The Effect of Energy Efficiency Obligations on Residential Energy Use: Empirical Evidence from France

Guillaume Wald *
Matthieu Glachant

CERNA, Mines Paris, PSL University

October 2024

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 62%. We then exploit the fact that obligations are tradable to recover the implied marginal abatement cost of carbon. Importantly, this cost exceeds EUR 160 per ton of CO_2 equivalent.

JEL No. L78, Q48, Q58.

*Corresponding author: guillaume.wald@minesparis.pls.eu

1 Introduction

Improving energy efficiency of the building stock is a key component for the energy transition. According to the International Energy Agency, global investment in building energy retrofits over 2015-2021 exceeded 160 bln USD/year. This represents 60% of the global energy efficiency investment, and more than twice the investment in transport (IEA 2022). Insulation and the use of energy-efficient heating and cooling devices has been advocated as a win-win opportunity since the end of the 1970's (Allcott and Greenstone 2012). In this view, government intervention is justified because energy efficiency decreases both the energy burden and the negative climate and health externalities. This argument has percolated through the public opinion: in a recent survey analysis, Dechezleprêtre et al. 2022 showed a particularly strong support for mandatory and subsidized insulation of buildings among OECD members population.

To achieve their energy efficiency targets, a growing number of governments rely on energy efficiency obligations (EEOs) (IEA 2022). They require market actors such as energy suppliers (France) or distribution system operators (Italy), to carry out a defined level of energy savings. In practice, obligated parties mostly fulfill their responsibilities by offering monetary incentives to energy consumers, including households, industries, and services, to invest in energy retrofits. They finance these subsidies and the associated transaction costs through an increase in energy prices (Rosenow, Cowart, and Thomas 2019). In 2022, the IEA identified no less than 48 energy efficiency obligation programs. In the US, 24 states have EEOs, called Energy Efficiency Resource Standards, and similar programs can be found in Australia, Brazil, Canada, China, South Korea, South Africa and Uruguay (Crampes and Léautier 2020). In the European Union, sixteen Member States and the UK operate EEOs.

Despite this widespread adoption, the literature lacks a proper econometric evaluation of the effects of retrofits subsidized through EEOs on energy consumption. To fill this gap, we focus on the French EEO program (in French, *Certificats d'Economie d'Energie*, hereafter CEE), which was in 2020 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). 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 a marginal 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 62%. We connect this result with the amount invested by energy suppliers, and find a marginal cost of carbon abatement above EUR 150/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 Description on the French CEE program

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, 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.

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 28 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. At the end of each four-year period, energy suppliers must demonstrate compliance by submitting the required quantity of certificates to the regulator.

This program is designed to encourage obligated parties to source the least-cost options. They are free to generate certificates independently or to subcontract this task to other firms, public organizations, or local governments. Alternatively, they can purchase certificates on the certificate market. In 2019 and 2018, trading volumes reached 288 TWhc and 179 TWhc, respectively, highlighting the significant role of trading in meeting the annual obligation of 533 TWhc.

Reducing energy consumption is the program historical objective. It is the cornerstone of the France's commitment to meeting the national target set out in the European Union's energy efficiency directive (European Commission 2012): an annual reduction of -1.5% in energy sales from

2014 to 2020 for all sectors except transport (article 7).

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 lifelong savings and the number of certificates as depicted in Figure 1. 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.

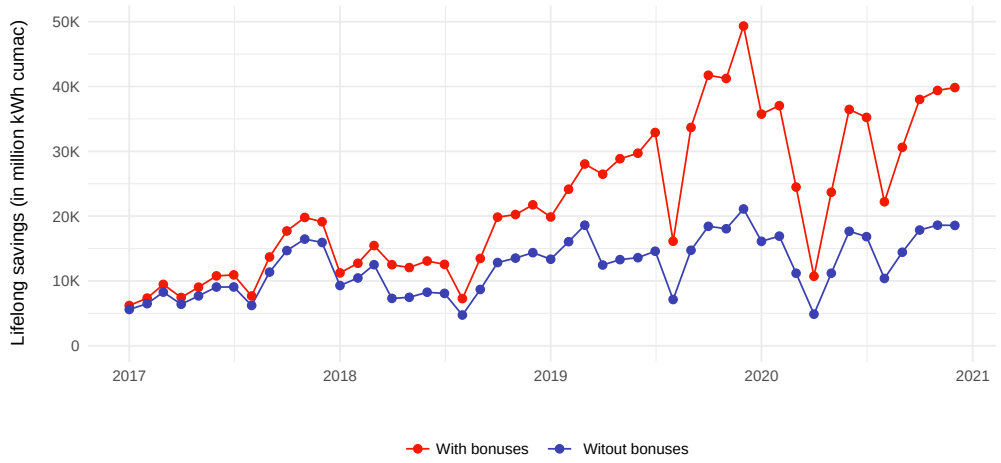


Figure 1: Lifelong savings and number of certificates over 2017-2021 (kWh cumac)

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.

[1]Source: https://www.statistiques.developpement-durable.gouv.fr/sites/default/files/2022-03/rapport$_onre_mars2022.pdf.Seepage20$.

3 Data

Our analysis builds on three main sources: residential electricity and gas consumption data, certificate data which gives information on the quantity and characteristics of the energy retrofits subsidized through the program, weather data, and city-level socio-demographics.

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, providing municipality-level data from 2018 to 2020. No information is available on the consumption of other energy sources, such as fuel oil, liquid gas or district heating. As we are not able to identify fuels used in retrofitted dwellings, we restrict the study sample to municipalities with the lowest dependence to these other sources. More specifically, we rely on population census (INSEE 2018) to exclude municipalities where fuel oil (respectively, liquid gas) is the main heating source for more than 10% of housing units (excluding holiday homes). As shown in Figure A1 and A2, this mostly removes rural municipalities. We also exclude all municipalities with a district heating system in operation over 2018-20, which, in practice corresponds to very densely populated urban centers such as Paris, Marseille or Lyon (see Figure A3). The final estimation sample gathers 4,774 municipalities, accounting for 5.18 million inhabitants. We present summary statistics for this perimeter in Table 1.

