The Effect of Energy Efficiency Obligations on Residential Energy Use and on Greenhouse Gas Emissions: Empirical Evidence from France

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Abstract: Energy Efficiency Obligations are widespread policy instruments to reduce energy use. They require energy suppliers to deliver a set amount of energy savings. The obligated parties then comply by offering subsidies for energy-efficient investments to energy users. We use a new dataset covering over 3.1 million energy retrofit projects from 2018 to 2020 to assess the impact of the French program on residential electricity and gas use. We find that the official reporting on the program's outcome significantly overstates the energy savings by at least 59%. We then exploit the fact that obligations are tradable to recover the implied average abatement cost of carbon. Importantly, this cost exceeds EUR 135 per ton of CO_2 equivalent.

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1 Introduction

Improving the energy efficiency of building stock is a cornerstone of the energy transition. The International Energy Agency reports that global investment in building energy retrofits averaged over $160 billion annually from 2015 to 2021. This figure accounts for 60% of global energy efficiency investments and more than double the amount allocated to the transportation sector (IEA 2022). Since the late 1970s, insulation and the adoption of energy-efficient heating and cooling technologies have been promoted as a win-win strategy for reducing energy consumption and associated costs. This perspective is closely linked to estimates derived from engineering models, which predict that energy savings will outweigh the upfront costs of such measures over time (Allcott and Greenstone 2012). Government intervention in this area is widely regarded as necessary, as improved energy efficiency not only alleviates energy burdens but also mitigates adverse climate and health impacts. This view has gained significant traction among the public; a recent survey by Dechezleprêtre et al. 2022 highlights strong support for mandatory and subsidized building insulation among populations in OECD member countries.

To meet their energy efficiency targets, an increasing number of governments are implementing energy efficiency obligations (EEOs) (IEA 2022). These programs require market actors, such as energy suppliers (e.g., in France) or distribution system operators (e.g., in Italy), to achieve a specified level of energy savings. In practice, obligated parties primarily fulfill these requirements by providing monetary incentives to energy consumers—including households, industries, and service providers—to invest in energy retrofits. These subsidies, along with the associated transaction costs, are typically financed through marginal increases in energy prices (Rosenow, Cowart, and Thomas 2019).

As of 2022, the International Energy Agency identified at least 48 active energy efficiency obligation programs globally. In the United States, 24 states operate EEOs, referred to as Energy Efficiency Resource Standards, while similar initiatives exist in countries such as Australia, Brazil, Canada, China, South Korea, South Africa, and Uruguay (Crampes and Léautier 2020).

This paper proposes an econometric evaluation of the effects of the French program on energy consumption, greenhouse gas emissions and the resulting the cost of avoided CO2. The French EEO program (in French, *Certificats d'Economie d'Energie*, hereafter CEE), is the largest in Europe with a total investment of nearly 4 billion EUR each year (Broc, Stańczyk, and Reidlinger 2020). The

French CEE program supports retrofit works in the residential, industrial, or tertiary sector, and to a lower extent in agriculture and transport. However, the residential sector gathers itself more than two thirds of the total energy savings (DGEC 2022).

As many of these programs, engineering estimates of the energy impact of individual investments play a key role in the program outcome. The primary objective of this article is to assess the program's compliance by comparing its actual energy impact with the theoretical predictions that underpin the issuance of certificates. Using a dataset of 4,774 municipalities where 306,035 energy efficiency investments were implemented in the residential sector between 2018 and 2020, our best estimate indicates that investments supported by the CEE program deliver, at most, 41% of the predicted gas and electricity savings. This corresponds to an annual reduction in gas and electricity consumption of 1.25%. Leveraging data on the carbon footprint of gas and electricity, we further estimate an annual carbon emissions reduction of 1.9%.

Certificates are tradable on a market, and under the assumption of a competitive market, their price reflects the marginal cost of certificate production. By combining this market information with our econometric analysis, we estimate the cost of avoided CO_2.

This approach is particularly valuable as the price reflects the full policy cost, not merely the direct cost of the subsidized investments. Encouraging these investments and persuading households to participate necessitates additional resources for outreach, informational campaigns, and engagement efforts, which can represent a significant expense. As an illustration, an experiment conducted by Fowlie, Greenstone, and Wolfram (2018) in Michigan found that these promotional costs accounted for 20% of the monetary investment cost. Moreover, the policy imposes administrative burdens on obligated firms, requiring them to process CEE investments into certificates to ensure compliance.

On the household side, investment costs and benefits go beyond the direct financial expenses and energy bill savings. Home retrofits may necessitate temporary relocation or, at a minimum, cause considerable disruptions and inconvenience during the work. The psychological burden of planning, managing, and monitoring renovation projects also adds to the costs. On the positive side, once completed, retrofits often result in non-monetary benefits, such as improved comfort through the rebound of the use of energy services.

Taking these factors into consideration, we estimate the average cost of avoided CO_2 to be EUR 135 per ton.

Grants allocated by obligated market actors account for 50% of the total financial support allocated to households (I4CE 2022), making CEE a pivotal tool for the achievement of the French European and international commitments regarding the energy transition. Therefore, our research question is twofold: first, this study assesses the impact of retrofits subsidized through the French CEE program on household electricity and gas consumption. Second, we evaluate an average price of CO_2 abatement associated to CEE works. To the best of our knowledge, this is the first empirical evaluation of this policy mechanism.

The theoretical literature on the economics of Energy Efficiency Obligations is well-developed. This includes analysis of the competition mechanisms at play between obligated actors, as in Giraudet, Glachant, and Nicolaï 2020, or moral hazard issues from the supply side as in Crampes and Léautier 2020. Studies at the national (Rosenow, Platt, and Brooke 2013), European (Rosenow and Bayer 2017) or international scale (Rosenow, Cowart, and Thomas 2019) have also enlightened regressivity issues. In the case of France, microsimulation methods used by Giraudet, Bourgeois, and Quirion 2021 find CEE to compare poorly with a carbon tax in terms of efficiency. These theoretical insights point to the same risk of underperformance for retrofit works achieved through the CEE program.

Because we look at the effect of energy retrofit works on energy use, our study is also connected to the literature on the energy efficiency gap. According to Hirst and Brown 1990, the actual level of energy efficiency investments is suboptimal, in the sense that many profitable insulation or heating system replacements are not undertaken by households. Researchers have looked for an explanation to this paradox since the end of 1980's; as noticed by Allcott and Greenstone 2012, favored rationales involve two distinct information asymmetries, leading to moral hazard and behavioral biases. On the one hand, the information asymmetry between beneficiaries and installers leads to a moral hazard situation: Giraudet, Houde, and Maher 2018 indeed find significantly lower realized energy savings for retrofit works which quality is hard to observe. On the other hand, information asymmetries on energy costs between landlords and tenants result in a behavioral bias from the latter group, known as the rebound effect. A larger rebound effect for tenants has indeed been documented by Aydin, Kok, and Brounen 2017 as well as Myers 2020.

Finally, our work has direct implications for the energy performance gap literature. While the energy efficiency gap framework relies on intrinsically difficult to test welfare predictions, the former focuses on the discrepancy between engineering predictions and realized energy savings (Giraudet and Missemer 2023). The effect of energy efficiency improvements (with or without subsidies) on final consumption, the energy bill as well as CO_2 emissions has been empirically estimated by Blaise and Glachant 2019 and Kahn 2022 on a panel of French households: both studies point to a very low return on investment. In the case of the US, the Energy Star program evaluation conducted by Houde and Aldy 2017 concluded to similar results. Policies targeting a narrower audience, with deeper support from third party actors to promote energy efficient behaviors have also been studied. Through their evaluation of the Weatherization Assistance Program (WAP), Fowlie, Greenstone, and Wolfram 2018 concluded to a 60% overestimation of the actual energy savings by ex-ante models. Looking at the same policy, Christensen et al. 2023 estimate that the so called energy efficiency gap can be disentangled between the bias in engineering models - hence, the energy efficiency gap (up to 41%), and workmanship heterogeneity (43%).

Following these recent developments, our analysis provides the first ex-post estimates of the wedge between announced and realized savings from the retrofits supported by the CEE. In line with the literature, we find an important overestimation of savings. The energy performance gap, defined as the difference between engineering predictions and actual energy conservation, is at least 59%. We connect this result with the amount invested by energy suppliers, and find an average cost of carbon abatement above EUR 135/t. CO_2-eq. This is way above the cost predicted by micro-simulation models used to calibrate energy efficiency policies. The French CEE therefore fail to fulfill their cost-effectiveness promise.

