and home extension) could be correlated with higher temperatures. The coefficient leading to this result in the logit model for other indoor improvements is only statistically significant at 10% and, consequently, precautions must be made at interpreting the results of the simulation that are derived from it. However, the category covered with all other indoor amenities constitutes the largest share of capital embodied in a home and can correspond, in practice, to a very large panel of improvements. In this sense, changes in temperatures are likely to produce changes in behaviour and in lifestyle that could go beyond protection from heat. In the long run, these changes could have strong impacts on electricity and gas consumption. Based on our model alone, we cannot be certain that they will increase the burden on electricity and gas systems, even though the statistical evidence goes in this direction.

### *Impacts in terms of GHG emissions*

We can convert the predicted changes in energy use in GHG emissions to analyse the impact of the adaptation of energy demand on climate change mitigation. To do so, we use the emissions factor of the Greenhouse Gas Equivalencies Calculator of EPA: one million btu of electricity corresponds to 202.16 kg of $CO_2$ equivalent and one million btu of natural gas to 53.02 kg $CO_2$ equivalent.[17] At using these emissions factors, we convert energy consumption from electricity and gas in GHG emissions while making the strong assumption of no change in the energy mix of electricity generation between today and the end of the century.

The results of this calculation, displayed in Figure 5, pinpoint that, if electricity goes on being generated with current energy mix, the GHG emissions produced from residential energy consumption could slightly increase (+0.7% by 2100) as a result of climate change, in spite of a total residential energy demand reduction by 6.1%.

[17] http://www.epa.gov/cleanenergy/energy-resources/calculator.html#results. Website consulted in March 2014.

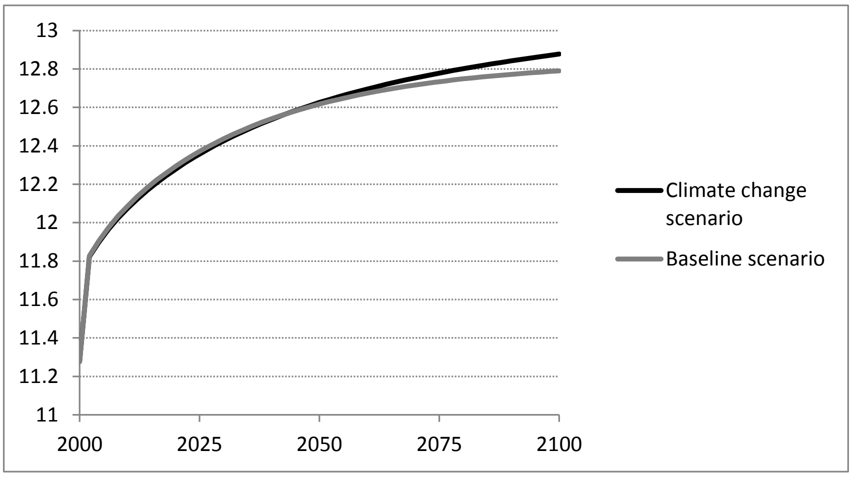


**Figure 5: GHG emissions (in metric tons of CO2 equivalent/year) from the energy consumption of the representative household**

On the other hand, assuming twice fewer emissions from electricity generation by 2100, the impact of residential adaptation to climate change could lead to a net reduction of GHG emissions by 2.8% for this same year. Therefore, if electricity generation was decarbonised, then the shift of residential demand from gas to electricity would not generate so many additional GHG emissions and long term adaptation to climate change in the residential sector could have a positive impact in terms of climate mitigation.

# 7. Conclusion

This research has developed a two-stage econometric model to analyse residential electricity and gas consumption. In the first stage, we have analysed the responsiveness of residential renovation efforts to climatic change. The results of our first stage have then been used in the second stage to predict how residential electricity and gas demand could evolve under climate change.

This research finds that total energy demand could decrease in the US as a result of climate change, with an estimated decrease by 6.1% in 2100. However, residential energy demand would shift from gas to electricity, which consumption has been simulated to rise by 7.7% by the end of the 21st century, assuming a 3°C inland temperature increase with respect to today's temperatures. From the perspective of climate mitigation and due to the high carbon content of US electricity, the reduction in total energy demand would not be enough to offset the additional GHG emissions created by a shift in residential demand from gas to electricity. Our research therefore pinpoints that, as electricity is likely to be more and more often used as a principal source of energy in residential units, particular attention should be paid by policy-makers to reduce the carbon footprint of electricity.

On the other hand, our model predicts that the increase in electricity consumption will be less due to a more frequent use of already installed air-conditioners than to the further adoption of new air conditioners and a shift from gas heating to electric heating. Furthermore, our model predicts that changes in housing that are not related to energy consumption could occur concomitantly and put more stress on energy systems.

Some of the results of this research have already been found by previous scholars, in particular Deschênes and Greenstone (2011) and Auffhammer and Aroonruengsawat (2011) regarding the relationship between temperature shocks and electricity consumption. Our contribution is to provide a statistical analysis of the reasons behind the likely increase in electricity consumption under climate change. Above all, we find that this increase should be compensated by a decrease in gas consumption, and that the principal driver of all these changes would be a modification in the composition of the equipment installed in dwellings.

