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$$\frac{n!}{(n-1)!} p^{m-1} (1-p)^{n-m} = p \sum_{\ell=0}^{n-1} \frac{\ell+1}{n} \frac{(n-1)!}{(n-1-\ell)! \ell!} p^{\ell} (1-p)^{n-1-\ell}$$
$$= p \frac{n-1}{n} \sum_{\ell=0}^{n-1} \left[\frac{\ell}{n-1} + \frac{1}{n-1} \right] \frac{(n-1)!}{(n-1-\ell)! \ell!} p^{\ell} (1-p)^{n-1-\ell} = p^2 \frac{n-1}{n} +$$

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The Elusive Effects of Residential Energy Efficiency Improvements: Evidence from Ukraine

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Abstract:

Untapped improvements in energy efficiency in the residential sector may deliver large savings in energy use and the CO₂ associated emissions. Yet empirical assessments have been difficult and controversial. We collect monthly natural gas meter readings from a sample of homes in Transcarpathia, in Western Ukraine, an early adopter of the country's trend away from district heating, from January 2013 to April 2017, a period over which the residential natural gas tariffs rose by over 700%. We combine the monthly meter readings with documentation about each household's heating-related energy efficiency upgrades to the home (wall, attic or basement insulation; new windows; boiler replacement, and insulation around pipes) to form a panel dataset. We estimate the effect of the energy efficiency renovations on natural gas consumption, controlling for weather, income and government energy assistance. The decision to do the renovations and natural gas consumption are likely endogenous (people do the renovations because they hope to consume less), so we instrument for the renovations by creating a cross-validation instrument based on a supply-side argument. Even for a given type of energy efficiency upgrades, the estimated effect of the renovations varies dramatically in magnitude, depending on whether the renovations are instrumented for and on how detailed the fixed effects are. The coefficients on the renovations are almost always negative in our regressions, but practically and statistically significant only when we

instrument for the renovations. This is in agreement with our respondents' difficulty assessing whether the renovations had saved them gas or money. The IV estimates indicate that insulation delivers 13-24% reductions in natural gas usage, and up to a 5% internal rate of return (IRR) to the investment over 20 years. Judicious use of an existing government program can yield positive IRRs and make energy efficiency upgrades a good investment in a generally poor-performing housing market.

JEL: D12, Q41, Q48

Keywords: Residential gas demand, long-run effects, tariff reforms, energy efficiency

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1. Introduction

Improving energy efficiency is credited as a low- (or even *negative*-) cost means of reducing greenhouse gas emissions, pressure on grids and energy delivery infrastructure, and dependence on imports (McKinsey, 2009; Eurostat, 2018). At many locations, the residential sector is a good candidate for an energy efficiency overhaul, but this has often occurred at a slower pace than expected, despite the obvious improvements in comfort and the savings brought about by energy efficient technologies (Jaffe and Stavins, 1994; Allcott and Greenstone, 2012; Gillingham et al., 2018).

Indeed, in empirical work both the “causes” and the “effects” of energy efficiency improvements have proven surprisingly elusive. Economic theory and common sense would suggest that the higher the price of energy inputs, the stronger—all else the same—the incentives to do energy efficiency improvements (Kilian, 2008). However, earlier research in this area has had mixed results and been generally inconclusive. Hastings and Shapiro (2013) document that when the price of gasoline increases, people substitute towards low-grade gasoline, but do not purchase cars with better fuel economy. Jacobsen (2015) finds that the shares of Energy Star appliances across the United States are not affected at all by the prices of electricity. Busse et al. (2013) find that the increasing motor fuel prices increase the share of fuel-efficient vehicles in the market for new cars, while in the used car market the prices will adjust to reflect the diminished desirability of older and less efficient models.

The effect of fuel or energy price changes may be masked by producers’ offers and discounts (Langer and Miller, 2013) or portfolio adjustments involving the launch of new efficient products and the withdrawal of less efficient models (Cohen et al., 2015). Even in the absence of such supply-side responses, energy prices may have little effect on the stock of

energy-using capital due to insufficient salience (Chetty et al., 2009) or inattention (Sallee, 2014), especially when energy efficiency is trumped by other attributes of the energy-using durable.

It is generally difficult to evaluate the effect of energy efficiency (EE) programs or private EE upgrade decisions, on actual consumption,¹ in part because they entail self-selection (people who are more productive or more motivated to reduce energy use will typically be attracted into EE programs) and in part because of possible rebound effects (Aydin et al., 2017) or other behavioral responses (Young, 2008).² Even when self-selection is addressed through appropriate study design and estimation techniques, the evidence is surprisingly weak and confusing (Nadel, 2016).

Metcalf and Hassett (1999) find that with several of the estimation procedures they attempted the reduction in energy use associated with renovations is small and statistically insignificant. In the two instances when it is appreciable and statistically significant, one approach produces an estimate that is twice as large as the other (-0.081 v. -0.04). Fowlie et al. (2018) exploit a randomized controlled trial where households eligible for the Weatherization Assistance Program (WAP), a federal program that subsidizes energy efficiency renovations and weather proofing to low-income households, are randomly assigned to an “encouragement” treatment, which is subsequently used as an instrument for the decision to undertake WAP

¹ Actual consumption reflects behavior, and is thus preferred by economists over ex ante engineering estimates, which have in some cases been concluded to overstate the energy savings (Fowlie et al., 2018; Graff Zivin and Novan, 2016). By contrast Alberini et al. (2016) find reasonable good agreement between estimated energy use reductions and those predicted by engineering models.

² The rebound effect results in the erosion of the efficiency gains after an improvement in energy efficiency (Sorrell et al., 2009). It may be attributed to the fact that energy efficiency improvements make energy services (e.g., a warm home, hot water, cooked food, lighting) cheaper, which in turn increases the demand for them. Young (2008) finds that the participants in an energy-efficiency program in Canada that subsidized new and highly efficient refrigerators did not replace their old and inefficient ones: They kept them and simply continued to use them as “beer fridges,” for a total net increase in electricity consumed.

renovations. Their “experimental” estimates of the effect based on this estimation approach range from -0.10 to -0.20, and are either statistically insignificant or have t statistics that are surprisingly low (2.5 to 2.625) for samples with over a million observations.

While Fowlie et al. examine energy (combined gas and electricity), attention is restricted to electricity in Graff Zivin and Novan (2016), who use a sample of 275 low-income households eligible for energy assistance, all of whom received free retrofits. An additional “behavioral” treatment (based primarily on education and on a voluntary commitment to reduce electricity usage) was administered to 38 households. Electricity usage declined by 7% in homes with air conditioning as a result of the retrofit, and an additional 24% reduction is attributable to the behavioral treatment. By contrast, no significant effects were observed in homes without air conditioning. The sample was a panel with no more than 12 monthly meter readings per household. Graff Zivin and Novan’s estimates are much more modest than the savings in electricity usage predicted by the engineering software used by the utility.

If even with randomized control trials the evidence is weak, is there something about residential energy consumption that makes it so difficult to assess the effects of EE upgrades? In this paper we explore this question using monthly, household-level data from homes in Transcarpathia in Western Ukraine. **Ukraine is one of the least energy-efficient countries in the world: It uses almost four times as much energy per unit of GDP as the European average (Rozwalka and Tordengren, 2016). Ukrainian households consume 32% more heat per square meter than the European average, after adjusting for heating degree days (Rozwalka and Tordengren, 2016), and housing is in bad need of EE upgrades.**

The stock of housing in our study area—the Uzhhorod metro area—is typical of that of many other cities and towns in Ukraine: Some 70% of the dwellings were built during the Soviet

era and are poorly insulated. Transcarpathia disconnected district heating in 2005-2012, which means that by the beginning of our study period (January 2013) all households in the region were fully in control of their heating system and heating fuel consumption, and were individually metered.

We collect detailed information about the timing of insulation, new windows, boiler replacement, etc. to see if natural gas consumption is lower after these measures are put in place, and, if so, by how much. Since EE renovation decisions are arguably endogenous with natural gas consumption, and we do not have a randomized controlled trial at our disposal, we instrument for the renovations using “leave-one-out” instruments based on a supply-side argument. We test the quality of these instruments extensively. An additional challenge is the fact that renovations are usually done in the summer but their benefits are experienced during the heating season, which prompts us to aggregate the observations to the “quadrimester” level. We use a rich set of fixed effects to capture as much unobserved heterogeneity as possible.

In sum, in our sample of homes in Uzhhorod the most popular types of EE upgrades tend to help reduce natural gas usage, although the exact magnitude of the reduction varies widely among specifications, and is practically and statistically significant at the conventional levels only when we i) instrument for the renovations, ii) focus on a “clean” set of renovations that are well-matched by the instruments (insulation and new windows), and iii) strike the right balance between capturing the unobserved heterogeneity and sacrificing too many degrees of freedom through multiple fixed effects. Our strongest results imply a 13% to 24% reduction in natural gas usage attributable to the renovations, but the full range is a 1% to 24% decline.

The percentage reduction in gas usage attributable to the renovations must be at least 16% for the internal rate of return (IRR) to the investment to be 1% or higher. An existing

government-supported loan program (“Warm Loans”) however helps private homeowners and helps increase the IRR, as long as the interest rate is not too high (or a larger down payment is made, thus lowering the principal of the loan and hence interest payments).

The remainder of this paper is organized as follows. Section 2 presents background information. Section 3 presents the data and section 4 the methods. Section 5 describes the results, and section 6 offers a discussion and conclusions.

2. Background

A. Household Consumption and Bills

In May-July 2017, we collected data about natural gas and electricity use by households in Uzhhorod, a city with some 113,000 residents in western Ukraine.³ Unlike other parts of Ukraine, where district heating still serves a significant share of the homes,⁴ Transcarpathia, the administrative region where Uzhhorod is located, started disconnecting dwellings from district heating in 2005 as part of a pilot project. Motivated by high costs, dilapidated infrastructure, major losses along the network, unreliable heat supply and district heating’s notorious wastefulness, Transcarpathia was actually the first region in Ukraine to cut district heating.