Energy retrofits. The Energy Efficiency Obligation database is hosted by the *Centre d'Accès Sécurisé aux Données*, a French public interest group implementing secure access services for confidential data for non-profit research (CASD 2023). The dataset encompasses more than 3.1 million energy efficiency operations conducted in the residential sector between 2018 and 2020. It provides detailed information on the type of work performed, the expected lifespan of each retrofit, its location (down to the city level) and the number of certificates generated.

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.

Table 1: Per capita municipal residential energy use, retrofit works, and demographics

	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 without bonuses (the blue dotted line in Figure 1), 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 95% of the 25 work-types displayed in Table A1). Investment in insulation alone (roof, floor, wall) accounts for 79% of projected savings.

Socio-demographics. The 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.

Weather data. Heating Degree Days (HDD) and Cooling Degree Days (CDD) are the usual metrics used by engineers to estimate the heating and cooling needs, and thus the influence of temperature on energy use. We compute HDDs and CDDs for each municipality taking 17 °C as the reference temperature[2]. The exact matching process is detailed in Appendix B.4.

Table 2: Shares of main work types

Code	Operation	% annual projected savings
BAR-EN-101	Roof insulation	53.7
BAR-EN-103	Floor insulation	16.9
BAR-EN-102	Wall insulation	8.4
BAR-EN-106	Heat pump (air-water, water-water)	8.0
BAR-EN-104	High energy efficient individual boiler	7.1

4 Empirical strategy

4.1 Identification

To estimate the effect on residential gas and electricity use of the retrofit works supported by the program, we start with a simple Two-Way Fixed-Effects (TWFE) design. More precisely, we exploit the year-to-year within-municipality variation 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 $Y_{i,t}$ is the residential electricity and gas consumption in municipality i in year t. Adding the two energy sources account for possible substitution effects (Giraudet, Houde, and Maher 2018). Fuel switching occurs, for instance, when gas boilers are replaced by heat pumps. We also estimate separate equations for electricity and gas. Municipality fixed effects are denoted α_i and year fixed effects are denoted γ_t.

The variable $X_{i,t}$ is the projected savings achieved by the investments made in municipality i between the beginning of the study period, 2018, and year t. The idea here is that the energy savings obtained in a given year are determined by the stock of past investments. We do not

[2]This 17°C threshold is used in the French national energy statistics (SDES 2024)

observe the investments made before 2018, but they are absorbed by the municipality fixed effects. In this specification, the coefficient β directly gives the share of projected savings achieved ex post.

The equation includes a vector $W_{i,t}$ of weather variables (contemporaneous CDD, HDD, and precipitations) which influence energy use and may have indirect impacts on the pace of energy efficiency investments and a vector of demographic controls. The vector $D_{i,t}$ accounts for demographic controls including median income and population. We apply a logarithmic transformation to population because its effect on energy use is likely to be non-linear due to agglomeration effects. Median income directly enters the regression in levels.

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. Omitting this variable will then lead to overestimate the energy savings. [3].

Moreover, some energy retrofits are undertaken without any support from the CEE program, meaning they go unobserved and generate no certificates. This might not be a significant concern, as our objective is to evaluate the impact of the CEE rather than energy efficiency investments as a whole. Except that energy efficiency measures supported through the CEE are likely not independent of other energy efficiency efforts – both types of investments respond to similar determinants. This introduces biases as some of these drivers are unobserved. As CEE- and non-CEE investments could either complement or substitute each other, the direction of the bias is unclear.

4.2 Instrumental Variation

To address these endogeneity issues, we instrument the year-to-year change in projected savings $X_{i,t}$. We exploit municipality-level data on heating and cooling degree days two years before the investment in energy efficiency. Indeed, variations in outdoor temperatures affect the salience of a building's energy efficiency attributes, hence future investment decisions regarding energy retrofits.

[3]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.

More specifically, the instrument writes:

$$Z_{i,t} = HDD_{i,t-2} + CDD_{i,t-2} \tag{2}$$

Turning next the exogeneity of the instrument, let's make the problem more explicit by decomposing the error term in 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 above discussion first points to the fact that we have $\text{Cov}(X_{i,t}, \varepsilon_{i,t}) \neq 0$ and that endogeneity issues plaguing CEE retrofits also affect non-CEE investments so that $\text{Cov}(R_{i,t}, \varepsilon_{i,t}) \neq 0$.

The exclusion restriction requires

$$\text{Cov}(Z_{i,t}, \phi\, R_{i,t}) + \text{Cov}(Z_{i,t}, \varepsilon_{i,t}) = 0. \tag{3}$$

Let's first consider the second member of this expression, i.e., the covariance between our instrument and within-municipality socio-economic variations. We argue that local temperatures from two years in the past do not influence current energy use via another channel than investment in home renovations. Thus, $\text{Cov}(Z_{i,t}, \varepsilon_{i,t}) = 0$.

However, the restriction does not hold if past temperatures also affect changes in energy efficiency investment outside of the CEE program scope. As our instrument leverages demand-side dynamics at a local level, it may also affect non-CEE energy efficiency improvements, hence we have: $\text{Cov}(Z_{i,t}, R_{i,t}) \neq 0 \Rightarrow \text{Cov}(Z_{i,t}, u_{i,t}) \neq 0$. This makes our IV strategy invalid, biasing our coefficient β^{2SLS}.

The good news is that we can identify the sign of the bias. To see, we write the second-stage equation as follows:

$$Y_{i,t} = \beta^{2SLS}\, \widehat{X}_{i,t} + \lambda_2\, W_{i,t} + \mu_2\, D_{i,t} + \alpha_i + \gamma_t + \phi\, R_{i,t} + \varepsilon_{i,t} \tag{4}$$

Because the exclusion restriction does not hold and under the assumption that, within each municipality i, $\text{Cov}(W_{i,t}, Z_{i,t}) = \text{Cov}(D_{i,t}, Z_{i,t}) = 0$, straightforward calculations give:

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

The bias of our 2SLS estimand is thus equal to $\phi \frac{\text{Cov}(R_{i,t},Z_{i,t})}{\text{Cov}(X_{i,t},Z_{i,t})}$, where ϕ, the marginal effect of $R_{i,t}$ on $Y_{i,t}$, is multiplied by a ratio between the covariance of the instrument with respect to $R_{i,t}$ and the covariance of the instrument with respect to $X_{i,t}$. Because the first stage effect of our instrument on CEE-funded investments does not rely on a specificity of the CEE program, it can be generalized to all types of energy efficiency retrofits so that $\text{Cov}(R_{i,t}, Z_{i,t}) > 0$. Consistently, the marginal effect of $R_{i,t}$ on energy use, ϕ, goes in the same direction than that of $X_{i,t}$. Thus, we expect non-CEE retrofits to decrease energy use, hence $\phi < 0$. This unique and fairly plausible assumption is enough to characterize the sign of the bias in our IV estimate. The ratio is positive, hence the bias is negative. Moreover, because the true effect of $X_{i,t}$ on $Y_{i,t}$ captured by β is expected to be negative, we take β^{2SLS} as a lower-bound estimate of β, i.e., an upper-bound estimate of the absolute value decrease in energy use.