The paper proceeds as follows. In section 2, we present some background information on the French program. We introduce the data used in the analysis in section 3, and the empirical strategy is exposed in section 4. Section 5 provides regression results and some robustness checks. We discuss implications in Section 6 and conclude in Section 7.

2 Institutional background

Reducing energy consumption has been the CEE program's primary objective since its inception. It serves as a cornerstone of France's commitment to achieving the national target outlined in the European Union's Energy Efficiency Directive (European Commission 2012), which mandates an annual energy sales reduction of -1.5% from 2014 to 2020 across all sectors except transport.

The evaluation conducted in this study requires starting with a detailed explanation of its operation. Every four years, new individual energy savings targets are assigned to retailers of electricity, gas, and gasoline in proportion to their sales, with differing coefficients depending on the type of fuel and their carbon content. Compliance with individual targets heavily relies on the distribution of subsidies to energy users investing in energy efficiency measures. In practice, around two thirds of these investments are made in the residential sector.

For each investment subsidized, the obligated parties receive a certain amount of energy savings certificates from the regulator upon providing proof of investment (e.g., an invoice for the installation of insulation). This quantity is supposed to reflect the energy impact of the investment over its entire lifetime. At the end of each four-year period, energy suppliers must demonstrate compliance by submitting the required quantity of certificates to the regulator.

The calculation of the standardized amount of energy savings certificates for a given type of energy efficiency investment is based on ex ante engineering estimates. In the residential sector, energy efficiency measures are classified into 23 work types, including 'roof insulation' and 'high-efficiency individual boiler(see Table A1). For each type, a formula gives the savings depending on the size of the project and location. For instance, 50 square meters of roof insulation installed in the coldest part of mainland France are worth 85,000 kWh over a 30 years life cycle, while the installation of a high energy efficiency individual boiler in the same area is expected to deliver 24,800 kWh in savings over 17 years. In the calculation, future savings accrued over the investment's lifetime are discounted at an annual rate of 4%. Each certificate represents 1 kWh of energy saved.

This program is designed to identify the most cost-effective options for meeting targets, offering significant flexibility to obligated parties. These parties can generate certificates independently by directly subsidizing energy users, or they may subcontract this responsibility to other firms, public organizations, or local governments. Alternatively, certificates can be acquired through the certificate market. Trading volumes in 2019 and 2018 reached 288 TWhc and 179 TWhc, respectively, underscoring the vital role of trading in fulfilling the annual obligation of 533 TWhc.

Since 2016, the program has also been helping to combat fuel poverty thanks to two social equity provisions: a sub-obligation whereby energy retailers are required to devote at least 25% of their energy-saving operations to low-income households, and a bonus system that doubles the amount of certificates issued for the energy renovation of homes occupied by households in the bottom quartile. The bonus system has mechanically created a gap between realized energy savings and the number of certificates as depicted in Figure A1. Obviously, these bonus certificates are not taken into account when the government reports the quantity of energy savings achieved through the CEE program to the EU Commission.

Finally, public subsidies and tax credits exist in parallel and can sometimes be combined with CEE incentives over our observation period (2017-2019). According to a study by the French Environment Agency on the projected energy savings made in 2018 and 2019, 26% combined CEE and public support[1]. The energy retrofits conducted without any support are not observed.

In any case, this raises the question of the program's "additionality". To limit the number of inframarginal renovations, energy suppliers are required to collect and submit to the regulator an affidavit in which the beneficiary household declares that the financial support received from the obligated actor was decisive in its investment decision. We will come back to the econometric implications of this later.

3 Data

Our analysis builds on three primary data sources: residential electricity and gas consumption data, certificate data detailing the quantity and characteristics of energy retrofits subsidized by the program, and weather and city-level socio-demographic data.

Residential electricity and gas use. The data is provided by the *Opérateurs des Réseaux d'Energie* agency. It gathers information from all French actors in the distribution of electricity and natural gas at the municipality-level data from 2018 to 2020. No information is available on the consumption of other energy sources, such as heating oil, liquid gas or district heating.

Energy retrofits. The Energy Efficiency Obligation database is hosted by the Centre d'Accès Sécurisé aux Données (CASD), a French public interest group that provides secure access to confidential data for non-profit research (CASD 2023). The dataset covers over 3.1 million energy

[1] Source: ONRE, SDES, 2022. See page 20.

efficiency operations carried out in the residential sector between 2018 and 2020. This three-year period corresponds to the program's fourth obligation phase[2]. The dataset offers detailed insights into the types of work performed, the expected lifespan of each retrofit, its location (at the city level), and the number of certificates issued.

This information allows for the calculation of projected energy savings for each subsidized retrofit. We first convert the number of certificates into lifelong savings by removing bonus certificates. Lifelong savings are then converted into annual savings using data on expected lifetimes and the applicable discount rate of 4%. We also know the month of completion of each renovation. When we aggregate savings over the year for the municipality, we only take into account savings from the following month onwards.

Weather data. Heating Degree Days (HDD) and liquid precipitation (mm) are standard metrics used by engineers to estimate heating needs, reflecting the impact of temperature and humidity on energy consumption. The data is provided by Météo France, the French national meteorological service, and is available on a grid of 9,892 cells, each covering an area of 64 square kilometers (8 km $\times$ 8 km). For each grid point and day, the average temperature (T°n,d) is recorded.

HDD values are calculated for each municipality using 17°C as the reference temperature. The detailed matching process is described in Appendix B.4.

Socio-demographics. Last, we extract data on population and income from official administrative datasets geographical distribution of population density follows that of energy use and is concentrated in urban areas. The average median income within our selected municipalities roughly equals that of the general population.

Study sample.

Since we are unable to identify the types of fuel used in retrofitted dwellings, we limit our study sample to municipalities with minimal reliance on alternative energy sources. Specifically, using data from the population census (INSEE 2018), we exclude municipalities where heating oil or liquid gas is the primary heating source for more than 10% of housing units (excluding holiday homes). As illustrated in Figures A2 and A3, this primarily affects rural municipalities.

Additionally, we exclude all municipalities with district heating systems operating between 2018 and 2020. In practice, this concerns densely populated urban centers such as Paris, Marseille, and

[2]This period was unexpectedly extended by one year due to the COVID-19 pandemic. However, 2021 is excluded from our analysis as it represents an anomalous year.

Lyon (see Figure A4). The final estimation sample consists of 4,774 municipalities, representing 5.18 million inhabitants. Table 1 presents summary statistics for this sample.

Table 1: Descriptive statistics for the study sample

	N = 4,774	
	Mean	SD
Panel A: Energy use		
Per capita annual electricity use (kWh)	3,429.959	1,213.841
Per capita gas use (kWh)	1,263.306	1,722.556
Panel B: Retrofit works		
Projected lifelong savings (kWh/capita)	2,816.795	2,001.76
Projected annual savings (kWh/capita)	77.643	61.008
Panel C: Demographics		
Median per capita income (EUR/year)	21,363.438	3,625.951
Population size	1,078	1,365
Panel D: Weather		
HDD	2,066	575
CDD	381	188
Precipitation (mm)	928	263

Panel B of Table 1 shows retrofit works over 2018-2020. The first line corresponds to lifelong savings, i.e., the engineering projection over the retrofits life cycle. The second line gives the annualized version of projected savings, used as the treatment variable in the analysis.

Table 2 displays the shares of the top 5 retrofit categories, which represents 92% of the 25 work-types displayed in Table A1). Investment in insulation alone (roof, floor, wall) accounts for 81% of projected savings and most of these savings are achieved in homes heated by electricity. This impact will be quantified in section 6.

Table 2: Share of projected savings, by type of energy retrofit

Code	Operation	% projected savings	% in gas-heated dwellings
BAR-EN-101	Roof insulation	53.6	81.0
BAR-EN-103	Floor insulation	16.1	88.5
BAR-EN-102	Wall insulation	11.3	79.9
BAR-EN-104	High energy efficient boiler	6.4	n.a.
BAR-EN-106	Heat pump	4.3	n.a.