The process was completed by 2012, which means that by the beginning of our study period (January 2013), everyone had installed and had been using their own separate heating

³ Ukraine, formerly a member of the USSR, achieved independence in August 1991. Since then the Ukrainian government liberalized most prices and established a legal framework for privatization. Ukraine’s economy fell into crisis after Russia’s annexation of Crimea in 2014, military conflict in the eastern part of the country, and a trade war with Russia, resulting in a 17% decline in GDP. GDP declined by 6.6% in 2014 and 9.8% in 2015, but recovered somewhat to real growth rates of 2.4% and 2.5% in 2016 and 2017, respectively. In 2017 GDP per capita was \$8,800 (2017 purchasing power parity dollars) (CIA Factbook, see <https://www.cia.gov/library/publications/the-world-factbook/>, last accessed 21 March 2019). For comparison, GDP per capita was \$50,800 in Germany, \$59,800 in the United States, and \$33,100 in Slovakia, a neighboring country (2017 purchasing power parity dollars).

⁴ Some 30-40% of the dwellings in Ukraine are served by district heating (Nithin Umaphathi, the World Bank, private communication, March 2019, and Emerson and Shemkin, 2015). District heating usually serves multifamily buildings.

systems, even in multifamily buildings. The majority of the homes in the Uzhhorod metropolitan area are heated by gas boilers (and radiators), and natural gas is supplied by PJSC Zakarpatgaz, a state-owned utility.⁵

People receive their gas bills every month, and charges are based on actual (not estimated or presumptive) consumption for that month, as per the monthly meter reading conducted by a representative of the utility. The bills (see Figure 1) display clearly the meter reading at the end of the current and previous billing periods, consumption as the difference between them, the tariffs, and any applicable “benefits” (described below). There is no fixed monthly charge: In other words, Transcarpathians pay a one-part tariff. Many households also maintain their own “utility book,” where they manually record the same information as the bill.

B. Tariffs and Tariff Reforms

The tariffs are set exogenously by the regulator and generally remain unchanged for about a year: Unlike in the US, they do not adjust monthly to mirror the higher or lower cost at which the utility has acquired natural gas (Auffhammer and Rubin, 2018). As shown in table A.1 in the Appendix and figure 2, over the course of three years (from 2013 to 2016) gas prices to residential customers increased dramatically—by over 700% in nominal terms—in part because of the deteriorating relationship, and eventual conflict, with Russia, which cancelled deliveries to Ukraine, and in part to help the gas utility, which had until then been selling natural gas for industrial and residential use at highly subsidized rates, recover costs.

⁵ Starting in 2015, PJSC Zakarpatgaz was made responsible for the distribution of natural gas, while the provision of gas itself was assigned to Zakarpatgaz zbut Ltd.

Until March 2015 consumers faced a fairly complicated increasing block rate tariff scheme based on annual consumption with a mid-year assessment.⁶ This scheme was replaced in April 2015 by a two-block system during the heating season, with the block cutoff set at 200 m³ per month, and uniform pricing the rest of the year, and dramatically higher rates per m³ (see Figure 2). In April 2016, the block system. The rate was set at 6.879 UAH/m³, seven times as high as the rate in the first block only 13 months earlier. Electricity tariffs likewise rose during the same four-year period, but at a much lower rate (no more than 50% from one tariff regime to the next) and more frequently (Alberini et al., 2019a).

What we have described above are the rates for normal residential customers. In practice, in Ukraine persons in certain professions (e.g., civil servants, the military, retirees, veterans, Chernobyl decontamination workers) receive so-called “benefits,” namely discounted tariffs for the portion of their consumption below their “allowance.” The allowance is calculated by the government following a precise formula that takes into account family size, dwelling size, the number of stories of the building, whether gas is used for heating, cooking and/or hot water, and is seasonally adjusted. The allowances thus create additional tiers and the discounts with respect to the regular tariffs bring additional variation in rates.⁷ People are automatically enrolled in the benefits program, and thus there is no issue of self-selection into the benefits.

⁶ To illustrate, initially there were a total of four blocks—from zero to 2500 m³/year, from 2500 to 6000 m³/year, from 6000 to 12000 m³/year, and more than 12000 m³/year. Suppose that a household in one year used 2000 m³. At the beginning of the next year, the household would be charged the first-block rate for each m³ consumed in each month. At the end of June, the utility would re-evaluate this household. If the household had used less than 60% of the block cutoff (namely, 0.60×2500=1500 m³), it would continue to be charged the first-block rates. If it had exceed that cutoff (having consumed, for example, 1850 m³), it would be bumped up to the second-block rate. At the end of the year, if the consumer had managed to stay below 2500 m³, it would be assigned the first-block rate starting the next January, while if it had consumed between 2500 and 6000 m³ over the year, it would be assigned the second block rate. This scheme was slightly simplified, and rates raised somewhat, in May 2014, when the regulator did away with the upper block, as can be seen in table A.1 in the Appendix.

⁷ For example, suppose a household was entitled to an allowance of 300 m³ per month and to a 50% discount off the regular rate per cubic meter. If this household used 250 m³ in April 2016, the bill would have been 250×(6.879×0.50)=859.87 UAH, and if it had used 350 m³, the bill would have been

C. Subsidies

The sharp increases in natural gas rates for residential customers in April 2015 and a year later triggered massive increases in the prices of all goods and were a major cause of distress among the population. Government assistance however was, and still is, available, as families that struggle to pay their utility bills may be entitled to “subsidies.”

The subsidies vary across eligible households and are lump-sum transfers. Households however do not actually receive cash: The subsidy amount is simply subtracted from the utility bill, thus reducing the balance due. The subsidy (usually referred to as Housing and Utility Subsidy, or HUS) is calculated following a non-linear formula that depends on (i) a means-tested eligibility threshold, (ii) the maximum amount of energy covered by the subsidy (i.e., normative consumption), and (iii) adjustment coefficients that vary across regions and seasons.

During our study period, the share of the population that received subsidies in Ukraine increased from 9.9% to 46.5%, with a sharp increase in September-October 2016. The figures for Transcarpathia mirror the national ones. Despite the financial pressure created by the new tariffs and the subsidy eligibility changes during our study period, observers generally point out that families kept up their payment compliance (Laderchi and Umapathi, 2017).

Because the subsidies are based on normative—not actual—consumption, which in turn is automatically determined by household and house size, and by the type of heating equipment and fuel, consumers have no incentive to manipulate their gas usage levels in order to qualify for the subsidies or influence the amount of subsidies they receive. To eliminate the incentive to

$300 \times (6.879 \times 0.50) + 50 \times 6.879 = 1375.80$ UAH. By contrast, a household that is not eligible to the benefits would have paid 1719.75 UAH and 2407.65 UAH, respectively.

misreport income in order to qualify for the subsidies, the government imposes exacting income documentation requirements, and persons who have recently liquidated assets are ineligible.

D. Energy Efficiency Incentive Programs

Government programs offering incentives to residential energy efficiency upgrades were put in place starting in October 2014. In the Warm Loan Program, the Ukrainian government partnered with private banks to provide loans to individual homeowners or homeowners' associations to help finance energy efficiency upgrades. After the completion of the project, the government reimburses the applicant for a portion of the principal amount, but the applicant is still responsible for the interest payments.⁸ For individual homeowners, this portion is 20% when a boiler is replaced and 35% for other energy efficiency upgrades (typically insulation and double- or triple-glazed windows). The share is in the 40-70% range for loans taken out by homeowners' associations.

Between October 2014 and January 2018, a total of 373,000 loans were issued in Ukraine.⁹ The average project cost was 18,000 UAH for individual homeowners and 120,000 UAH for homeowners' associations.¹⁰ Since the housing stock is comprised of approximately 6,740,000 residential buildings (single-family homes plus multi-family buildings as of 2011; Emerson and Shimkin, 2015), 70% of which were built during the Soviet era (Emerson and Shimkin, 2015), this implies that 5.5% of them were renovated through this program in 40 months (an annual rate of 1.66%). Two assessments of the program (US AID, 2016, and SAE, 2016),

⁸ During our study period the average interest rates charged by the banks for Warm Loans were on average 12-18%, depending on the year. The rates however varied dramatically across banking institutions, with some charging rates as high as 27% per annum.

⁹ See http://sae.gov.ua/sites/default/files/Ocinka_0.pdf.

¹⁰ See <http://sae.gov.ua/uk/consumers/derzh-pidtrymka-energozabespechenya>.

2016a, 2016b, 2018) suggest that the savings in gas consumption from the renovations were in some cases as large as 40%.

In the Transcarpathia region specifically individual homeowners received a total of 4062 loans for energy efficient upgrades and 772 loans for boiler replacement in 2014-16, and only 12 loans were made to homeowners' associations.¹¹ The average loan amounts during that period were 21,566 UAH, 18,005 UAH and 77,333 UAH respectively (ZRSA, 2018).

In April 2016 international organizations managed by the European Bank for Reconstruction and Development started the IQ Energy program, which offered both loans and grants (capped at €3000) to individual households living in either single-family homes or multi-family buildings. Over 30,000 households in all of Ukraine have availed themselves of this program as of September 2018.¹²

EE programs and individual household decisions to do EE upgrades in the home are and will continue to be important as other parts of the country disconnect district heating, forcing households to install autonomous heating systems under their own control. Major cities like Kiev, the capital (population 2.888 million), and Lviv (population 721,000), and entire regions (e.g., Dnipropetrovsk) have for most part transitioned away from district heating.¹³

E. Effects of Price Changes

¹¹ Since the population of Transcarpathia is 1.259 million, assuming that each household is comprised of 3 members, this implies that approximately 1% of the households renovated their homes under the auspices of this program.

¹² See <http://www.iqenergy.org.ua/en/news/results-in-investments-in-energy-efficiency-of-housing-2018-09-24>.

