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

Guillaume Wald *
Matthieu Glachant

CERNA, Mines Paris - PSL

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Abstract: Energy Efficiency Obligations (EEOs) are widespread instruments to attain energy efficiency goals. They have been adopted by 16 EU Member States, as well as in the US, the UK, and in China. EEOs require obligated parties, usually energy suppliers, to deliver a set amount of energy savings. This is achieved by granting energy efficiency investment subsidies to households. In France, this mechanism plays a leading role with around 4 billion EUR granted each year. This study assesses the impact of the French EEOs program on household electricity and gas consumption. To the best of our knowledge, this is the first empirical evaluation of an EEO program. Using a new dataset gathering more than 2.7 million energy retrofits subsidized over 2017-2019, we compute the expected savings imputable to the policy each year in each municipality. We then estimate the effect of investments on municipality-level electricity and gas consumption. Energy efficiency investments are endogenous with respect to household's characteristics, hence, with energy consumption. We thus instrument energy efficiency investment at the municipality level using mean deviation in local heating degree days in the months before investment. Overall, the policy achieves in the best case scenario 27.9% of its energy efficiency targets. This deceiving result is primarily driven by a minimum 49% energy performance gap plaguing EEOs-funded retrofits.

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

1 Introduction

Energy efficiency (EE) of the building stock is a key component for the energy transition. According to the International Energy Agency, global investment in buiding energy efficiency 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 market-based instruments (MBIs). Within this class of policy tools, EEOs remain the overwhelming majority, accounting for 96% of all MBIs (IEA 2022). They require *obligated* market actors such as energy suppliers (France) or distribution system operators (Italy), to carry out a defined level of energy savings. Actual implementation therefore involves monetary incentives from obligated parties to consumers (households, industries or services) to invest in energy retrofit operations. This way, subsidies from obligated parties do not increase public expenditures as utilities pass on their costs to consumers through energy prices (Rosenow, Cowart, and Thomas 2019). In 2022, the IEA identified no less than 48 energy efficiency obligation programs in 23 distinct jurisdictions: Energy Efficiency Resource Standards (EERS) are in place in 24 US states, and similar programs can be found in four Australian States and Territories, Brazil, Canada, China, South Korea, South Africa and Uruguay (Crampes and Léautier 2020). In the EU, Hungary became the 16^{th} country to operate EEOs in 2021 (MEHI 2021).

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 EEO 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 2022b). Grants allocated by obliged market actors account for 50% of the total financial support allocated to households (I4CE 2022), making EEOs 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 EEOs program on household electricity and gas consumption; second, we dig into two potential explanations for the difference between policy objectives and our estimates of realized savings. 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 EEOs 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 EEOs.

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 EEOs, namely the French *Certificats d'Economie d'Energie* policy. In line with the literature, we find an important overestimation of official saving records, which are at the very least three times higher than the actual decrease in energy use. We also measure the contribution of two distinct factors to this wedge: the energy performance gap, defined as the difference between engineering models predictions and actual energy conservation, is responsible for 68% of the overall missing savings; the remainder can be attributed to the political economy of the French EEOs, which involves *bonus certificates* for specific operations, way above engineering projections. The paper proceeds as follows. In section 2, we present some background information on the French EEOs. 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 section 6 details some robustness checks. We discuss implications in Section 7 and conclude in Section 8.

2 Background information on the French EEOs

2.1 Baseline mechanism

Launched in 2006, the French EEOs consists of periods of three to four years, with a global energy savings target imposed on energy suppliers (electricity, gas, heating oil, liquefied petroleum gas, heat, refrigeration). These *obligated* market actors are assigned individual objectives based on their sales as well as the carbon content of the energy sold (to reflect the lower carbon intensity of nuclear electricity generation for instance). The official unit of the policy is the kWh *cumac*, for *cum*ulative, *ac*tualized over the life cycle of the installed energy efficiency equipment. A first phase of scheme experimentation ran from 2006 to 2009, with an overall energy savings target of 54 TWh cumac - about 10% of the annual final energy consumption of the French residential sector (486 TWh in 2021). The second (2011-2013) and third (2015-2017) periods increased the overall target to 345 and 660 TWh cumac, respectively. Thus, EEOs-funded retrofits over 2011-2017 are expected to save the equivalent of two years of residential energy use through their life cycle. The 2018-2021 period has been characterized by a surge in the overall objective, fixed at 1,600 TWh cumac (IEA 2023). Finally, the fifth period has started on January 1st, 2022 with an overall target of 3,100 TWh cumac (DGEC 2022a). At the end of each period, energy providers have to justify compliance with their obligation using the *certificates* - the so-called *Certificats d'Economie d'Energie (CEE)* - they have collected; each certificate is worth 1 kWh cumac. If they do not fully comply, they are fined in proportion to their remaining obligation at a rate of 0.015 EUR for each missing kWh cumac.

Obligated parties have two possibilities to fulfill their obligation: they can either directly encourage energy consumers (not necessarily their own customers) to achieve energy efficiency retrofit works, or rely on the secondary market, where energy providers exceeding their objectives can trade certificates. So called *authorized actors* such as regional and local public authorities, the National Agency for Housing (Agence Nationale de l'Habitat - ANAH), and social landlord, can also generate and sell *white certificates* on this market. Obligated and authorized actors can choose among a wide list of standardized energy retrofit operations, as shown in Table A1: in the residential sector, works tackle either the building envelope or its heating and cooling equipment. Lump evaluation of each work's projected savings is based on a pre-set formula (one per standardized operation), with adjustments based on a set of specific parameters. Savings are expressed in kWh of final energy (not consumed), accumulated and discounted (at a rate of 4% a year) over the life-cycle of the equipment. For instance, 50 square meters of roof insulation (*BAR-EN-101*) installed in the coldest part of mainland France (the *H1* thermic zone) are worth 85,000 kWh cumac 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 cumac in savings over 17 years.

The generation process for certificates relies on the *active and incentivizing role (AIR)* played by obligated and authorized actors. Energy providers should indeed bring evidence that they *directly contributed* to the energy efficiency investment decision for which they claim certificates. The proof for this *AIR* takes the form of a sworn statement by which the beneficiary household declares that the financial support received from the obligated actor has been pivotal in the investment decision. This document is part of the file sent by obligated or authorized actors to the administration, and should be signed before the beginning of the energy retrofit. Despite all those efforts to make EEOs-funded retrofits *additive*, the existence and quantification of a windfall-effect is still an open and debated question. Theoretical contribution such as Crampes and Léautier 2023 point to the existence of *infra marginal* retrofits that would have taken place without the energy supplier's grant. Empirical contributions are scarce, but an evaluation from the French Energy Management Agency (ADEME 2020) reported that EEOs grants had been pivotal in the investment decision process of only 40% of non-low-income beneficiaries. Such a low additivity of EEOs-funded works is not a surprise given the large panel of other funding sources which households could cumulate with energy suppliers grants over our observation period (2017-2019). Overall, public support included nearly 2 billion EUR of tax credit for energy transition (*Crédit d'impôt pour la Transition Energétique, CITE*), 1 billion EUR in grants from the National Agency for Housing (ANAH), namely the *Habiter Mieux Sérénité* subsidy for step-by-step retrofit operations, 500 million EUR of zero-insterest loan (*Eco-Prêt à Taux Zéro, Eco-PTZ*), as well as local communities support (ANIL 2019).

2.2 Political economy of the French EEOs

In addition to the above characteristics, the French EEOs has known some major changes in the last decade. Those specific components have had dramatic impacts on the policy's overall efficiency (Glachant, Kahn, and Lévêque 2020). A first inflexion happened in 2016, when fuel poverty reduction was added to the official goals of the EEOs. This decision directly followed from concerns by the French government about potential regressive effects such as those highlighted by Rosenow, Platt, and Brooke 2013 in the case of the British EEOs. Indeed, theoretical analysis predict that suppliers may price energy strategically, passing their increased operating costs to their less elastic consumers. This leads to a first regressive mechanism, as households facing fuel poverty consume a lower level of energy services as compared with their satiation level, resulting in a lower elasticity to prices. Moreover, a second regressive mechanism is implied by the lower financial capacity of fuel poor households, who require higher financial incentives from suppliers to achieve a given retrofit operation. Without any corrective policy, EEOs could therefore create a situation where fuel poor households pay higher electricity prices to subsidize energy efficiency of richer households. As a result, a sub-obligation dedicated to households facing energy precariousness (CEE *précarité*) has been implemented as of 2016 to correct these negative consequences. In practice, energy suppliers are required to dedicate at least 25% of their energy saving operations to low-income households (first and second income quartiles). Moreover, a bonus system was designed: the so-called *Grande Précarité Energétique (GPE)* - in English *extreme energy precariousness* - mechanism granted any retrofit operation to the benefit of households from the first income quartile twice the amount of certificates it would have generated otherwise.

A bonus mechanism has two main consequences on an EEOs. On the one hand, increasing the number of certificates generated by a given operation makes it more valuable for energy suppliers because it allows a quicker fulfilment of their individual obligation. This leads to an increase in the associated grants proposed by obligated actors, which in turn compensates for the regressive effects. On the other hand, bonus certificates can be seen as fictive energy savings, which imply a decrease in the actual overall obligation. Bonuses therefore create an equity-efficiency trade-off. In February, 2018, the bonus mechanism was reinforced with (1) an extension of the GPE bonus to all households below the median income (hence, to households in the second quartile) for five standardized operations, namely: attic and floor insulation, installation of a biomass boiler, a gas boiler or a heat pump, and (2) additional bonuses for all income quartiles under the branding *Coups de Pouce* - in English *nudges* - for the above five retrofit works. Notice that households in the first and second income quartiles could cumulate bonuses from the GPE and Coup de Pouce mechanisms: for instance, the total amount of certificates generated by floor insulation could be increased up to 4 times. While dimension (1) directly follows from the need for corrective mechanisms against regressive effects, dimension (2) is subject to some debates. Indeed, increasing certificates for all households and a specific subset of operations has been advocated by the government as a way to focus industrialization efforts towards these core skills (namely, insulation and heating devices). However, this second bonuses wave dramatically impacted the overall policy targets, as the five targeted operations accounted for more than 85% of all certificates generated in 2019. The efficiency of the policy therefore shrank, while equity was also reduced (because households in upper income deciles also benefited from bonuses). Moreover, the inflation in the amount of certificates was so strong that households combining the *GPE* and *Coups de Pouce* bonuses could obtain up to full coverage of their investment cost. This per se had detrimental effects on the overall industry because the so-called *1 EUR operations* attracted many opportunistic actors, with negative, long-lasting reputation effects on all energy efficiency activities even outside the EEOs' scope.