4 Empirical strategy

4.1 Identification problem

To estimate the impact of retrofit works supported by the program on residential gas and electricity, let us begin with a simple Two-Way Fixed-Effects (TWFE) model which leverages year-to-year within-municipality variations in energy use and energy efficiency investment. The baseline estimating equation writes as:

$$Y_{i,t} = \beta\, X_{i,t} + \lambda W_{i,t} + \mu D_{i,t} + \alpha_i + \gamma_t + u_{i,t} \tag{1}$$

The outcome variable $Y_{i,t}$ represents residential electricity and gas consumption in municipality i during year t. Combining these two energy sources allows us to account for potential substitution effects (Giraudet, Houde, and Maher 2018), such as the replacement of a gas boiler by a heat pump. Municipality fixed effects are denoted as α_i, while region-year fixed effects are represented by γ_t.

The variable $X_{i,t}$ represents the cumulative projected savings achieved through works completed annually since 2018. The underlying idea is that the energy savings in a given year are determined by the stock of previous investments. Formally, we have

$$X_{i,t} = \sum_{\tau=2018}^{t} x_{i,\tau}$$

where $x_{i,\tau}$ represents the energy savings achieved in year t. Although investments made before 2018 are not observed, they are accounted for through the municipality fixed effect. In this specification, the coefficient β directly indicates the share of projected savings that are realized ex post.

The equation also includes a vector $W_{i,t}$ of weather variables (contemporaneous annual HDD and precipitations) that influence energy use and may indirectly affect the pace of energy efficiency investments. Additionally, a vector $D_{i,t}$ of demographic controls is included including median income and population. We apply a logarithmic transformation to population because its effect on energy use is likely non-linear due to agglomeration effects.

Self-selection is the main threat to identification. Households choose to renovate their homes. Unobserved time-varying factors such as anticipated demand shocks that influence their decision can then lead to biased results if they are correlated with energy consumption. For example, a local positive shock on the population environmental awareness will increase both its propensity to invest, but also its short-term efforts to reduce energy use, e.g. by reducing indoor temperature during winter months. Omitting this shock will then lead to overestimate the energy savings. Unlike most existing research on energy efficiency investments that relies on micro-data, our study aggregates individual behaviors at the municipality level. This partly alleviates the omitted variable problem if the individual shocks are not correlated. However, this is not always the case. For example, environmental awareness is a factor for which individual variations are unlikely to balance out at the population level.

Energy retrofits done without support from the CEE program also go unobserved and do not generate certificates. While this omitted variable problem may seem irrelevant since the focus is on the program's impact rather than total energy efficiency investments, CEE-supported and non-CEE retrofits are likely interconnected. Both are influenced by similar factors, potentially introducing bias from unobserved variables.

4.2 Instrumental Variation

Our solution is to instrument the year-to-year change in projected savings $X_{i,t}$. We exploit municipality-level data on degree days and liquid precipitations two years before the investment in energy efficiency is completed. More specifically, the instrument is

$$Z_{i,t} = \text{HDD}_{\,i,t-2} \times \text{Precipitation}_{\,i,t-2}$$

The assumption is that deviations from the average HDD and precipitations increase the salience of heating- and cooling-related home characteristics, thereby influencing the decision to invest in energy efficiency. The two-year lag is considered a reasonable estimate for the time between the weather shock and the completion of the retrofits.

Exogeneity would arise from the fact that past temperature and precipitation shocks are not correlated with changes in energy use two years later through channels other than energy efficiency investments. [3]

The presence of non-CEE investments presents a specific challenge, however. To clarify the issue and outline a potential solution, we decompose the error term in the equation 1 as follows: $u_{i,t} = \phi\, R_{i,t} + \varepsilon_{i,t}$, where $\varepsilon_{i,t}$ includes all within-municipality dynamics that we do not control for, and $R_{i,t}$ represents projected savings imputable to retrofit investments not generating certificates in municipality i in year t. The second stage equation thus writes:

$$Y_{i,t} = \beta^{2SLS}\, \widehat{X}_{i,t} + \delta_2\, W_{i,t} + \lambda_2\, D_{i,t} + \alpha_i + \gamma_t + \phi R_{i,t} + \varepsilon_{i,t}$$

where $\widehat{X}_{i,t}$ is the fitted value of $X_{i,t}$. The exclusion restriction requires

$$\mathrm{Cov}(Z_{i,t}, \varepsilon_{i,t}) + \mathrm{Cov}(Z_{i,t}, \phi\, R_{i,t}) = 0. \tag{2}$$

The above argument asserts that temperatures from two years prior do not affect current changes in energy use through any channel other than energy retrofits, regardless of whether the investment is subsidized by the program. As a result, we posit that $\mathrm{Cov}(Z_{i,t}, \varepsilon_{i,t}) = 0$. However, there is no reason to doubt that past temperature shocks also influence non-CEE energy efficiency investments, leading to $\mathrm{Cov}(Z_{i,t}, R_{i,t}) \neq 0$. As a results, Equation 2 no longer holds, resulting in a biased estimate of the coefficient β^{2SLS}.

The good news is that we can sign the bias. Assuming that the control variables are uncorrelated with the instrument, i.e., $\mathrm{Cov}(W_{i,t}, Z_{i,t}) = \mathrm{Cov}(D_{i,t}, Z_{i,t}) = 0$, straightforward calculations give:

$$\beta^{2SLS} = \beta + \phi\, \frac{\mathrm{Cov}(R_{i,t}, Z_{i,t})}{\mathrm{Cov}(X_{i,t}, Z_{i,t})}$$

Focusing on the final term of this expression, it is clear that $\phi < 0$ because non-CEE investments naturally reduce energy consumption. Furthermore, since the first-stage effect of the instrument on CEE-funded investments is not driven by any unique characteristic of the CEE program, it can be

[3]The focus on *changes* in energy use is crucial for identification, as previous temperatures and precipitation may have a persistent effect on energy use behavior.

extended to all types of energy efficiency retrofits. It follows that $\mathrm{Cov}(R_{i,t}, Z_{i,t})$ and $\mathrm{Cov}(X_{i,t}, Z_{i,t})$ exhibit the same sign. These two statements implies a negative bias: $|\beta^{2SLS}| > |\beta|$. β^{2SLS} can be interpreted as a lower-bound estimate of the program's impact on energy use.[4]

5 Econometric results

5.1 Main estimation

We estimate both the OLS-FD and 2SLS-FD regressions for savings, clustering standard errors at the municipality level to account for potential within-municipality correlation patterns.

Table 3: Regression results for the effect of projected savings on energy use

	OLS-FE	2SLS-FE
Expected Savings	−0.474***	
	(0.073)	
Fitted Expected Savings		−0.411**
		(0.137)
Log. of Pop.	746 741.953***	740 670.975***
	(169 332.700)	(169 630.600)
HDD	579.140**	560.989**
	(219.638)	(203.402)
Precipitation (mm)	112.085+	109.794+
	(64.536)	(62.550)
Num.Obs.	12 207	12 207
R2	0.999	0.999
R2 Adj.	0.998	0.998
R2 Within	0.079	0.078
FE: Code_commune_INSEE	X	X
FE: dep_year	X	X
F-test (1st stage)		318.974

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001
Clustered standard errors at the municipality level

The two columns of Table 3 present the estimated effects of projected savings. The coefficients represent the impact of one kWh of projected savings at time t on energy use in the same year. In column (1), the results indicate that an additional kWh of projected savings at t is negatively correlated with energy use. However, this observed correlation is highly endogenous due to the

[4]Christensen et al. 2023 compare retrofitted homes with those yet to be retrofitted, offering another solution to this problem under the assumption that households renovate only once during their study period.

potential selection effects among retrofitting households influenced by within-municipality dynamics, as discussed in Section 4. This endogeneity is further exacerbated by the influence of non-CEE investments. Nevertheless, the coefficient is statistically significant, which motivates the search for a better identification strategy.

Column (2) presents the results of the IV estimation, which is based on the framework outlined in Section 4. Compared to the OLS estimate, the magnitude of the 2SLS coefficient decreases by around 15%. This suggests that failing to account for potential confounders leads to an overestimation of the impact of CEE retrofits on energy use. The discrepancy between $\widehat{\beta}^{OLS}$ and $\widehat{\beta}^{2SLS}$ likely stems from pre-existing downward trends in energy use within municipalities that implement more retrofits.