¹³ See <https://gazeta.ua/articles/kiev-life/kiyani-pochali-masovo-vidmovlyatisya-vid-centralizovanogo-opalennya/739074>; <https://www.unian.ua/economics/realestate/10313919-centralizovane-opalennya-i-vodopostachannya-v-ukrajini-pomiraye-golova-naftogazu.html>; <https://zaxid.net/opalennya-navivorit-n1373420>; <http://www.mis.dp.ua/news/u-kamyanskomu-rozpochato-vidednannya-budinkiv-vid-tsentralizovanogo-opalennya> <https://www.epravda.com.ua/publications/2017/11/16/631216/>.

Economic theory suggests that tariff hikes should have two main effects. First, in the short run the demand for natural gas should fall, even holding the equipment and energy-using capital stock the same, as long as the demand is not completely inelastic. These short-run reductions might be attained by turning down the heat, taking shorter showers, etc. In Alberini et al. (2019b) we report evidence that this is indeed the case.

Second, rising gas prices should encourage people to make energy efficiency investments in hopes of reducing gas usage and hence expenditure. Findings from earlier literature in this regard have been mixed, with some documenting no effect whatsoever of higher energy prices on the purchases of efficient durables (e.g., Hastings and Shapiro, 2013; Jacobsen, 2015; Cohen et al., 2015), and others finding that increases in the price of the energy input (motor fuel) increase the share of efficient new durables (cars) and lower the prices of used and inefficient durables relative to their more efficient counterparts (Busse et al., 2013). Sahari (2019) documents that in Finland changing electricity prices influence the choice of heating system in new single-family homes, and Myers (2019) exploits different trends in heating oil and electricity prices to show that heating costs differentials do make homes in Massachusetts with different heating systems more or less attractive, and are thus capitalized in home prices.

If rapidly rising prices do in fact put pressure on consumers to do EE upgrades, this pressure would have been very high during our study period. In this kind of setting, we ask two research questions. First, do EE upgrades truly deliver savings in energy use? Second, how sensitive are the estimates of such savings to controlling for unobserved heterogeneity and endogenous EE upgrade decisions?

3. The Data

A. Data Collection

We use a panel dataset that documents monthly natural gas consumption in a sample of Uzhhorod homes from January 2013 to April 2017. We collected this information directly from households in the course of interviews conducted in person by trained local enumerators. The enumerators were instructed to ask each respondent to produce as many electricity and natural gas bills as possible, going back to January 2013, and to transcribe the exact consumption (in m³) during each billing period, the tariffs and marginal price as shown on the bill, and any “benefits” or subsidies information.

The enumerators also recorded information about the type and size of the dwelling, space-heating energy efficiency renovations (cavity wall insulation, attic insulation, double- or triple-glazed windows, new boiler, basement insulation, jackets around hot water pipes¹⁴) that were done since January 2013, the type of heating system(s) and heating fuel(s) used, major electric appliances, and the mode of payment of the utility bills. Each respondent (a person in the household that was familiar with the utility bills) was also asked about expected natural gas tariff changes, any switch to a different heating system or newer equipment, ways in which the household tried to reduce their natural gas bills, and whether such efforts were successful. The questionnaire ended with the usual sociodemographic questions.

The questionnaire was administered to the owner-occupants of 500 residences in Uzhhorod in May-July 2017.¹⁵ A total of 250 interviews were conducted at homes selected to be

¹⁴ These types of renovations are basic and appropriate for the stock of housing in Ukraine, about 70% of which was built during the Soviet era (Emerson and Shemkin, 2015) using prefabricated concrete slabs and with no insulation.

¹⁵ The sample included only homeowners, who are presumably responsible for energy consumption and bills, and in charge of any decisions about home energy efficiency upgrades, appliance purchases, etc. As of 2013, the homeownership rate in Ukraine was 93.7% (United Nations Economic Commission for Europe, 2013), which is comparable to those in other former Soviet republics in Europe (Lithuania: 89.4%; Russia: 84.0%; Estonia: 81.5%; Latvia: 80.2%) and former Eastern bloc countries (Romania: 96.4%; Hungary: 86.3%; Poland: 83.5%; Bulgaria: 82.3%) (see https://en.wikipedia.org/wiki/List_of_countries_by_home_ownership_rate).

representative of the housing stock,¹⁶ and the remaining 250 were conducted at homes that we knew had at some point been thermally insulated, because such renovations were visible from the outside. The outside walls of individual units in multifamily buildings where insulation was recently installed, for example, tend to be of different color and appear to be thicker than the adjacent ones. We instructed the enumerators to scout for dwellings exhibiting such signs in the same neighborhoods as the remainder of the sample. Table 1 summarizes the sampling frame. Table 2 reports details about the survey administration and shows that it resulted in a response rate (out of valid contacts) of about 79%.

B. The Data

We merged the monthly natural gas consumption, benefits and subsidies data with weather records and the tariffs, creating a panel dataset where the cross-sectional unit of observation is the family/dwelling and observations are collected at monthly frequency. The panel is unbalanced, since not everyone was able to find all of monthly gas bills going back to January 2013, and the maximum length of the panel is $T=52$.

Table 3 presents descriptive statistics of dwellings and households. The average home is about 80 square meters and was built in 1978. About 69% of the homes were built during the Soviet era (before 1991). The shares of units in multifamily buildings and single-family homes

¹⁶ The city of Uzhhorod has a population of 113,000 and is divided into nine districts. The total adult population (persons aged 18 and older) is 93,354. The total sample size was allocated to each district in proportion to its population. The sample was to mirror the distribution of housing types in Uzhhorod—57% units in multi-family buildings, 40% single-family homes, and some 3% row homes. A list of candidate addresses was drawn from each district using the Uzhhorod's resident registry, which documents the head of the household and the number of family members that live in each dwelling. The registry does not specify whether the family on the premises owns or rents the premises, and so the enumerators elicited that information at the very beginning, and terminated the interview if a prospective respondent was a renter. To encourage participation in the survey, we offered prospective respondents a card that entitled them to \$3 worth of phone calls from their cellular phones. About half of the participants declined this offer and still completed the interview.

are similar to those in the population. About 72% of the homes have gas heat and 21% electric heat. The remainder are heated with solid and other fuels. Importantly, in over 90% of the dwellings in the sample the gas meters are *inside* the home (see Alberini et al., 2019b).

The second panel of table 3 summarizes the EE renovations that occurred since January 2013. **About 50% of the households in our sample actually implemented one or more of these measures during our sample period (January 2013-April 2017). This is a consequence of our sampling decisions, as the population rate of renovations is very low in Ukraine (Rozwalka and Tordengren, 2016).** The most popular appear to be window replacements, and cavity wall or attic insulation.¹⁷ Respondents were asked whether they have received government assistance or sought a private loan to finance these renovations. Almost everyone used their own savings.¹⁸

We also asked respondents whether they had switched from one heating fuel to another since January 2013, and found that only one respondent had switched to solid fuels, and no one had gone from using natural gas to electric heat, or viceversa. This is in sharp contrast with Krauss (2016), who finds that between 2009 and 2011 some 8% of the households in Armenia, another former Soviet republic, shifted away from natural gas after the gas tariffs were increased by 40%.

As expected, the energy efficiency renovations were more frequent among the dwellings that were included in the survey because of their visible renovations (table 4). However these

¹⁷ We wish to emphasize that in this paper we restrict attention to the renovations done from January 2013 to the time of the survey. A number of people that did not do any upgrades after January 2013 still had done energy efficiency upgrades including insulation, new windows, new heating equipment, etc. *before* January 2013: 139 out of the 227 non-renovators had done upgrades in the 5-10 years before the time of the survey.

¹⁸ A total of 351 (91%) of the 386 households who had done EE renovations, including those who did them before 2013, financed them entirely on their own; 33 financed them in part from government programs, including government loans and “Warm Loans,” and the remaining 2 availed themselves exclusively of “Warm loans.”

homes are similar to the rest of the sample in terms of heating fuels, number of household members, and household income.¹⁹

On comparing those who did and those who did not do any energy efficiency upgrades during our study period (table 5), we find little evidence of differences across the two groups **in terms of dwelling or household characteristics**, with the only exceptions that single-family homes and homes heated using electricity appear more often among the renovated homes, **and households who renovated appear to have faced higher marginal gas prices.**

Attention in this paper is restricted to the 447 households who use gas for heating, hot water and/or cooking in their homes. That natural gas usage follows a seasonal pattern is apparent in Figure 4.²⁰ It also apparent that overall natural gas consumption has been declining over our study period, even though the 2016-17 winter was colder than the 2015-16 and 2014-15 winters, which in turn were colder than the 2013-14 winter.²¹

4. The Model

A. Main Equation

¹⁹ Our respondents' average monthly household income is a bit lower than the official figures for Transcarpathia (about 10,000 UAH/month; see http://www.uz.ukrstat.gov.ua/statinfo/vitrat/2018/struct_resurs_1999-2017.pdf) and approximately the same as the average monthly salary (6,500 UAH/month; see http://www.yz.ukrstat.gov.ua/statinfo/dohodi/2018/dinam_zar_econ_2010-2017.pdf).

²⁰ The annual heating degree days (base: 65° F) are typically 5400-5700. Heating degree days are calculated each day as 65° F minus the average temperature over the 24 hours. They are then summed over a month to produce the heating degree days for that month, and over the year to compute the annual heating degree days.

²¹ The weather data come from the Global Summary of the Day provided by the National Centers for Environmental Information of the National Oceanographic and Atmospheric Agency (weather station: Uzhhorod International Airport) and Reliable Forecast, which also relies from measurements from the Uzhhorod International Airport: [http://rp5.ua/Weather_archive_in_Uzhgorod_\(airport\)\)](http://rp5.ua/Weather_archive_in_Uzhgorod_(airport))). Briefly, there were a total of 5,589 heating degree days during the 2016-17 heating season (October through April), 4,706 during the 2015-16 heating season, 4,722 during the 2014-15 heating season, and 4,298 during the 2013-14 heating season. The coldest months are generally December and January. The heating degree days for December and January alone were 2,511.4 (2016-17), 1,987 (2015-16), 1,851 (2014-15), and 1,862 (2013-14).

