Policies for low-carbon and affordable home heating: A French outlook

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Preprint for *Energy Policy**

Abstract. Energy demand for residential heating is targeted in France by a number of subsidy programmes (tax credits, zero-interest loans, reduced VAT, white certificates and the carbon tax. We assess the cost-effectiveness and distributional impacts of these policies using Res-IRF, an energy-economy model that integrates relevant economic, behavioural and technological processes. We find that, without further specification of revenue recycling, the carbon tax is the most effective, yet most regressive, policy. Subsidy programmes save energy at a cost of €0.05-0.08 per lifetime discounted kilowatt-hour, or €300-800/tCO2-eq; one euro of public money spent on subsidy programmes induces €1.0-1.4 private investment in home energy retrofits. Targeting subsidies towards low-income households, who tend to live in energy inefficient dwellings, increases leverage, thus reconciling economic efficiency and equity. The public cost of subsidies – €3 billion in 2013 – is outweighed by carbon tax proceeds from 2025 onwards, were the tax rate to grow as initially planned by the government. Meeting the long-term energy saving targets set by the government however requires adjusting subsidy programmes to better address rental housing. Lastly, an order-of-magnitude discrepancy between simulated and observed numbers of zero-interest loans points to economic and psychological barriers that require further investigation.

Keywords. residential heating, energy-economy modelling, energy efficiency subsidies, carbon tax, white certificate obligations, zero-interest rate loans, fuel poverty, Res-IRF model, rebound effect

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* Paper ID: 112140. Submitted 23 April 2020. Revised 18 November 2020. Accepted 4 January 2021. Proofs edited 15 January 2021.

1 Introduction

Saving energy in the building sector is set as a priority in many of the nationally-determined contributions submitted by parties in the Paris Agreement. As a result, a general pattern of ambitious energy saving targets, coupled with numerous instruments meant to fulfil them, prevails in many countries. In the EU alone, 809 energy efficiency policies have been documented in the residential sector (Filippini et al., 2014). A majority of them address space heating, where the greatest potential for mitigation opportunities lies (Ó Broin et al., 2015). Policies take a variety of forms – regulatory (e.g., building codes), financial (e.g., taxes and subsidies), and, to a lesser extent, informative. While financial policies tend to be considered the most effective, their performance is possibly undermined by the so-called free riding (or infra-marginal participation) problem (Laes et al., 2018). In addition, financial policies are sometimes criticized for their socially regressive effects, as subsidies tend to mostly benefit the rich (e.g., Nauleau, 2014) while taxes mostly fall on the poor (Berry, 2019).

Such a crowded policy landscape raises a number of questions: Do existing policies allow environmental targets to be met? Do they deliver cost-effectively? What kind of interactions do they entail? Do they equally affect households with differing socio-economic characteristics? We examine these questions in the French context, using a modelling tool that provides a rich description of the processes by which policies operate.

France's case is interesting in several respects. First, France has assigned a number of policy objectives to the residential sector (IGF and CGEDD, 2017). These include: a 20% reduction in energy use by 2030 and 50% by 2050, as compared to 2012 levels (Target 1); yearly renovation of 500,000 dwellings, including 120,000 in social housing (Target 2); upgrade of the most inefficient dwellings – labels G and F of the Energy Performance Certificate (EPC), representing nearly 8 million units – by 2025 (Target 3); a minimum performance equivalent to EPC label B imposed on all dwellings by 2050 (Target 4); a 15% alleviation of fuel poverty by 2020 (Target 5). Second, France has primarily relied on energy efficiency subsidy programmes to achieve these targets. Income tax credits (ITC) and value-added tax reductions (VAT) were implemented in 2005, utility-sponsored programmes were rolled-out from 2006 onwards to comply with the newly imposed white certificate obligations (WCO), and zero-interest loans (ZIL) were implemented in 2009. These programmes overlap and entail differing subsidy rates, regimes – ad valorem (ITC, VAT and ZIL) vs. per-unit (WCO) –, and scopes – uniform (ITC, VAT) vs. targeted on either high performance (ZIL) or fuel-poor eligibility requirements (WCO). An interesting question is whether such diversity produces synergies or antagonisms. Third, subsidy programmes were complemented in 2014 with a carbon tax (CAT), the proceeds of which are allocated to France's general budget without specific earmarking. The rise of the carbon tax rate that was enacted in the Finance Bill sparked social upheaval in 2018, resulting in its subsequent freezing by the government.[1] As carbon taxes are gaining traction across OECD countries, better understanding the merits and pitfalls of the instrument is of broad interest. Against these peculiarities, France's role as the second largest economy of the EU and its geographical position at the centre of Western Europe makes it a good candidate for studying policy impacts on heating patterns from a broad perspective.

[1] Wanted: a fair carbon tax, 2018. Nature 564, 161. https://doi.org/10.1038/d41586-018-07717-y

Our assessment relies on Res-IRF, an energy-economy model of energy demand for space heating in France (Giraudet et al., 2011, 2012). Developed with the purpose of improving the behavioural realism typically lacking in bottom-up models (Mundaca et al., 2010; McCollum et al., 2017), Res-IRF incorporates all relevant margins of energy demand in residential buildings – the intensive and extensive margins of energy efficiency investment and a demand for comfort determining the intensity with which heating systems are used. These processes are mediated by parameters mimicking barriers at the source of the so-called energy efficiency gap – the wedge between supposedly optimal and actual energy efficiency levels (Jaffe and Stavins, 1994; Sorrell, 2004; Gillingham et al., 2009). Such barriers include the landlord-tenant dilemma, difficulties associated with collective decision-making within homeowner associations, non-energy attributes of home energy retrofits and rebound effects. The version of the model used in this paper additionally incorporates a segmentation of households by income categories. This new development allows us to account for the negative association between credit constraints and income and to assess the distributional impacts of policies. Previous analyses have demonstrated the fitness-for-purpose of the model (Branger et al., 2015) and its ability to reproduce past trends with great accuracy (Glotin et al., 2019).

We assess the effectiveness to targets, cost-effectiveness and distributional impacts of the five policies outlined above, both taken together and in isolation. We run all possible combinations of policies and take an original approach to estimating stand-alone policy impacts and their interactions. Altogether, the added value of our assessment lies in the breadth of the policies covered and the depth of the processes studied.

We find that fulfilment of the different targets requires policies be set at their most ambitious level and maintained until 2050. In particular, subsidy programmes should be adjusted to better address rented dwellings, which remain unaffected by energy efficiency policies. The cost-effectiveness of subsidy programmes could be improved by negatively linking subsidy rates to recipients' income. Thus targeting low-income households indeed is a way to address the most inefficient dwellings – where a euro of public money spent on retrofits maximizes energy savings –, owing to a negative correlation found in the data between occupants' income and the energy efficiency of their dwelling. We see this adjustment as a politically palatable opportunity to increase cost-effectiveness while alleviating fuel poverty. Taken as a closed system, the policy mix produces significant benefits in the medium and long term, with carbon tax revenues exceeding subsidy payments from 2025 on. Looking at policies separately, the carbon tax stands out as the most effective, yet most socially regressive, instrument.[2] Subsidies save energy at a cost of €0.05 to €0.08 per lifetime discounted kilowatt-hour and carbon dioxide at a cost of €300 to €800 per lifetime discounted tCO_2-eq. We estimate leverage ratios to fall within the 1.0-1.4 range; that is, one euro of public spending on a subsidy programme induces around one euro of extra-investment in energy efficiency improvements. This result leads us to reconsider the claim that subsidy programmes are strongly undermined by free riding. Specifically, it highlights the importance of considering the intensive margin of investment in the infra-marginal participants' response to subsidy programmes. The income

[2] This result is obtained with tax proceeds left unspecified, as is the case in practice. In a related paper (Bourgeois et al., 2019), we explore different recycling options and find that a carbon tax would be more cost-effective, fairer, and possibly more politically acceptable if its revenues were recycled as energy efficiency subsidies.

tax credit is the most effective, yet least efficient, subsidy programme. The model accurately reproduces recent estimates of ex post policy effects, save for the zero-interest loan programme, the effectiveness of which it over-estimates by an order of magnitude. This important gap points to unaccounted for barriers that require further research. Policy interactions are mild but positive, typically inducing a 10% increase in an instrument's effectiveness.

Beyond the specific case of France, our modelling exercise generates a few general insights. First, the positive correlation between household income and housing energy efficiency that is responsible for the win-win aspect to low-income targeted subsidies is arguably quite general to EU member states. So is the lack of energy efficiency policy support in rental housing. Second, the discrepancy between simulated and observed numbers of ZILs suggests that some important yet little understood barriers hinder participation in this programme. As the instrument has counterparts in other EU member states, notably in Germany, this points to the need for further applied microeconomic work seeking to identify these barriers.

The remaining of this paper is organized as follows. Section 2 provides an overview of the Res-IRF model, emphasizing its latest developments. Section 3 proposes an evaluation method and details policy specifications. Section 4 presents the results. Section 5 discusses policy implications and concludes.

2 The Res-IRF 3.0 model in a nutshell

Initiated in 2009, the development of Res-IRF has been motivated by improving behavioural realism in integrated assessments of residential energy demand (Giraudet et al., 2012). The model has been used in previous policy assessments (Giraudet et al., 2011; Mathy et al., 2015). Meanwhile, its robustness and accuracy have been assessed through global sensitivity analysis (Branger et al., 2015) and hindcasting (Glotin, 2019).The vintage used in this paper, Res-IRF 3.0, improves on previous ones by incorporating a segmentation of households by income category. It is fully described in the online appendix. As detailed in Section 3.1 of the online appendix, the sensitivity of the model can be summarized by a price-elasticity of energy demand of -0.23 in the short term and -0.35 in the long term and a direct rebound effect of 20% – in line with estimates found in the literature (Sorrell et al., 2009; Gillingham et al., 2009; Labandeira et al., 2017).

The section below provides an overview of the key processes and emphasizes the newest developments of the model.

2.1 Structure

With residential buildings contributing 26% of final energy demand, of which 67% is dedicated to space heating, the scope considered in Res-IRF covers 18% of final energy demand in France. The dwelling stock is parameterized with data from the Phébus survey that elicits the socio-economic characteristics of households and the energy efficiency of the dwellings they inhabit[3]. The stock considered is that of

[3] *Performance de l'Habitat, Equipements, Besoins et Usages de l'énergie*. http://www.statistiques.developpement-durable.gouv.fr/sources-methodes/enquete-nomenclature/1541/0/enquete-performance-lhabitat-equipements-besoins-usages.html

principal residences in Metropolitan France, which contains 23.9 million units. It is segmented in 1,080 categories, split as follows:

- Nine categories of energy performance, corresponding to labels A to G of the French energy performance certificate (EPC) in dwellings built before 2012, and labels 'low energy' and 'net zero energy' in dwellings built after 2012.[4] These categories summarize the technical characteristics of the envelope and the heating system. They represent national averages, as the model does not include regional differences in specific energy consumption.
- Four fuels used as the primary source for space heating: electricity, natural gas, fuel oil and fuel wood.[5] The life-cycle CO_2-equivalent (in gCO_2-eq/kWh) contents we consider for these fuels are 147, 227, 329 and 0, respectively.[6] This produces a weighted average carbon content of 150 gCO_2-eq/kWh in 2012.
- Two categories of housing: single- and multi-family units, respectively weighing 61% and 39%.
- Three categories of property owners: owner-occupiers, landlords of rented dwellings, and social-housing organizations, respectively weighing 61%, 24% and 15% of dwellings.
- Five levels of income for both owners and occupiers, closely aligned with the income quintiles of the French population given by INSEE, the national statistical office (Figure 1).