5 Results

5.1 Main estimation

We estimate both the OLS-FD and the 2SLS-FD regressions for savings. For each regression, we cluster the standard errors at the municipality level to account for possible within-municipality correlation patterns.

The two columns of Table 3 describe the effect of savings as defined in the standardized formulas from the Energy Management Agency (ADEME). The coefficient should be read as the effect of one kWh of savings at t on energy use the same year. Such kWh of savings can be imputed to CEE retrofits undertaken at t or earlier. According to column (1), one additional kWh of savings at t is negatively correlated with energy use. This correlation is highly endogenous because we do not account for the potential selection effect on retrofitting households triggered by within-municipality dynamics as detailed in section 4. This bias is worsened by the effect of non-CEE investments. Nevertheless, the coefficient for savings is statistically significant, which motivates the search for a better identification strategy.

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

	OLS-FD	2SLS-FD
Expected Savings	−0.477***	
	(0.072)	
Fitted Expected Savings		−0.381**
		(0.142)
Log. of Pop.	737 987.767***	728 072.622***
	(173 463.938)	(170 708.251)
Median income	−3.450	−3.665
	(5.527)	(5.561)
HDD	547.740**	528.126**
	(192.062)	(190.967)
CDD	−390.121	−293.162
	(409.870)	(404.581)
Precipitation	109.785+	106.562+
	(62.948)	(62.405)
Num.Obs.	12 207	12 207
R2	0.999	0.999
R2 Adj.	0.998	0.998
R2 Within	0.080	0.076
FE: Municipality	X	X
FE: Dep. × Year	X	X
F-test (1st stage)		88.442

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

Column (2) reports the effect of our IV estimation, wihch relies on the setting exposed in section 4. The magnitude of the 2SLS coefficient is around four fifths that of its OLS counterpart. Not accounting for the selection effect therefore yields an overestimation of the effect of CEE retrofits on energy use. The difference between $\widehat{\beta}^{OLS}$ and $\widehat{\beta}^{2SLS}$ may come from pre-existing downward trends in energy use within municipalities which retrofit more.

As a result, our 2SLS strategy identifies that each kWh of savings implemented through a CEE operation actually reduces energy use by at most 0.381 kWh. This effect is significant at the 1% level, and relies on a solid first stage F-statistic (88.4), well above the Staiger and Stock 1997 rule of thumb. $\widehat{\beta}^{2SLS}$ can be interpreted as our estimate of the energy performance gap plaguing the French program. It implies an overestimation of engineering predictions used by the Energy Management Agency by at least 62%.

5.2 Impact on electricity and gas

We run the same specification separately for electricity and natural gas. Table 4, column (1), shows that electricity use is unchanged by additional savings. The effect measured in our main specification in Table 3 is thus mostly triggered by a decrease in natural gas consumption. The reason is simple. Around 80% of the savings result from retrofits to non-electricity heated dwellings (see Table 2, column 4).

Table 4: Effect of projected savings on electricity and gas

	Electricity	Natural Gas
Fitted Expected Savings	0.049	−0.429***
	(0.078)	(0.112)
Log. of Pop.	475 406.893***	252 665.729+
	(59 789.986)	(149 213.842)
Median income	0.911	−4.576
	(2.072)	(5.047)
HDD	181.237*	346.889*
	(71.647)	(175.817)
CDD	282.448**	−575.610
	(108.269)	(387.703)
Precipitation	−13.721	120.282*
	(25.592)	(56.319)
Num.Obs.	12 207	12 207
R2	0.999	0.997
R2 Adj.	0.999	0.994
R2 Within	0.006	0.102
FE: Municipality	X	X
FE: Dep. × Year	X	X
F-test (1st stage)	88.442	88.442

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

5.3 Robustness checks

We perform two types of robustness checks for our 2SLS-FD specification. First, we focus on the potential estimation bias implied by households switching out from residential fuel oil or liquid gas. Although we focus on municipalities in the lowest decile for the consumption of both fuels, there still are some scope for such behavior. We thus exclude all municipalities where the change in the share of housing units using fuel oil (respectively, liquid gas) exceeds 1 percentage point over

2018-20. Estimation results over these sub-samples are presented in column 1 and 2, Table 5. The estimation precision for the coefficient on fitted savings slightly decreases but remains below 5% for both sources. It is of the same magnitude as in the main regression, implying at best the realization of 40% of all savings.

Second, we investigate the role of potential dependence based on spatial proximity between individual observations. While clustered standard errors consider within-municipality, cross-period correlation, a spatial-error model (SEM) accounts for the contemporaneous, cross-municipality correlation. In our context, it is likely that the error terms $u_{i,t}$ and $u_{j,t}$ for two adjacent municipalities i and j are not perfectly orthogonal: the unobserved non-CEE retrofitting investments $R_{i,t}$ and $R_{j,t}$ respond to local supply and demand shocks, within and across municipality borders. We rely on Conley 1999 for the specification of the variance covariance matrix estimator, which models relative proximity of two adjacent municipalities according to a set 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 $\vartheta_{i,t} \overset{i.i.d.}{\sim} \mathcal{N}(0, \sigma^2)$:

$$u_{i,t} = \xi \sum_{i \neq j} \omega_{ij} u_{j,t} + \vartheta_{i,t} \tag{5}$$

We present results for the 10 and 20 km thresholds. The only change with respect to our baseline estimation happens in the computation of the standard errors, which are not clustered at the municipality level anymore. Still, the p-value for the effect of contemporaneous savings remains below 5% at both 10 and 20 km. This test is not perfect, as the actual perimeter of spatial diffusion is specific to each observation, and its radius size is ultimately an empirical question. Still, the persistence of a significant effect of CEE-funded retrofits when considering this spatial autoregressive specification brings support to the case of our upper bound estimate.