Although our data are originally a panel with monthly frequency, the seasonal nature of gas usage and the fact that the majority of the renovations appear to have been done in the summer (when consumption is low; see Figure 4) suggest that for our empirical work we aggregate the data to the “quadrimester” level. In each year quadrimester 1 covers January through April, quadrimester 2 May through August, and quadrimester 3 September through December. The quadrimesters match nicely the utility’s “heating season” and the corresponding tariffs, and the tariff reforms implemented in Ukraine during our study period. When the data are aggregated to the quadrimester level, we have at most 13 observations per respondent.

If households make energy-efficiency improvements to their homes, does this help them, all else the same, reduce consumption? To answer this question, we specify the regression equation:

$$(1) \quad \ln G_{iqt} = \alpha_{iq} + \tau_{qt} + \mu_{it} + \mathbf{X}_{iqt}\beta + \gamma \cdot EE\ Reno_{iqt} + \varepsilon_{iqt}.$$

In equation (1) subscript i denotes the household, q the quadrimester, and t the year. The dependent variable is the log of G , the average gas usage per month during each quadrimester, and the regressors are similarly constructed. $EE\ Reno_{iqt}$ is thus the share of the quadrimester with renovations in place (usually, but not always, 0 or 1), and vector \mathbf{X} includes the average heating degree days per month and other weather variables, since the demand for heating depends on the weather and is highly seasonal.²² Vector \mathbf{X} also includes an above-median-income dummy interacted with quadrimester dummies, a single-family home dummy likewise interacted with

²² Our weather variables are the average monthly heating degree days, the share of the time with no wind, the share of the time with completely clear skies, the share of the days with humidity between 25% and 75%, the share of the days with humidity between 75% and 92%, the share of the time with humidity greater than 92%, the average monthly number of days with outdoor temperature greater than 30°C, and the average monthly number of days with outdoor temperature lower than 0° C.

quadrimester dummies, vintage of the home-by-heating-season effects, plus benefits and subsidy variables.²³

Equation (1) is a difference-in-difference-in-difference (DDD) regression and our broadest model. It includes household-by-quadrimester fixed effects, quadrimester-by-year fixed effects, and household-by-year fixed effects.

The household-by-quadrimester fixed effects account for unobserved heterogeneity among households, capture the effect of any pre-existing insulation measures, and are the appropriate way to handle our sampling frame (which entails some choice-based sampling), since the analysis is conditional on the fixed effects. They allow for seasonal use patterns that are specific to the household and may be due to preferences for a warm home as well as unobserved structural or locational characteristics of the home (e.g., northern exposure and trees, construction materials) whose effects vary depending on the time of the year.

The quadrimester-by-year fixed effects control for economy-wide or local events (e.g., the state of the economy, conflict with Russia, etc.), seasonal effects that may affect everyone's consumption in any given period (e.g., holidays), and capture the independent, direct effect that the tariff hikes may have had on consumption. The household-by-year fixed effects capture changes in the economic circumstances and/or composition of the household over the study period. (We remind the reader that we collected information about each household's income and members at the time of the survey, but not their month-by-month income and family status history over the study period.)

²³ Specifically, we enter in the model the log average monthly subsidies over the quadrimester, the log average allowance, and the log average discount off the regular tariff (applicable when consumption is within the allowance). The averages are taken over the months in each quadrimester.

We assume that this rich set of fixed effects captures all of the unobserved heterogeneity and that the error terms are independent within and across households. The error terms are however heteroskedastic, since not everyone produced all possible monthly bills, forcing us in some cases to compute the averages over the quadrimester with fewer than four observations. For this reason we use robust standard errors and t statistics.²⁴

Simplified variants of equation (1) are possible. For example, if one is prepared to assume that trends are common to all households and the household-specific fixed effects are constant over the seasons and the year, equation (1) becomes a difference-in-difference model:

$$(2) \quad \ln G_{iqt} = \alpha'_i + \tau'_p + \mathbf{X}_{iqt} \beta' + \gamma' \cdot EE\ Reno_{iqt} + \varepsilon_{iqt}$$

where i denotes the household and p is an appropriately defined time period (see below).

B. Endogeneity of the EE Renovations

We expect coefficient γ in equations (1) and (2) to be negative: Presumably EE improvements help reduce usage, all else the same. However, one concern with equations (1) and (2) is that undertaking EE upgrades is likely endogenous with gas consumption: Heavy users presumably do the renovations *because* they are heavy users and wish to reduce consumption (and bills). The resulting positive correlation between the adoption of energy-saving measures and consumption would bias the OLS estimate of coefficient γ towards zero—or even result in a positive estimate.

The fixed effects included in equations (1) and (2) should help reduce the bias of the least-squares coefficient on the renovations, but do not necessarily eliminate it. To get around this problem, we must instrument for the decision to do the renovations. In the absence of a

²⁴ The dynamic panel model (see below) relies crucially on the assumption that the errors terms are independent within a household.

randomized controlled trial or experiment setup (as in Fowlie et al., 2018, Graff Zivin and Novan, 2016), it is not easy to find suitable instruments. The gas tariffs, for example, are certainly exogenous to individuals and change over time, but fail the exclusion restriction: People may curtail usage directly in response to tariff hikes, in addition to seeking do efficiency-improving renovations as a consequence of the tariff hikes (Alberini et al., 2019b).

We develop a total of three excluded instruments for the renovations. Two are “leave-one-out” instruments that we construct using a “supply-side” argument. We rely on conversations with suppliers of insulation materials and representatives of local construction companies, and with our survey participants, who all report that it is typical for a crew that just installed insulation or replaced the windows in one unit in a building (or a house) to approach the owners of other units (or nearby homes) and offer similar services.

We thus build two “leave-one-out” instruments, namely i) the share of *other* units within the same multifamily building as household *i* that have EE renovations in place at time *t* (coded to zero for single-family homes), and ii) the shares of *other* dwellings in the same street as household *i* that have EE renovations in place at time *t*. These variables should be correlated with a household’s decision to renovate, but should be uncorrelated with that household’s consumption.^{25, 26} The third instrument is the share of a multifamily building that appears to have been insulated, based on visual inspection and photographic evidence from roughly the

²⁵ This assumption would be violated if, for example, insulating one unit in a building helps conserve heat in another unit in that building. We don’t believe that happens in our sample: the sampling plan specifically ruled out units on the same floor or in the same tier of the same building, or adjacent homes. We checked one by one the addresses where the interviews took place, and verified that the enumerators complied with this requirement.

²⁶ This is related to the jackknife instrumental variable estimator (JIVE) in Angrist et al. (1999), Akerberg and Devereux (2009), and Kolesár et al. (2015), with dummies denoting membership in a specified neighborhood as the instruments.

middle of the study period,²⁷ interacted with i). All instruments are expressed as household i 's average over the quadrimester.

The first stage is thus:

$$(3) \quad EEReno_{iqt} = \theta_{iq} + \delta_{qt} + \varphi_{it} + \mathbf{X}_{iqt}\lambda + \mathbf{Z}_{iqt}\pi + e_{iqt}$$

where \mathbf{Z} is the vector of the three excluded instruments described above. Equation (1) and (3) are estimated using the “within” estimator combined with 2SLS.

C. Quality of the Instruments

We test the quality of the excluded instruments (\mathbf{Z} in equation (3)) using two test statistics. The first is the Kleibergen-Paap rk Lagrange Multiplier (LM) test, which tests the null that the \mathbf{Z} are irrelevant in the first stage. Clearly, we hope to reject the null hypothesis.

The second is a test for weak instruments. If the instruments are weak (i.e., only weakly correlated with $EEReno$), the 2SLS estimator is biased towards OLS, is not asymptotically normally distributed, and tests based on it have the wrong size (Nelson and Startz, 1990a, 1990b). Staiger and Stock (1997) propose a rule of thumb based the first-stage F test, which must exceed 10 for the instruments to be considered strong. Stock and Yogo (2005) derive the critical limits that the first-stage F test statistic must exceed for i) the worst-case bias of the 2SLS estimator to be less than a specified fraction (e.g., 10%) of that of the worst-case OLS estimator, and ii) for the empirical size of the Wald statistic for the parameter of interest (γ in our case) to be less than specified levels (e.g., 10% when the nominal size is 5%), respectively. However, the

²⁷ We use the Google Map street view feature, which displays photos from 2015. The residential gas tariffs were abruptly tripled in April 2015, and by May 2015 were 700% of the March 2015 levels, suggesting that if the tariff hikes encouraged consumers to do EE renovations, this pressure would have existed after mid-2015, generally after the photos were taken.

first-stage F statistic and the Stock-Yogo limits are not robust to the presence of heteroskedasticity, autocorrelated error terms, and clustering.

Montiel Olea and Pflueger (2013) propose a correction to the regular F test (the “effective F statistic”) that is valid under heteroskedasticity and clustering, and compute critical limits that the statistic must exceed for the bias of the 2SLS and LIML estimators to be small compared to the worst-case bias. They also provide a rule-of-thumb critical limit that is asymptotically valid for the 2SLS estimator: The null of weak instruments is rejected at 5% significance when the effective F is greater than 23.11.

Should the effective F statistic fail to reject the null, we turn to the Anderson-Rubin test to make inference about γ , as this statistic does not depend on the distribution of the estimated γ (Andrews et al., 2018). The null is that $\gamma=0$, and the Anderson-Rubin statistic tests it using the coefficients from the reduced form, whose distribution does not depend on the (potentially problematic) IV estimator. The statistic assumes that the error terms are independently and identically distributed, so rejection of the null may occur because $\gamma \neq 0$ and/or because the error terms are not i.i.d. Under the null, the Anderson-Rubin statistic is distributed as a chi square with as many degrees of freedom as the number of excluded instruments.