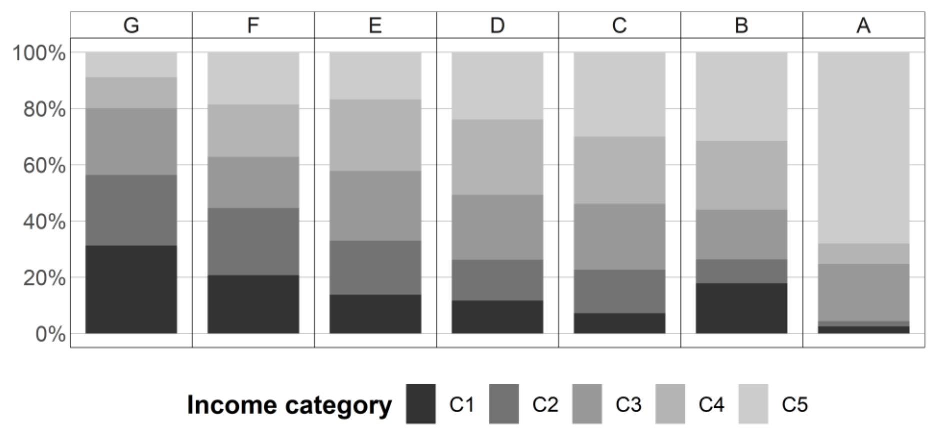

Figure 1: Distribution of income categories across EPC labels (C1: bottom 20%; C5: top 20%)

The model is fed with three exogenous inputs: population, total income, and energy prices. These variables determine improvements in energy efficiency through new constructions, the renovation and existing dwellings, and the intensity with which occupants heat their dwelling.

[4] Based on the Phébus survey, we consider the following primary energy consumption for EPC labels (in $kWh.m^{-2}.yr^{-1}$): G=507; F=321; E=216; D=141; C=90; B=59; A=45; Low-energy=20; Net-zero=16. See online appendix for further information.

[5] Fuel wood here aggregates all forms of wood used for residential heating, including log, pellet, and chip. The four fuels considered in the model together cover 91% of French residential energy demand for heating. The remaining part (not considered in the model) is met by district heating for the most part, followed by LPG and coal (1% each).

[6] https://www.bilans-ges.ademe.fr/

2.2 Construction of new dwellings

The construction of new dwellings is determined by:

- An exogenous population projection, which determines annual housing needs. Our reference scenario is based on a widely-used projection (INSEE, 2006) that can be summarized into an average annual growth rate of 0.3%.
- An exogenous household income projection, which determines the average square footage per capita. This, combined with the above projection of dwelling numbers, determines total housing needs in square footage. We assume that income grows at a constant annual rate of 1.2%, in line with the trend that prevailed over the 2009-2013 period.[7]
- Part of these housing needs are met with existing dwellings – that is, dwellings built before 2012 – the stock of which however depreciates at a constant annual rate of 0.35%.

New constructions are thus determined each year as total housing needs less the remaining stock of existing dwellings. Our specification results in a cumulative stock of pre-2012 dwellings contributing 66% of the total surface and 75% of the total number of dwellings in 2050.

The energy efficiency and principal heating fuel of each new dwelling are jointly determined by discrete choice functions allocating market shares to each option according to its life-cycle cost, discounted at 7% over 35 years. Policies can affect choices in several ways: energy efficiency subsidies reduce investment costs while energy taxes increase operating costs, both affecting life-cycle costs; building codes restrict choice options, irrespective of associated life-cycle costs.

Table 1 details the construction cost of each option. Heat resulting from the combustion of natural gas, fuel oil and wood is assumed to be distributed via hot-water radiators. Electricity is used to power radiators in low-energy units and heat pumps in net-zero energy units (hence a higher cost in the latter).

Table 1: Construction costs, in €/m² (Source: CGDD, 2015)

Principal source of energy	Single-family units		Multi-family units	
	Low energy	Net zero energy	Low energy	Net zero energy
Electricity	979	1,112	1,199	1,308
Natural gas	1,032	1,059	1,242	1,253
Fuel oil	1,032	1,059	1,242	1,253
Fuel wood	1,094	1,121	1,323	1,350

2.3 Renovation decisions

Renovation decisions are made by homeowners – owner-occupiers, landlords and social housing providers. For of a dwelling labelled *i*, they proceed along two margins:

- **Intensive margin**: selection of one final label *f* among higher labels $\{i+1, \dots, A\}$. This process is similar to that of new constructions, in that the market share of each option is determined by a discrete-choice function based on the life-cycle cost comparisons. It is however more detailed in

[7] This is based on gross disposable household income of €1,318 billion in 2012 (https://www.insee.fr/fr/statistiques/2569356?sommaire=2587886).

four respects. First, heterogeneous credit constraints are captured by a negative association between discount rates and income (Table 2), as first estimated by Hausman (1979). Second, frictions inherent in collective decision-making within homeowner associations are captured by higher discount rates in multi-family units, as compared to those applied to single-family units (Table 2). Third, under-capitalization of energy savings in rents are captured by a short investment horizon of three years in rented dwellings, as opposed to 30 years in owner-occupied dwellings and social housing.[8] Fourth, residuals are calibrated by confronting the model to observed upgrade patterns; these residuals are interpreted as intangible costs, capturing, for instance, the inconvenience caused by renovation works.

- **Extensive margin**: the decision-maker decides whether or not to upgrade a dwelling of label i to a higher label $f>i$. This decision depends on the net present value of an average renovation project, measured as the difference in life-cycle costs between the status quo and the different upgrade options weighted by their market share. The correspondence between net present value and renovation numbers follows a logistic function capturing heterogeneity in heating tastes and habits. It is calibrated against a renovation target of 3% of existing dwellings in 2012. This base renovation rate captures the natural turn-over of the housing stock, including retrofit works routinely performed when households move into a new home and the replacement of obsolete or defective heating systems.

These decisions are based on contemporaneous energy prices, building on evidence from the transport sector that consumers form myopic expectations when it comes to energy-related decisions (Anderson et al., 2013). As the model is not geographically differentiated, the prices used are national averages. Furthermore, they are average prices, as evidence suggests residential consumers more effectively respond to this kind of signal than to the marginal prices included in two-part tariffs (Ito, 2014).

Our representation of energy efficiency improvements through EPC label upgrades relies on a cost matrix in which part of the data is based on observations while the remaining is interpolated according to two standard economic rules: the marginal cost of energy efficiency is increasing; economies of scale make it cheaper to perform a given upgrade at once rather than sequentially. The resulting matrix is displayed in Table 3. When savings are cumulated over 26 years and discounted at 4%, the matrix produces an average cost of €83 per MWh saved, with a range of 25 to 446. With an indicative carbon content of 0.150 tCO_2-eq/MWh in 2012, these values are equivalent to an average cost of €533/tCO_2-eq, with a range of 167 to 2,967. As detailed in Appendix A, these orders of magnitude are consistent with those otherwise estimated for France (DG Tresor, 2017, fig. 1; Quinet et al., 2019, fig. 50) and other countries (Jakob, 2006; Löffler and Hecking, 2016; Toleikyte et al., 2018).

[8] At least in the residential market, the phenomenon is more pregnant than under-capitalization in property value (Giraudet, 2020).

Table 2: Discount rates, by decision-maker and type of housing

Income quintile	Single-family units	Multi-family units	Social housing
C1 (bottom 20%)	15%	37%	4%
C2	10%	25%	4%
C3	7%	15%	4%
C4	5%	7%	4%
C5 (top 20%)	4%	5%	4%
Weighted average	**8%**	**17%**	**4%**

Table 3: Renovation costs, in €/m²

		Final label					
		F	**E**	**D**	**C**	**B**	**A**
Initial label	**G**	76	136	201	271	351	442
	F		63	130	204	287	382
	E			70	146	232	331
	D				79	169	271
	C					93	199
	B						110

Both construction and renovation costs are subject to endogenous decrease through learning-by-doing functions parameterized with learning rates of 25% and 10%, respectively.

It is important to recall that our parameterization of discount rates and renovation costs relies on data that are inherently difficult to obtain. Global sensitivity analysis however revealed that these parameters were not among the most influential of the model (Branger et al., 2015). The uncertainty surrounding them is therefore unlikely to overturn our policy results. In the online appendix, we confirm the modest influence of the discount rates in scenario variants (Section 3.3).

2.4 Heating behaviour

It is well documented in practice that actual energy use, i.e., the one appearing in an occupant's energy statement, differs from the conventional one predicted by her dwelling's EPC label (Hirst and Goeltz, 1985; Metcalf and Hassett, 1999; Fowlie et al., 2018). The gap is known to arise from a variety of problems, including rebound effects (Sorrell et al., 2009), the pre-bound effect (Sunikka-Blank and Galvin, 2012) and issues with the quality with which retrofits are completed (Giraudet et al., 2018).

In the model, we take the gap into account and consider how it varies in response to rebound effects. Specifically, we define a dimensionless heating intensity variable as the ratio between actual and conventional energy use and assume it to be negatively associated with the income share occupants dedicate to heating. We thus build on an empirical relationship estimated by Cayla and Osso (2013) and corroborated in other settings by Aydin et al. (2017) and Cozza et al. (2020). The relationship reads:

$$Heating\ Intensity = -0{,}191 * \log(Income\ Share\ ) + 0{,}1105,$$

where income share is the energy expenditure – the price of energy times the conventional energy use of the dwelling (as disclosed in its EPC label) – divided by the occupant's income. Heating intensity can be interpreted as a proxy for heating comfort. It can increase either due to higher energy efficiency (i.e., a lower specific energy use), a lower energy price or a higher income, respectively causing an efficiency-induced, a price-induced and an income-induced rebound effect. In the analysis conducted here, we focus on how policies generate both efficiency-induced and price-induced rebound effects.

3 Evaluation method

The exercise conducted here follows up on previous assessments by Giraudet et al. (2011) and Charlier and Risch (2012) of energy efficiency policies in the French residential sector. These works are the only ones we are aware of that consider multiple policies and their interactions at a national scale, with processes detailed at a highly disaggregated level. We improve on them by using more up-to-date data, considering a broader set of policies (including white certificate obligations and an updated carbon tax) and examining a richer set of policy outcomes (including cost-effectiveness, leverage, a systematic quantification of policy interactions and distributional impacts).

3.1 Reference scenario

As stated earlier, the model is fed with the following inputs: population, growing at 0.3% p.a.; total household income, growing at 1.2% p.a.; and energy prices growing according to a scenario borrowed from French authorities.[9] Prices grow at average annual rates of 1.4% for natural gas, 2.2% for fuel oil, 1.1% for electricity and 1.2% for fuel wood (See Appendix B, Table B1). These trends result in a price index growing at an average annual rate of 1.5% in the 'AP' scenario (see specification below).

3.2 Policy specifications

We consider the five policies outlined in the introduction – ITC, VAT, WCO, ZIL and CAT. In addition, we embody both the building code of 2012 and the upcoming tighter code in our reference scenario. In turn, we ignore some important policies that either have a restricted eligibility – ANAH's subsidies targeting low-income households – or cannot easily be modelled – information campaigns. We assess progress towards achieving the five targets outlined in the introduction, considering two variants for each policy: the reference variant and a tighter one, labelled '+.' Policy parameters are detailed in the section below and summarized in Table 4.