To investigate the effects of the French EEOs on residential energy use, it is important to make a clear distinction between three measures of an operation's associated savings. First, (standardized) operations generate certificates: in what follows, we refer to the amount of certificates generated as the *official* measure of savings. Because of the different bonuses mechanisms, the engineering prediction of energy savings used as a benchmark by the energy performance gap literature differs from the official one. We refer to it as the *projected* savings. Finally, the measure that we want to identify in this study are the *actual* savings. To highlight the difference between *official* and *projected* savings, we show the evolution of lifelong savings in *official* and *projected* terms over 2017-19 in Figure 1:

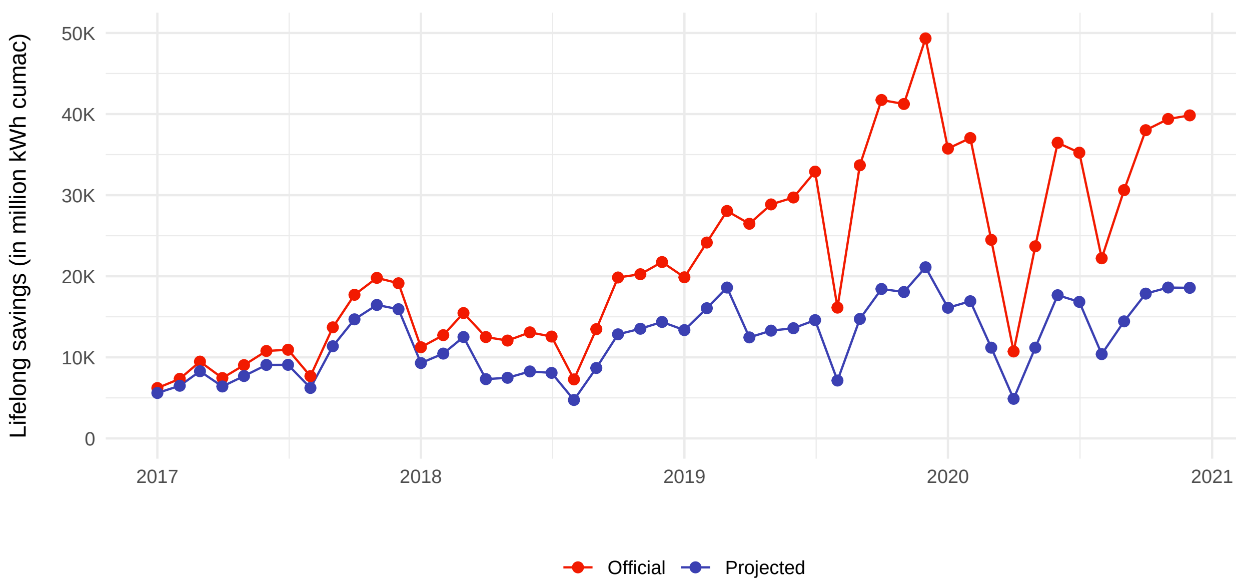


Figure 1: Lifelong savings over 2017-2019 (kWh cumac)

On average over 2017 to 2019, each kWh of official lifelong savings was inflated by +74% as compared with projected ones, implying a proportional decrease in the global ambition for the energy conservation effort achieved through the French EEOs.

Mapping the two measures allows us to identify the geographical distribution of certificates generation. As shown in Figure A1, both official and projected savings are higher in per capita terms in municipalities located in the so-called *empty diagonal* (from the Pyrenees mountains in the South West to Lorraine in the North East). This reflects both the need for energy efficiency renovation of an aging building stock, as well as higher energy consumption per households, in line with the lower population density. However, the deflated estimation of lifelong savings (Figure A1d) leads to a stronger decrease for southern areas, as compared to North-eastern France. This is a direct consequence of the bonus mechanism implementation, which ignores thermal zones while projected lifelong savings do not.

3 Data

Our analysis builds on 3 main sources: EEOs-retrofit operations details, residential energy consumption data and city level characteristics such as population, median income or heating degree days (HDD).

3.1 Treatment variable

The *Energy Efficiency Obligation* (in French, the *Certificats d'Economies d'Energie*) 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). Access is restricted to researchers authorized by the statistical secrecy committee and approved by the Directorate General of Energy and Climate (DGEC). The original dataset gathers more than 5.5 million energy efficiency operations over 2015-2022, with detailed information on the type of standardized operation, its life expectancy, the location (down to the city level), dates and the *official* savings (amount of certificates generated, or *CEE* in TWh cumac) for the *classic* and *precarious* sub-obligations. Moreover, we are provided with all relevant information required to compute the *projected* lifelong savings without bonuses, depicted in Figure 1. For instance in the case of roof insulation (*BAR-EN-101*), we know the exact surface insulated (in square meters) as well as the heating fuel used; for the installation of a high energy efficiency individual boiler (*BAR-TH-106*), we know the housing unit type (flat versus detached house), the surface area in sq. meters and the associated correction factor. We therefore aggregate each measures (the official and projected lifelong savings) to the city-level, which yields a panel with 34,513 municipalities (over 34,816 in metropolitan France). We observe both types of savings from 2017 to 2022, hence the overall dataset gathers 183,538 observations over 6 years.

Table 1: Trends in retrofit works, energy use, HDD, population and income

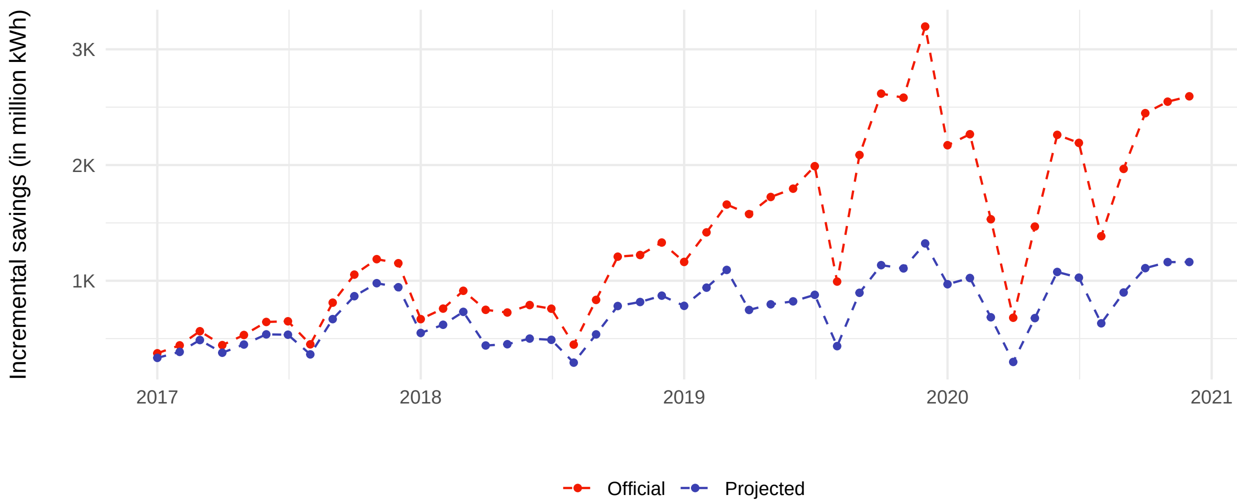
	2017	**2018**	**2019**	**2020**
Panel A: Retrofit works - National				
Lifelong official savings (TWh cumac)	137.806	170.217	368.074	
Incremental official savings (TWh)		8.212	10.283	22.552
Contemporaneous official savings (TWh)		8.212	18.495	41.047
Lifelong projected savings (TWh cumac)	110.522	111.033	178.572	
Incremental projected savings (TWh)		6.458	6.632	10.776
Contemporaneous projected savings (TWh)		6.458	13.090	23.866
Panel B: Energy use - National				
Electricity (TWh)		158.527	157.486	158.205
Gas (TWh)		138.083	136.061	124.379
Electricity + Gas (TWh)		296.611	293.547	282.584
Panel C: HDD - Municipality				
Average HDD from t-5 to t-1		2323.184	2236.295	2270.867
Rel. HDD at t		-152.962	-5.008	-242.646
Rel. HDD at t-1		-16.740	-152.962	-5.008
Rel. HDD at t-2		106.392	-16.740	-152.962
IV (HDD)		-1781.000	2560.582	766.043
Panel D: Demographics - National				
Population (mln.)		62.119	62.653	62.738
Median income (EUR)		21,698.98	21,744.50	22,083.03

Panel A of Table 1 shows descriptive statistics for the years 2017 to 2019 used in the analysis: the 1^{st} and 4^{th} lines correspond to official and projected *lifelong* savings, respectively. Looking at the annual volumes of certificates generated each year, we clearly see the two-fold increase in official savings that occurred from 2018 to 2019. This is a direct consequence of the bonus mechanism: indeed, while the two years were part of the same 4 year period (P4 from 2018 to 2021), the implementation of the *Coup de Pouce* bonus dramatically increased the gap with respect to projected lifelong savings, from 59 to 189 TWh cumac (+220%). This divergence is illustrated in Figure 1.