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

	Fuel Oil	Liq. Gas	SEM 10km	SEM 20km
Fitted Expected Savings	−0.402*	−0.370*	−0.381*	−0.381*
	(0.158)	(0.147)	(0.156)	(0.158)
Log. of Pop.	712 024.448***	712 761.761***	728 072.622***	728 072.622**
	(186 297.551)	(184 838.022)	(178 498.095)	(225 585.566)
Median income	−3.389	−5.003	−3.665	−3.665
	(6.101)	(6.090)	(5.783)	(6.653)
HDD	611.639**	562.314**	528.126*	528.126*
	(207.999)	(194.563)	(207.245)	(244.895)
CDD	−408.897	−291.237	−293.162	−293.162
	(456.083)	(386.298)	(436.375)	(595.845)
Precipitation	136.835+	111.329+	106.562	106.562
	(71.548)	(64.255)	(70.034)	(86.834)
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	0.077	0.076	0.076
FE: Municipality	X	X	X	X
FE: Dep. × Year	X	X	X	X
F-test (1st stage)	73.771	86.752	88.442	88.442

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

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

6 Discussion

6.1 The policy implications of the performance gap

We estimate that the realized savings on residential electricity and gas are, at best, only 38% of the savings. This implies a minimum energy performance gap of 62%, 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. savings are routinely communicated by obligated firms and their subcontractors to persuade households to invest in energy efficiency. Closing the gap between 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. If we adjust these estimates with our findings, the realized energy savings actually resulted in a 1.4% annual reduction in energy consumption, falling short of the -1.5% target set by the Directive (European Commission 2012).

6.2 Estimating the carbon marginal abatement cost

We can also use our results to estimate the carbon abatement cost of CEE-funded operations. A particularly useful feature of the program is that certificates are tradable. Provided the market is competitive, the certificate price reveals the marginal cost of saving energy through the CEE. Let us discuss first the relationship between this price and the different cost components.

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

The general principle of our calculation is simple. It basically involves dividing the certificate price by the amount of carbon avoided through its production. We assume a carbon content of 79 g CO_2 eq./kWh for electricity (ADEME 2020) and 227g/kWh for natural gas(CGDD 2019). 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 160 $[120 - 240]$ EUR/ton CO_2 eq. [4] It is slightly 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 marginal cost of abatement, specifically for energy retrofit investments.

This figure of 160 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 50% through retrofits costing less than 160 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 190 [140-290] EUR/t. CO_2 eq, slightly above our marginal CO_2 abatement cost. Hence, non-monetary benefits are priced on the market of certificates at a value of at least 30 [20-50] EUR/t. CO_2 eq.

[4] 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 $165\ [115 - 280]$ 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 0.381 kWh of realized savings. The French CEE is therefore plagued by a minimum 62% energy performance gap. Second, the marginal cost of carbon abatement through CEE retrofits is equal to 160 EUR per ton of CO_2 equivalent. Relying on EEOs is thus an inefficient and costly way to reduce GHG emissions.

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.

References

ADEME (2020). *Positionnement de l'ADEME sur le calcul du contenu CO_2 de l'électricité, cas du chauffage électrique*. URL: https://librairie.ademe.fr/ged/84/fiche-technique-ademe-contenu-co2-electricite-2020-v2.pdf.

— (2024). *Base Carbone*. URL: https://cired.github.io/Res-IRF/.

Allcott, Hunt and Greenstone, Michael (Feb. 2012). "Is There an Energy Efficiency Gap?" In: *Journal of Economic Perspectives* 26.1, pp. 3–28. DOI: 10.1257/jep.26.1.3. URL: https://www.aeaweb.org/articles?id=10.1257/jep.26.1.3.

Aydin, Erdal, Kok, Nils, and Brounen, Dirk (2017). "Energy efficiency and household behavior: the rebound effect in the residential sector". In: *The RAND Journal of Economics* 48.3, pp. 749–782.

Blaise, Gaël and Glachant, Matthieu (2019). "Quel est l'impact des travaux de rénovation énergétique des logements sur la consommation d'énergie". In: *La Revue de l'énergie* 646, pp. 46–60.

Broc, Jean-Sébastien, Stańczyk, Wojciech, and Reidlinger, Bettin (May 2020). *Snapshot of Energy Efficiency Obligation Schemes in Europe*. Report Provisional version.

CASD (2023). *CEE : Energy saving certificates*. URL: https://www.casd.eu/en/source/energy-saving-certificates/.

CGDD, Commissariat général au développement durable (2019). *Les facteurs d'émission de gaz à effet de serre*. URL: https://www.notre-environnement.gouv.fr/themes/climat/les-emissions-de-gaz-a-effet-de-serre-et-l-empreinte-carbone-ressources/article/les-facteurs-d-emission-de-gaz-a-effet-de-serre/.

Christensen, Peter et al. (July 2023). "Decomposing the Wedge between Projected and Realized Returns in Energy Efficiency Programs". In: *The Review of Economics and Statistics* 105.4, pp. 798–817. ISSN: 0034-6535. DOI: 10.1162/rest_a_01087. eprint: https://direct.mit.edu/rest/article-pdf/105/4/798/2142634/rest_a_01087.pdf. URL: https://doi.org/10.1162/rest%5C_a%5C_01087.

Cired (2021). *Res-IRF*. URL: https://cired.github.io/Res-IRF/.

CITEPA (2023). *Gaz à effets de serre et polluants atmosphériques, Bilan des émissions en France de 1990 à 2022*. Tech. rep.

Conley, T.G. (1999). "GMM estimation with cross sectional dependence". In: *Journal of Econometrics* 92.1, pp. 1–45. ISSN: 0304-4076. DOI: https://doi.org/10.1016/S0304-4076(98)00084-0. URL: https://www.sciencedirect.com/science/article/pii/S0304407698000840.