Table 4: Summary of key policy parameters

		Reference variant (with all policies, AP)	Tighter variant (AP+)
Income tax credit	**ITC**	Subsidy with a uniform rate of 17%	Subsidy with 17% rate targeting high performance
Zero-interest loan	**ZIL**	Subsidy targeting high performance, rate~9% of investment cost	Subsidy targeting high performance, rate~23% of investment cost
White certificate obligation	**WCO**	Subsidy of €5/MWh lifet. disc. in 2017 (doubled for C1 households), growing at +2% p.a., + fee on energy sales	Subsidy of €15/MWh lifet. disc. in 2017 (doubled for C1 households), growing at +2% p.a., + fee on energy sales

[9] https://ec.europa.eu/energy/sites/ener/files/documents/france_draftnecp.pdf

Carbon tax	**CAT**	Myopic expectation	Perfect foresight
Reduced VAT	**VAT**	5.5% rate	
Building code	**BCO**	Net zero energy level mandatory for new constructions in 2020	

3.2.1 Carbon tax (CAT)

The carbon tax has been in effect in France since 2014. We apply the rate schedule outlined in Table 5 to fuel oil and natural gas,[10] with respective carbon contents of 271 and 206 gCO_2/kWh.[11] We further assume that the latter content decreases from 2020 onwards at 1% p.a. so as to meet a governmental target of incorporating 10% biomass into natural gas supply by 2030.[12] The carbon tax is subject to a 20% VAT. As is done in practice, we do not earmark tax revenue recycling.

Table 5: Carbon tax, in euros per ton of CO_2-equivalent (excluding VAT)

2014	2015	2016	2017	2018	2019	2020	2020-30	2030-50
€7	€14.5	€22	€30.5	€39	€47.5	€56	+6% p.a., €100 in 2030	+4% p.a.

In the reference variant, the carbon tax is, just like the price of energy, myopically expected. In the CAT+ variant, in contrast, it is perfectly expected. The two scenarios are meant to cover the full range of possible investment behaviour. Note that these variants do not affect utilization behaviour, which relies on contemporaneous price signals.

3.2.2 Zero-interest loan (ZIL)

The ZIL programme has been in effect since 2009. It allows households to borrow money at zero-interest rate from any eligible credit institution in order to invest in home energy retrofit. The lending institution in turn receives a compensatory payment from the government. The programme does not impose restrictions on the socio-economic characteristics of borrowers, but does impose restrictions on the measures undertaken, which need to comply with certain performance requirements. We interpret these as a threshold set at label D (191 kWh/m²/year) for upgrades from labels G to E and a threshold set at label B (76 kWh/m²/year) for upgrades from labels D and C.

The instrument is modelled as a subsidy equal to the interest payments the borrower would be charged for a conventional unsecured loan of the same amount and duration. The ‘reference’ variant incorporates a range of restrictions based on key statistics provided by SGFGAS, the authority supervising the programme.[13] These restrictions force the instrument to reproduce as closely as possible observed outcomes. They are all removed in the ‘ZIL+’ variant, which is meant to gauge the full potential of the

[10] This schedule is the one that was enacted in 2014. The official schedule was revised upward in 2017. Yet in the wake of the ‘Yellow vest’ protest movement, the tax rate has been frozen at €44.6/tCO2 since 2018. We therefore take a conservative approach and stick to the initial schedule.

[11] These carbon contents are the legal ones to which the carbon tax applies. They have not been revised since implementation in 2014. They differ from the contents we use to compute CO_2 emissions (provided by ADEME; see our Section 2.1), which take into account the broader life-cycle emissions relevant to climate change. Note that no carbon tax is levied on final electricity use, considered by the government to be already covered by the EU ETS.

[12] LOI n° 2015-992 du 17 août 2015 relative à la transition énergétique pour la croissance verte, Article 1.

[13] https://www2.sgfgas.fr/web/site-public/statistiques

instrument. When expressed in ad valorem terms, the ZIL variant has an average rate of 9% and the ZIL+ variant a 23% rate. The main differences between the two scenarios are outlined in Table 6.

Table 6: Parameters of the ZIL variants

	ZIL	ZIL+
Counterfactual interest rate	**3% (ADEME, 2016)**	4%
Loan duration	**5 years (ADEME, 2016)**	10 years
Borrowing ceiling	**€21,000 for top quintile … €16,800 for bottom quintile (SFGAS)**	€60,000
Performance targeting	**Yes**	Yes
Equivalent subsidy rate	*9%*	*23%*

3.2.3 Income tax credit (ITC)

The ITC programme has been in effect since 2005 (Nauleau, 2015). It offers income tax deductions for investments in home energy retrofit. Eligible measures and subsidy rates are updated on an annual basis. The latest regime in order has a flat ad valorem rate of 30%. Eligibility covers equipment costs, plus installation costs for insulation measures.

We model the instrument as a 17% rate subsidy applied to the full cost of a measure, which implicitly includes both equipment and installation. This value corresponds to the average rate faced by households in practice (ADEME, 2016). In the reference scenario, the same rate is applied to all measures; in the ITC+ scenario, the restrictions of the ZIL apply so as to mimic a more aggressive subsidy schedule shifting effort towards high performance.

3.2.4 White certificate obligations (WCO)

White certificate obligations have been in effect in France since 2006. The programme imposes energy saving obligations on energy suppliers, which they can fulfil either by sponsoring energy efficiency measures undertaken by their customers or by purchasing energy savings from another obligated party that exceeded its target. Either way, tradable energy savings are certified by pre-agreed calculations of lifetime discounted savings – the so-called white certificates. Energy suppliers can, to different extents depending on regulations specific to the fuel market in which they operate, pass-through compliance cost onto their retail prices. In case they do not comply, they have to pay a €20 fee per missing lifetime discounted MWh.

Following Giraudet and Quirion (2008), we model the instrument as a hybrid tax-subsidy instrument as follows:

- The subsidy component is proportional to the energy savings generated by a given upgrade, discounted at 4% over 15 years. The proportionality is given by the price of white certificates.
- The fee component is given by obligation coefficients (in kWh lifetime discounted to save per kWh sold) multiplied by the price of white certificates. The profile of obligation coefficients

follows that set by the government from 2012 to 2020;[14] we increase the 2020 coefficients at 1% p.a. in subsequent years. A VAT of 20% is applied on these fees.

The price of white certificates is set at 4€ per lifetime discounted MWh from 2012 to 2015, as prevailed in practice. It starts diverging in 2016 in the two scenarios – 5€ in WCO and 15€ in the WCO+, the latter reflecting a high price close to the 20€ upper bound. In subsequent years, in both scenarios, the price increases at an annual rate of 2% and is capped at 20 € per lifetime discounted MWh. Expressed in ad valorem terms against the renovation costs of Table 3, and valued at 4€ per lifetime discounted MWh over 15 years, the subsidy component exhibits a decreasing regime (Table 7). Weighted by the upgrades observed in 2012, the average rate is 5%.

Table 7: Equivalent ad valorem rates of the subsidy component of WCO

	F	E	D	C	B	A
G	11%	10%	8%	7%	6%	5%
F		8%	6%	5%	4%	3%
E			5%	4%	3%	2%
D				3%	2%	2%
C					2%	1%
B						1%

3.2.5 Reduced VAT (VAT)

Renovation measures are subject to a reduced VAT rate of 5.5%, instead of the normal rate of 10% which applies in the building sector. This assumption is embodied in our cost matrix.

3.2.6 Building code (BCO)

The low-energy ceiling (50 kWh/m²/year) is mandatory for new constructions since 2012. The upcoming building code imposes the net zero energy standard in 2020. Both ceilings are embodied in our reference scenario.

3.3 Evaluation criteria

We run four key scenarios:

- **AP**, standing for ‘all policies,’ which incorporates all policies in their reference variant. This is the scenario against which the model is calibrated.
- **AP+**, which incorporates all policies in their ‘+’ variant.
- **ZP**, standing for ‘zero policy,’ in which all policies are removed.
- **AP-LTD**, in which the so-called landlord-tenant dilemma is removed. This is modelled by aligning landlords’ behaviour (captured by investment horizon) with that of owner-occupiers.

As is the case in practice, subsidy programmes largely overlap. We additionally make the strong assumption that all subsidies to which a household or a measure is entitled are effectively claimed.

[14] https://www.ecologique-solidaire.gouv.fr/politiques/certificats-economies-denergie

3.3.1 Choice of a counterfactual

Given that multiple policies are combined, a variety of counterfactual situations can be thought of against which to assess the impact of each policy. Two polar cases delimit the impact of a given instrument. On the one hand, the reference scenario that includes all policies (AP) can be compared to a scenario including all instruments but one. This method, which we refer to as 'AP-1,' provides an assessment of the impact of the missing instrument in interaction with all others. On the other hand, a scenario in which all policies have been removed (ZP) can be compared to the same scenario, only augmented with one policy. This method, which we refer to as 'ZP+1,' provides an assessment of the pure impact of the instrument, immune from interactions with other instruments. In between these two methods, a range of comparisons can be made between scenarios AP$-k$ and AP$-(k+1)$ (or, equivalently, between ZP$+k$ and ZP$+k+1$) which quantify the interaction of the $(k+1)$-th instrument with k others. Considering all possible combinations, 64 scenarios can be run (including AP and ZP) and the impact of each instrument can be assessed in 32 different scenario comparisons.

3.3.2 Cost-effectiveness

We measure the cost-effectiveness of subsidy programmes at a given year as the ratio between total subsidy payments that year and the lifetime discounted energy savings they generate, assessed by comparing a scenario with the instrument (and possibly others) to one in which the instrument is removed that year but maintained in all previous years. We compute two variants of that indicator which respectively factor in actual and conventional energy savings at the denominator. In both cases, energy savings are discounted at 4% over 26 years, the typical lifetime of energy efficiency investments (DGEC, 2018).

3.3.3 Leverage

We measure leverage as the ratio between the extra renovation expenditure induced by a subsidy programme and the total payments associated with it. Extra expenditure here again is assessed by comparing two scenarios with and without the instrument in place that year but in both cases present in all previous years. Thus defined, our leverage ratio aggregates effects on the intensive and extensive margins of investment.

High leverage and low cost-effectiveness both indicate a high degree of efficiency in public spending.

3.3.4 Distributional impacts

We assess fuel poverty with the commonly used energy-to-income ratio (EIR), which collects the number of households allocating more than 10% of their income to heating expenditure. In 2012, 2.7 million households fell in this category.[15] We assess heating inequalities by comparing trends in heating intensities across income categories.

[15] The EIR has been criticized for missing truly fuel-poor households with low expenditure and unduly counting wealthy households with high energy expenditure (see Charlier and Legendre, 2019). In a related paper (Bourgeois et al., 2019), we test a broader set of indices and find trends that are qualitatively similar to those obtained with the EIR.

4 Results

All numerical results are detailed in Appendix B.

4.1 Effectiveness of policy packages

4.1.1 Energy services and associated CO_2 emissions

Figure 2 displays final energy use under the four main scenarios. Actual energy use is reduced by 18% in 2020 and 45% by 2050 with all policies (AP), as compared to 2012. These savings slightly fall short of Target 1. The target is met with policies either set at more ambitious levels (AP+) or redesigned so as to overcome the landlord-tenant dilemma (AP-LTD). One caveat is in order. Recall that Target 1 applies to all end-uses. Envisaged in the specific context of residential energy use for space heating – which in reality is already declining at 1% p.a., the most pronounced rate of all end-uses (ADEME, 2015) –, it appears as a relatively modest target. Comparing scenarios AP and ZP suggests that the bulk of energy savings is due to autonomous progress driven by increasing energy prices and the building code of 2012.[16] Policies contribute about one third of energy savings. Looking at each fuel separately, we see that most reductions come from fossil fuels – natural gas, and, to a lesser extent, fuel oil (Appendix B). Heating intensity increases over the period by about 20% in ZP and AP scenarios (Figure 3). This can be interpreted as a 20% rebound effect – in line with estimates found in the literature (Sorrell et al., 2009). As will be clear in Section 4.2.1, this rebound effect is primarily efficiency-induced and caused by subsidy programmes.