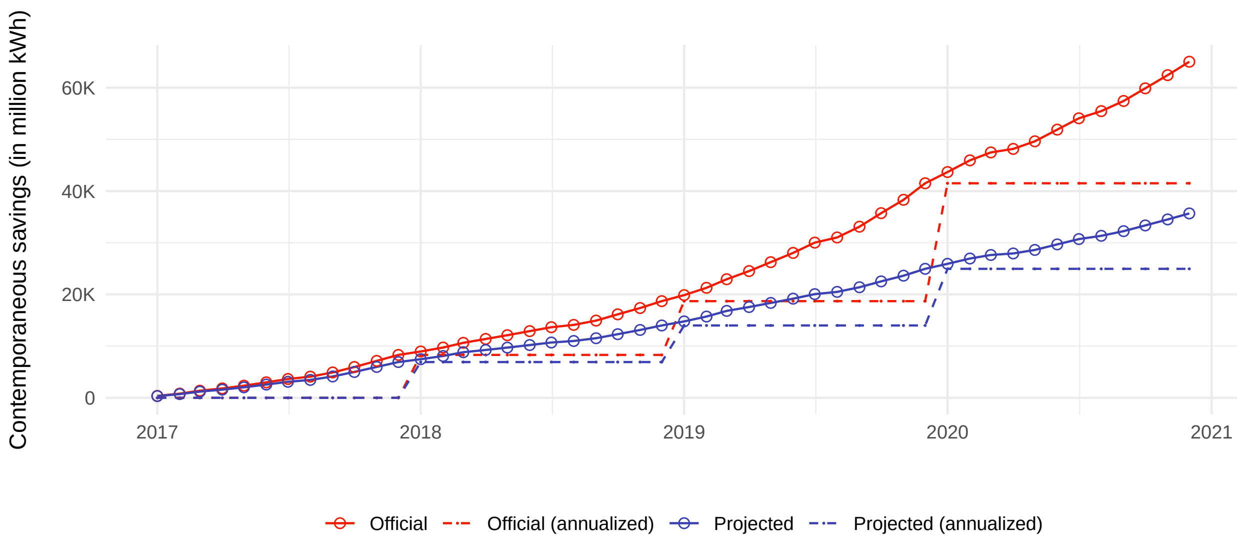
Because we want to evaluate the realized savings from EEOs-funded energy efficiency works on the *yearly residential energy use*, we need a measure of the *contemporaneous expected savings* imputable to works achieved in previous years. Hopefully, the expected *lifelong* savings associated to each operation are defined as the cumulative sum of the yearly *incremental* expected savings, discounted by 4% each year. Lifelong savings over the life cycle in kWh *cumac* can therefore be expressed as a discounted sum of their incremental counterpart, with N the conventional life expectancy of the equipment:

$$\begin{aligned}
\text{Lifelong savings (kWh cumac)} = \quad & \text{Incremental savings} + \frac{\text{Incremental savings}}{1+0.04} \\
& + \frac{\text{Incremental savings}}{(1+0.04)^2} + ... + \frac{\text{Incremental savings}}{(1+0.04)^{(N-1)}} \\
= \quad & \text{Incremental savings} \times \frac{1-1.04^{-N}}{1-1.04^{-1}} \\
\Leftrightarrow \text{Incremental savings (kWh)} = \quad & \text{Lifelong savings} \quad \times \quad \frac{1-1.04^{-1}}{1-1.04^{-N}}
\end{aligned}$$

As a result, we define the *incremental expected savings* for t (in TWh) imputable to energy efficiency retrofits achieved in $t-1$, converting both the official and projected measures (Table 1 Panel A, lines 2 and 5, respectively). The dynamics follow, of course, those of the *cumac* measures. This is straightforward when we look at Figure 2a. Moreover, we also take into account that energy efficiency retrofits are *staggered* treatments: each year's energy consumption is affected by previous years investments, up to the limit fixed by the conventional life cycle of the installed equipment. The relevant measure of the EEOs treatment on domestic energy use at each point in time is therefore the cumulative sum of the *incremental expected savings* imputable to retrofit works installed in previous years (see B.4 for details), which we call *contemporaneous savings.* This cumulative sum is depicted by the solid lines in Figure 2b for both official and projected savings. Moreover, because we need an annualized version of this treatment, we compute the annualized savings (the dotted, step lines in Figure 2b). We describe both the official and projected (annualized) contemporaneous savings in lines 3 and 6 of Table 1, Panel A: these will be our regressors of interest in the empirical strategy presented in section 4.



(a) Incremental savings



(b) Contemporaneous savings - Monthly and annualized

Figure 2: Incremental and contemporaneous savings

3.2 Energy use

Residential energy use data is provided by the *Opérateurs des Réseaux d'Energie (ORE)* (in English, Energy Network Operators) agency. It gathers information from all French actors in the distribution of electricity and gas, providing municipality-level data from 2018 to 2020. Summary statistcs are presented in Table 1, panel B. We see that gas consumption is concentrated in some specific areas (mostly urban and peri urban areas), as more than 50% of all municipalities have a zero consumption for this energy source (they appear in white on the map in Figure A2b). Electricity consumption is also more stable across municipalities, as shown by the lower standard deviation. However, it is lower in more densely populated areas such as in and around Paris, Marseille, Lyon, etc. as shown in Figure A2. In our analysis, we exploit consumption dynamics: Table 1 Panel B shows the evolution for both electricity, gas and the sum of the two sources (in TWh) between 2018 and 2020. The stability of electricity use is striking, with a single 1 TWh deviation between the highest (2018) and the lowest (2019) points: this is a direct consequence of the multiple use of this energy source, as opposed to gas consumption. Indeed, the latter is more volatile, with a -10% decrease from 2018 to 2020: these diverging patterns are illustrated in Figure A3.

3.3 Heating Degree Days and other determinants

We also consider three key determinants of energy use at the municipality level, namely heating degree days (HDD), median income and population.

HDD are provided by *Météo France*, the French national meteorological service, on a 9,892 cells grid: each cell covers 64 square km (8km × 8km). For each node and day, we know the average temperature ($\text{T°}_{n,d}$): we use this information to define HDD for each day using the *SDES* methodology:

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

We then sum HDD over one year to get yearly HDD for each node ($HDD_{n,y} = \sum_{d=1}^{365} HDD_{n,d}$), and define the yearly HDD for each municipality ($HDD_{m,y}$) to match with the definition of our energy use data. Doing so, we apply 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. Table 1 Panel C presents averaged values at the municipality level for HDD. In the first line, we show the evolution of Average HDD from $t-5$ to $t-1$, defined as the within-year, within-municipality mean of HDD. This measure is used as a proxy for mid-run climate in a given place; geographical variations are made explicit when plotting the within-year, municipality-specific average on a map as in Figure A5a. We clearly see the cooler climate along the Atlantic and Mediterranean coasts, which contrasts with areas recording higher HDD in the mountainous regions (the Massif Central, the Pyrenees and of course the Alps). More generally, HDD are higher in the North-Eastern regions (3000-4000 HDD/year), and lower in the South (¡2000), which is in line with the official *thermal zones* H1, H2 and H3 depicted in Figure A5. Average HDD over the 5 previous years are also useful to define de-trended measures of climate for each year: we therefore compute the relative HDD at t, $t-1$ and $t-2$ for the three years 2018, 2019 and 2020 (Table 1 Panel C, lines 2 to 4). Our instrumental variable used in the empirical strategy in section 4 is defined as the product between the relative HDD at $t-1$ and $t-2$.

Finally, median income and population are obvious determinant of energy use at the municipality level. French administrative data do not currently cover the year 2021, hence we loose one year of observation by introducing median income and population in our regressions. As shown in Table 1 Panel D, France still has a growing population, with +.86% between 2018 and 2019 and +.14% between 2019 and 2020. The geographical distribution of population density follows that of energy use as it is concentrated in urban areas. Figure A4, which plots population density, identifies Paris, Marseille and Lyon as the more densely populated areas. On the reverse, the *empty diagonal* indeed records very low levels of population density, below 10 inhabitant per square km.

4 Empirical strategy

4.1 Within variation and endogeneity issues

To estimate the effect of each additional certificate (hence, of the retrofit works supported by EEOs) on residential energy use, we adopt a two-way fixed effect (TWFE) strategy. More precisely, we exploit the year-to-year within-municipality variation using municipality (μ_i), year (η_t) and department-year ($\theta_{k(i),t}$) fixed effects. We use the sum of electricity and gas consumption ($y_{i,t}$) in municipality i in year t as our outcome variable because we want to embrace a comprehensive view on energy consumption, accounting for possible substitution effects (Giraudet, Houde, and Maher 2018). So-called *fuel switching* may occur for instance when gas boilers are replaced by heat-pumps, and such *electrification* of domestic heating is indeed a stated objective of the policy. To quantify the EEOs treatment, we need an ex-ante evaluation of contemporaneous expected savings imputable to past years EEO-funded retrofit operations. Indeed, we only consider the effect on energy use at t of retrofit operations achieved as of December 31, $t-1$. Because our outcome variable is defined on a yearly basis, we do not use the amount of certificates (as kWh *cumac* are only valid for the life cycle of each standardized operation). We rather rely on the *contemporaneous expected savings*, as defined in section 3. We use this measure for both official and projected savings in municipality i at t, which we denote $CES_{i,t}$. It allows a direct comparison between ex-ante and ex-post savings associated to EEOs-funded retrofits.