We estimate that one kWh of projected savings achieved through a CEE operation reduces actual energy use by no more than 0.411 kWh. This represents an overestimation of engineering predictions by at least 59%. The effect is statistically significant at the 1% level and supported by a strong first-stage F-statistic (319), well above the threshold suggested by Staiger and Stock 1997.

We run the same IV regression separately for electricity and natural gas. Table 4, column (1), shows that electricity use remains unaffected by additional savings. The effect measured in our main specification in Table 3 is thus mostly triggered by a decrease in natural gas consumption. This outcome is straightforward to explain: over 80% of the savings are attributed to insulation works in dwellings that do not use electricity for heating. Furthermore, the installation of air-to-water or water-to-water heat pumps – frequently associated with a switch from natural gas to electricity for heating – account for less than 5% of the total savings (see Table 2 and Table A1 in the appendix).

Table 4: Effect of projected savings on electricity and gas

	Electricity	Natural Gas
Fitted Expected Savings	−0.040	−0.371**
	(0.051)	(0.126)
Log. of Pop.	481 664.692***	259 006.283+
	(60 217.343)	(146 045.155)
HDD	183.242**	377.747*
	(67.292)	(190.333)
Precipitation (mm)	−11.767	121.562*
	(25.218)	(56.313)
Num.Obs.	12 207	12 207
R2	0.999	0.997
R2 Adj.	0.999	0.994
R2 Within	0.005	0.097
FE: Code_commune_INSEE	X	X
FE: dep_year	X	X
F-test (1st stage)	318.974	318.974

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001
Clustered standard errors at the municipality level

5.2 Robustness checks

We perform three types of robustness checks for our 2SLS-FD specification. First, we address potential estimation bias arising from households transitioning away from residential heating oil or liquid gas. While our analysis focuses on municipalities in the lowest decile for the consumption of these fuels, some scope for such behavior remains. To mitigate this, we exclude municipalities where the share of housing units using heating oil (or liquid gas) changed by more than 1 percentage point between 2018 and 2020. The estimation results for these sub-samples are shown in columns (1) and (2) of Table 5. Although the precision of the coefficient on fitted savings slightly decreases, it remains significant at the 5% level for both fuel sources. The coefficients are of a similar magnitude to those in the main regression, suggesting that at best, only 40% of the projected savings are realized.

Table 5: Robustness checks for the effect of savings on energy use

	Fuel Oil	Liq. Gas	SEM 10km	SEM 20km
Fitted Expected Savings	−0.401**	−0.392**	−0.411**	−0.411**
	(0.155)	(0.150)	(0.151)	(0.158)
Log. of Pop.	722 113.896***	728 092.995***	740 670.975***	740 670.975***
	(183 157.870)	(181 607.367)	(176 997.319)	(223 732.967)
HDD	644.666**	592.342**	560.989*	560.989*
	(224.196)	(206.189)	(220.538)	(269.547)
Precipitation (mm)	137.235*	114.078+	109.794	109.794
	(69.587)	(63.762)	(69.517)	(87.301)
Num.Obs.	10 991	11 796	12 207	12 207
R2	0.999	0.999	0.999	0.999
R2 Adj.	0.998	0.998	0.998	0.998
R2 Within	0.074	0.078	0.078	0.078
FE: Code_commune_INSEE	X	X	X	X
FE: dep_year	X	X	X	X
F-test (1st stage)	280.142	313.242	318.974	318.974

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Clustered standard errors at the municipality level (1-2) / Spatial Error Model (3-4)

Second, we examine the potential influence of spatial dependence between individual observations. While clustered standard errors account for within-municipality, cross-period correlation, a spatial-error model (SEM) explicitly addresses contemporaneous cross-municipality correlations. In this context, it is plausible that the error term $u_{i,t}$ and $u_{j,t}$ for two adjacent municipalities i and j are not perfectly orthogonal. This may arise because unobserved non-CEE retrofitting investments $R_{i,t}$ and $R_{j,t}$ are influenced by local supply and demand shocks that span across municipal boundaries. To address this, we apply the variance-covariance matrix estimator proposed by Conley 1999, which incorporates the relative proximity of adjacent municipalities using a defined threshold.

The error term $u_{i,t}$ of our second stage equation is thus a function of contemporaneous adjacent municipalities error terms $u_{j,t}$ and $\vartheta_{i,t} \overset{i.i.d.}{\sim} \mathcal{N}(0, \sigma^2)$:

$$u_{i,t} = \xi \sum_{i \neq j} \omega_{ij} u_{j,t} + \vartheta_{i,t} \tag{3}$$

We present results for the 10 km and 20 km thresholds. The only deviation from the baseline estimation lies in the computation of standard errors, which are no longer clustered at the municipality level. Nonetheless, the p-value for the effect of contemporaneous savings remains below 5%

for both thresholds. While this test has limitations – since the spatial diffusion perimeter likely varies across observations, making the optimal radius an empirical question – the consistent significance of the effect of CEE-funded retrofits under this spatial autoregressive specification provides further support for our upper-bound estimate.

Third, we perform an alternative IV estimation, using a shift-share instrument to explore the internal validity of the analysis. We exploit municipality-level data on the volume of projected energy savings available for each of the 23 work categories (e.g, wall insulation, floor insulation, air-to-air heat pumps). We construct the instrument by decomposing the local variation in savings derived from a work of type s in municipality i into two components: the national growth rate of work-type s' projected savings, which may reflect the dynamics of the global supply chain or national policy shocks, with the initial local share of this work type, which reflects the exposure of the municipality i to the national shock.

Formally, the instrument writes:

$$\sum_{s=1}^{S} \alpha_{i,s,t_0} \Delta X_{s,t} \tag{4}$$

where α_{i,s,t_0} denotes the local share of investment of type s in the pre-sample period t_0, the year 2016 in our case. $X_{s,t}$ is the projected energy savings in year t from work of type s carried out in all municipalities in the sample.

The fact that past α_{i,s,t_0} shares predict future shares may result from local supply dynamics and learning-by-doing. For example, past heat pump installations in municipality i have increased the productivity of local installers. Demand spillovers can also play a role, as a household's choice of renovation type may be influenced by feedback from neighbors who have retrofitted their homes in previous years.

Table 6: Bartik IV

	OLS-FD	2SLS-FD
Expected Savings	−0.438***	
	(0.060)	
Fitted Expected Savings		−0.414***
		(0.067)
Log. of Pop.	633 833.696***	629 536.981***
	(90 307.486)	(91 228.938)
Median income	4.059	3.890
	(3.038)	(3.093)
HDD	313.655***	318.157***
	(30.266)	(27.845)
CDD	−57.471	−51.485
	(93.795)	(88.237)
Precipitation (mm)	78.218***	75.673***
	(14.553)	(16.439)
Num.Obs.	8723	8723
R2	0.068	0.068
R2 Adj.	0.067	0.067
F-test (1st stage)		1132.702

+ $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
Clustered standard errors at the municipality level

This alternative IV strategy yields very similar estimates of the energy performance gap affecting EEOs supported works. In line with our previous results, each kWh of expected savings decreases actual energy use by at most -0.41 kWh.

5.3 Discussion

We estimate that the realized savings on residential electricity and gas are, at best, only 41% of the savings. This implies a minimum energy performance gap of 59%, which roughly equals the estimates of Fowlie, Greenstone, and Wolfram 2018 (around 60%) and exceeds that of Christensen et al. 2023 (up to 41%). Although these estimates were obtained in the context of the Weatherization Assistance Program in the US, they highlight the same issue: a significant overestimation of engineering projections.

This gap is especially relevant given the central role of ex-ante evaluations of standardized operations in the French CEE. Projected savings are routinely communicated by obligated firms and their subcontractors to persuade households to invest in energy efficiency. Closing the gap between projected and realized savings is thus crucial to restore consumer confidence in energy retrofits.

Furthermore, the existence of such a gap gives a misleading picture of the degree of compliance with national policy objectives. The European Energy Efficiency Directive requires Member States to report annually on the energy savings achieved to meet their national target. Based on the engineering estimates of the CEE, the government reported an overall energy savings volume of 2.827 TWh over the 2018-2020 period covered by our study, leading to a compliance rate of 114% for the period 2014-2021. Extrapolating our local results to the entire CEE period and all sectors covered by the program, the actual rate would be 47%.