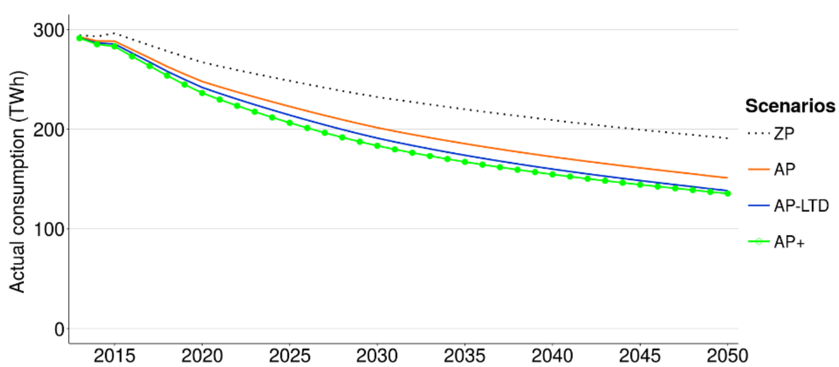

Figure 2: Final energy use

[16] In the online appendix (fig. 16), we find that our baseline assumption of an energy price growing at 1.5% per year contributes 40% of autonomous energy savings.

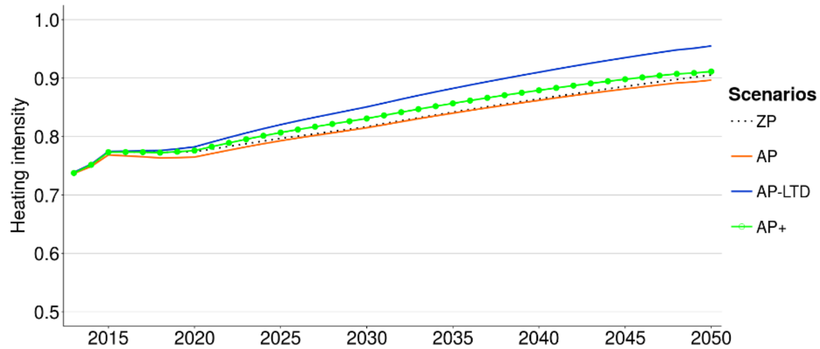

Figure 3: Heating intensity

4.1.2 Energy efficiency improvements

Retrofitting flows are displayed in Figure 4 and detailed in Appendix B. In the AP scenario, 687,000 dwellings are retrofitted in 2012, of which 115,000 can be attributed to policies (AP minus ZP). At first sight, Target 2 is over-shot, even in the absence of any policy. Two caveats however are in order. First, we count as retrofits any upgrade by at least one EPC label. Against this, no proper definition has been given by the government as to what measure should be counted as a retrofit. Absent such a definition, our comparison is hardly conclusive. Second, we find that social housing contributes about 40,000 retrofits, hence 6% of total retrofits, whereas Target 2 would command 24%. Retrofit numbers increase in the AP+ scenario and even further in the AP-LTD scenario; on the other hand, the two scenarios produce very close demand reductions (cf. Figure 2). These contrasting trends highlight the different margins on which each scenario operates – the intensive one with AP+ (inducing more significant upgrades), the extensive one with AP-LTD (inducing upgrades from the previously untapped potential of privately rented dwellings). The more significant upgrades undertaken in the AP+ scenario deplete the potential for subsequent upgrades, causing retrofits to decrease more sharply than in the ZP and AP scenarios.

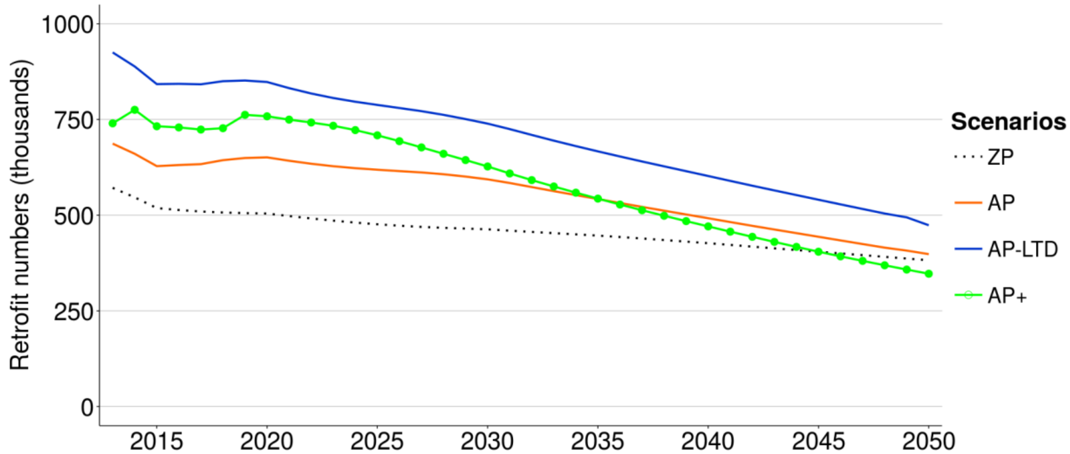

Figure 4: Retrofitting flows

The evolution of the dwelling stock, split by EPC, is displayed in Figure 5. The least energy efficient labels G and F follow a very similar evolution under scenarios ZP, AP and AP+. Their stock sharply declines by 75% by 2025, and more steadily thereafter. Target 3, mandating elimination of these two labels by 2025, therefore seems out of reach, at least not unless the landlord-tenant dilemma is overcome, as illustrated in the AP-LTD scenario; yet even then, a near elimination of labels G and F is only achieved by 2040.[17] At the other end of the performance spectrum, in the ZP scenario, no building code is enforced and the two construction options are undertaken in proportion to the inverse of their life-cycle cost; in other scenarios, the low-energy level (BBC) ceases to be available in 2012 and all new constructions meet the net-zero (BEPOS) level. Taken together, the group of most energy efficient dwellings – EPC labels B and A plus low energy and net-zero energy – weighs, depending on the scenario considered, 50% to 70% of the total building stock in 2050. Anyway, these figures miss by a fair margin the 100% target (Target 4).

[17] The model incorporates, in each EPC label, a constraint that prevents 5% of their 2012 stock to be renovated. These constraints are meant to mimic architectural or urban lock-ins.

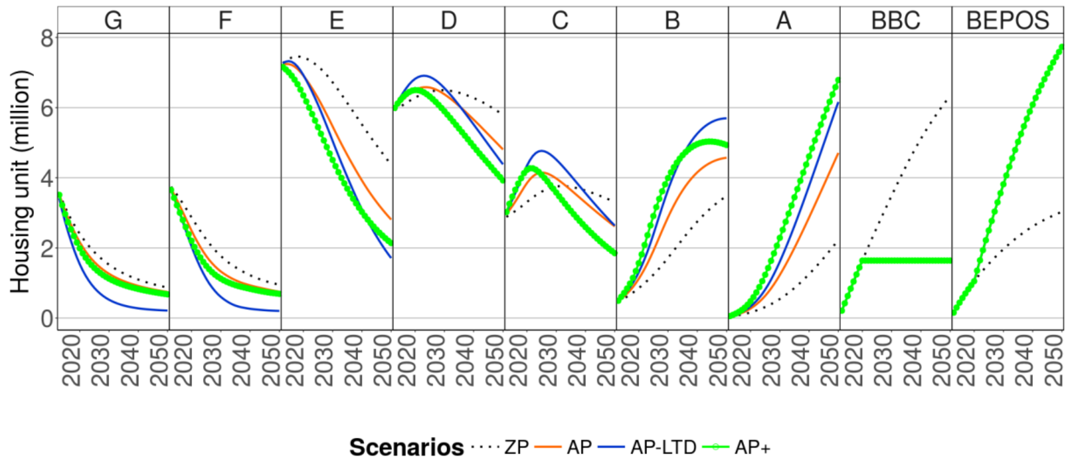

Figure 5: Structure of the dwelling stock, by EPC (BBC: low energy; BEPOS: net zero energy)

4.1.3 Fuel poverty and inequality trends

Figure 6 displays the evolution of the EIR that collects households dedicating more than 10% of their income to heating. Thus measured, fuel poverty recedes by two thirds by 2050 in the ZP scenario. The AP scenario slows this process down, with only a 7% reduction by 2020, which falls short of the 15% mark of Target 5. In contrast, AP+ and, to a greater extent, AP-LTD, accelerate the process and allow the target to be met. As the EIR relies on energy expenditure, the key difference it produces between the AP scenario on the one hand and AP+ and AP-LTD on the other is due to more generous subsidies in the latter.[18] The slowdown in scenario AP can therefore be attributed to the relatively higher weight of the carbon tax in the policy mix. This result confirms the regressive effect of a carbon tax when revenue recycling is not earmarked, which is documented elsewhere (Klenert et al., 2018) and further investigated in Bourgeois et al. (2019). The regressive effect is offset if accompanying subsidies are set at a sufficiently high rate (AP+), or adjusted to better target rented dwellings (AP-LTD), to the point of almost eliminating fuel poverty by 2050. Besides reductions in fuel poverty, comfort levels, as measured by heating intensities, grow at a similar rate across income categories, though from initial levels strongly correlated with income (Figure 7). This reminds us that fuel poverty alleviation and inequality reduction do not necessarily go hand-in-hand.

[18] The effect of the carbon tax on energy expenditure is very close in the AP and AP+ scenarios.

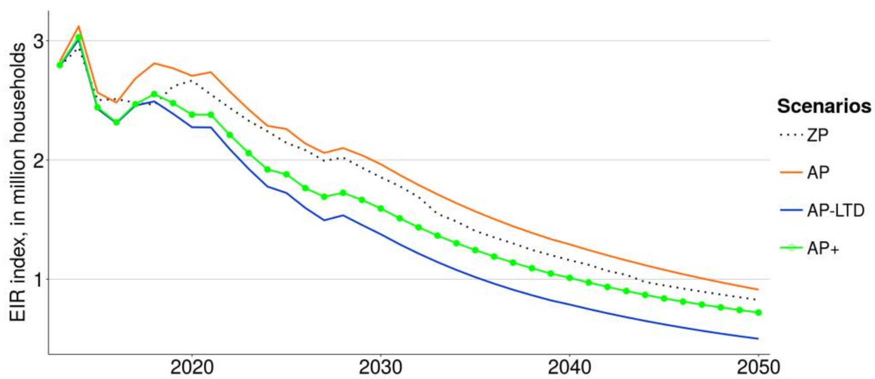

Figure 6: Fuel poverty

Figure 7: Inequality in heating intensities across income categories (C1: bottom 20%; C5: top 20%)

Overall, our assessment suggests that progressing towards targets requires at the very least that instruments be set at their most ambitious levels and maintained until 2050.