Moreover, we need to account for the year-to-year within-municipality variation that could affect energy use outside of the policy intervention, resulting in an endogeneity issue. First, we consider three control variables in our TWFE setting, namely heating degree days (HDD), median income and population. Indeed, municipality-level energy use is expected to increase with colder temperatures, higher income and population growth. Because we use local variations, we control for the contemporaneous effect of HDD in relative terms with respect to an average over $t-5$ to $t-1$. This allows us to avoid extrapolation between places with similar HDD in levels but different mid-run climate. Thus, we introduce both the 5 years average ($\overline{HDD}_{i,t}$) and the contemporaneous deviation relative to this average $\widetilde{HDD}_{i,t}$ in our baseline equation. Regarding population, we control for its log value $log(Pop_{i,t})$, because its effect on energy use is likely to be non-linear due to agglomeration effects (see for instance the correlation pattern between Figure A2 mapping energy use per capita, and Figure A4 mapping population density). Finally, median income $inc_{i,t}$ is included in levels only for matters of scarcity in the amount of included regressors. Our baseline estimating equation therefore writes as:

$$y_{i,t} = \beta\, CES_{i,t} + \delta\, log(Pop_{i,t}) + \kappa\, inc_{i,t} + \lambda \widetilde{HDD}_{i,t} + \gamma \overline{HDD}_{i,t} + \mu_i + \eta_t + \theta_{k(i),t} + u_{i,t} \qquad (1)$$

When estimating the above equation, a key empirical challenge arises. We make this challenge explicit by decomposing the error term as follows: $u_{i,t} = \phi\, w_{i,t} + \varepsilon_{i,t}$, where $\varepsilon_{i,t}$ includes all within-municipality socio-economic dynamics that we do not control for, and $w_{i,t}$ represents expected savings imputable to retrofit investments not generating certificates in municipality i in year t. Considering first the effect of $\varepsilon_{i,t}$, the literature points to the endogeneity of energy efficiency retrofit investments with housing unit occupiers and owners characteristics (Fowlie, Greenstone, and Wolfram 2018; Blaise and Glachant 2019). Our TWFE setting does not control for household level dynamics (it only handles long-term fixed characteristics) which could affect both households energy use ($y_{i,t}$) and their investment decision in home improvements, such as energy efficiency retrofit works. This may lead to spurious correlations: on the one hand, if retrofitting households invest in reaction to a rise in income, energy use and investment could increase at the same time leading to an under-estimation of the effect of retrofit works; on the other hand, a rise in environmental consciousness could trigger both an increase in retrofits and a decrease in energy use. Second, we also have an omitted variable bias because we do not control for the effect of $w_{i,t}$ on $y_{i,t}$. Indeed, energy efficiency measures supported through the EEOs are probably not orthogonal to other energy efficiency works: the two types of investments respond basically to the same determinants. Omitting $w_{i,t}$ in our estimation will not be a big empirical issue per se, as we could be interested in the overall effect of EEOs-funded retrofits on energy use (the direct effect, and the indirect one going through non-EEOs investments). However, it is likely that the endogeneity issue plaguing EEOs retrofits also affects non-EEOs investments. As a result, we have both $Cov(CES_{i,t}, \varepsilon_{i,t}) \neq 0$ and $Cov(w_{i,t}, \varepsilon_{i,t}) \neq 0$, with $CES_{i,t}$ an endogenous regressor and $w_{i,t}$ an endogenous omitted variable. Following Angrist and Pischke 2017, we therefore have a violation of the Zero Conditional Mean assumption: $E(CES_{i,t}, u_{i,t}|CES_{i,t}) \neq 0$. To deal with these two empirical issues, we implement an instrumental variation (IV) strategy.

4.2 Instrumental Variation

4.2.1 Motivation

To tackle the endogeneity issue plaguing EEOs-funded investments, we instrument expected savings ($CES_{i,t}$) using vintages of local HDD. According to official statistics from the Ministry of Ecological Transition (*Statistiques de délivrance des CEE* 2023), the timing between an operation initiation and the generation of related certificates is comprised between 6 and 18 months. We therefore postulate that households are more likely to undertake an energy efficiency retrofit operation at $t-1$, hence to have higher expected savings ($CES_{i,t}$) at t, if they experienced lower temperatures in previous months. As a result, our instrument is the product of the two first vintages in the relative HDD, namely: $Z_{i,t} = \widetilde{HDD}_{i,t-1} \times \widetilde{HDD}_{i,t-2}$.

We estimate the following Two-Stage Least-Squares regression (2SLS):

$$
\begin{aligned}
CES_{i,t} = \alpha\, Z_{i,t} + \delta_1\, log(Pop_{i,t}) + \kappa_1\, inc_{i,t} + \lambda_1 \widetilde{HDD}_{i,t} + \gamma_1 \overline{HDD}_{i,t} \\
+ \mu_{1i} + \eta_{1t} + \theta_{1\,k(i),t} + v_{i,t} \quad (2)
\end{aligned}
$$

$$
\begin{aligned}
y_{i,t} = \beta^{2SLS}\, \widehat{CES}_{i,t} + \delta_2\, log(Pop_{i,t}) + \kappa_2\, inc_{i,t} + \lambda_2 \widetilde{HDD}_{i,t} + \gamma_2 \overline{HDD}_{i,t} \\
+ \mu_{2i} + \eta_{2t} + \theta_{2\,k(i),t} + u_{i,t} \quad (3)
\end{aligned}
$$

We test the relevance of this instrument, and provide evidence of a first stage effect of $Z_{i,t}$ on both *official* and *projected* savings in Table A2. Indeed, expected savings increase with the value of our instrument, such that years with colder temperatures indeed precede years with higher levels of expected savings imputable to the EEOs.

Our reasoning regarding the exogeneity of our instrument comes in two steps. Indeed, the exclusion restriction requires that $Cov(Z_{i,t}, u_{i,t}) = 0$. Recalling the decomposition in 4.1, our exclusion restriction rewrites as $Cov(Z_{i,t}, \phi w_{i,t} + \varepsilon_{i,t}) = Cov(Z_{i,t}, \phi w_{i,t}) + Cov(Z_{i,t}, \varepsilon_{i,t})$. We first consider the second member of the above expression, i.e the covariance between our instrument and within-municipality socio-economic variations. Using relative measures of HDD with respect to a mid-run local trend allows us to exploit slight year-to-year variations that are arguably randomly assigned within each municipality. Indeed, the instrument is defined over a 5-years average, hence we abstract from climate change and global warming concerns. Most importantly, because those variations cannot be anticipated by households, we consider them as uncorrelated with local socio-economic trends observed over several years. Moreover, weather-related instruments are fairly usual in the IV literature (Angrist and Krueger 2001), and relative HDD measures are less subject to the risk of exclusion restriction violation, as compared to other meteorological phenomenon such as rain (Mellon 2022). Thus, we assume that there is no causal link between our instrument and socio-economic dynamics at the municipality level: $Cov(Z_{i,t}, \varepsilon_{i,t}) = 0$.

However, the exclusion restriction does not hold if retrofit works outside of the EEOs scope also respond to variations in HDD. Indeed, the rationale behind the relevance condition also applies to *non-EEOs* energy efficiency improvements, hence we have: $Cov(Z_{i,t}, w_{i,t}) \neq 0 \Rightarrow Cov(Z_{i,t}, u_{i,t}) \neq 0$. This makes our IV strategy invalid, biasing our coefficient β^{2SLS}.

4.2.2 Bias of the 2SLS estimator

We rely on Pischke 2018 to characterize this bias: indeed, the exclusion restriction is violated because $Z_{i,t}$ affects $y_{i,t}$ not only through $CES_{i,t}$, but also through $w_{i,t}$. To explicit the resulting bias in our 2SLS estimand, we introduce non-EEOs retrofits, rewriting equation 3 as follows:

$$\begin{aligned} y_{i,t} = \beta^{2SLS}\,\widehat{CES}_{i,t} + \delta_2\,log(Pop_{i,t}) + \kappa_2\,inc_{i,t} + \lambda_2\widetilde{HDD}_{i,t} + \gamma_2\overline{HDD}_{i,t} \\ + \mu_{2i} + \eta_{2t} + \theta_{2\,k(i),t} + \phi w_{i,t} + \varepsilon_{i,t} \end{aligned} \tag{4}$$

The exclusion restriction amounts to the assumption that $Cov(Z_{i,t}, w_{i,t}) = 0$, i.e that energy efficiency investments not supported by energy suppliers are insensitive to variations in HDD. Because this assumption doesn't hold, the IV estimate of β writes as follows:

$$\beta^{2SLS} = \frac{Cov(y_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \tag{5}$$

$$\begin{aligned} &= \frac{Cov(\beta\,CES_{i,t} + \delta_2\,log(Pop_{i,t}) + \kappa_2\,inc_{i,t} + \lambda_2\widetilde{HDD}_{i,t} + \gamma_2\overline{HDD}_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \\ &+ \frac{Cov(\mu_{2i} + \eta_{2t} + \theta_{2\,k(i),t} + \phi\,w_{i,t} + \varepsilon_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \end{aligned} \tag{6}$$

$$\begin{aligned} &= \frac{\beta\,Cov(CES_{i,t}, Z_{i,t}) + \delta_2 Cov(log(Pop_{i,t}), Z_{i,t}) + \kappa_2 Cov(inc_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \\ &+ \frac{\lambda_2 Cov(\widetilde{HDD}_{i,t}, Z_{i,t}) + \gamma_2 Cov(\overline{HDD}_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \\ &+ \frac{\phi\,Cov(w_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \end{aligned} \tag{7}$$

Recall that: $Cov(log(Pop_{i,t}), Z_{i,t}) = Cov(inc_{i,t}, Z_{i,t}) = Cov(\widetilde{HDD}_{i,t}, Z_{i,t}) = Cov(\overline{HDD}_{i,t}, Z_{i,t}) = 0$ by assumption. Thus, we can rewrite β^{2SLS} as:

$$\beta^{2SLS} = \beta + \phi\,\frac{Cov(w_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})} \tag{8}$$

This last rewriting allows us to identify the bias of our 2SLS estimand. Indeed, it is equal to $\phi\,\frac{Cov(w_{i,t}, Z_{i,t})}{Cov(CES_{i,t}, Z_{i,t})}$, where ϕ, the marginal effect of $w_{i,t}$ on energy use, is multiplied by a ratio between the covariance of the instrument with respect to $w_{i,t}$ and the covariance of the instrument with respect to $CES_{i,t}$. By assumption, the first stage effect of our instrument on EEOs-funded investments (relevance condition) can be generalized to all types of energy efficiency retrofits, because it does not rely on a specificity of the EEOs, hence $Cov(w_{i,t}, Z_{i,t}) > 0$. Consistently, the marginal effect of $w_{i,t}$ on energy use, ϕ, goes in the same direction than that of $CES_{i,t}$, namely it causes a reduction in the yearly amount of kWh used, hence $\phi < 0$. This unique and fairly plausible set of assumptions 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 $CES_{i,t}$ on $y_{i,t}$ as captured by β is expected to be negative, we take β^{2SLS} as a lower-bound estimate of β, or an upper-bound estimate of the absolute value decrease in energy use.