D. Dynamic Panel Model

We also experiment with a dynamic panel model:

$$(4) \quad \ln G_{is} = \alpha_i'' + \tau_p'' + \rho \cdot \ln G_{i,s-1} + \mathbf{X}_{is} \beta'' + \gamma'' \cdot EE Reno_{is} + u_{is},$$

where s denotes the quadrimester and year ($s=1, 2, \dots, 13$), and u is a serially independent but potentially heteroskedastic error term.

This dynamic panel model is the empirical counterpart of a partial adjustment model of consumption (Houtakker, 1980).²⁸ We estimate it using the system generalized method of moment (GMM) approach devised by Blundell and Bond (1995), and regard both lagged consumption and $EEReno$ as endogenous. With quadrimester-level data, it is unclear whether $\frac{\gamma''}{1-\rho}$ represents the true long-run effect of EE upgrades. We interpret it as a “mid-run” effect.

E. Choice of EE Improvements

In this paper we report results for three alternate definitions of renovation. To construct the first, we begin by creating a dummy variable that takes on value of one when any one of the seven possible renovations (wall or attic insulation, basement insulation, double- or triple-glazed windows, boiler replacement, pipes insulation) is in place for household i in month m and year y . Cases where a household does more than one efficiency upgrades are not numerous in our data, but they do exist, and when they occur our dummy indicator takes on a value of one when the latest one is complete. The dummy is then averaged over the quadrimester to yield the share of the quadrimester when the renovations were in place. This is usually, but not always, zero or one.

The second is similarly constructed, but attention is restricted to insulation of walls, attic and basement, and windows. To construct a clean sample, households that replaced the boiler or insulated the pipes during our study period are excluded. For the third definition we focus on just insulation, and the sample accordingly drops households that replaced the boiler, installed

²⁸ The partial adjustment model posits that the long-run equilibrium is given by $G^* = A \cdot (Price)^a (Income)^b X^c$, and that consumption adjusts from one period to the next as follows: $\frac{G_t}{G_{t-1}} = \left(\frac{G^*}{G_{t-1}}\right)^d$. On combining the two expressions, letting the prices be captured by time dummies and the benefits variables, and income by the subsidies, and then taking logs, one gets equation (4), where d , the speed of adjustment, is $(1-\rho)$.

insulation around the pipes, or replaced the windows. The instruments (the shares of neighbors with renovations in place) are likewise strictly based on the same type of renovations.

5. Results

A. Checking for Sample Selection Bias.

While not everyone was able to produce all of his or her monthly gas bills from January 2013 to April 2017, most respondents were able to find quite a few: Only two people contributed fewer than 10 gas bills (and hence meter readings) to the sample, 158 (35.35%) contributed 10-19, 155 (34.67%) 20-29, 40 (about 9%) 30-39, and 92 (20.58%) forty or more.

We first check for any evidence of sample selection bias, in case those who contribute more bills to the sample are those with very high (or very low) consumption. In practice, there seems to be no evidence of it. As shown in figure A.1 in the Appendix, which displays the share of the 447 respondents for whom gas consumption is available in any given month during our study period, the farther back in time, the fewer the records available, as is consistent with the idea that people might throw away older records while keeping the more recent ones.

An OLS regression (Wooldridge, 2010, p. 823-824) of log monthly gas consumption on month-year effects, respondent-specific effects, exogenous covariates, and an indicator for the availability of the gas bill in the previous month finds that the coefficient on the latter to be -0.0122 (t statistic -0.53 based on standard errors clustered at the respondent level). We conclude that there is no evidence of sample-selection bias: People with heavy or, conversely, light usage, do not appear to have contributed systematically more or fewer bills to the sample, and the sample doesn't seem to be biased in their favor.

B. Effect of Energy Efficiency Measures on Consumption

Do the energy efficiency upgrade reduce gas consumption, all else the same? One would expect the coefficients on the renovations dummy to be negative, but examples from the literature abound that find little or no such effect, despite favorable ex ante engineering calculations (Fowlie et al., 2018; Graff Zivin and Novan, 2016; Alberini et al., 2016). Our respondents themselves appear to be somewhat agnostic about the effectiveness of the renovations in reducing gas usage, with 35% answering that they did not know, 33% saying that they had helped, 17% saying that they hadn't, and almost 15% not providing an assessment at all (table A.2 in the Appendix). This is surprising in light of the fact that gas meters are generally *inside* the home, requiring little effort to monitor usage between bills.

Results from fitting equations (1)-(3) are displayed in table 6 for the broadest definition of EE upgrades (any one of the seven measures). We begin with the specification with the simplified set of fixed effects, namely equation (2), which is displayed in cols. (A) and (B). Since the time fixed effects are common to all households, this specification is for all practical purposes a “difference-in-difference” type of model.²⁹

When the renovations are regarded as exogenous (col. (A)), the coefficient on them is negative, but extremely small and insignificant. By contrast, the time fixed effects (aligned with the most important tariff reforms, but not displayed in the table) are negative and significant, showing that everyone was seeking to reduce consumption as gas prices went up dramatically

²⁹ This model, and a “difference-in-difference” setup, assume that the trends are common among “treated” and “control” households, where the former are the households with renovations in place and the latter are households who don't do renovations, or haven't done them yet. This assumption may be reasonable with our data. We test it by forming a sample with observations from homes that were not renovated during our study period, plus observations *before* the renovations from homes that subsequently underwent EE upgrades. We then regress log gas on weather, tariff periods, interaction terms between the tariff period dummies and the “subsequent renovator” dummy, plus the other covariates. The F statistic of the null that the coefficients on the interactions are zero is 0.38, with a p value of 0.7711, failing to reject the null at the conventional levels.

(see Alberini et al., 2019b). On instrumenting for the EE upgrades (col. (B)), the renovations do not appear to bring any meaningful reductions in gas usage, despite the fact that the excluded instruments are strong predictors of the decision to do the renovations (Kleibergen-Paap LM statistic 32.85, p value 0.0096) and that the effective F statistic rejects the null of weak instruments at 5%.

The dynamic panel version of the model (equation (4)), estimated using the Blundell-Bond approach, suggests a 15% reduction in usage from the renovations, but the coefficient is not significant at the conventional levels (t statistic -1.58), and (surprisingly) the coefficient on the lagged dependent variable is very small and insignificant.

Only when we instrument for the renovations is the coefficient on renovations sizeable in the specifications with the richer sets of fixed effects (cols. (E)-(G)). It is equal to -0.2117 (significant at 5% **and implying a 19% reduction in consumption**) in the specification with household-by-quadrimester and quadrimester-by-year fixed effects, and to -0.1204 in that with the full triple-difference set of fixed effects.³⁰ The latter coefficient is however insignificant at the conventional levels, likely because of the large number of fixed effects, which reduce the degrees of freedom of the regression. The instrument diagnostics suggest that in the models of cols. (E) and (G) the instruments are significant predictors of the renovations, and are reasonably strong.³¹

In table 7 attention is restricted to insulation and windows. For good measure homes where boiler replacement or pipes insulation took place over the sample period are excluded

³⁰ The specifications in columns (D) and (E) are special cases of that in columns (F) and (G), in that they suppress the household-by-year fixed effects.

³¹ The effective F tests are less than 23.1, the critical limit that Montiel Olea and Pflueger derive as an asymptotically valid rule of thumb for rejecting the null of weak instruments at 5% significance. However they reject the null of weak instruments at 5% significance if one is prepared to accept a bias of the 2SLS estimator compared to the worst-case benchmark between 5 and 10%.

from the sample. The effects of the renovations are generally stronger than their counterparts in table 6, and the coefficients range from -0.2745 to -0.03, although they are not always significant at the 5% level. The IV estimates (-0.2745 to -0.1415) tend to fall in the middle or lower half of this range, implying, all else the same, a 13% to 24% reduction in usage. The Kleibergen-Paap LM statistic rejects the null of irrelevant instruments in the equations of cols. (B), (E), and (G). The effective F statistic rejects the null of weak instruments in the specification of col. (B), and approaches the 23.11 5% critical limit in the specifications of cols. (E) and (G), allowing us to reject the null in the latter two if we are prepared to accept a 5-10% of the worst-case bias.

It is not surprising that the instruments perform better with this definition of the possible EE renovations than in the one of table 6. We remind the reader that we use leave-one-out instruments based on the share of neighbors that have renovations in place, since construction crews tend to approach neighbors and offer similar services and products. But “similar services and products” means insulation and new windows, and does not include new boilers, which are the purview of HVAC firms and are typically replaced when they are old and broken, and not just because workers are insulating homes in the area. Our estimated reductions in gas usage from the IV estimates (13% to 24%) fall roughly in the middle of the range of those estimated in assessments of the Warm Loan Program by US AID (2016) and SAEI (2016a, 2016b), although we believe that the former is likely to overstate the savings in consumption because it lacks a control group.

In table 8 we further restrict the analysis to insulation (or walls, of the attic, and/or of the basement) and exclude from the sample observations from dwellings where the boiler was replaced, the pipes insulated, or the windows changed during our sample period. This time even IV estimation produces smaller and insignificant (-0.08 to -0.05), or even positive, coefficients

on the renovations. The tests on the quality of the instruments suggest that they are significantly associated with the renovations, but the effective F statistics indicate that the instruments become progressively weaker as further fixed effects are added in the model. In the broadest specification, for example, one would be able to reject the null of weak instruments at 5% only if he or she was prepared to accept a 2SLS bias that was 20-30% of the worst case. The Anderson-Rubin statistic fails to reject the null, leading us to conclude that this limited set of renovations have no statistically discernible effect on gas usage.