If we adjust these estimates with our findings, the realized energy savings actually resulted in a 1.25% annual reduction in energy consumption, falling short of the -1.5% target set by the Directive (European Commission 2012).

Part of the explanation likely stems from the program's design. Unlike other foreign energy efficiency schemes (e.g. the Weatherization Assistance Program in the US, the Federal subsidy for efficient buildings in Germany), this program neither mandates an energy audit before investments nor includes quality checks upon project completion. More broadly, the program adopts an approach that grants obligated parties maximum flexibility in deciding how to achieve their targets. However, in the absence of quality controls, this flexibility may incentivize prioritization of lower-quality, less expensive work or a focus on infra-marginal investments.

6 Estimating the CO_2 abatement cost

In this section, we develop an original methodology to estimate the cost of reducing carbon emissions through the program, leveraging the fact that certificates are tradable. Assuming a competitive market, the certificate price indirectly reflects the marginal cost of saving energy under the CEE scheme. The basic approach for calculating the implied CO_2 abatement cost then consists in multiplying the certificate price with the amount of carbon avoided through its production. A key advantage of this revealed-preference approach is that the certificate price captures all private costs and benefits incurred by the actors involved in certificate generation. This includes transaction and administrative costs borne by obligated parties, as well as both monetary and non-monetary costs and benefits experienced by participating households.

The primary input variables for calculating the CO_2 abatement cost include the certificate price, the coefficients from Table 4—which estimate the projected savings on natural gas and electricity consumption—and additional data on the carbon footprints of these two fuels. The latter is sourced from the French Environmental Agency and the Ministry for Ecology, which report a carbon content of 79 g CO_2 eq./kWh for electricity (ADEME 2020) and 227 g CO_2 eq./kWh for natural gas (CGDD 2019)[5]. The main methodological challenge lies in reconciling the certificate price—assumed to reflect the production cost of the *marginal* certificate—with our econometric estimates and the carbon footprints, which represent the *average* energy impact and emissions.

We argue that the spot price observed on a given date reflects the marginal cost of producing a certificate. The regulator determines the total number of certificates to be issued for each triennial obligation period—in this case, from 2018 to 2020. As a result, cumulative demand is fixed and intersects with a supply curve characterized by rising marginal costs, ultimately setting the equilibrium price in the spot market. Assuming a linear cost function, the average cost of producing a certificate can be approximated as half of the spot price.

$$\text{Average Cost}_{\text{CEE}} = \frac{\text{Price}_{\text{CEE}}}{2}$$

The cost borne by the energy retailers and their subcontractors to produce certificates includes the transaction and commercialization costs to source investment opportunities, and the subsidies they need to offer to persuade households to invest. Interviews with obligated parties reveal that the former are highly significant. In a different context, Fowlie, Greenstone, and Wolfram 2015 entrusted companies with a campaign to encourage participation to the Weatherization Assistance Program in Michigan. The field activities only managed to increase the participation rate by 5 percentage points at a cost of more than 1,000 USD per weatherized household, around 20% of the renovation investment cost.

The subsidy level is set by the obligated parties in a competitive context, aiming for the minimum amount satisfying the household participation constraint. Its level thus reflects the costs and benefits for the household undertaking the retrofit, including the monetary cost of the investment, the reduction in the energy bill, but also non-monetary costs and benefits such as the inconvenience of the work, the information collection and processing information, the comfort gains and the private health benefits. This scope is thus much broader than that of traditional cost evaluations, which

[5] The difference between the two footprints is due to the high share of nuclear energy in France's electricity mix.

only consider the monetary cost of the investment and the reduction in energy expenditures.

We then take spot price of the certificate from the official register on the date the work is launched (Emmy 2023). We rely on official records of savings with bonus in this calculation, because the value of each work is defined by the (annualized) amount of certificates it delivers, including bonuses.

In the end, we obtain an estimate of EUR 135 per ton CO_2 eq. [6] It is below that of Fowlie, Greenstone, and Wolfram 2018, who estimate it at $200 per ton in the context of the Weatherization Assistance Program. Two key differences with our work are worth noting. First, Fowlie and coauthors had to make assumptions on the emission factors of local pollutants and the private benefits associated with their avoidance. Our revealed preference approach does not impose such a restriction. Second, our estimate covers all non-monetary costs and benefits that are priced by the market for certificates, including the discomfort incurred during installation, comfort gains, and the transaction and commercialization costs. To the best of our knowledge, we are the first to estimate such a comprehensive cost of abatement, specifically for energy retrofit investments.

This figure of 135 EUR per ton significantly surpasses the current EU carbon market price (75 EUR/ton CO_2 in May 2024). It also diverges significantly from the forecasts of micro-simulation models such as Res-IRF (Cired 2021), which simulates energy consumption and energy efficiency improvements in the French residential building sector. In a recent report heavily based on this tool, the governmental agency *France Stratégie* evaluated that residential emissions could be slashed by 35% through retrofits costing less than 135 EUR/t. CO_2 eq. (France Stratégie 2023). However, these emissions only decreased by 8.7% between 2018 and 2020 (CITEPA 2023), which suggests the existence of infra-marginal works financed through the French CEE.

We also define a narrower net private cost of energy efficiency investments reflecting the trade-off between monetary costs and benefits of CEE retrofits. In this accounting exercise, we rely on the average investment costs provided by the *Base Carbone* of the French Energy Management Agency (ADEME 2024) for each work type. We a apply an annual rental cost of capital of 4% to mirror the official discount rate of projected energy savings. Monetary gains are evaluated using the local residential electricity and gas prices value. The resulting average net private cost is 195 EUR/t. CO_2 eq, way above the average cost from the revealed preferences approach. Hence, non-monetary benefits are priced on the market of certificates at a value of around 60 EUR/t. CO_2 eq.

[6] We also perform one robustness test using the 150 g/kWh carbon content of electricity according to the usage-based, seasonally-adjusted method from ADEME's Base Carbone®. The resulting MCCA is 130 EUR/ton CO_2 eq.

7 Conclusion

Relying on a new administrative dataset recording all EEOs-supported energy efficiency retrofits in the French residential sector between 2018 and 2020, we investigate their impact on gas and electricity consumption in 4,774 peri-urban municipalities. We compute the ex-ante prediction of savings associated to these operations to measure the wedge between and realized savings. We document two primary findings. First, each kWh of savings predicted by engineering models yields in the best case scenario only 0.411 kWh of realized savings. The French CEE is therefore plagued by a minimum 59% energy performance gap. Second, the average cost of carbon abatement through CEE retrofits is equal to 135 EUR per ton of CO_2 equivalent.

We consider these results as a first step towards a better understanding of the effect of an EEOs on residential energy use. Our research agenda is still vast, and includes the analysis of interactions with other energy efficiency policies and the investigation of the distributive effects of the low-income households sub-obligation. On a broader point of view, one should keep in mind that energy efficiency works may have other effects than energy reduction, such as health improvements or unemployment reduction through the creation of green jobs.

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A Background information on the French EEOs

A.1 Baseline mechanism

Table A1: Summary statistics on the 23 standardized energy retrofit operations used in the residential sector