A last step in our methodological reasoning regards the magnitude of this bias. It is increasing in ϕ, the effect of non-EEOs retrofit works on energy use, as well as in the marginal effect of HDD on those non-EEOs retrofit works. Conversely, it is a decreasing function of the first stage effect of $Z_{i,t}$ on EEOs retrofits. Thus, characterizing the magnitude of the bias amounts to a comparison of the dependence to past meteorological conditions between retrofits in- or outside the scope of the EEOs. We do not know the answer of what is ultimately an empirical question: we can only postulate that the effect of HDD vintages should be decreasing with the amount of subsidies received by beneficiaries, because of the well-known wind-fall effect of any policy of this type. In this view, the effect of HDD is all the higher in the case of private energy efficiency investments undertaken without any kind of public or energy suppliers support. However, non-EEOs retrofits also include investments receiving important financial support from programs such as the *Energy Transition* tax credit (CITE), plagued by serious wind-fall effects - up to 55% of households according to the OPEN survey (ADEME 2014). To sum up, the magnitude of the bias cannot be approximated because we lack evidence on the composition of non-EEOs retrofits (supported versus stand-alone investments), as well as on the effectiveness of non-EEOs energy efficiency works (ϕ). We therefore stick to the interpretation of β^{2SLS} as an upper-bound estimand of the effect of EEOs retrofits on energy use.

5 Results

We estimate both the OLS-FE and the 2SLS-FE regressions for the official and projected contemporaneous expected savings. For each of these 4 regressions, we cluster the standard errors at the municipality level to account for possible within-municipality correlation patterns following Bertrand, Duflo, and Mullainathan 2004.

The two first columns of Table 2 describe the effect of *official* contemporaneous expected savings. The coefficient should be read as the effect of one kWh of expected savings at t on energy use the same year. Such kWh of expected savings can be imputable to EEOs retrofits undertaken at $t-1$ or earlier. According to column (1), one kWh of expected 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 worsen by the effect of non-EEOs investments. Nevertheless, the coefficient for contemporaneous expected savings (CES) is statistically significant, which motivates the search of a better identification strategy.

Table 2: Regression results for the effect of Contemporaneous Expected Savings on energy use

	Official		Projected	
	(1) OLS-FE	(2) 2SLS-FE	(3) OLS-FE	(4) 2SLS-FE
Contemporaneous Savings	**-0.741*****		**-1.304*****	
	(**0.150**)		(**0.281**)	
Fitted Contemporaneous Savings		**-0.279***		**-0.510***
		(**0.132**)		(**0.242**)
Log. of Pop.	311 233.039	392 493.377+	398 924.345	424 774.150+
	(259 358.254)	(233 630.429)	(243 975.497)	(242 795.592)
Median income	−6.653	16.919*	−4.709	17.094**
	(8.407)	(6.685)	(8.385)	(6.550)
Rel. HDD	1375.681**	1069.641*	1316.435**	1054.070*
	(485.046)	(447.227)	(494.502)	(450.910)
Avg. HDD	3217.071*	638.700	2969.591*	605.954
	(1378.252)	(2158.948)	(1327.988)	(2138.030)
Num.Obs.	93 730	93 730	93 730	93 730
R2	0.998	0.997	0.998	0.997
R2 Adj.	0.996	0.996	0.996	0.996
R2 Within	0.217	0.133	0.224	0.141
FE: Year	X	X	X	X
FE: Municipality	X	X	X	X
FE: Dep. × Year	X	X	X	X
F-test (1st stage)		81.387		72.757

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

Column (2) reports the effect of our IV estimation, which relies on the setting exposed in section 4. Under the assumption that non-EEOs energy efficiency retrofits increase with past HDD and decrease energy use (i.e. that they resemble EEOs-funded investments), the coefficient on the fitted expected savings is an upper bound estimate (in absolute terms) of the effect of EEOs retrofits on energy use. The magnitude of the 2SLS coefficient is three times lower than that of its OLS counterpart: not accounting for the selection effect yields an overestimation of the effect of EEOs retrofits on energy use. The difference between $\widehat{\beta_{(1)}^{OLS}}$ and $\widehat{\beta_{(2)}^{2SLS}}$ can be seen as an evidence of pre-existing downward trends in energy use within municipalities where we identify the effect of EEOs works.

As a result, our 2SLS strategy identifies that each kWh of official expected savings implemented through an EEOs operation actually reduces energy use by at most 0.279 kWh. This effect is significant at the 5% level, and relies on a solid first stage F-statistic (81.4), well above the Staiger and Stock 1997 rule of thumb of 10. $\widehat{\beta_{(2)}^{2SLS}}$ has a direct interpretation from the policy evaluation perspective, as it implies that only 27.9% of official expected savings are met in the best case scenario, namely the one where all energy retrofit works would have generated certificates.

To investigate the determinants of unrealized EEOs savings, we rely on our *projected* savings variable (columns 3 and 4 in Table 2). The results of the OLS-FE estimation using projected savings as an outcome variable in column (3) resemble a lot those of column (1). Indeed, the same selection bias apply to our specification, with a mechanically larger magnitude for the coefficient on contemporaneous expected savings due to lower numerical values (as shown in section 2.2, projected savings are a deflated version of the official ones). However, one can directly identify a puzzle in the results, because the regression attributes each kWh of expected savings a decrease more than proportional in energy use. This is completely at odds with the literature and validates our search for an instrument tackling the selection bias. Looking at column (4), our 2SLS strategy identifies that each kWh of projected expected savings implemented through an EEOs operation actually reduces energy use by at most 0.510 kWh. This effect is significant at the 5% level, and relies on a first stage F-statistic (72.8), again well above the Staiger and Stock 1997 rule of thumb of 10. $\widehat{\beta_{(4)}^{2SLS}}$ has a direct interpretation as an energy performance gap, as it implies an overestimation of engineering projected savings by at least 49%.

We provide robustness checks for our 2SLS-FE specification in section 6, and discuss policy implications in section 7.

6 Robustness checks

We conduct 3 robustness checks related to the effect of contemporaneous weather conditions, residential fuel oil use and spatial correlation; results for official savings are displayed in Table 3.

Table 3: Robustness checks for the effect of Official Contemporaneous Savings on energy use

	Degree Days		Fuel Oil		Spatial error	
	(1) CDD	(2) $HDD^{2,3}$	(3) Stable	(4) Decreasing	(5) SEM 2km	(6) SEM 10km
Fitted Savings	**-0.301****	**-0.302****	**-0.240**+	**-0.296**	**-0.279****	**-0.279**+
	(**0.119**)	(**0.131**)	(**0.136**)	(**0.246**)	(**0.142**)	(**0.162**)
Log. of Pop.	407 045.681+	390 006.400+	454 095.596	355 013.560	392 493.377+	392 493.377
	(235 611.854)	(227 420.588)	(278 950.360)	(237 062.790)	(238 571.673)	(248 796.267)
Median income	15.286*	15.235*	23.916**	5.281	16.919*	16.919+
	(6.534)	(6.419)	(8.642)	(5.906)	(7.335)	(8.673)
Rel. HDD	1380.626**	483.550	1220.316*	253.737	1069.641*	1069.641*
	(463.779)	(372.485)	(550.190)	(316.199)	(456.831)	(471.263)
Avg. HDD	1384.586	9799.037*	215.160	−55.805	638.700	638.700
	(1885.606)	(4150.227)	(2624.294)	(1139.933)	(2281.021)	(2671.053)
Rel. CDD	2570.060*					
	(1251.036)					
Avg. CDD	2976.541					
	(2894.666)					
Rel. HDD^2		−4.642*				
		(2.185)				
Rel. HDD^3		−0.009+				
		(0.005)				
Num.Obs.	93 730	93 730	77 851	15 100	93 730	93 730
R2	0.997	0.997	0.997	0.998	0.997	0.997
R2 Adj.	0.996	0.996	0.995	0.997	0.996	0.996
R2 Within	0.141	0.141	0.118	0.100	0.133	0.133
FE: Year	X	X	X	X	X	X
FE: Municipality	X	X	X	X	X	X
FE: Dep. × Year	X	X	X	X	X	X
F-test (1st stage)	47.801	86.992	79.744	17.525	81.387	81.387

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

Clustered standard errors at the municipality level for columns (1)-(4)

Looking first at contemporaneous weather conditions, our baseline model only accounts for a linear effect of HDD: however, the rising use of electric cooling appliances in France gives us a rationale to also account for Cooling Degree Days (CDD). As for HDD, we include the 5-years average CDD as well as the relative contemporaneous CDD with respect to this average. Column 1 in table 3 indeed shows a positive and statistically significant effect of relative CDD on energy use. Although our first-stage F-stat shrinks by almost 2, it still lies well above the Stock and Yogo rule of thumb, while the coefficient on the fitted contemporaneous savings remains of the same magnitude and significance. In column 2, Table 3, we investigate a potential non-linear relationship between HDD and energy use. Although the coefficient on the squared term is statistically significant, it is two orders of magnitude below that of relative HDD, hence we stick to the linear fit for our main model. In any case, the effect of fitted contemporaneous savings appears as robust to this polynomial specification, with a slight improvement of the F-stat as compared to column 2 in Table 2.

Second, we focus on the potential estimation bias implied by residential fuel oil consumption. Indeed, we are unable to include fuel oil in our composite energy use outcome variable, because distributors do not share their customers data. As a result, any fuel switching from fuel oil to gas or electricity would appear as a pure increase in energy use. To account for this bias, we use the French population census, which records each household main heating source: so called *fioul* or *mazout* was still used by 7.71 % of the population as of 2017, mostly in rural and Northeastern regions (INSEE 2017). In 2019, this share was down to 6.70 % nationwide, in line with the global phasing out engaged in the 1980's. However, these dynamics imply shrinking shares within the most dependent areas: as a result, we discard observations from municipalities where the share of households relying on residential fuel oil changed by 1 percentage point or more between 2017 and 2019. This does not heavily reduce the sample size, as we remain with $28,743$ municipalities (out of $34,325$). Results from this sub-sample regression are presented in column 3, Table 3. The estimation precision for the coefficient on fitted savings decreases (with a p-value down to 7.76 %); still, it is of the same magnitude as in the main regression, implying at best the realization of one fourth of all expected savings. Median income and relative contemporaneous HDD remain of the same sign and significance as in column 2, Table 2, and so does the F-statistic. We also tested the same specification on the counterpart sub-sample of municipalities where the prevalence of fuel oil decreased over the period (by more than one percentage point). Although this analysis is limited to descriptive purposes (with only $5,582$ observations over 3 years), we recover in column 4 an effect of around -30% for each kWh of energy savings, in line with all our previous results.