4.2 Stand-alone policy outcomes

4.2.1 Stand-alone effects and interactions

Figure 8 compares energy savings brought about by each instrument over the 32 scenario comparisons in which an instrument can be assessed. The histograms picture average savings, thus allowing us to compare the effectiveness of the different instruments. The carbon tax ranks first, due to a combination of two incentives: an incentive to renovate coupled with an incentive to reduce energy use after renovation. While the former causes an efficiency-induced rebound effect, the latter counters any price-induced rebound effect (Giraudet et al., 2011). In contrast, subsidies only consist of the former incentive. Another factor explaining the higher effectiveness of the carbon tax is that it is tightened over time, whereas subsidies (except WCO, which anyway are set at a low level) are kept constant. Among subsidy programmes, the ITC has the strongest impact, which is due to its highest rate. The standard errors in

Figure 8 provide a proxy for the degree to which, on average over all possible policy combinations, an instrument interacts with its counterparts. As the coefficient of variation indicate in Figure 9, interactions are most significant with the ZIL programme, accounting for 18% of its average effect, and least significant with the carbon tax, accounting for 2% of its average effect. The former result owes to the targeting of the instrument towards high performance, which makes it highly sensitive to accompanying incentives. The latter owes to the fact that the carbon tax is the only instrument affecting yearly energy expenditure. Overall, the central estimate in Figure 9 suggests that policy interactions are responsible for a 10% variation in an instrument's effectiveness. The fact that 'AP-1' estimates – capturing an instrument's effect in interaction with all others – systematically entail smaller energy savings than their 'ZP+1' counterpart – capturing an instrument's effect in interaction with no other – in Figure 8 indicates that interactions are over-additive. In other words, combining multiple incentives each harnessing different margins creates synergies that amplify energy savings. We thereby confirm earlier findings by Giraudet et al. (2011) and Charlier and Risch (2012) established in a simpler framework where interactions were assessed by comparing the impact of a policy package with the sum of each policy's stand-alone impacts. In the remaining of the analysis, when evaluating each instrument, we confine our attention to the results obtained with the 'AP-1' method, which arguably is the most realistic counterfactual.

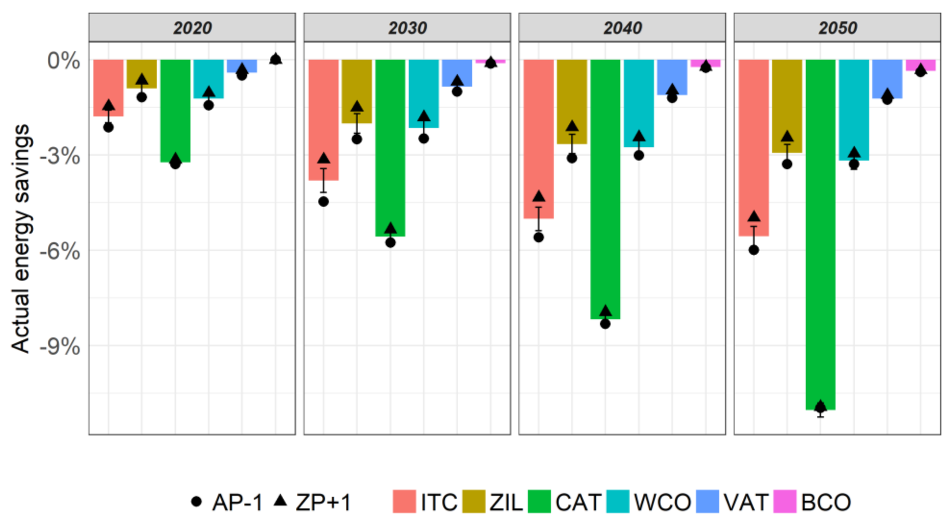

Figure 8: Policy effectiveness

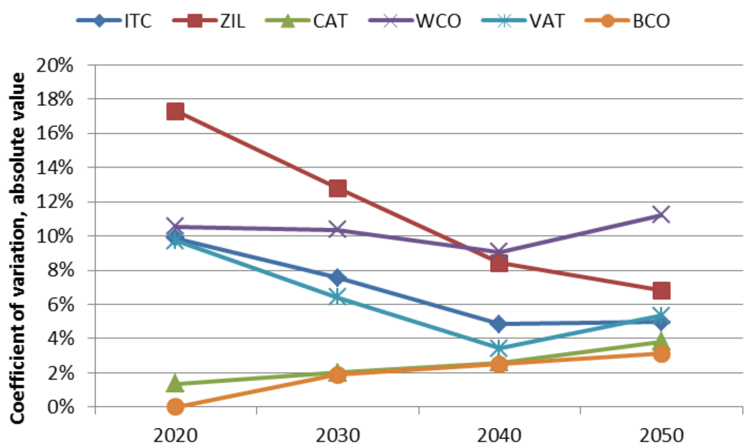

Figure 9: Coefficients of variation of policy effectiveness

4.2.2 Policy costs

Figure 10 compares the simulated costs of public subsidies to those estimated by the French authorities in recent years (IGF and CGEDD, 2017; I4CE, 2017). The orders of magnitude between observations and simulations are consistent for the VAT and ITC policies. They differ substantially when it comes to the ZIL programme. The discrepancy is confirmed by an order-of-magnitude difference between the simulated and observed numbers of ZIL: around 400,000 in the simulations (see Table B6, number of beneficiaries in the AP scenario) against a yearly average of 40,000 recorded between 2013 and 2016 by SGFGAS. Such a mismatch points to potential barriers to ZIL adoption not accounted for in the model: on the demand side, one can think of debt aversion or cognitive barriers that prevent borrowers from computing interests and expressing them into an equivalent subsidy; on the supply side, one can think of credit institutions devoting little effort to promoting the programme in an attempt to sell their own loan products that have proven highly profitable (Giraudet et al., 2021). Carefully eliciting these barriers is a promising area for economic research and an important pre-requisite for policy adjustments.
Notwithstanding, cost projections suggest that, taking all policies together – both public programmes (CAT, ZIL, ITC, VAT) and private ones (WCO) –, tax receipts will likely outweigh subsidy payments by 2025 (Figure 11).[19] This opens room for a better coordination between subsidy regimes and tax-revenue recycling options. Net policy costs amount to €3 billion in the initial year 2012. Meanwhile, total investment in home energy retrofits amounts to €7.5 billion in the ZP scenario, 10 billion in the AP scenario and 12.5 billion in both AP+ and AP-LTD scenarios.

[19] We do not include building codes in the analysis, for they do not raise any direct public cost, though they obviously imply welfare costs which are not quantified in the model.

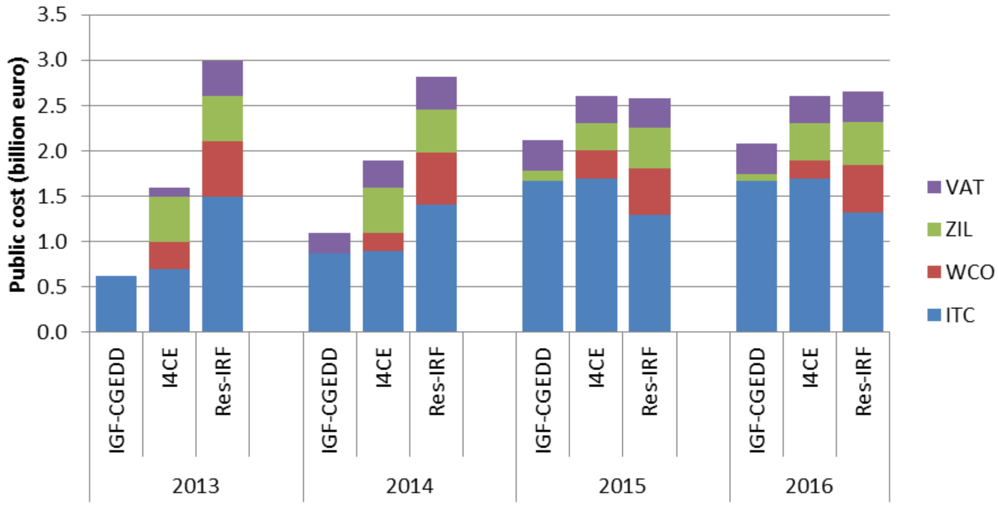

Figure 10: Simulated versus observed cost of the main subsidy programmes

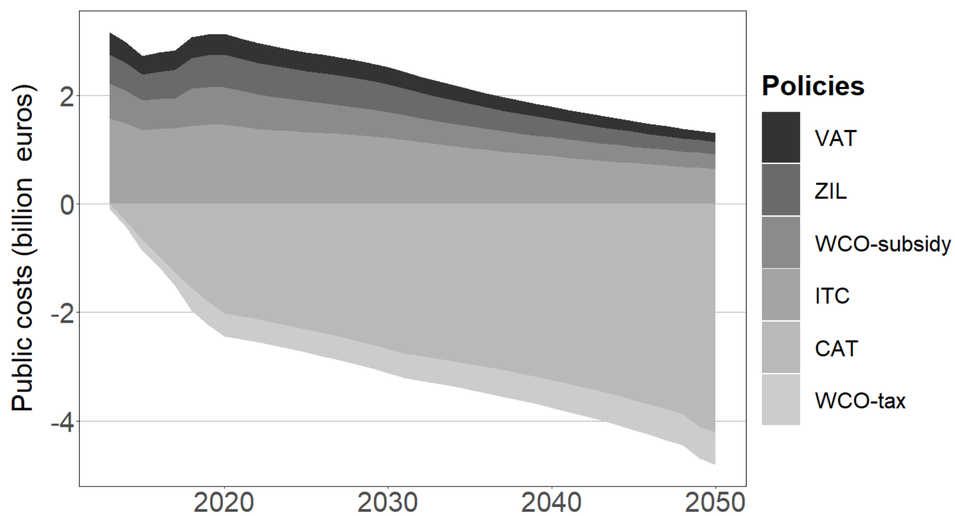

Figure 11: Projection of public costs. Positive values indicate subsidy cost, negative values indicate tax proceeds

4.2.3 Comparative cost-effectiveness and leverage

Figure 12 compares the cost-effectiveness of each instrument for selected years.[20] Looking at the conventional-energy metric, we see that subsidies save energy at a cost per lifetime discounted kWh in

[20] If we were to apply the method described in Section 3.3.2. to the whole period, we would need to compute as many simulations as the number of years considered. Focusing on selected years is meant to avoid that cost. Preliminary tests indicate that the interpolations we make in Figure 9 approximate fairly well what occurs between the selected years.

the €0.05 to €0.08 range in 2015; among them, the ITC and the VAT are the least efficient. The indicator increases over time as the potential for energy saving opportunities depletes. The actual-energy metric draws a different picture, with slightly higher values. As predicted in Section 3.3.2, this is due to the latter metric taking into account variations in heating intensity unaccounted for by the former.[21] When expressed in carbon metric, savings are achieved at a cost of €300-800/tCO_2.