Precautions should be however taken at analysing our model results, as we have assumed no economic growth or demographic evolution. Furthermore, we have assumed no change in the technologies available to households for space heating and air-conditioning, in terms of energy efficiency, but also in terms of fuel choice for space heating or air-conditioning: our results are conditional on gas not being used more often for air-conditioning.

Additionally, note that the US housing stock is relatively specific to the extent that gas consumption is high and air-conditioning is already present in many US homes: 83% of units in our sample are in neighbourhoods that have access to pipe gas whereas 89% of households declared having at least one air-conditioner at home. Thus, there is clearly a need in conducting similar studies on the relationship between climate change and energy demand in other countries, in particular developing countries that face high constraints in terms of energy security. There is furthermore a need to understand better the relationship between climate change and the demand for primary goods, such as electricity but also water and food. Demand for basic products is likely to evolve due to the many changes in lifestyle that could arise due to changes in temperatures and precipitation levels. In this direction, more research is required to understand how climate change could interact with lifestyles.

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# Housing capital in the simulation

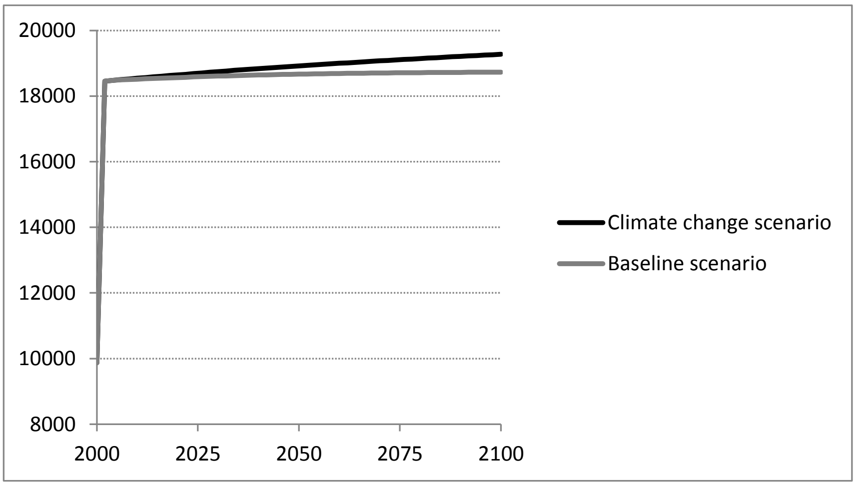


**Figure A.1: Capital invested in major equipment (2011 dollars)**

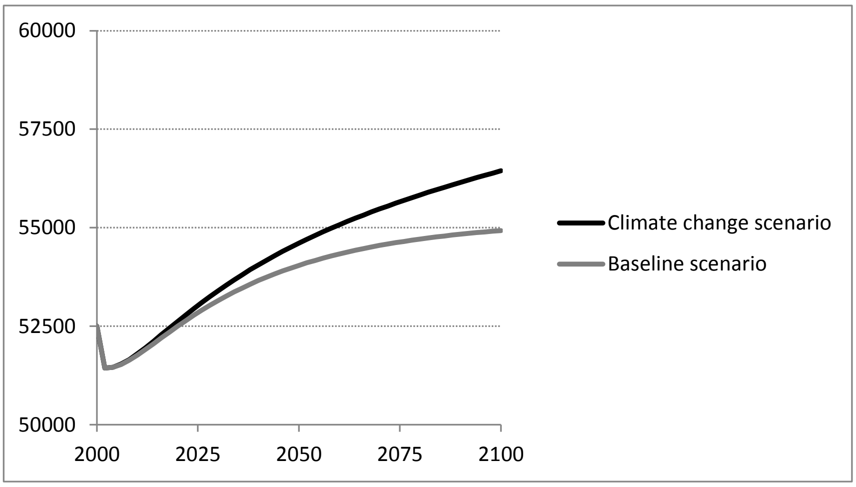


**Figure A.2: Capital invested in energy integrity (2011 dollars)**

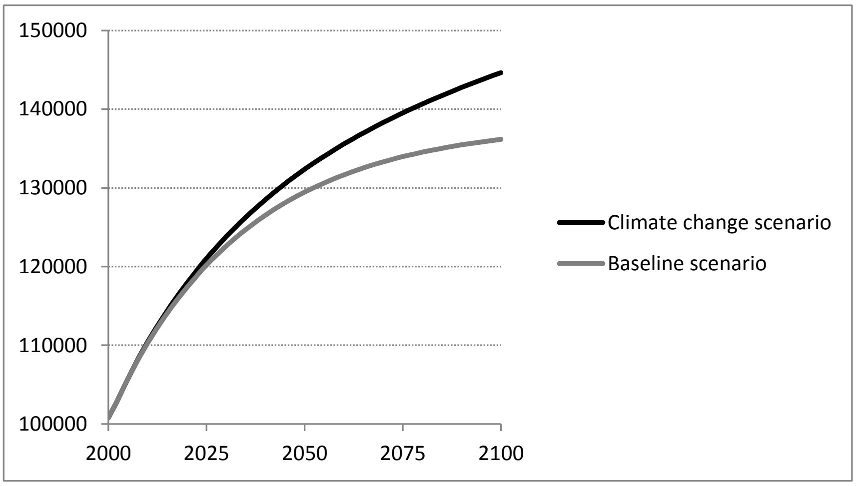


**Figure A.3: Capital invested in other indoor amenities (2011 dollars)**