Finally, 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-EEOs retrofitting investments $w_{i,t}$ and $w_{j,t}$ 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 second stage of our 2SLS estimation therefore writes as a modified version of equation 3, where the error term $u_{i,t}$ is a function of contemporaneous adjacent municipalities error terms $u_{j,t}$ and $u_{i,t} \overset{i.i.d.}{\sim} \mathcal{N}(0, \sigma^2)$:

$$
\begin{aligned}
y_{i,t} =& \beta^{2SLS}\, \widehat{CES}_{i,t} + \delta_2\, log(Pop_{i,t}) + \kappa_2\, inc_{i,t} + \lambda_2 \widetilde{HDD}_{i,t} + \gamma_2 \overline{HDD}_{i,t} \\
& + \mu_{2i} + \eta_{2t} + \theta_{2\,k(i),t} + u_{i,t} \qquad (9) \\
u_{i,t} =& \xi \sum_{i \neq j} \omega_{ij} u_{j,t} + \vartheta_{i,t} \qquad (10)
\end{aligned}
$$

We present results for the 2 and 10 km thresholds. Notice that 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. As expected, the significance shrinks from column 5 to 6 in Table 3, but the p-value for the effect of contemporaneous savings always remains below 9%. 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 EEOs-funded retrofits when considering this spatial autoregressive specification brings support to the case of our upper bound estimate.

7 Discussion

Our results have major implications for the French international energy efficiency and climate commitments. According to our estimate of the effect of contemporaneous official savings, the policy achieves in the best case scenario only 27.9 % of its overall target. While official records acknowledge 13.682 TWh [1] of incremental savings each year, we estimate an upper bound average effect of −3.817 TWh each year (13.682 × −0.279). This corresponds to an annual decrease by less than .85% in residential energy use (−3.817 TWh over 453.028 TWh for the 2018-2020 period

[1] $(8.212 + 10.283 + 22.552)/3 = 13.682$.

according to the SDES 2023 report). These results have important consequences given the weight of the EEOs in the French strategy for residential energy efficiency (EE). Within the class of supported EE investments (CITE tax-credit + ANAH grants + EEOs), 57.49% of expected savings generated certificates (ONRE 2022). Thus, the overall French energy saving targets are threatened; by extension, because the French EEOs is the largest in Europe, the EU's own targets could be missed.

We also uncover a key result regarding the origin of non-realized savings. Our estimate of a minimum 49% energy performance gap (EPG) lies in between the estimates of Fowlie, Greenstone, and Wolfram 2018 (around 60%) and that of Christensen et al. 2023 (up to 41%). Although obtained in a different context, namely the Weatherization Assistance Program (WAP) in the US, these estimates point to the same issue, namely a serious overestimation of engineering projections. This finding is all the more worrying given that ex-ante evaluation of standardized operations plays a central role in the French EEOs. So-called projected savings have a huge normative power on the implementation of energy efficiency improvements, because the amount of certificates depends directly on it: identifying such an EPG is therefore an important step in the quest for policy improvements. Comparing this gap to the overall wedge between official and realized savings, we find that over-confident engineering estimations are responsible for 68%[2] of all unrealized official savings. By contrast, bonuses certificates *only* account for 32% [3] of this wedge. Stated differently, the major problem of the French EEOs over the 2017-2019 period was not the bonuses mechanism, but rather the over-confident engineering estimations. This finding has implications beyond the sole case of France. While the role of bonuses are specific to the French political context, ex-ante predictions are common to all obligation systems relying on engineering models to calibrate the value of operations. Over-confident projections are all the more worrying that EEOs are expected to become more and more important for the energy transition in a post-pandemic context with rising interest rates and tightening public budget constraints. This discrepancy could fuel one key driver of the energy efficiency gap highlighted in the literature, namely a lack of confidence in the profitability of such EE investments. This, of course, would have detrimental effects not only on EEOs-funded works but on the overall market for energy efficiency.

Finally, we acknowledge some important limits of the present study. First of all, we are unable to provide a definitive estimation of the actual energy savings allowed by the French EEOs. This is

[2] The ratio between the EPG and unrealized official savings: $0.490/(1-0.279) = 0.68$

[3] The remainder of unrealized official savings: $(0.510-0.279)/(1-0.279) = 0.32$

mostly due to the fact that we cannot control for contemporaneous EE investments not supported by the EEOs. However, this may be the case in future years, as the French Statistical Data and Studies Department (SDES) currently runs a large survey (2 million households) covering all types of retrofit investments. Second, we deliver a lower-bound estimate of the energy performance gap but we remain agnostic on its determinants. We do not dig into the two information asymmetries highlighted by the literature, namely the moral hazard caused by the information asymmetry between beneficiaries and installers, and the behavioral bias from beneficiary households known as the *rebound effect*. Our contribution is bounded to an estimation of the bias in engineering models. Third, we plan to investigate concerns related to heterogeneous treatment effects, as highlighted by the recent developments in the econometric literature surveyed in Chaisemartin and D'Haultfœuille 2022. Our setting pushes us at the very frontier of research as it involves a staggered treatment continuously distributed at every period, as in Chaisemartin, D'Haultfoeuille, et al. 2023. In such a framework, negative weights of individual treatment effects could bias our estimates downward, implying an even smaller underlying effect of the policy. Finally, the French EEOs has received important fuel poverty reduction targets through the precariousness sub-obligation. We are not able to disentangle between the *classic* and the *precariousness* sub-obligations in our modelling of the energy use, because this would require to instrument two variables while we only have one instrument. However, the distributive effects of the EEOs is a promising field of research: we plan to analyze the effect of the precariousness sub-obligation on projected savings (hence, on the ex-ante energy saving target of operations), as well as on the energy performance gap.

8 Conclusion

We analyzed a new administrative dataset recording all EEOs-supported energy efficiency retrofits in the French residential sector between 2017 and 2019, and matched the resulting expected savings for years 2018-2020 to contemporaneous residential energy use in 34,513 municipalities. We also computed an ex-ante engineering prediction of those operations to account for the debated effect of *bonuses* certificates on the overall policy's efficiency. We document two primary findings. First, the overall efficiency of the policy is disappointing. Indeed, it achieves in the best case scenario only 27.9% of its official energy saving targets, which has dramatic implications for the achievements of France environmental policy objectives. Second, and most importantly, we investigate the determinants of the gap between official and realized savings. It is widely acknowledged that the bonuses granted for specific obligations have had detrimental consequences on the policy's overall efficiency: this follows mechanically from the decrease in *projected* savings required to fulfill a given obligation. However, this political economy of the French EEOs has somewhat stolen the show in recent years, while more traditional rationales remain very relevant. We identify an energy performance gap of at least 49%, which accounts for more than two thirds of the wedge between official and realized savings. On this precise aspect, the French EEOs resembles a lot other subsidized EE policies such as the Weatherization Assistance Program (WAP) in the US, plagued by an energy performance gap of similar magnitude.

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, the search for alternative identification strategies and the investigation of the distributive effects of the precariousness 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 comfort and health improvements or unemployment reduction through the creation of so-called *green-jobs*.

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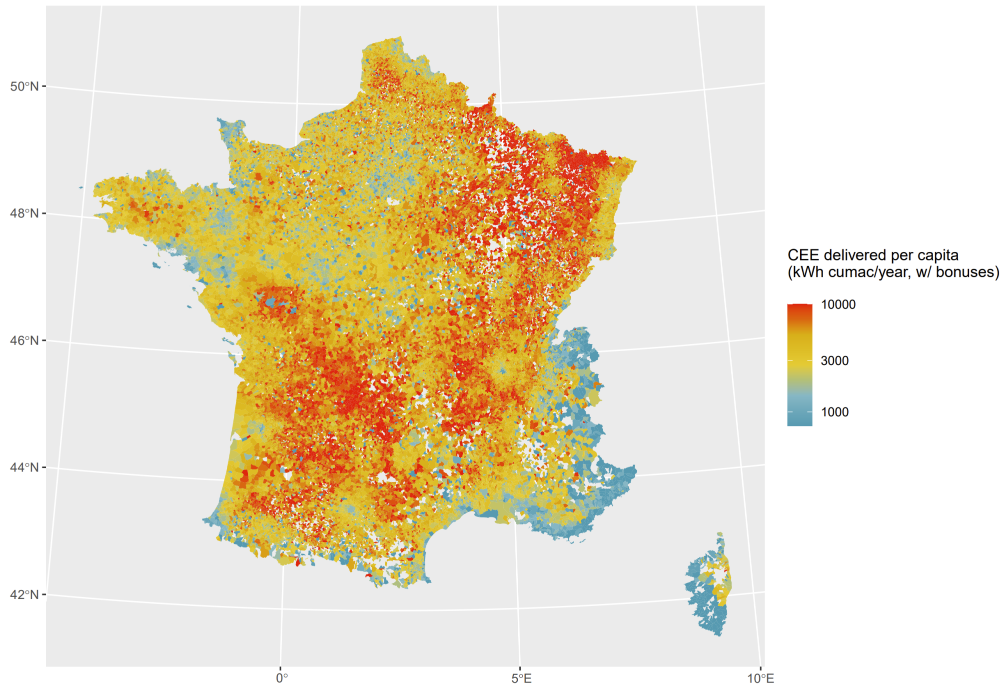
A Background information on the French EEOs