Crampes, Claude and Léautier, Thomas-Olivier (2020). *White certificates and competition*. TSE Working Papers 20-1167. Toulouse School of Economics (TSE).

Dechezleprêtre, Antoine et al. (July 2022). *Fighting Climate Change: International Attitudes Toward Climate Policies*. Working Paper 30265. National Bureau of Economic Research. DOI: 10.3386/w30265. URL: http://www.nber.org/papers/w30265.

DGEC (2022). *BILAN DE LA 4EME PERIODE DES CEE, 2018-2021*. Tech. rep. Direction Générale de l'Energie et du Climat.

Emmy, Registre National des Certificats d'Economie d'Energie (2023). *Cotation du kWh cumac*. URL: https://www.emmy.fr/public/donnees-mensuelles.

European Commission (2012). "Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC". In: *Off Journal of the European Union, E. Parliament, Editor*.

Fowlie, Meredith, Greenstone, Michael, and Wolfram, Catherine (2015). "Are the non-monetary costs of energy efficiency investments large? Understanding low take-up of a free energy efficiency program". In: *American Economic Review* 105.5, pp. 201–204.

Fowlie, Meredith, Greenstone, Michael, and Wolfram, Catherine (2018). "Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program". In: *The Quarterly Journal of Economics* 133.3, pp. 1597–1644. URL: https://academic.oup.com/qje/article-abstract/133/3/1597/4828342.

France Stratégie (2023). *Les coûts d'abattement en France*. Tech. rep.

Giraudet, Louis-Gaëtan, Bourgeois, Cyril, and Quirion, Philippe (2021). "Policies for low-carbon and affordable home heating: A French outlook". In: *Energy Policy* 151, p. 112140. ISSN: 0301-4215. DOI: https://doi.org/10.1016/j.enpol.2021.112140. URL: https://www.sciencedirect.com/science/article/pii/S0301421521000094.

Giraudet, Louis-Gaëtan, Glachant, Matthieu, and Nicolaï, Jean-Philippe (2020). "Selling and Saving Energy: Energy Efficiency Obligations in Liberalized Energy Markets". In: *The Energy Journal* 41.Special I. URL: https://ideas.repec.org/a/aen/journl/ej41-si1-giraudet.html.

Giraudet, Louis-Gaëtan, Houde, Sébastien, and Maher, Joseph (2018). "Moral Hazard and the Energy Efficiency Gap: Theory and Evidence". In: *Journal of the Association of Environmental and Resource Economists* 5.4, pp. 755–790. URL: https://EconPapers.repec.org/RePEc:ucp:jaerec:doi:10.1086/698446.

Giraudet, Louis-Gaëtan and Missemer, Antoine (2023). "The history of energy efficiency in economics: Breakpoints and regularities". In: *Energy Research Social Science* 97, p. 102973. ISSN: 2214-6296. DOI: https://doi.org/10.1016/j.erss.2023.102973. URL: https://www.sciencedirect.com/science/article/pii/S2214629623000336.

Hirst, Eric and Brown, Marilyn (1990). "Closing the efficiency gap: barriers to the efficient use of energy". In: *Resources, Conservation and Recycling* 3.4, pp. 267–281. ISSN: 0921-3449. DOI: https://doi.org/10.1016/0921-3449(90)90023-W. URL: https://www.sciencedirect.com/science/article/pii/092134499090023W.

Houde, Sébastien and Aldy, Joseph E. (Nov. 2017). "Consumers' Response to State Energy Efficient Appliance Rebate Programs". In: *American Economic Journal: Economic Policy* 9.4, pp. 227–55. DOI: 10.1257/pol.20140383. URL: https://www.aeaweb.org/articles?id=10.1257/pol.20140383.

I4CE (2022). *Quelles aides publiques pour la rénovation énergétique des logements ?* Tech. rep. Institute for Climate Economics.

IEA (2022). *Energy Efficiency*. Tech. rep. International Energy Agency.

INSEE (2018). *Logement en 2018, Recensement de la population - Base infracommunale (IRIS)*. URL: https://www.insee.fr/fr/statistiques/4799305.

Kahn, Victor (Dec. 2022). "The impact of energy retrofit and energy efficiency obligations in France". Theses. Université Paris sciences et lettres. URL: https://pastel.hal.science/tel-04012264.

Myers, Erica (2020). "Asymmetric information in residential rental markets: Implications for the energy efficiency gap". In: *Journal of Public Economics* 190, p. 104251. ISSN: 0047-2727. DOI: https://doi.org/10.1016/j.jpubeco.2020.104251. URL: https://www.sciencedirect.com/science/article/pii/S0047272720301158.

Rosenow, Jan and Bayer, Edith (2017). "Costs and benefits of Energy Efficiency Obligations: A review of European programmes". In: *Energy Policy* 107, pp. 53–62. ISSN: 0301-4215. DOI: https:

//doi.org/10.1016/j.enpol.2017.04.014. URL: https://www.sciencedirect.com/science/article/pii/S0301421517302379.

Rosenow, Jan, Cowart, Richard, and Thomas, Samuel (2019). "Market-based instruments for energy efficiency: a global review". In: *Energy Efficiency* 12.5, pp. 1379–1398.

Rosenow, Jan, Platt, Reg, and Brooke, Flanagan (2013). "Fuel poverty and energy efficiency obligations – A critical assessment of the supplier obligation in the UK". In: *Energy Policy*. URL: https://www.sciencedirect.com/science/article/abs/pii/S0301421513007465.

SDES, Service des données et études statistiques (2024). *Tous les concepts*. URL: https://www.statistiques.developpement-durable.gouv.fr/tous-les-concepts.

Staiger, Douglas and Stock, James H. (1997). "Instrumental Variables Regression with Weak Instruments". In: *Econometrica* 65.3, pp. 557–586. ISSN: 00129682, 14680262. URL: http://www.jstor.org/stable/2171753 (visited on 09/06/2023).