	Operation	Life exp. (years)	Mean (MWh c.)	Median (MWh c.)	Sum 2017-19 (GWh c.)	Classic (%)	Preca. (%)	Total (%)	Rank
EN-101	Roof insulation	30	240.11	207.000	49527.841	25.73	74.27	52.82	1
EN-103	Floor insulation	30	354.38	308.000	16694.019	30.63	69.37	17.80	2
EN-102	Wall insulation	30	350.58	209.000	8163.930	33.00	67.00	8.71	3
TH-104	HP air-water / water-water	17	489.80	454.500	7494.935	37.14	62.86	7.99	4
TH-106	High EE individual boiler	17	124.01	109.100	6669.954	44.93	55.07	7.11	5
EN-104	Window w/ insulated glazing	24	51.62	32.800	1361.083	56.84	43.16	1.45	6
TH-112	Wood-burning system	12	29.53	29.600	1178.195	77.99	22.01	1.26	7
TH-129	HP air-air	17	54.06	44.590	869.218	65.70	34.30	0.93	8
TH-113	Individual biomass boiler	17	442.72	454.500	716.768	39.64	60.36	0.76	9
TH-127	Hygro-adjustable CMV	17	62.11	46.357	209.885	11.60	88.40	0.22	10
TH-160	Hot water network insulation	20	2217.54	899.810	175.185	74.04	25.96	0.19	11
TH-159	Hybrid individual HP	17	576.96	454.500	167.317	37.25	62.75	0.18	12
TH-131	Water network insulation	20	8861.70	9259.200	150.649	87.03	12.97	0.16	13
TH-148	HP water-heater	17	21.21	21.100	138.965	58.20	41.80	0.15	14
EN-105	Rooftop insulation	30	566.98	148.500	86.180	23.54	76.46	0.09	15
TH-145	Comprehensive renovation	30	13384.10	8029.547	53.536	9.93	90.07	0.06	16
TH-115	Heating network insulation	20	3146.14	1848.000	34.608	46.59	53.41	0.04	17
TH-107	High EE collective boiler	22	1219.98	805.806	29.280	40.39	59.61	0.03	18
TH-110	Low-temperature radiator	35	33.73	16.932	27.219	6.69	93.31	0.03	19
EN-108	Insulating closure	24	4.63	3.900	5.362	92.11	7.89	0.01	20
TH-101	Individual solar water heater	20	33.21	27.600	4.882	37.44	62.56	0.01	21
TH-125	Dual-flow ventilation	17	50.59	43.890	4.047	27.52	72.48	0.00	22
TH-107-SE	Collective boiler w/ contract	22	1230.54	1251.188	3.692	67.77	32.23	0.00	23
TH-116	Underfloor heating system	50	31.51	27.000	1.733	75.67	24.33	0.00	24
TH-137	Connection to a heating network	30	72.10	63.085	0.505	7.74	92.26	0.00	25

A.2 CEE production

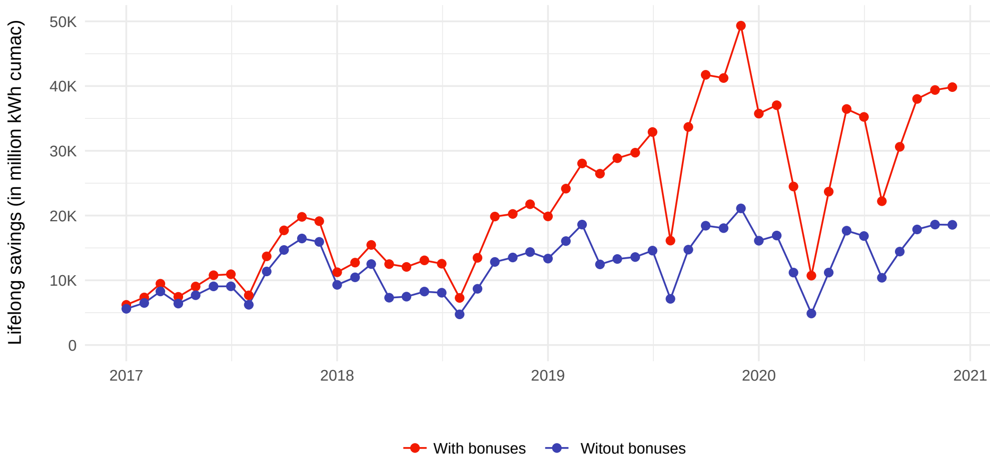


Figure A1: Lifelong savings and number of certificates over 2017-2021 (kWh cumac)

B Data

B.1 Sample selection

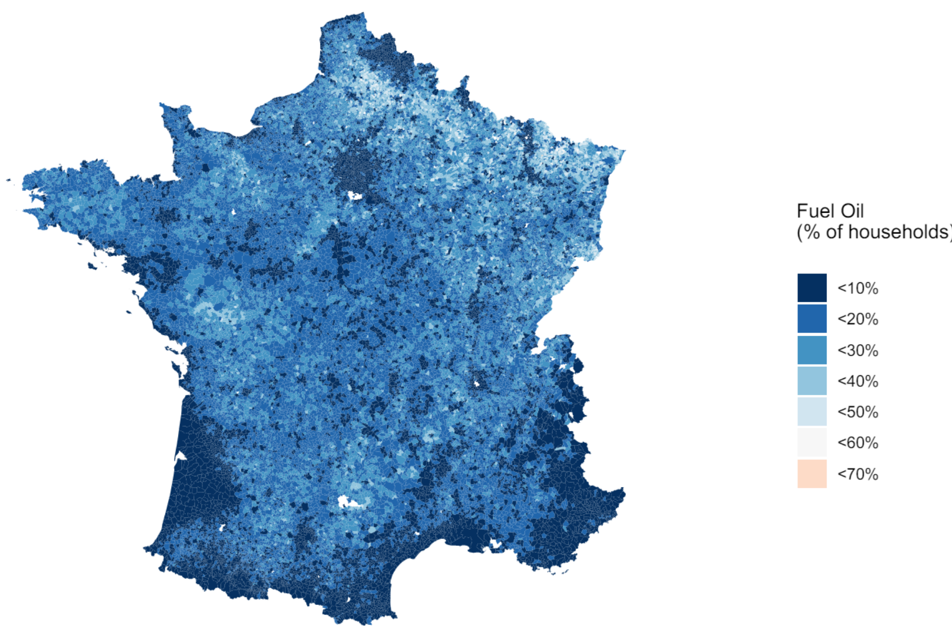


Figure A2: Average % of Housing Units which main heat source is heating Oil, 2018-2020

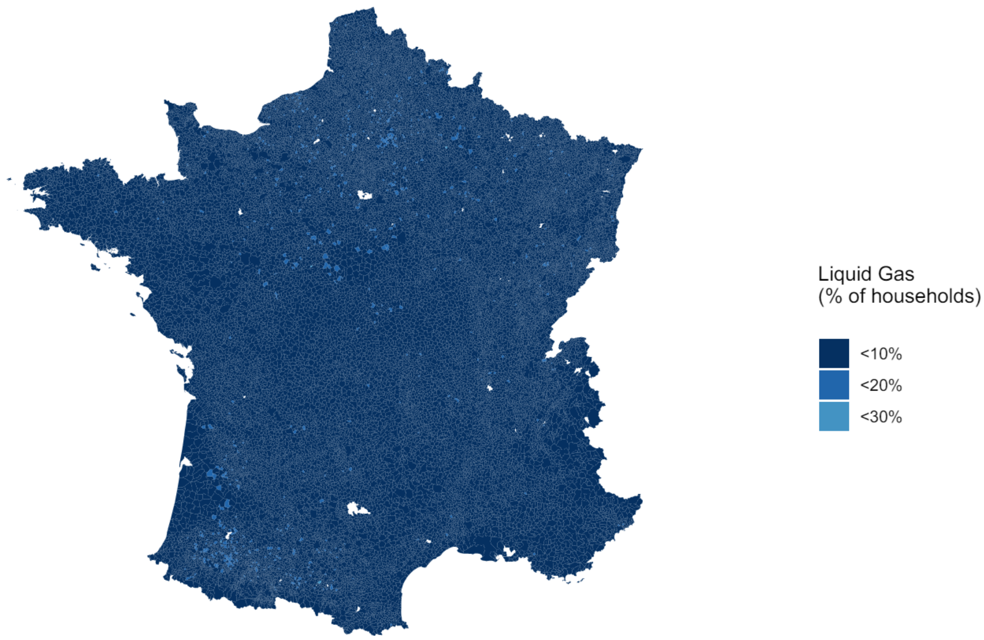


Figure A3: Average % of Housing Units which main heat source is Liquid Gas, 2018-2020