A.1 Baseline mechanism

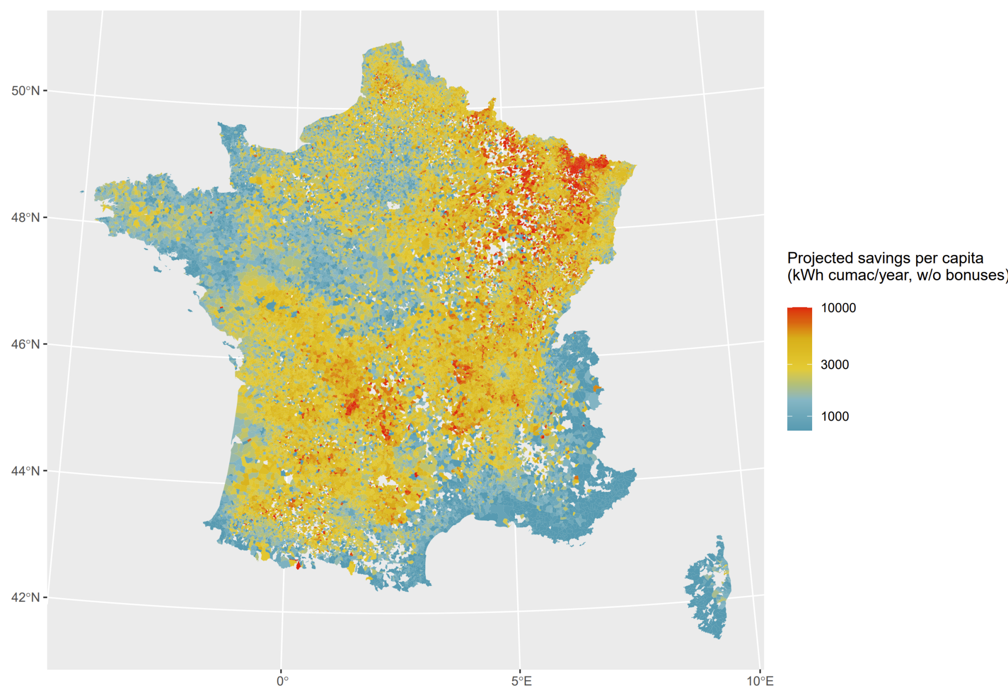
Table A1: Summary statistics on the 28 standardized energy retrofit operations used in the residential sector

BAR-	Operation	Life exp. (years)	Mean (MWh c.)	Median (MWh c.)	Sum 2017-19 (GWh c.)	Classic (%)	Preca. (%)	Total (%)	Rank
EN-101	Roof insulation	30	246.67	207.000	254037.309	18.97	81.03	37.16	1
EN-102	Wall insulation	30	498.02	205.200	66525.598	33.30	66.70	9.73	3
EN-103	Floor insulation	30	416.33	330.000	171974.153	28.02	71.98	25.15	2
EN-104	Window w/ insulated glazing	24	93.97	36.400	12387.957	37.05	62.95	1.81	8
EN-105	Rooftop insulation	30	1291.02	718.200	6314.358	35.29	64.71	0.92	11
EN-108	Insulating closure	24	9.88	3.900	56.973	49.24	50.76	0.01	23
TH-101	Ind. solar water heater	20	26.66	24.100	12.797	69.83	30.17	0.00	25
TH-102	Coll. solar water heater	22	435.45	459.289	3.919	23.28	76.72	0.00	27
TH-104	HP air-water / water-water	17	463.70	454.500	34564.825	42.78	57.22	5.06	6
TH-106	High EE ind. boiler	17	141.82	109.100	40617.610	32.75	67.25	5.94	4
TH-107	Collective boiler	22	2263.25	1140.000	7901.015	49.50	50.50	1.16	10
TH-107-SE	Collective boiler w/ contract	22	4162.24	2600.150	3616.989	63.72	36.28	0.53	14
TH-110	Low-temperature radiator	35	59.32	18.207	245.054	8.46	91.54	0.04	21
TH-112	Indep. wood-burner	12	30.85	29.600	4457.604	76.33	23.67	0.65	13
TH-113	Ind. biomass boiler	17	414.62	454.500	5169.070	48.40	51.60	0.76	12
TH-115	Heating network insulation	20	3552.32	2133.936	15655.072	45.23	54.77	2.29	7
TH-116	Underfloor heating system	50	34.37	28.200	12.203	73.30	26.70	0.00	26
TH-125	Dual-flow ventilation	17	97.58	47.525	33.568	31.21	68.79	0.00	24
TH-127	Simple-flow hygro-adj. CMV	17	163.04	54.756	2643.769	17.77	82.23	0.39	16
TH-129	HP air-air	17	53.60	44.590	2959.383	66.63	33.37	0.43	15
TH-131	Hot water network insulation	20	4067.76	2357.100	12134.138	53.82	46.18	1.77	9
TH-137	Connexion to a heating network	30	5885.32	2825.670	1494.870	24.23	75.77	0.22	17
TH-145	Comprehensive renovation	30	8498.93	5391.305	518.435	13.58	86.42	0.08	20
TH-148	HP water-heater	17	23.45	15.600	588.412	43.33	56.67	0.09	19
TH-150	Collective HP air-wat. / wat.-wat.	22	263.20	263.200	0.526	100.00	0.00	0.00	28
TH-155	Hygo-adjust. hybrid ventil.	17	1087.35	873.120	178.325	26.90	73.10	0.03	22
TH-159	Hybrid ind. HP	17	548.97	454.500	818.514	44.16	55.84	0.12	18
TH-160	Network insulation	20	2400.40	864.300	38747.304	55.08	44.92	5.67	5

A.2 Political economy of the French EEOs



(c) Official savings

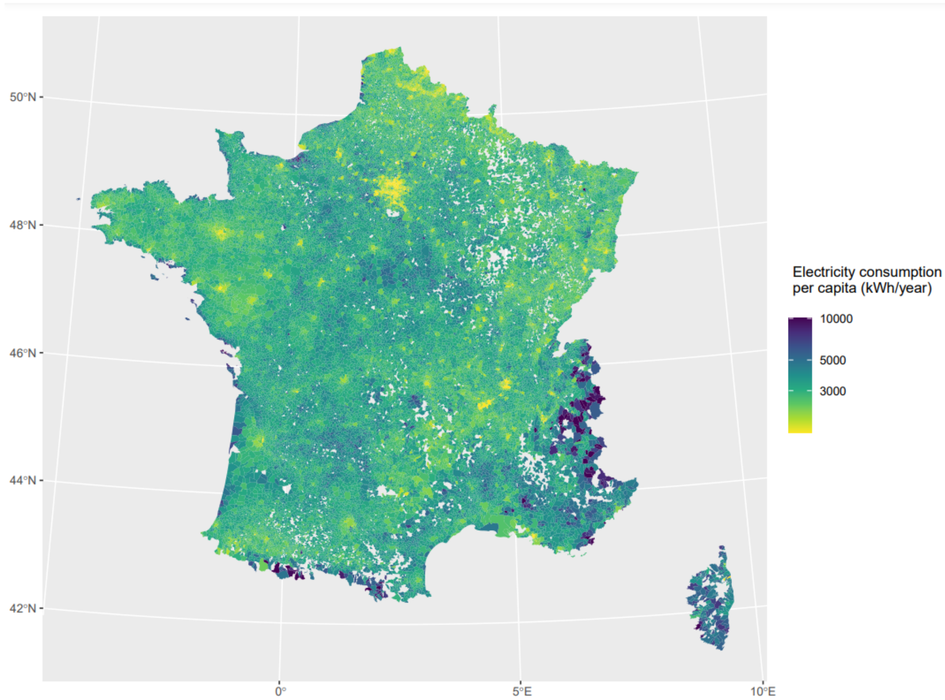


(d) Projected savings

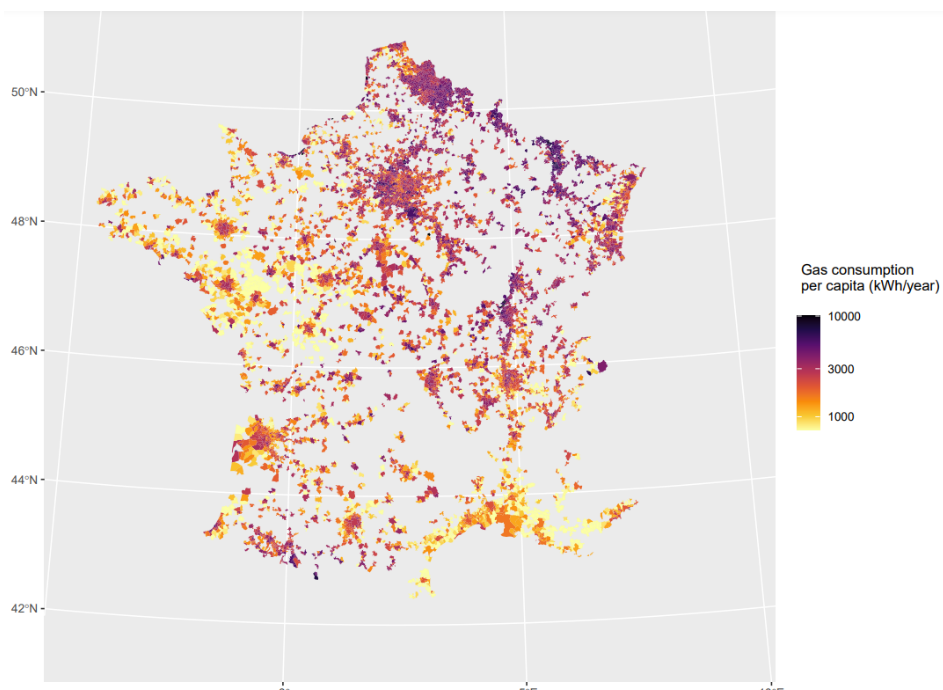
Figure A1: Official versus projected savings: disruptive effect of the bonuses