A Background information on the French EEOs

A.1 Baseline mechanism

Table A1: Summary statistics on the 28 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

B Data

B.1 Sample selection

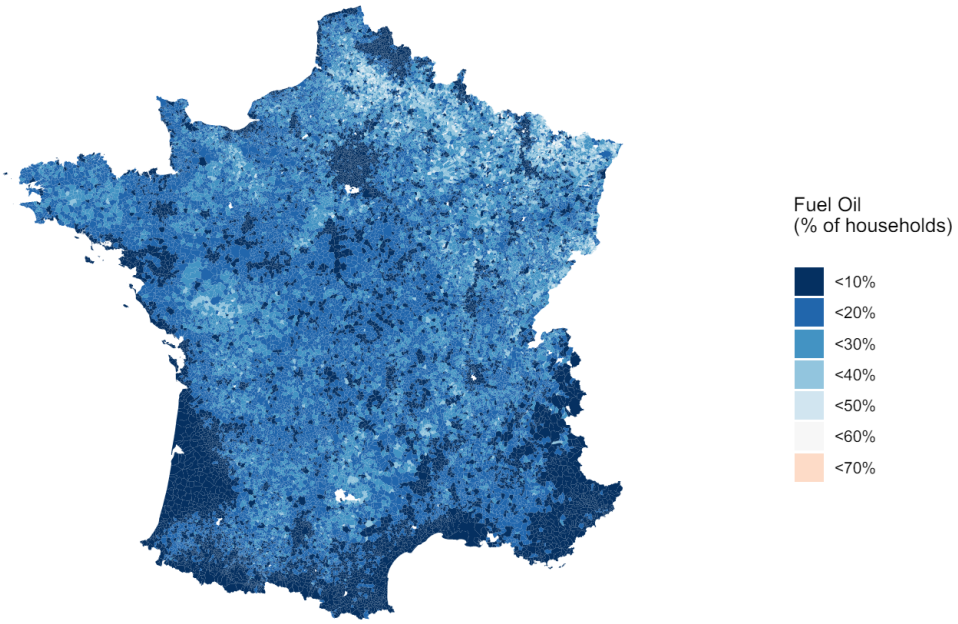


Figure A1: Average % of Housing Units which main heat source is Fuel Oil, 2018-2020

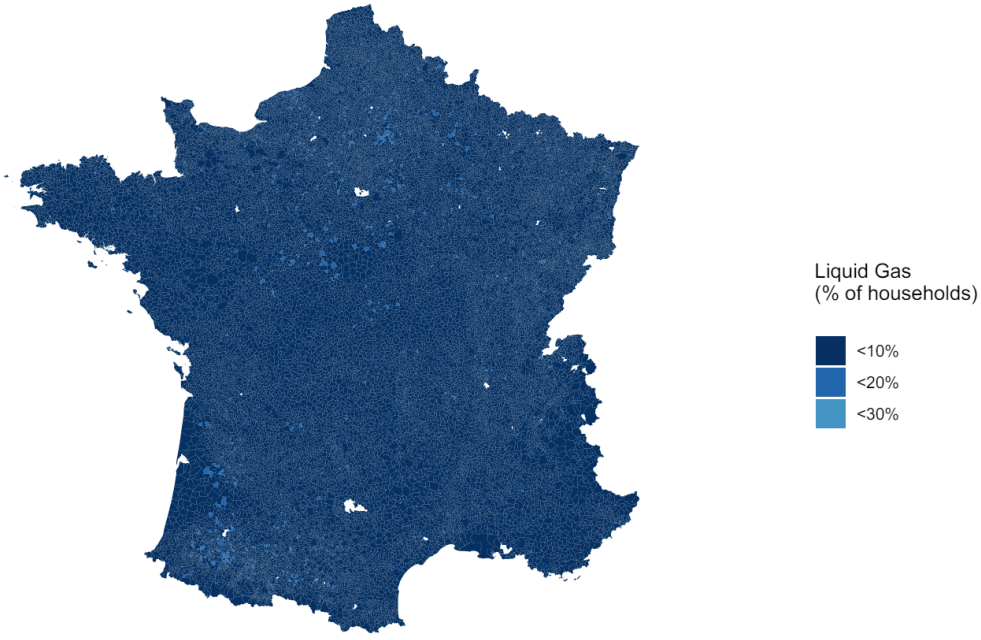


Figure A2: Average % of Housing Units which main heat source is Liquid Gas, 2018-2020