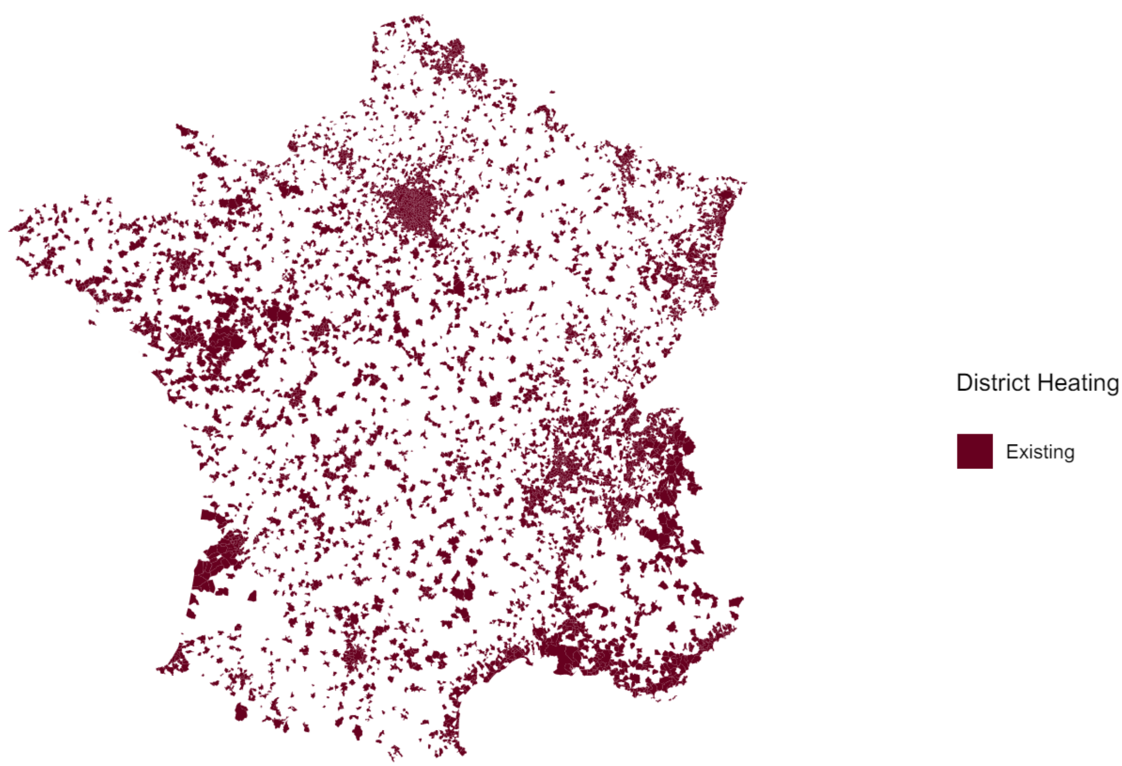
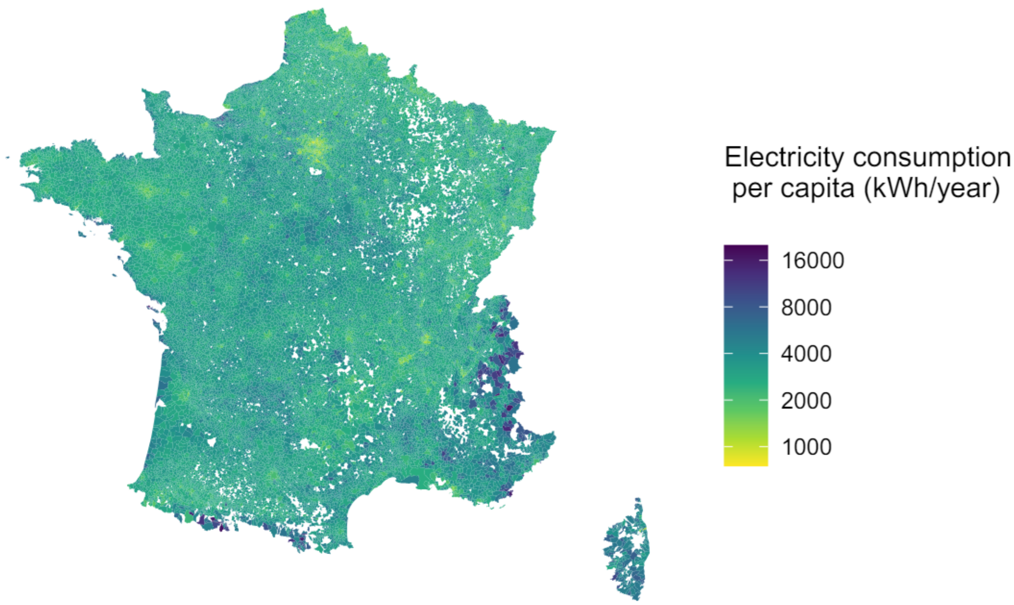


Figure A4: Municipalities connected to a District Heating network, 2018-2020

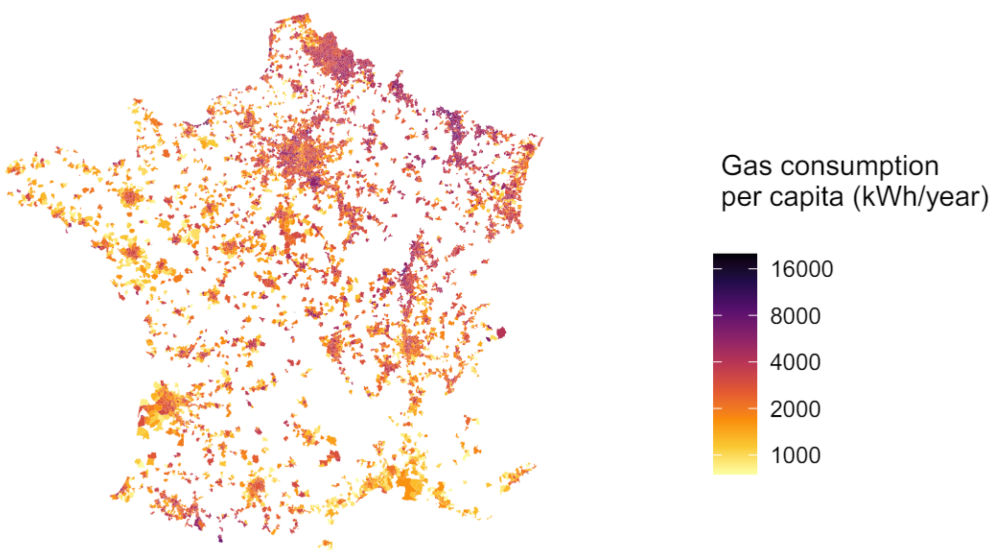
Table A2: Per capita municipal residential energy use, retrofit works, and demographics

	Estimation sample (N = 4,774)		Mainland France (N = 34,868)	
	Mean	SD	Mean	SD
Panel A: Energy use				
Electricity (kWh)	3,429.959	1,213.841	3,168.284	830.544
Gas (kWh)	1,263.306	1,722.556	745.262	1,384.025
Panel B: Retrofit works				
Projected lifelong savings (kWh)	2,816.795	2,001.76	3,416.708	2,945.592
Projected annual savings (kWh)	77.643	61.008	96.349	84.181
Panel C: Demographics				
Med. Inc. (EUR/y)	21,363.438	3,625.951	21,833.585	3,692.437
Population	1,078	1,365	1,991	8,262
Panel D: Weather				
HDD	2,066	575	2,143	435
CDD	381	188	356	157
Precipitation (mm)	928	263	881	210