B Data

B.1 Energy use



(a) Electricity consumption



(b) Gas consumption

Figure A2: Average electricity and gas consumption per capita, 2018-2020

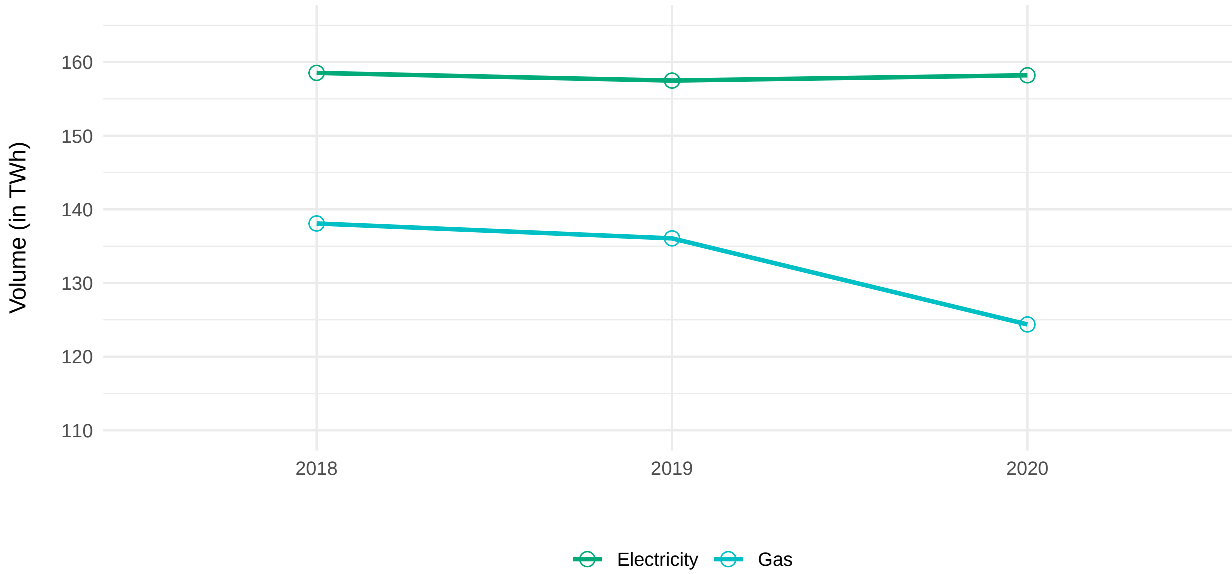


Figure A3: Evolution of electricity and gas consumption, 2018-2020

B.2 Population

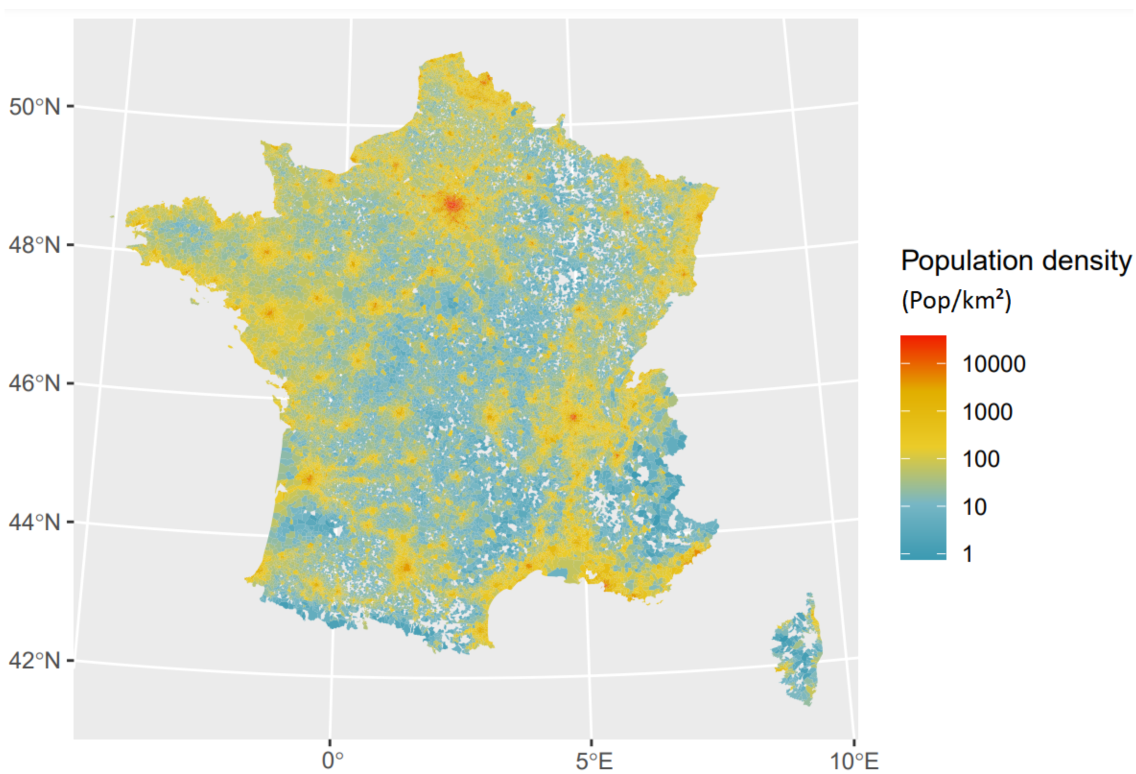
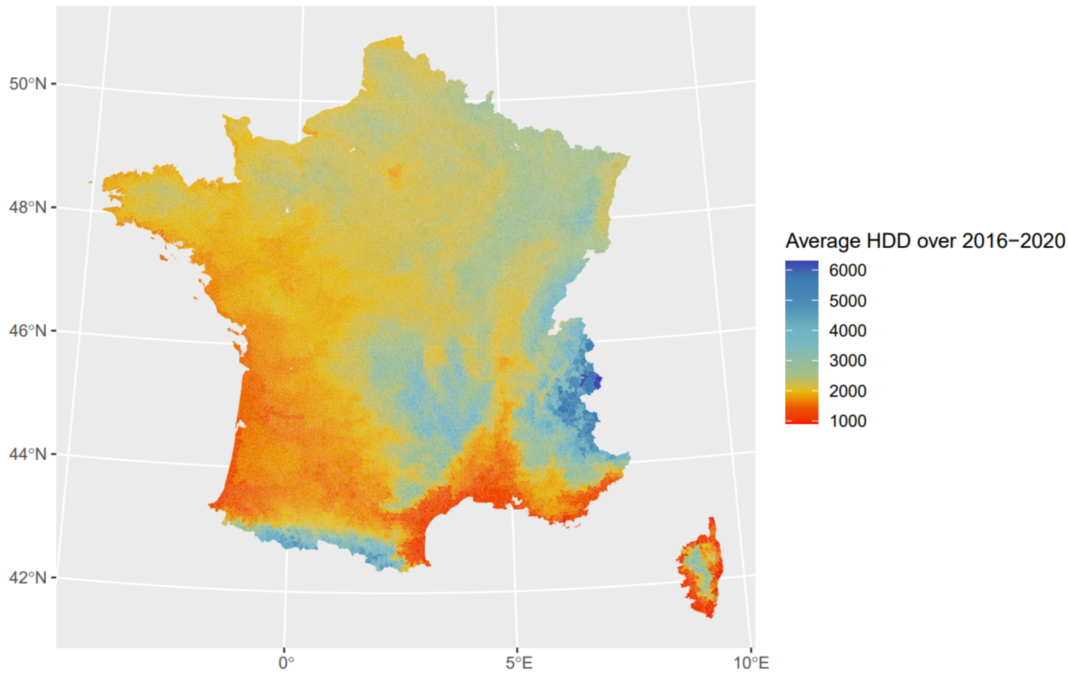
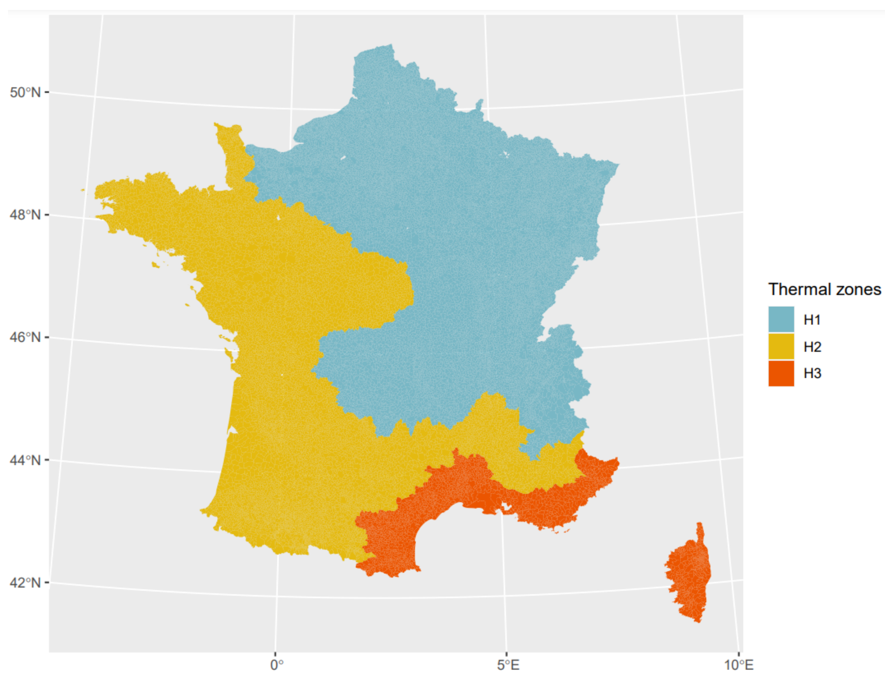


Figure A4: Population density in 2020

B.3 Climate



(a) Average Heating Degree Days between 2016 and 2020



(b) Thermal zones

Figure A5: Climate

B.4 Treatment definition

$$
\begin{aligned}
\text{Lifelong savings}_{t-1} &= \text{Incremental savings}_{\,t|t-1} \times \frac{1-1.04^{-N}}{1-1.04^{-1}} \\
\Leftrightarrow\ \text{Incremental savings}_{\,t|t-1} &= \text{Lifelong savings}_{t-1} \times \frac{1-1.04^{-1}}{1-1.04^{-N}} \\
\Rightarrow\ \text{Contemporaneous savings}_{\,t} &= \sum_{t'=1}^{t-1} \text{Incremental savings}_{\,t|t-t'}
\end{aligned}
$$

C Empirical strategy

C.1 Instrumental Variation

Table A2: First-stage effect of the Instrumental Variable on Contemporaneous Expected Savings

	Official	Projected
	(1)	(2)
Instrumental Variable	8.843^{***}	4.829^{***}
	(1.084)	(0.629)
Log. of Pop.	-188222.449	-39489.658
	(121981.879)	(68354.840)
Median income	-51.921^{***}	-28.008^{***}
	(5.102)	(2.971)
Rel. HDD	758.549^{**}	383.663^{*}
	(272.565)	(174.639)
Avg. HDD	8892.592^{***}	4791.404^{***}
	(832.558)	(507.060)
Num.Obs.	93730	93730
R^2	0.788	0.810
R^2 Adj.	0.680	0.712
FE: Year	X	X
FE: Municipality	X	X
FE: Dep. × Year	X	X

Clustered standard errors at the municipality level

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