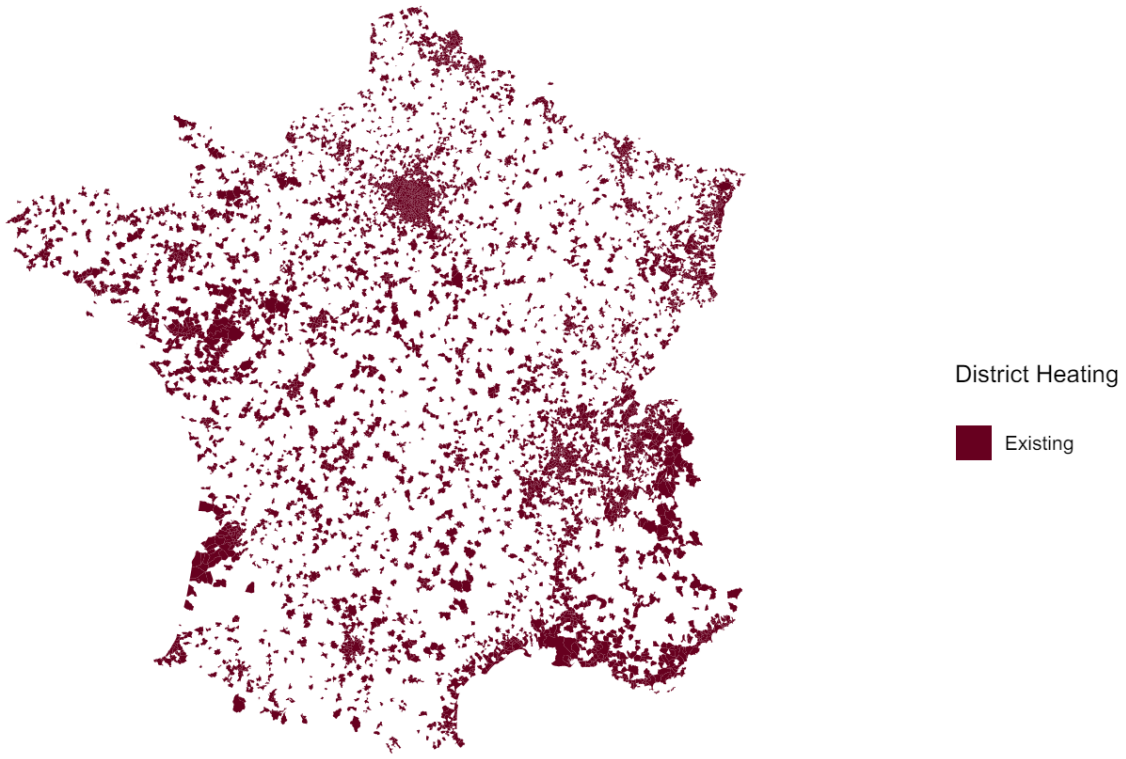
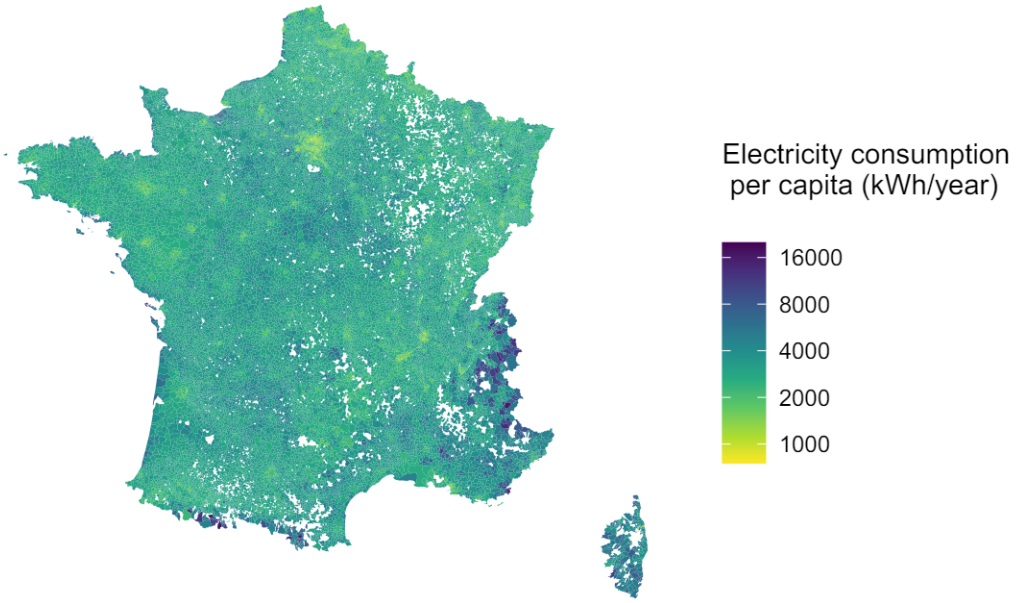


Figure A3: Municipalities connected to a District Heating network, 2018-2020

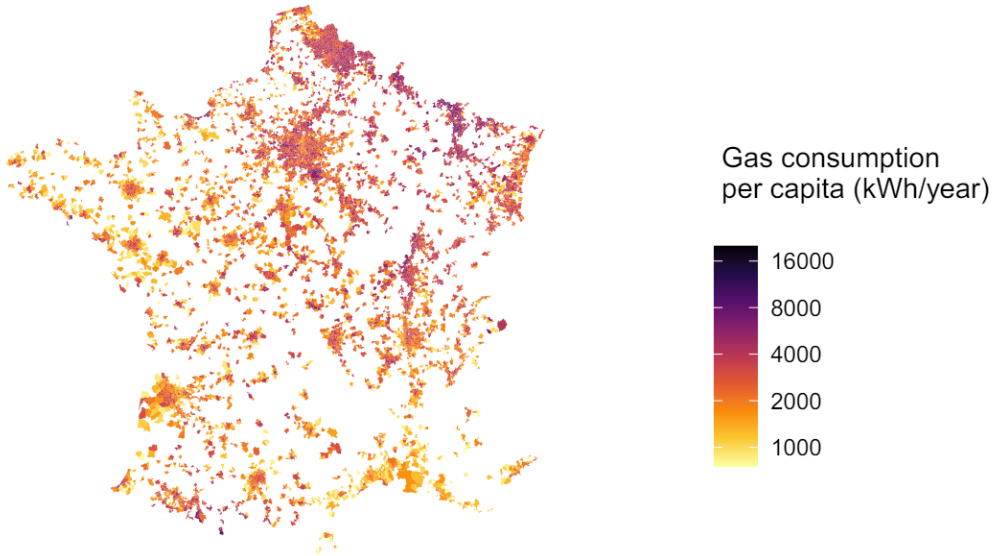
Table A2: Per capita municipal residential energy use, retrofit works, and demographics

	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 A4: Average electricity and gas consumption per capita, 2018-2020