C. Returns to EE Investments

Based on information reported by our respondents, doing insulation and/or windows cost an average 25,875 UAH (April 2016 UAH). The largest effect (coefficient on renovations equal to -0.2745, or a 24% reduction in gas usage) implies savings of 34.26 m³ per month. Assuming that these would be experienced over 8.5 months in a year (the heating season, plus late spring and early fall), at the most recent gas price during our study period (about 7 UAH/m³), the annual savings on the bills would thus be $34.26 \times 8.5 \times 7 \approx 2039$ UAH.³² Assuming that these measures have a lifetime of 20 years, the total undiscounted savings would be 40,775 UAH and would thus exceed the cost of the renovations. The corresponding internal rate of return (IRR, namely the discount rate at which the future savings just equal the initial cost of the investment) is about 5.4% per year.

The IRR would be positive, under the same assumptions, if we use other, and less optimistic, estimates of the effect of the renovations. If the coefficients on the renovations were -0.2110, and hence the effect a 19% reduction in gas usage per month, the IRR would be about

³² This calculation is thus consistent with the assumption that gas prices are a random walk process, or that gas price expectations are static.

2.5% per annum (p.a.). It would fall to about 1% p.a. for a coefficient on the renovations equal to -0.1801 (16.5% reduction in gas consumption).

While at first blush these figures may not seem like much, they do suggest that energy efficiency upgrades were a profitable investment compared to the general state of the housing market in Ukraine and in the Transcarpathia region during the same period. Housing prices in Ukraine declined by 2-3% *per month* in 2014 and 0.5% per month in 2017 (Konovalova and Pyrohova, 2017). In Uzhhorod, they fell by at least 10% in 2017 alone and by up to 30% over 2014-2017.³³

Moreover, the investment calculus of homeowners is even more promising upon participation in the Warm Loan program, which refunds homeowners 35% of the principal of the loan meant to finance renovations. Assuming that the effect of the renovations is to reduce consumption by 16.5%, a 10% down payment, and an 8% interest rate on a 5-year loan, for example, thanks to the reimbursement of 35% of the loan principal, a homeowner would incur an IRR of 1.6%. The savings on the bill over the 5-year loan period would be sufficient to cover about one-third of the total disbursement.

6. Conclusions

Energy efficiency improvements in the residential sector are often touted as a promising avenue for reducing energy use, CO₂ emissions, reliance on the electricity grid and gas distribution network, and dependence on imports. *Measuring* the actual energy savings attributable to energy efficiency improvements, however, has proven challenging for a variety of

³³ Personal communication with Natalia Petrosian, Association of Independent Real Estate Agents “Avangard,” Uzhhorod, October 10th, 2018, and Viacheslav Mishchenko, LLC “Nerukhomist Zakarpattia,” Uzhhorod, March 14th, 2019. Also see <https://www.globalpropertyguide.com/Europe/Ukraine/Price-History>.

reasons, including the possibility of rebound effects, unobserved heterogeneity and self-selection. Even when attempting to address these issues, earlier studies have produced wide ranges of energy savings estimates, and these have often been imprecisely estimated.

We have used monthly natural gas consumption records from a metropolitan area in Western Ukraine in a regime of rapidly rising prices to assess the effects of energy efficiency renovations meant to improve the thermal integrity of homes. In the absence of a randomized controlled trial and associated “intention to treat” estimator (Fowlie et al., 2018; Graff Zivin and Novan, 2016) we have developed leave-one-out instruments for the renovations based on a supply-side argument.

In our sample of homes in Uzhhorod the most popular types of EE upgrades tend to help reduce natural gas usage, although the exact magnitude of the reduction varies widely among specifications, and is practically and statistically significant at the conventional levels only when we i) instrument for the renovations, ii) focus on a “clean” set of renovations that are well-matched by the instruments (insulation and new windows), and iii) strike the right balance between capturing the unobserved heterogeneity and sacrificing too many degrees of freedom to a rich set of fixed effects. In these cases the coefficients on the renovations are -0.2745 and -0.2110,³⁴ respectively, which imply a 24% and 19% reduction in gas usage, respectively. The full triple-difference setting suggests a 13% gas usage reduction (the coefficient is -0.1415 in column (G) table 7).

Reductions in consumption of this magnitude are sufficient for the IRR on the investment to be positive, suggesting that the EE upgrades were a reasonable investment in an otherwise

³⁴ These are from cols. (E) in tables 6 and 7. The dynamic panel model suggests 13-16% reductions (cols. (C) in tables 6 and 7).

poorly performing housing market. Judicious use of the Warm Loan offerings can help defray the initial cost of the renovations and still result in a positive IRR.

Earlier research has suggested that consumers have little interest in weatherization and EE improvements because they “don’t deliver” energy savings sufficient to justify their costs. Our research shows that it is difficult—for *both* analysts *and* consumers—to assess the savings attributable to EE upgrades, even in a setting with rapidly increasing energy prices, salience, and low-effort monitoring. Consumer assessment may have been impaired by the seasonal nature of natural gas consumption and recall of cold v. milder winters.

Such difficulty itself, along with the cost of the upgrades and the disruption caused by construction in the home, may discourage EE investments in the home—unless the upgrades are seen as a way to boost property values. It has been suggested that energy efficiency investments, and certification of such investments, are more likely in markets with more difficult selling conditions (Brounen and Kok, 2011), presumably to outcompete other sellers and appeal to potential buyers. Our Western Ukraine homeowners may have been at least in part motivated by this desire.

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Figure 1. Sample Gas Bill.

Постачальник: ПАТ "Закарпатгаз" ВОРФО м. Ужгород, вул. Погорелова, 2 тел.(0312) 61-21-46, 66-39-98, р/р 26037301083700 МФО 312356 Код 05448610

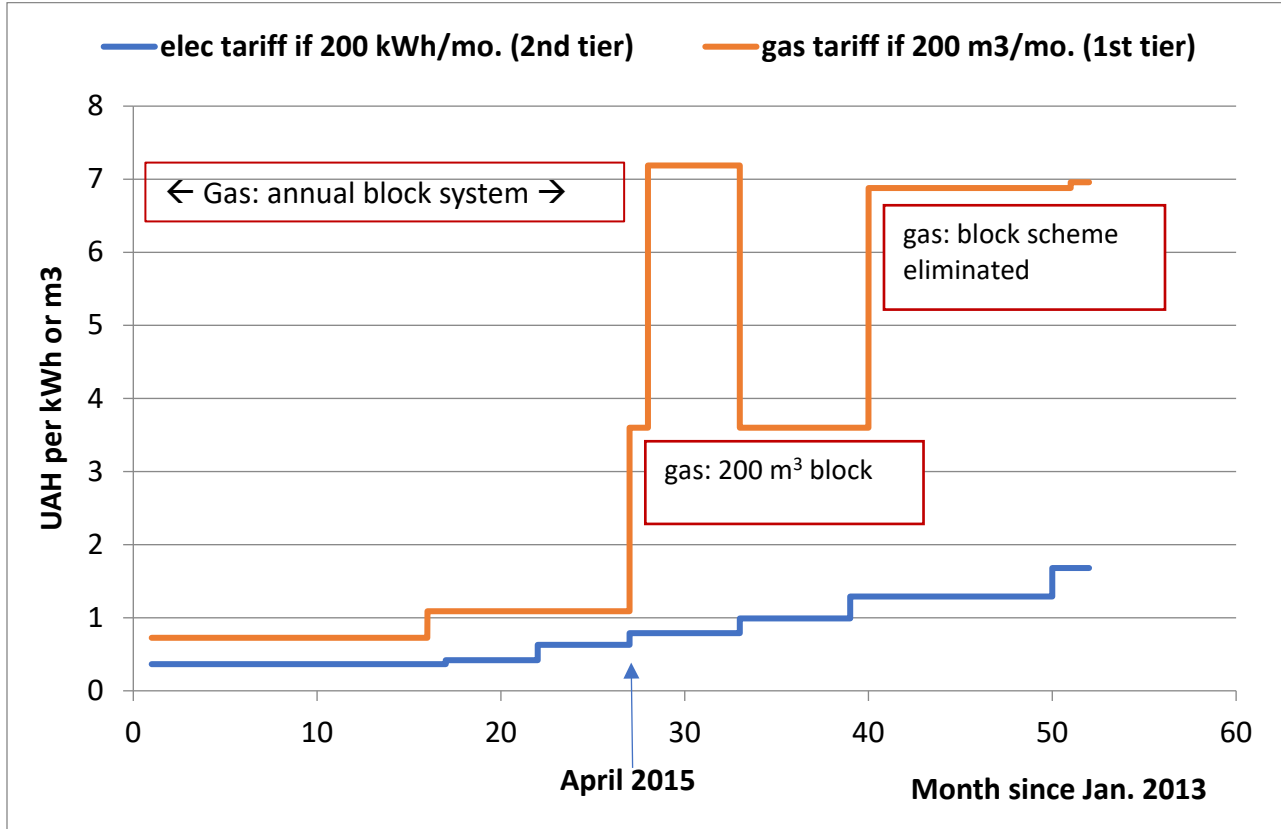
Рахунок сплатити протягом 10 днів. Виправленню не підлягає.

РАХУНОК №821489/11
на оплату за спожитий природний газ за **Листопад 2014р.**

Споживач: [REDACTED] **Адреса:** Ужгород, вул. Можайського, буд. 34, кв. 19.
Пільги- Осо 50%- 2 . **Лічильник** G4, №8046180.

Показники лічильника			Ціна, 1м3: 1,089 грн.			Нараховано всього, грн.	Пільги, грн.	Рекомендована сума до сплати, грн.
Попередній	Фактичний на дату 30.11.2014	Плановий, на кінець місяця рекомендов.	під час відсутності лічильника, м3.	в т.ч. по пільзі, м3.	Всього нараховано, м3.			
444	647	0	м3.			221,07	104,05	117,02
203 м3			0 м3	0,00	191,09	203,00		
Увага! Сплачувати за газ можливо через платіжну систему на сайті http://irau.ua Детальна інформація на сайті http://zk.104.ua						Залишок на рахунку		75,67
						Коригування		0,00
						Субсидія		0,00
						Оплачено:		75,67
						Всього до сплати, грн.:		117,02

Figure 2. Electricity and Gas Tariffs (2013-2017).