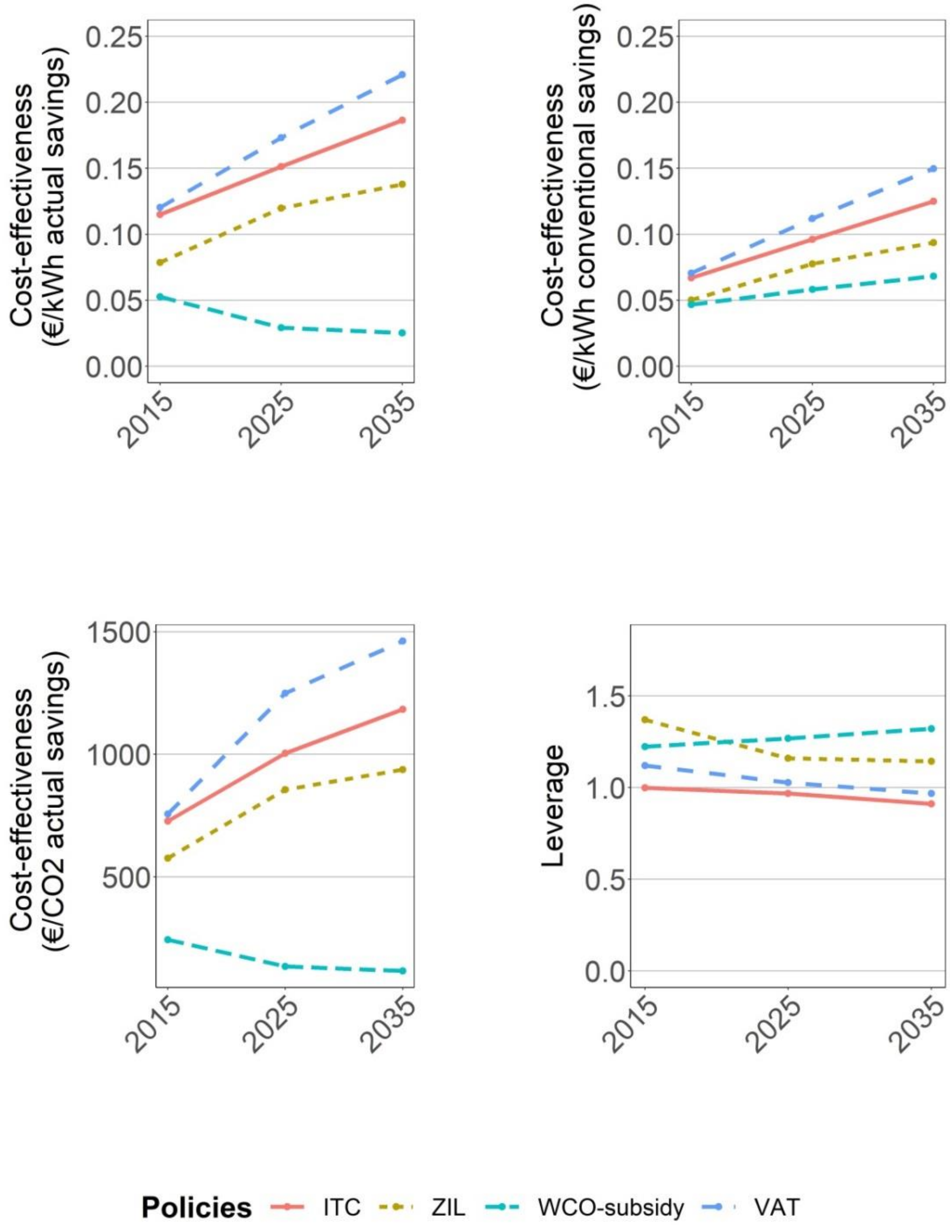

Figure 12: Policy cost-effectiveness (kWh and CO_2 savings are lifetime discounted)

[21] The fact that the cost-effectiveness of WCO decreases over time when measured in actual energy is due to the tax component, which produces additional energy savings not directly attributable to the subsidy cost considered in the index.

Figure 12 (bottom right) confirms insights derived from the conventional energy metric through a different indicator: leverage. Recall that a high leverage ratio and a low cost per kWh saved are two faces of the same coin – high efficiency in public spending. Leverage however decreases at a slower rate than that at which the cost per kWh increases, which can be explained by the marginally increasing energy efficiency cost matrix embodied in the model (Table 7). The leverage of subsidy programmes falls in the 1.0-1.4 range in 2015, which is in line with estimates available for other public subsidy programmes (e.g., Gobillon et al., 2005; Lentile and Mairesse, 2009). Importantly, this result confirms that free riding is not so much of a problem as long as infra-marginal participants increase spending upon receiving subsidies. It is also consistent with the result that cost-effectiveness indices are of the same order of magnitude as the cost curves embodied in the model. Figure 13 shows how estimates vary across the 32 possible combinations of instruments for the year 2015. It confirms the overall over-additive interactions discussed above.

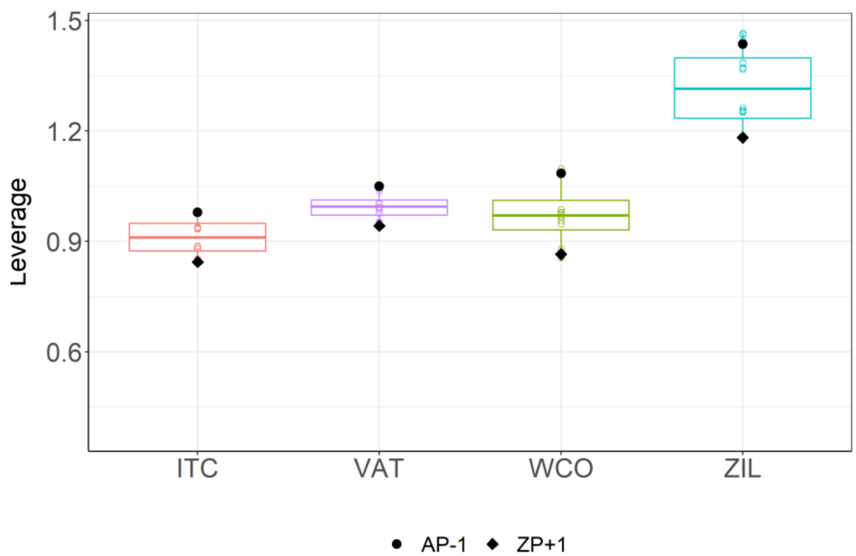

Figure 13: Leverage in 2015 over all policy combinations

4.2.4 Influence of subsidy regimes

The variety of subsidy regimes considered – uniform ad valorem for the ITC, uniform ad valorem with a lower rate for the reduced VAT, targeted uniform ad valorem for the ZIL with still another rate, regressive ad valorem for WCO – makes them difficult to compare to one another. To better understand the merit order exposed in Figures 12 and 13, and in particular to disentangle shape effects from level effects, we focus on one instrument, the ITC, and run additional simulations in which we vary its regime. In addition to the reference and ITC+ (which borrows the restrictions of the ZIL on high performance) variants, we consider the following others: one with the rate kept uniform but halved (which mimics the low subsidy rate of the reduced VAT); one with eligibility restricted to the bottom two categories of the income distribution; one that interacts the latter eligibility restriction with that of the ZIL on high performance. The results displayed in Figure 14 suggest that these adjustments all increase leverage. The channels through which they operate however differ:

- The slightly higher leverage induced by lowering the uniform rate is due to a reorientation of investment towards the least-cost measures. This contributes to explaining the difference in performance between the reduced VAT and the ITC in Figure 12.
- The higher leverage induced by targeting low-income households is also due to a reorientation of investment toward least-cost measures, thanks to the correlation between income and energy efficiency depicted in Figure 1. It opens room for policies reconciling economic efficiency and fuel poverty alleviation.
- The higher leverage induced by targeting the most energy efficient upgrades has a more persistent effect than do the former two adjustments. This can be explained by a strong effect on the intensive margin of investment. Such an energy efficiency targeting effect, together with that of a lower uniform rate, contribute to explaining the difference in performance between the ITC and the ZIL in Figure 12.

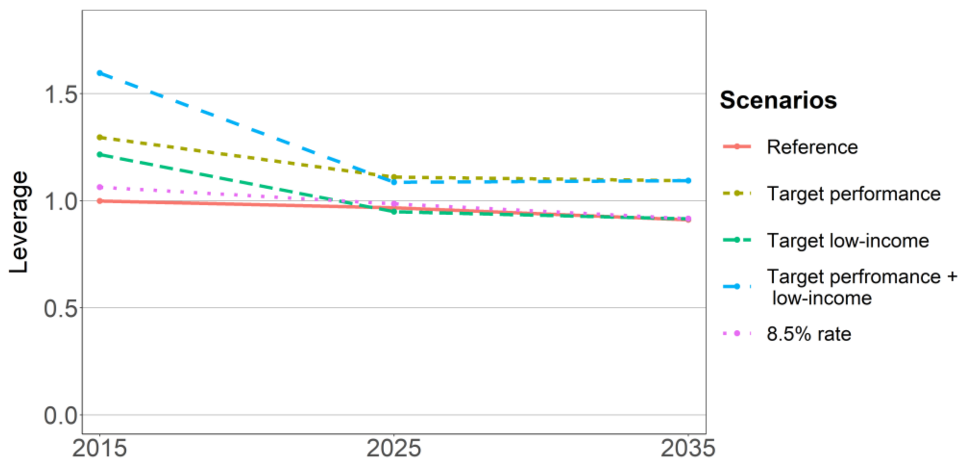

Figure 14: Leverage with further variants of ITC

5 Conclusion and policy implications

Our study examines the short- and long-term impact of key policies implemented in the French residential sector. It uses the latest version of Res-IRF, a behaviourally-rich model of energy demand recently extended with household income data. We focus on electricity, natural gas, fuel oil and fuel wood demand for space heating in main residences. This scope covers 18% of France's energy end-use. Previous analyses have built confidence in the model's fitness for purpose (Branger et al., 2015) and its ability to reproduce past and present trends (Glotin et al., 2019; online appendix, Section 3.1).

We assess the cost-effectiveness and distributional impacts of various energy efficiency subsidy programmes – income tax credits, zero-interest loans, reduced VAT and white certificate obligations – together with that of the carbon tax. We find that the model accurately reproduces the few ex post statistics available, except for the ZIL programme, the performance of which it over-estimates by an order of magnitude. Balancing this shortcoming with the fact that we ignore other important policies – in particular subsidy programmes targeting low-income households and granted by the French Housing Agency (ANAH), and recent information campaigns –, we consider that our study provides a credible assessment of whether and how the targets set out by the French government might be fulfilled.

We find that meeting targets requires at the very least that instruments be set at their most ambitious level and kept in effect until 2050. In particular, the eligibility criteria of subsidy programmes should be revised so as to better target rented dwellings, which undergo much fewer renovations than owner-occupied ones. Our assessment produces mixed results against one target – retrofitting 500,000 dwellings annually, including 120,000 in social housing. Specifically, we find that the aggregate target is significantly over-shot, while the social-housing sub-target is significantly under-shot. Such a bewildering outcome highlights the need for stakeholders to agree upon a common metric to assess this politically sensible target.[22]

Generally speaking, energy efficiency subsidies generate a rebound effect while carbon taxes impose restrictions on energy usage. This makes the carbon tax the most effective instrument, but also the most regressive one, at least without further specification of revenue recycling. Among subsidy programmes, the ITC is the most effective to target, yet the least cost-effective. Lowering subsidy rates, or restricting eligibility to either most energy efficient upgrades or low-income households increases leverage. Taking the policy portfolio as a whole, budget constraints should no longer bind by 2025, when carbon tax revenues begin to exceed total subsidy payments. Lastly, the leverage of energy efficiency subsidies is in line with the one estimated in other, non-environmental subsidy programmes (e.g., Gobillon et al., 2005; Lentile and Mairesse, 2009).

Our assessment both confirms earlier findings and generates new insights. On the one hand, our comprehensive approach to policy interactions gives more substance to the synergies pointed out by Giraudet et al. (2011) and Charlier and Risch (2012) in simpler settings. On the other hand, our use of up-to-date data on household income highlights opportunities for improving leverage while reducing fuel poverty. This could be achieved by negatively linking subsidy rates to recipients' income. As discussed in a related paper (Bourgeois et al., 2019), such an adjustment could be included in a broader policy reform where the revenue from the carbon tax is earmarked to fund subsidy programmes.