B.2 Energy use



(a) Electricity consumption



(b) Gas consumption

Figure A5: Average electricity and gas consumption per capita, 2018-2020

B.3 Population

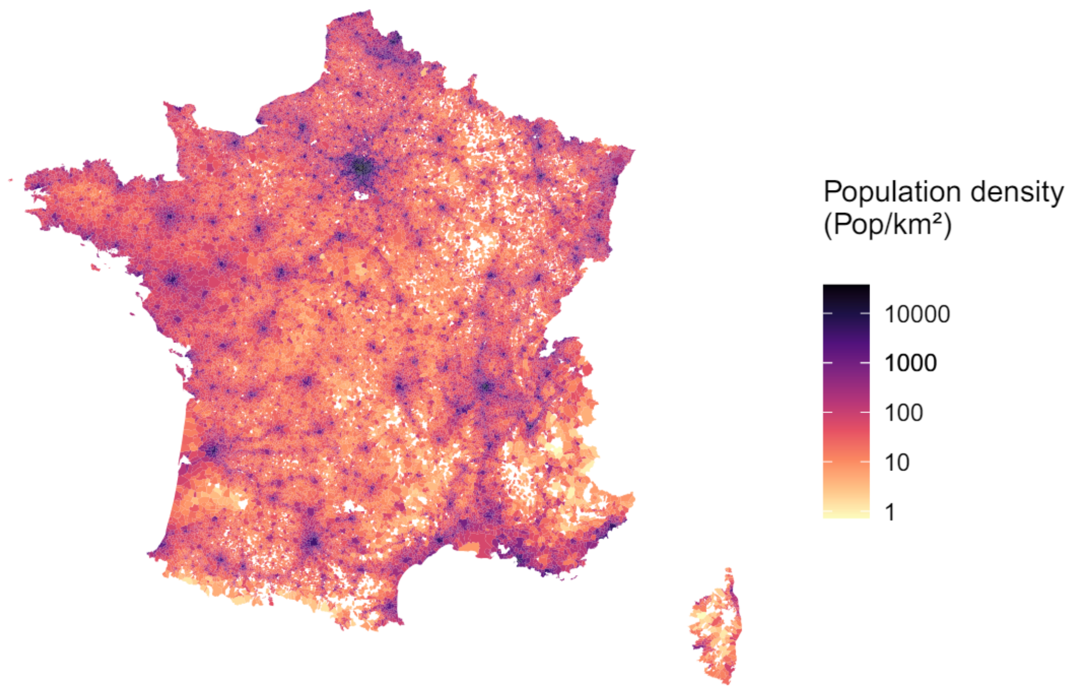
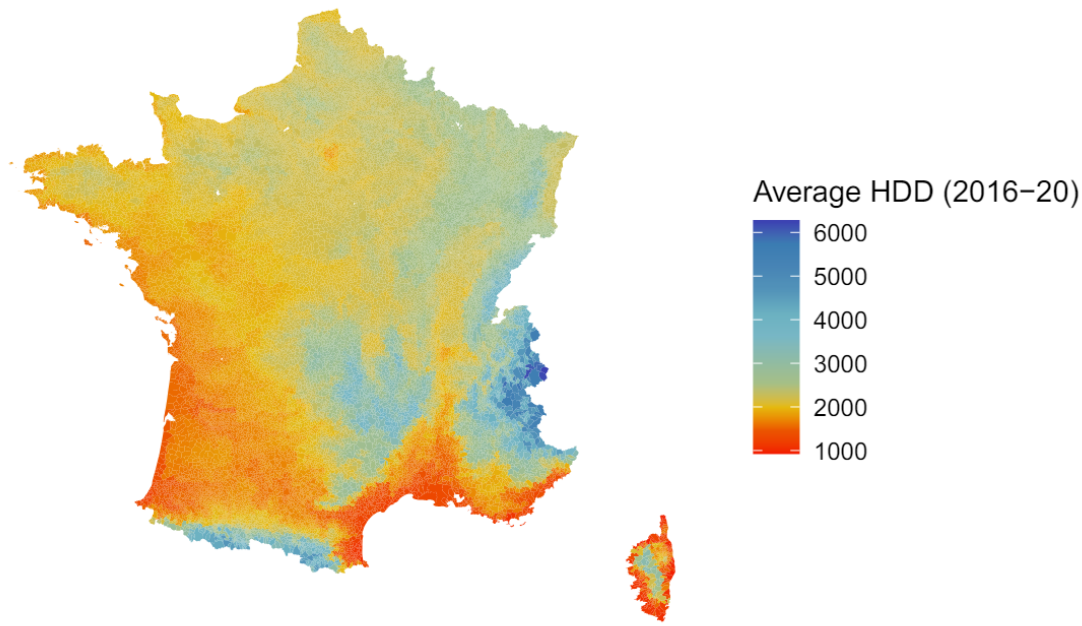
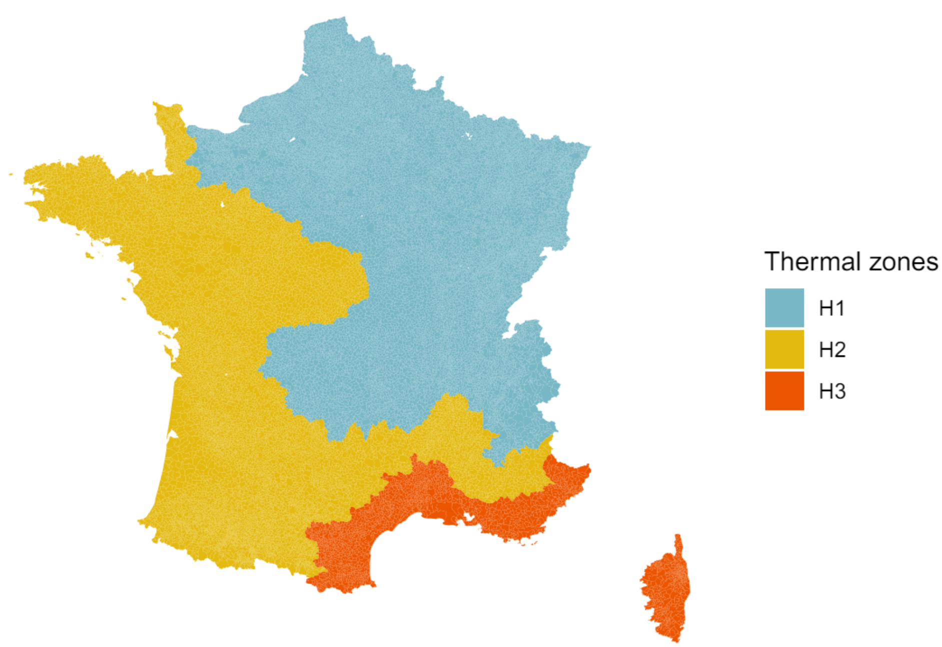


Figure A6: Population density in 2020

B.4 Heating Degree Days



(a) Average Heating Degree Days between 2016 and 2020



(b) Thermal zones

Figure A7: Mid-run climate

Degree days are based on the assumption that when the outside temperature is 17°C, we don't need heating or cooling to be comfortable. Degree days are the difference between the daily temperature mean and 17°C. If the temperature mean is above 17°C, we subtract 17 from the mean and the result is Cooling Degree Days. If the temperature mean is below 17°C, we subtract the mean from 65 and the result is Heating Degree Days.

More specifically, for each node and day, we use the average temperature ($\mathrm{T°}_{n,d}$) to define HDD for each day using the SDES methodology:

$$HDD_{n,d} = \begin{cases} 17 - \mathrm{T°}_{n,d} & \text{if } \mathrm{T°}_{n,d} < 17°\mathrm{C} \\ 0 & \text{otherwise.} \end{cases}$$

We then sum HDD over one year to get yearly values for each node (e.g., $HDD_{n,y} = \sum_{d=1}^{365} HDD_{n,d}$), and derive the yearly HDD for each municipality ($HDD_{m,y}$).

We map Heating Degree Days (HDD) at the municipality level using the following rule:

$$HDD_{m,y} = \begin{cases} HDD_{n,y} & \text{if } n \subset m \text{ and } \nexists\, n' \neq n \text{ such that } n' \subset m \\ \frac{1}{k}\sum_{1=n_1}^{n_k} HDD_{n,y} & \text{if } \exists\, k > 1 \text{ such that } \forall\, n \in [n_1, n_k],\ n \subset m \\ HDD_{n,y},\ n = \arg\min_n \|C_m - n\| & \text{if } \nexists\, n \subset m \end{cases}$$

where C_m is the centroid of each municipality used for 1 nearest-neighbor matching when there is no node n within the boundaries of municipality m. Using this re-projected version of our HDD data, we can produce some HDD-related variables at the level of each municipality.

B.5 Alternative Instrumental Variable Specification

Table A3: Alternative IV specification

	HDD (t-2)	Rain (t-2)	[HDD + Rain] (t-2)
Fitted Expected Savings	−0.417***	−0.411*	−0.415***
	(0.111)	(0.199)	(0.122)
Log. of Pop.	741 278.602***	740 729.911***	741 038.689***
	(165 266.373)	(173 162.622)	(168 504.516)
HDD	562.806*	561.165**	562.088**
	(224.841)	(186.463)	(207.029)
Precipitation (mm)	110.024+	109.817+	109.933+
	(64.876)	(60.667)	(62.970)
Num.Obs.	12 207	12 207	12 207
R2	0.999	0.999	0.999
R2 Adj.	0.998	0.998	0.998
R2 Within	0.078	0.078	0.078
FE: Code_commune_INSEE	X	X	X
FE: dep_year	X	X	X
F-test (1st stage)	219.63	175.123	179.164

+ p < 0.1, * p < 0.05, ** p < 0.01, *** p < 0.001

Clustered standard errors at the municipality level