The figure displays the natural gas tariff per m³ for a consumer that uses 200 m³ per month, and the electricity tariff for a consumer that uses 200 kWh per month.

Figure 3. Example of visible EE renovations (addition of wall insulation) in Uzhhorod.



Figure 4. Average log monthly gas consumption by month in homes in wave 2.

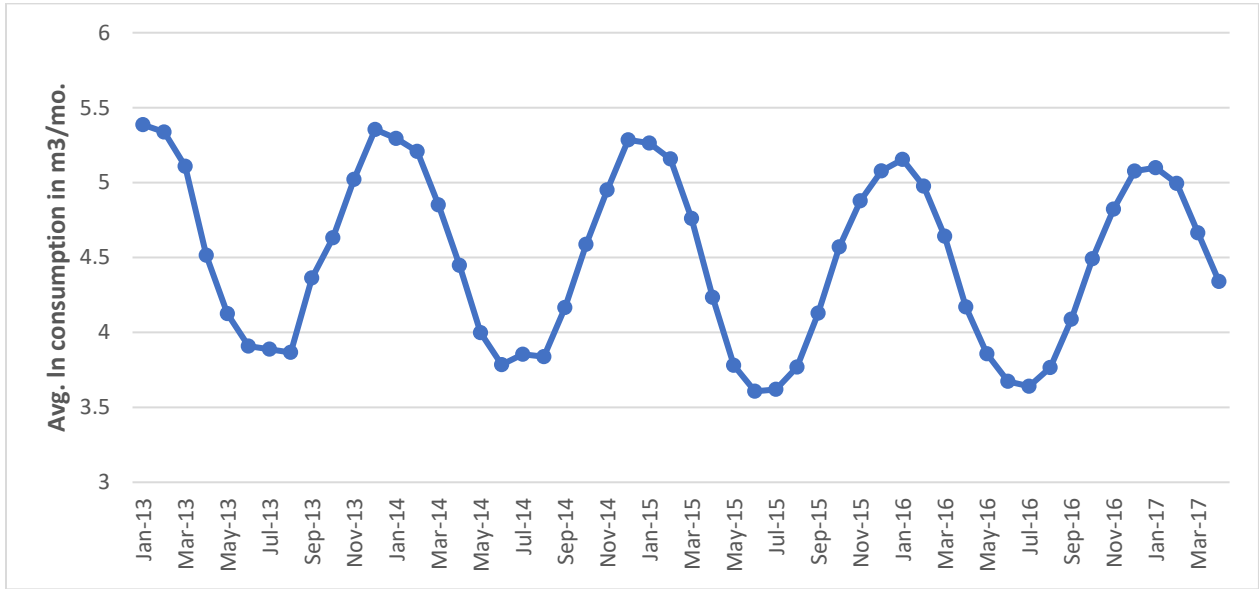


Figure 5. Wave 2. Actual share of homes in the sample with renovations in place in each month of the study.

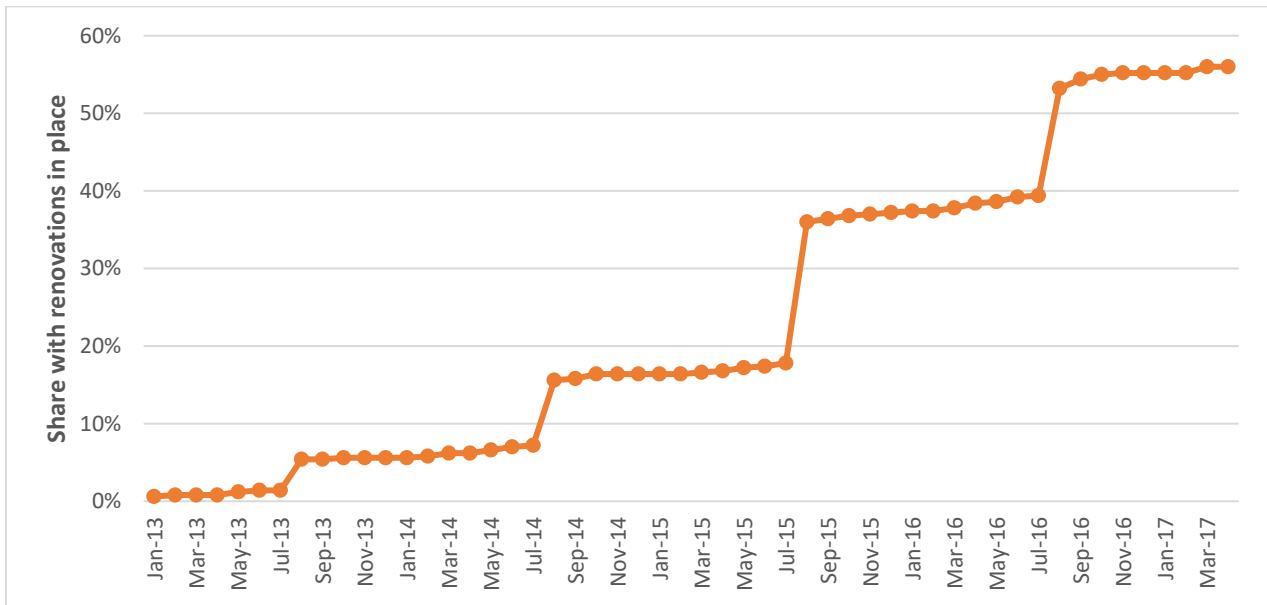


Table 1. Sampling frame

2017 Survey	
•	N=500 homes: <ul style="list-style-type: none"> • N=250 representative of the stock of housing • N=250 wall insulation visible from the outside (choice-based sampling)
•	Energy bills from Jan 2013 to Apr 2017
•	Max T=52

Table 2. Survey Administration Details and Response Rates.

	Count
total contact attempts	802
address not found	20
unable to access building	11
no response at door	94
ineligible (renters)	42
total invalid or failed contacts	167
Valid contacts made	635
declined to participate	117
completed questionnaires	500
bad questionnaires	18
Response rate out of valid contacts	78.74%

Table 3. Descriptive Statistics: Dwelling and Household.

	Average or percent of the sample
<i>A. Dwelling and Household</i>	
Type of home	
– Single family home	35.2%
– Apartment in multi-family building	61.4%
– Rowhome	3.2%
Size of the home (m ²)	78.34
Year built	1978
Main heating fuel	
– Natural gas	72.0%
– Electricity	21.2%
– Solid fuels	6.0%
Monthly household income (UAH)	6,457
<i>B. Energy Efficiency Renovations Done Since Jan. 2013</i>	
Cavity wall or attic insulation	36.8%
Double-glazed windows	33.9%
Triple-glazed windows	3.8%
Basement	2.2%
Hot water pipes	1.2%
Boiler replacement	10.62%
Any of the above	54.6%
<i>C. Gas Usage Information</i>	
Monthly gas consumption (m ³)	142.77
Marginal price paid per m ³ (April 2016 UAH)	4.99
Gas benefits – percentage of the sample	5.04%
– allowance (m ³ /month)	159.6

Table 4. Comparison between regularly sampled home and homes sampled because of visible insulation.

	Homes included in the survey because of visible insulation	All others	t test statistic	Difference sign. at 5%?
<i>Dwelling characteristics</i>				
square meters	87.93	68.57	4.74	Yes
Unit in multi-family building	0.488	0.74	-5.98	Yes
SF home	0.484	0.22	6.42	Yes
Year built	1979.84	1976.73	1.69	No
gas heat	0.72	0.72	0.00	No
electric heat	0.196	0.228	-0.87	No
<i>EE renovations since Jan.2013</i>				
Cavity wall or attic insulation	0.728	0.008	25.03	Yes
Boiler replacement	0.132	0.080	1.91	No
Double windows	0.395	0.284	2.63	Yes
Triple windows	0.048	0.036	0.68	No
Basement insulation	0.044	0.009	3.38	Yes
Pipes insulation	0.020	0.004	1.65	No
Any of the above	0.772	0.32	11.37	Yes
<i>Household characteristics</i>				
household size	3.084	2.99	0.89	No
Elderly (65 or older) living in the home	0.336	0.268	-1.34	No
Monthly household income (UAH)	6819.481	6737.991	-0.28	No
<i>Natural gas consumption</i>				
Log monthly gas consumption	4.5993	4.3539	12.62	Yes
Marginal price of gas (April 2016 UAH)	5.008	4.9049	4.07	Yes

Table 5. Comparison between homes that did and did not energy efficiency renovations since Jan. 2013

	Has done EE upgrades since Jan 2013	No EE upgrades since Jan 2013	t test statistic	Difference sign. at 5%?
<i>Dwelling characteristics</i>				
square meters	77.3263	79.9502	0.53	No
Unit in multi-family building	0.5787	0.6564	-1.78	No
SF home	0.3956	0.2996	2.26	Yes
Year built	1976.95	1980.18	-1.68	No
gas heat	0.7032	0.74	-0.91	No
electric heat	0.2454	0.1718	-2.03	Yes
<i>Household characteristics</i>				
household size	3.0586	3.0085	0.46	No
Elderly (65 or older) in the household	0.337	0.2599	1.54	No
Monthly household income (UAH)	6610.078	6994.554	-1.33	No
<i>Natural gas consumption</i>				
Log monthly gas consumption	4.4829	4.4729	0.51	No
Marginal price of natural gas (April 2016 UAH)	5.0802	4.9048	4.07	Yes

Table 6. Estimation results. Dep. Var.: ln Gas Consumption. The renovation dummy takes on a value of one if any type of insulation, double- or triple-glazed windows, boiler replacement, pipe insulation are done. T statistics in parentheses based on robust standard errors.