We see three directions for further research. First, as not all targets are met even with the most extensive policy portfolio, new policies might be needed. We could therefore model some instruments discussed in policy circles, such as a retrofit obligation or a feebate scheme applied to housing taxes. Second, the economic and psychological barriers that hinder participation in the ZIL programme should be taken into account. This however requires prior identification through applied microeconomic work, a research programme in itself. Third, a more comprehensive assessment would take into account general-equilibrium effects and endogenous CO_2 emissions. This could be achieved by linking the most recent version of Res-IRF to a computable general equilibrium model and a bottom-up model of electricity

[22] When Nicolas Hulot resigned from his position of Ministry of Sustainable Development on September 4th, 2018, one of the arguments he put forward was that insufficient public funds were allocated to meeting the 500,000 renovations target. It is striking that according to our estimate, this target is already met by a fair margin.

generation, thus continuing a research effort initiated by Mathy et al. (2015). Such a framework would allow us to examine the broader distributional impacts of climate policy, in particular the extent to which effective emission reductions may reduce tax proceeds and thus the public resources available for subsidizing fuel-poor households.

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Appendix A: Comparative estimates of the cost-effectiveness of residential energy efficiency upgrades

Table A1: Cost-effectiveness estimates

Country	Estimate	Source
France	Estimates for 28 measures ranging from €15 to €946/MWh. Median estimate €82/MWh, unweighted average €166/MWh.	DG Tresor, 2017, fig.1
France	7 estimates (based on DG Tresor, 2017) ranging from €50 to €750/tCO_2-eq. Median estimate €450/ tCO_2-eq.	Quinet et al., 2019, fig.50
Switzerland	Marginal cost curve spanning €5 to €40/MWh	Jakob, 2006, fig.9
Germany	Tax rate needed to reduce GHG emissions spanning €0 to €1,600/ tCO_2-eq, with €500/tCO_2-eq as median estimate.	Löffler and Hecking, 2016, fig. 1
Lithuania	Cost of conserved energy varying from €50 to €80/MWh	Toleikyte et al., 2018, p.152

Appendix B: Numerical results

Table B1: Evolution of key inputs and outputs

			2013	2015	2020	2025	2030	2035	2040	2050
Inputs	Total population	million	56.2	56.7	57.8	58.9	59.9	60.8	61.5	62.4
	Price of fuel wood	c€/kWh	4.02	3.69	3.92	4.16	4.42	4.69	4.98	5.61
	Price of electricity	c€/kWh	13.74	15.01	15.85	16.75	17.69	18.68	19.73	22.01
	Price of fuel oil	c€/kWh	8.71	6.54	10.00	11.50	12.87	13.21	13.70	14.11
	Price of natural gas	c€/kWh	7.07	6.56	8.22	9.05	9.93	10.28	10.48	10.75
	Household income	billion euro	1 161	1 189	1 262	1 340	1 422	1 510	1 602	1 806
Outputs	Dwelling count	million	24.3	24.8	26.0	27.0	28.0	28.8	29.5	30.4
	Total surface area	billion m²	2.32	2.37	2.50	2.62	2.72	2.81	2.89	3.01

Table B2: Evolution of key outputs in the ZP scenario

					2013	2015	2020	2025	2030	2035	2040	2045	2050
Final annual energy use				**TWh**	**294**	**296**	**267**	**248**	**232**	**220**	**209**	**200**	**191**
Incl.	Electricity			TWh	45	43	41	39	37	36	35	33	32
	Natural gas			TWh	120	119	106	97	89	84	80	76	73
	Fuel oil			TWh	56	59	47	41	36	33	31	29	28
	Fuel wood			TWh	74	75	74	72	70	67	64	61	59
Heating intensity					**0.75**	**0.78**	**0.80**	**0.83**	**0.86**	**0.89**	**0.91**	**0.94**	**0.96**
to	Income category C1				0.58	0.62	0.64	0.68	0.71	0.74	0.77	0.79	0.81
	Income category C2				0.65	0.69	0.71	0.74	0.77	0.80	0.82	0.85	0.87
	Income category C3				0.76	0.80	0.81	0.84	0.87	0.89	0.92	0.94	0.96
	Income category C4				0.84	0.87	0.89	0.92	0.94	0.97	0.99	1.01	1.03
	Income category C5				0.86	0.90	0.92	0.96	0.98	1.01	1.04	1.07	1.09
Dwelling count				**thousand**	**24 254**	**24 793**	**26 003**	**27 048**	**27 971**	**28 793**	**29 475**	**29 989**	**30 381**
Incl.	Built before 2012			thousand	23 889	23 723	23 313	22 911	22 517	22 130	21 750	21 377	21 010
		Incl.	*EPC label G*	*thousand*	*3 573*	*3 163*	*2 402*	*1 881*	*1 522*	*1 273*	*1 097*	*969*	*871*
			EPC label F	*thousand*	*3 745*	*3 519*	*2 870*	*2 246*	*1 770*	*1 450*	*1 221*	*1 060*	*952*
			EPC label E	*thousand*	*7 269*	*7 388*	*7 429*	*7 176*	*6 719*	*6 133*	*5 520*	*4 927*	*4 371*
			EPC label D	*thousand*	*5 918*	*6 030*	*6 285*	*6 453*	*6 495*	*6 424*	*6 274*	*6 060*	*5 800*
			EPC label C	*thousand*	*2 883*	*2 996*	*3 310*	*3 602*	*3 750*	*3 741*	*3 635*	*3 484*	*3 310*
			EPC label B	*thousand*	*456*	*558*	*854*	*1 237*	*1 717*	*2 251*	*2 750*	*3 162*	*3 479*
			EPC label A	*thousand*	*44*	*69*	*163*	*316*	*544*	*858*	*1 253*	*1 714*	*2 228*
	Built after 2012			thousand	365	1 071	2 690	4 137	5 455	6 663	7 725	8 612	9 370
		Incl.	*Low energy*	*thousand*	*211*	*631*	*1 640*	*2 590*	*3 490*	*4 343*	*5 112*	*5 768*	*6 339*
			Net-zero energy	*thousand*	*155*	*440*	*1 050*	*1 547*	*1 964*	*2 320*	*2 613*	*2 844*	*3 031*
Annual retrofit count				**thousand**	**571**	**518**	**504**	**476**	**463**	**447**	**427**	**404**	**382**
Incl.	Upgrade by one EPC label			thousand	399	387	346	332	329	327	321	312	301
Incl.	*Owner-occupied*	*Single-family*		*thousand*	*398*	*359*	*343*	*321*	*314*	*306*	*294*	*279*	*263*
		Multi-family		*thousand*	*88*	*79*	*74*	*67*	*64*	*60*	*58*	*55*	*53*
	Privately rented	*Single-family*		*thousand*	*40*	*38*	*37*	*35*	*33*	*30*	*28*	*26*	*24*
		Multi-family		*thousand*	*7*	*7*	*7*	*7*	*7*	*7*	*7*	*6*	*6*
	Social housing	*Single-family*		*thousand*	*10*	*9*	*10*	*10*	*10*	*10*	*10*	*9*	*8*
		Multi-family		*thousand*	*28*	*26*	*33*	*35*	*36*	*33*	*31*	*29*	*27*
Annual retrofit expenditure				**billion euro**	**7.5**	**6.0**	**6.3**	**5.7**	**5.4**	**5.0**	**4.5**	**4.1**	**3.7**
Annual heating expenditure				**billion euro**	**22.5**	**20.9**	**22.7**	**23.0**	**23.2**	**22.9**	**22.6**	**22.3**	**22.0**
Share of fuel-poor households (EIR>10%)					**11%**	**10%**	**10%**	**8%**	**7%**	**5%**	**4%**	**3%**	**3%**

Table B3: Evolution of key outputs in the AP scenario

					2013	2015	2020	2025	2030	2035	2040	2045	2050
Final annual energy use				**TWh**	**292**	**288**	**248**	**223**	**201**	**185**	**172**	**161**	**151**
Incl.	Electricity			TWh	44	42	39	37	35	34	32	31	29
	Natural gas			TWh	119	116	96	84	75	67	61	56	52
	Fuel oil			TWh	56	56	42	34	28	25	22	20	18
	Fuel wood			TWh	73	74	71	67	63	60	57	54	52
Heating intensity					**0.75**	**0.78**	**0.79**	**0.83**	**0.86**	**0.89**	**0.91**	**0.93**	**0.94**
to	Income category C1				0.58	0.61	0.64	0.68	0.71	0.74	0.77	0.79	0.80
	Income category C2				0.65	0.68	0.70	0.73	0.76	0.79	0.82	0.84	0.85
	Income category C3				0.76	0.79	0.80	0.83	0.86	0.89	0.91	0.93	0.94
	Income category C4				0.84	0.87	0.88	0.91	0.94	0.97	0.99	1.01	1.03
	Income category C5				0.86	0.90	0.91	0.95	0.98	1.01	1.04	1.06	1.08
Dwelling count				**thousand**	**24 254**	**24 793**	**26 003**	**27 048**	**27 971**	**28 792**	**29 473**	**29 986**	**30 377**
Incl.	Built before 2012			thousand	23 889	23 722	23 313	22 911	22 516	22 128	21 747	21 374	21 007
		Incl.	*EPC label G*	*thousand*	*3 533*	*3 059*	*2 164*	*1 598*	*1 263*	*1 055*	*918*	*819*	*745*
			EPC label F	*thousand*	*3 694*	*3 369*	*2 491*	*1 770*	*1 328*	*1 080*	*933*	*834*	*752*
			EPC label E	*thousand*	*7 226*	*7 240*	*6 913*	*6 270*	*5 463*	*4 650*	*3 924*	*3 310*	*2 809*
			EPC label D	*thousand*	*5 961*	*6 153*	*6 505*	*6 571*	*6 379*	*6 049*	*5 656*	*5 235*	*4 808*
			EPC label C	*thousand*	*2 949*	*3 192*	*3 849*	*4 149*	*3 981*	*3 651*	*3 291*	*2 941*	*2 614*
			EPC label B	*thousand*	*474*	*619*	*1 119*	*1 918*	*2 873*	*3 643*	*4 156*	*4 450*	*4 571*
			EPC label A	*thousand*	*50*	*91*	*272*	*634*	*1 229*	*2 000*	*2 869*	*3 784*	*4 709*
	Built after 2012			thousand	365	1 071	2 690	4 137	5 455	6 663	7 725	8 612	9 370
		Incl.	*Low energy*	*thousand*	*211*	*631*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*
			Net-zero energy	*thousand*	*155*	*440*	*1 050*	*2 497*	*3 815*	*5 023*	*6 085*	*6 972*	*7 731*
Annual retrofit count				**thousand**	**687**	**628**	**651**	**619**	**594**	**542**	**492**	**443**	**398**
Incl.	Upgrade by one EPC label			thousand	371	355	321	327	326	319	306	288	267
Incl.	*Owner-occupied*		*Single-family*	*thousand*	*474*	*430*	*433*	*416*	*403*	*368*	*331*	*295*	*260*
			Multi-family	*thousand*	*106*	*96*	*94*	*85*	*80*	*73*	*67*	*62*	*56*
	Privately rented		*Single-family*	*thousand*	*49*	*47*	*47*	*43*	*39*	*34*	*31*	*28*	*26*
			Multi-family	*thousand*	*8*	*8*	*9*	*9*	*9*	*9*	*9*	*9*	*9*
	Social housing		*Single-family*	*thousand*	*12*	*11*	*15*	*15*	*15*	*14*	*12*	*11*	*10*
			Multi-family	*thousand*	*37*	*35*	*54*	*51*	*48*	*44*	*41*	*39*	*37*
Annual retrofit expenditure				**billion euro**	**10.1**	**8.4**	**9.4**	**8.4**	**7.8**	**6.6**	**5.6**	**4.8**	**4.2**
Annual heating expenditure				**billion euro**	**22.4**	**21.2**	**23.5**	**23.3**	**23.2**	**22.7**	**22.4**	**22.2**	**22.4**
Share of fuel-poor households (EIR>10%)					**12%**	**10%**	**10%**	**8%**	**7%**	**5%**	**4%**	**4%**	**3%**