B.3 Population

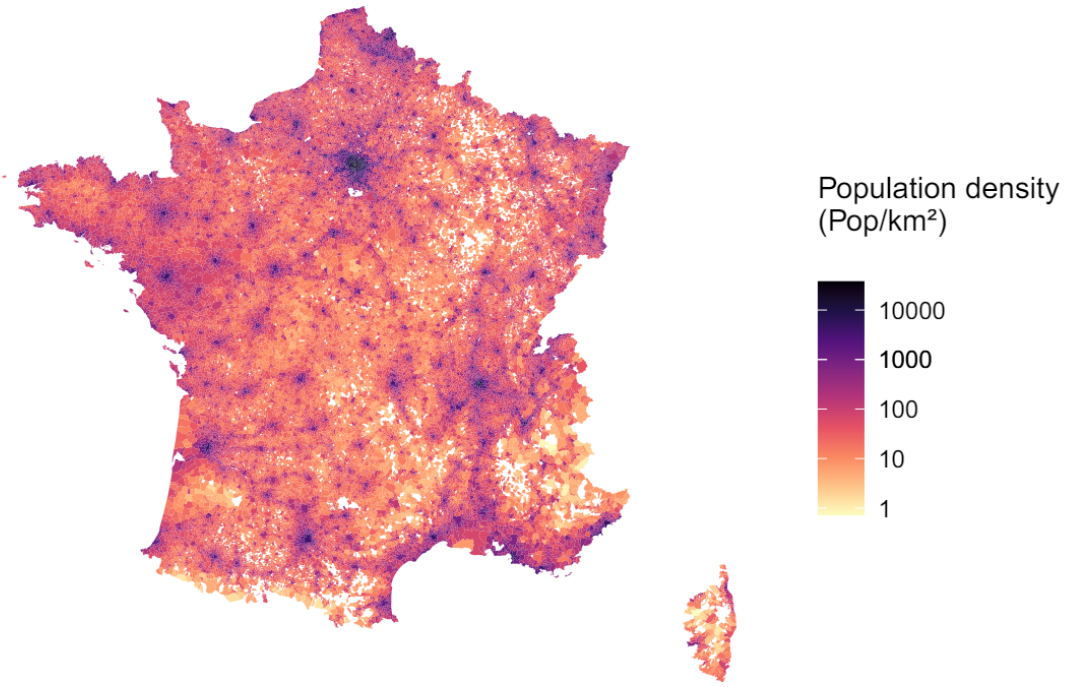
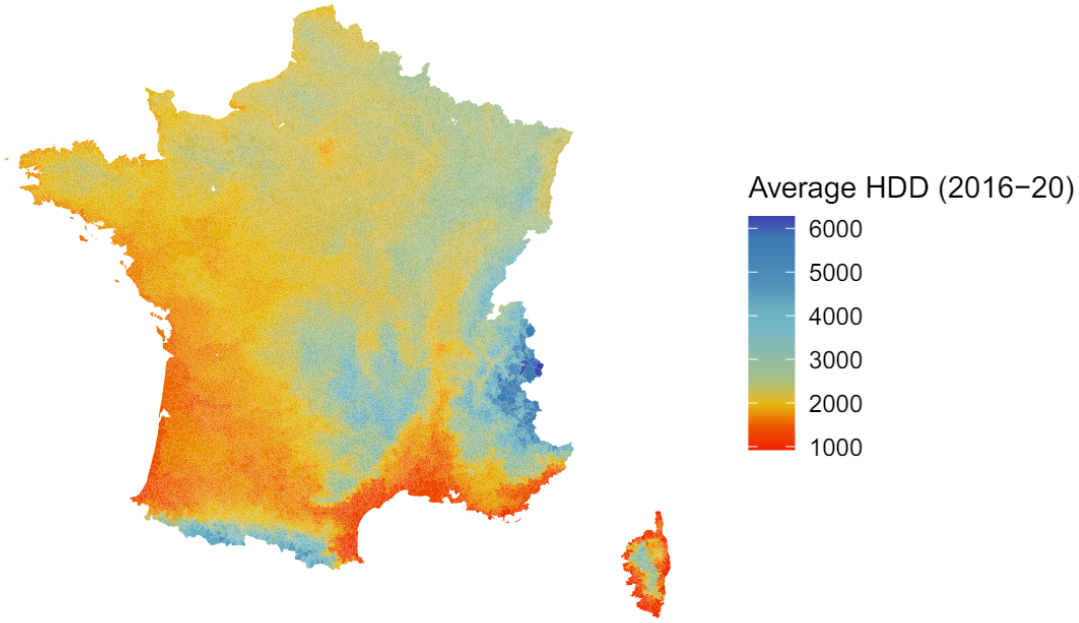
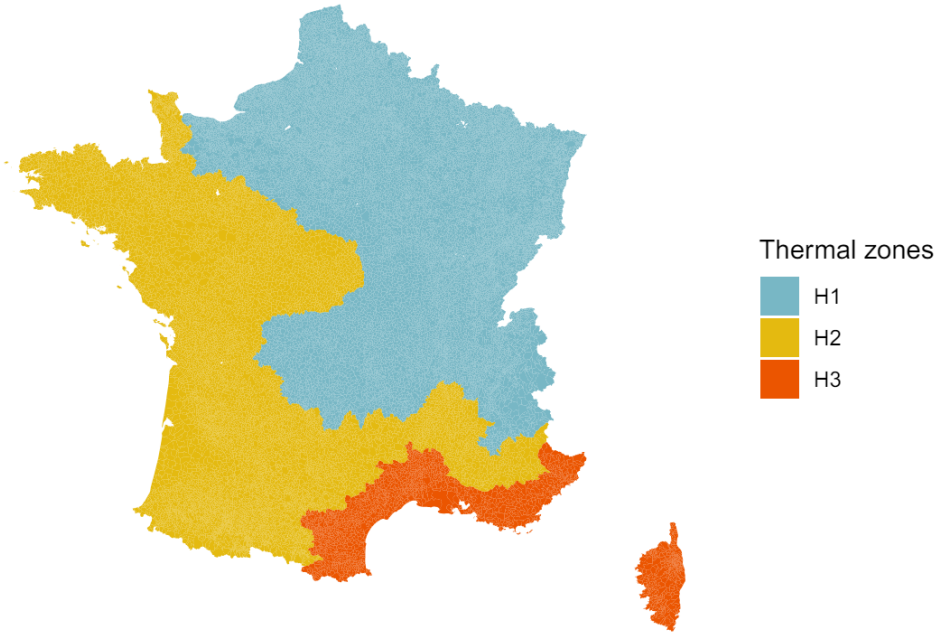


Figure A5: Population density in 2020

B.4 Heating Degree Days



(a) Average Heating Degree Days between 2016 and 2020



(b) Thermal zones

Figure A6: 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 (T°$_{n,d}$) to define HDD and CDD for each day using the SDES methodology:

$$HDD_{n,d} = \begin{cases} 17 - \text{T}^\circ_{n,d} & \text{if T}^\circ_{n,d} < 17^\circ\text{C} \\ 0 & \text{otherwise.} \end{cases}$$

$$CDD_{n,d} = \begin{cases} \text{T}^\circ_{n,d} - 17 & \text{if T}^\circ_{n,d} > 17^\circ\text{C} \\ 0 & \text{otherwise.} \end{cases}$$

We then sum HDD and CDD 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.