	(A) Least squares	(B) 2SLS	(C) Blundell Bond IV	(D) Least squares	(E) 2SLS	(F) Least squares (DDD model)	(G) 2SLS (DDD model)
EE renovations dummy	-0.0080 (-0.22)	-0.0215 (-0.18)	-0.1450 (-1.58)	-0.0181 (-0.69)	-0.2117 (-1.96)	-0.0244 (-0.88)	-0.1204 (-1.09)
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time varying controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household FEs	Yes	Yes	Yes				
Quadr. FEs and Policy period FEs	Yes	Yes	Yes				
Household-by- quadrimester FEs				Yes	Yes	Yes	Yes
Quadr.-by-year FEs				Yes	Yes	Yes	Yes
Household-by-year FEs						Yes	Yes
<i>First-stage diagnostics</i>							
Kleibergen-Paap rk LM (p value)		32.85 (<0.0001)			40.908 (<0.0001)		42.122 (<0.0001)
Montiel Olea-Pflueger Effective F		29.842			18.474		17.758
Anderson Rubin Wald test (p value)		6.90 (0.0758)			5.02 (0.0016)		6.96 (0.0732)
Nobs	3288	3288	2858	3090	3090	3031	3031
Households	430	430	430	429	429	429	429

Note: t statistics in parentheses; * significant at 10%, ** significant at 5%, *** significant at 1%.

The excluded instruments are (i) the share of *other* apartments in the same multifamily building, (ii) the share of *other* single-family homes in the same street as respondent i that have done renovations by time t of the study, and iii) the share of the façade of a multifamily building that appears to have been insulated as of 2015, interacted with (i).

Table 7. Estimation results. Dep. var.: ln Gas Consumption. The renovation dummy takes on a value of one if any type of insulation, double- or triple-glazed windows are done. T statistics in parentheses based on robust standard errors.

	(A) Least squares	(B) 2SLS	(C) Blundell Bond IV	(D) Least squares	(E) 2SLS	(F) Least squares (DDD model)	(G) 2SLS (DDD model)
EE renovations dummy	-0.0303 (-0.75)	-0.0872 (-0.66)	-0.1801 (-1.71)	-0.0404 (-1.47)	-0.2745 (-2.39)	-0.0497 (-1.48)	-0.1415 (-1.64)
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time varying controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household FEs	Yes	Yes	Yes				
Quadr. FEs and Policy period FEs	Yes	Yes	Yes				
Household-by- quadrimester FEs				Yes	Yes	Yes	Yes
Quadr.-by-year FEs				Yes	Yes	Yes	Yes
Household-by-year FEs						Yes	Yes
<i>First-stage diagnostics</i>							
Kleibergen-Paap rk LM (p value)		37.342 (<0.0001)			45.124 (<0.0001)		45.818 (<0.0001)
Montiel Olea-Pflueger effective F		33.387			21.025		21.341
Anderson Rubin Wald test (p value)		10.76 (0.0131)			20.47 (0.0001)		8.72 (0.0332)
Nobs	3041	3041	2649	2865	2865	2808	2808
Households	393	393	393	392	392	392	392

Note: t statistics in parentheses; * significant at 10%, ** significant at 5%, *** significant at 1%.

The excluded instruments are (i) the share of *other* apartments in the same multifamily building, (ii) the share of *other* single-family homes in the same street as respondent *i* that have done renovations by time *t* of the study, and iii) the share of the façade of a multifamily building that appears to have been insulated as of 2015, interacted with (i).

Table 8. Estimation results. Dep. Var.: ln Gas Consumption. The renovation dummy takes on a value of one if any type of insulation is done. T statistics in parentheses based on robust standard errors.

	(A) Least squares	(B) 2SLS	(C) Blundell Bond IV	(D) Least squares	(E) 2SLS	(F) Least squares (DDD model)	(G) 2SLS (DDD model)
EE renovations dummy	0.0099 (0.21)	0.0659 (0.44)	0.0274 (0.16)	-0.0080 (-1.51)	-0.1979 (-1.50)	-0.0166 (-0.39)	-0.0276 (-0.25)
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time varying controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Household FEs	Yes	Yes	Yes				
Quadr. FEs and Policy period FEs	Yes	Yes	Yes				
Household-by- quadrimester FEs				Yes	Yes	Yes	Yes
Quadr.-by-year FEs				Yes	Yes	Yes	Yes
Household-by-year FEs						Yes	Yes
<i>First-stage diagnostics</i>							
Kleibergen-Paap rk LM (p value)		19.32 (0.0002)			23.706 (<0.0001)		23.706 (<0.0001)
Montiel Olea-Pflueger effective F		14.898			10.055		8.476
Anderson Rubin Wald test (p value)		7.23 (0.0649)			10.36 (0.0157)		4.66 (0.1987)
Nobs	1997	1997	1733	1866	1866	1829	1829
Households	264	264	264	263	263	263	263

Note: t statistics in parentheses; * significant at 10%, ** significant at 5%, *** significant at 1%.

The excluded instruments are (i) the share of *other* apartments in the same multifamily building, (ii) the share of *other* single-family homes in the same street as respondent *i* that have done renovations by time *t* of the study, and iii) the share of the façade of a multifamily building that appears to have been insulated as of 2015, interacted with (i).

Appendix

Table A.1. Natural gas tariffs for residential customers in Transcarpathia.

	Unit	2010 Aug 1 to 2014 Apr 30	2014 May 1 to 2015 Mar 31	2015 Apr 1 to 2016 Apr 30	2016 May 1 to 2017 Mar 31	from 2017 April 1
upper bound of block 1	m ³ a year	2,500	2,500	200 a moth	NA	NA
upper bound of block 2	m ³ a year	6,000	6,000	NA	NA	NA
upper bound of block 3	m ³ a year	12,000	NA	NA	NA	NA
variable cost 1 with meter	UAH per m ³	0.7254	1.089			
variable cost 2 with meter	UAH per m ³	1.0980	1.788			
variable cost 3 with meter	UAH per m ³	2.2482	3.645			
variable cost 4 with meter	UAH per m ³	2.6856				
use gas for cooking and/or water heating in <i>multifamily</i> buildings, with meter	UAH per m ³		1.182			
variable cost 1 without meter	UAH per m ³	0.7980	1.197			
variable cost 2 without meter	UAH per m ³	1.2078	1.965			
variable cost 3 without meter	UAH per m ³	2.4732	4.011			
variable cost 4 without meter	UAH per m ³	2.9541				
use gas for cooking and/or water heating in <i>multifamily</i> buildings, without meter	UAH per m ³		1.299			
use gas for individual heating or cooking and/or water heating (May 1 – Sept. 30), households without gas heating (whole year)	UAH per m ³			7.188		
variable cost 1 - use gas for individual heating or cooking and/or water heating (Oct. 1 – Apr. 30)	UAH per m ³			3.600		
variable cost 2 - use gas for individual heating or cooking and/or water heating (Oct. 1 – Apr. 30)	UAH per m ³			7.188		
gas for all residential users (unit price for all households users, regardless of quantity used and/or conditions of consumption)	UAH per m ³				6.879	6.958

Note: Tariffs include VAT.

Figure A.1. Share of gas bills available each month of the study period.

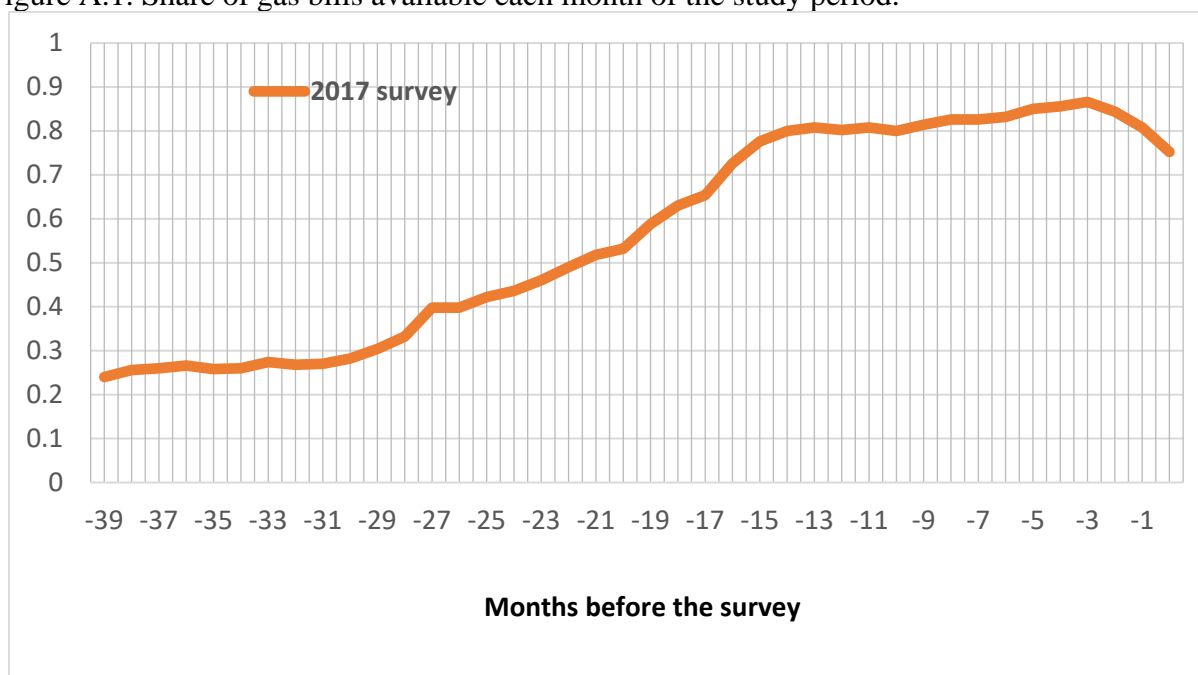


Table A.2. Respondent assessment of the effectiveness of the energy efficiency renovations (based on N=280 households who did energy efficiency renovations since Jan 2013). Percent who selected the specified responses.

	Yes	No	Don't know	Did not answer
Did they reduce your gas consumption?	33.57%	17.14%	34.64%	14.64%
Did they reduce the gas bills?	25.00%	21.79%	36.43	16.58%

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