Table B4: Evolution of key outputs in the AP+ scenario

				2013	2015	2020	2025	2030	2035	2040	2045	2050
Final annual energy use			**TWh**	**291**	**283**	**234**	**202**	**179**	**163**	**150**	**141**	**132**
Incl.	Electricity		TWh	44	42	38	35	32	30	29	28	26
	Natural gas		TWh	119	114	91	77	67	59	54	49	45
	Fuel oil		TWh	55	55	38	30	24	21	19	18	16
	Fuel wood		TWh	73	73	67	60	55	52	49	46	44
Heating intensity				**0.75**	**0.78**	**0.80**	**0.84**	**0.87**	**0.90**	**0.93**	**0.95**	**0.96**
to	Income category C1			0.58	0.62	0.65	0.70	0.73	0.76	0.78	0.80	0.82
	Income category C2			0.65	0.69	0.70	0.75	0.78	0.81	0.83	0.85	0.87
	Income category C3			0.76	0.80	0.81	0.85	0.88	0.90	0.93	0.95	0.96
	Income category C4			0.84	0.87	0.88	0.92	0.96	0.99	1.01	1.03	1.04
	Income category C5			0.86	0.90	0.92	0.96	1.00	1.03	1.05	1.07	1.09
Dwelling count			**thousand**	**24 254**	**24 793**	**26 002**	**27 046**	**27 968**	**28 788**	**29 469**	**29 981**	**30 372**
Incl.	Built before 2012		thousand	23 889	23 722	23 312	22 909	22 513	22 125	21 744	21 369	21 002
	Incl.	*EPC label G*	*thousand*	*3 513*	*2 967*	*1 962*	*1 380*	*1 078*	*905*	*794*	*714*	*651*
		EPC label F	*thousand*	*3 654*	*3 216*	*2 177*	*1 441*	*1 081*	*907*	*805*	*728*	*676*
		EPC label E	*thousand*	*7 157*	*7 008*	*6 312*	*5 325*	*4 339*	*3 501*	*2 852*	*2 372*	*2 030*
		EPC label D	*thousand*	*5 992*	*6 222*	*6 472*	*6 202*	*5 707*	*5 161*	*4 626*	*4 133*	*3 656*
		EPC label C	*thousand*	*3 022*	*3 463*	*4 282*	*4 121*	*3 560*	*2 991*	*2 503*	*2 096*	*1 766*
		EPC label B	*thousand*	*494*	*717*	*1 612*	*3 105*	*4 249*	*4 905*	*5 177*	*5 185*	*5 025*
		EPC label A	*thousand*	*57*	*129*	*495*	*1 335*	*2 499*	*3 755*	*4 986*	*6 142*	*7 199*
	Built after 2012		thousand	365	1 071	2 690	4 137	5 455	6 663	7 725	8 612	9 370
	Incl.	*Low energy*	*thousand*	*211*	*631*	*1 639*	*1 639*	*1 639*	*1 639*	*1 639*	*1 639*	*1 639*
		Net-zero energy	*thousand*	*155*	*440*	*1 051*	*2 497*	*3 815*	*5 024*	*6 086*	*6 973*	*7 731*
Annual retrofit count			**thousand**	**740**	**732**	**806**	**744**	**648**	**553**	**468**	**394**	**333**
Incl.	Upgrade by one EPC label		milliers	301	286	274	290	288	275	256	233	209
Incl.	*Owner-occupied*	*Single-family*	*thousand*	*508*	*493*	*528*	*496*	*430*	*361*	*301*	*247*	*201*
		Multi-family	*thousand*	*115*	*111*	*113*	*100*	*88*	*76*	*66*	*58*	*50*
	Privately rented	*Single-family*	*thousand*	*54*	*52*	*61*	*51*	*42*	*35*	*31*	*28*	*26*
		Multi-family	*thousand*	*9*	*9*	*13*	*13*	*13*	*13*	*12*	*12*	*11*
	Social housing	*Single-family*	*thousand*	*12*	*15*	*20*	*20*	*18*	*15*	*12*	*10*	*8*
		Multi-family	*thousand*	*41*	*51*	*71*	*64*	*58*	*52*	*46*	*40*	*36*
Annual retrofit expenditure			**billion euro**	**12.6**	**12.0**	**13.5**	**11.4**	**9.0**	**7.0**	**5.5**	**4.3**	**3.5**
Annual heating expenditure			**billion euro**	**22.3**	**20.8**	**22.9**	**21.9**	**21.4**	**20.7**	**20.3**	**20.1**	**20.3**
Share of fuel-poor households (EIR>10%)				**12%**	**10%**	**10%**	**7%**	**5%**	**4%**	**3%**	**3%**	**2%**

Table B5: Evolution of key outputs in the AP-LTD scenario

					2013	2015	2020	2025	2030	2035	2040	2045	2050
Final annual energy use				**TWh**	**291**	**285**	**242**	**214**	**191**	**174**	**160**	**148**	**138**
Incl.	Electricity			TWh	44	41	37	34	32	30	29	27	26
	Natural gas			TWh	119	115	94	81	70	62	56	51	46
	Fuel oil			TWh	55	55	39	30	24	21	18	16	15
	Fuel wood			TWh	73	74	72	69	64	61	57	55	52
Heating intensity					**0.75**	**0.78**	**0.81**	**0.85**	**0.88**	**0.92**	**0.94**	**0.96**	**0.98**
to	Income category C1				0.58	0.62	0.66	0.72	0.75	0.79	0.81	0.83	0.85
	Income category C2				0.65	0.69	0.71	0.76	0.79	0.83	0.85	0.88	0.89
	Income category C3				0.76	0.80	0.82	0.85	0.88	0.91	0.94	0.96	0.98
	Income category C4				0.84	0.87	0.89	0.92	0.95	0.98	1.01	1.03	1.05
	Income category C5				0.86	0.90	0.92	0.96	0.99	1.03	1.05	1.07	1.09
Dwelling count				**thousand**	**24 254**	**24 793**	**26 003**	**27 048**	**27 971**	**28 792**	**29 473**	**29 986**	**30 377**
Incl.	Built before 2012			thousand	23 889	23 722	23 313	22 911	22 516	22 128	21 747	21 373	21 006
		Incl.	*EPC label G*	*thousand*	*3 416*	*2 747*	*1 537*	*860*	*523*	*359*	*278*	*236*	*215*
			EPC label F	*thousand*	*3 641*	*3 208*	*2 043*	*1 127*	*604*	*355*	*265*	*223*	*204*
			EPC label E	*thousand*	*7 266*	*7 325*	*6 927*	*6 084*	*5 051*	*4 027*	*3 098*	*2 330*	*1 711*
			EPC label D	*thousand*	*6 014*	*6 305*	*6 822*	*6 875*	*6 555*	*6 067*	*5 517*	*4 947*	*4 384*
			EPC label C	*thousand*	*3 009*	*3 369*	*4 346*	*4 767*	*4 519*	*4 059*	*3 561*	*3 080*	*2 637*
			EPC label B	*thousand*	*489*	*666*	*1 307*	*2 386*	*3 655*	*4 632*	*5 259*	*5 593*	*5 696*
			EPC label A	*thousand*	*54*	*103*	*332*	*813*	*1 609*	*2 629*	*3 770*	*4 964*	*6 161*
	Built after 2012			thousand	365	1 071	2 690	4 137	5 455	6 663	7 725	8 612	9 370
		Incl.	*Low energy*	*thousand*	*211*	*631*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*	*1 640*
			Net-zero energy	*thousand*	*155*	*440*	*1 050*	*2 497*	*3 815*	*5 023*	*6 085*	*6 972*	*7 731*
Annual retrofit count				**thousand**	**925**	**842**	**848**	**788**	**739**	**667**	**602**	**540**	**474**
Incl.	Upgrade by one EPC label			thousand	459	436	393	403	404	395	378	355	326
Incl.	*Owner-occupied*		*Single-family*	*thousand*	*474*	*431*	*436*	*421*	*405*	*368*	*330*	*293*	*253*
			Multi-family	*thousand*	*106*	*96*	*94*	*86*	*80*	*73*	*67*	*61*	*55*
	Privately rented		*Single-family*	*thousand*	*118*	*102*	*99*	*88*	*79*	*68*	*60*	*52*	*44*
			Multi-family	*thousand*	*178*	*167*	*149*	*127*	*112*	*99*	*91*	*83*	*75*
	Social housing		*Single-family*	*thousand*	*12*	*11*	*15*	*15*	*15*	*14*	*12*	*11*	*10*
			Multi-family	*thousand*	*37*	*35*	*54*	*52*	*48*	*44*	*41*	*39*	*37*
Annual retrofit expenditure				**billion euro**	**12.4**	**10.4**	**11.3**	**9.9**	**8.9**	**7.4**	**6.3**	**5.3**	**4.6**
Annual heating expenditure				**billion euro**	**22.3**	**20.9**	**22.7**	**22.0**	**21.5**	**20.7**	**20.2**	**19.8**	**19.8**
Share of fuel-poor households (EIR>10%)					**11%**	**10%**	**9%**	**6%**	**5%**	**4%**	**3%**	**2%**	**2%**

Table B6: Evolution of key policy outcomes across scenarios

				2013	2015	2020	2025	2030	2035	2040	2045	2050
ITC	Number of beneficiaries	thousand	AP	687	628	651	619	594	542	492	443	398
		thousand	AP-LTD	925	842	848	788	739	667	602	540	474
		thousand	AP+	740	732	806	744	648	553	468	394	333
	Public spending	million euro	AP	1 574	1 360	1 459	1 321	1 210	1 029	878	751	644
		million euro	AP-LTD	1 937	1 671	1 750	1 559	1 383	1 152	975	828	716
		million euro	AP+	2 050	1 967	2 166	1 836	1 422	1 094	851	667	529
VAT	Number of beneficiaries	thousand	AP	687	628	651	619	594	542	492	443	398
		thousand	AP-LTD	925	842	848	788	739	667	602	540	474
		thousand	AP+	740	732	806	744	648	553	468	394	333
	Public spending	million euro	AP	412	345	384	345	319	271	231	198	171
		million euro	AP-LTD	508	424	461	406	364	303	256	218	190
		million euro	AP+	514	490	551	468	369	286	224	177	142
ZIL	Number of beneficiaries	thousand	AP	397	381	482	474	446	381	322	270	227
		thousand	AP-LTD	537	522	644	617	559	466	389	323	261
		thousand	AP+	539	572	698	628	502	388	297	226	174
	Public spending	million euro	AP	529	480	598	558	508	414	335	271	220
		million euro	AP-LTD	671	610	740	674	588	466	372	297	238
		million euro	AP+	2 311	2 323	2 723	2 258	1 648	1 176	843	605	439
WCO	Number of beneficiaries	thousand	AP	687	628	651	619	594	542	492	443	398
		thousand	AP-LTD	925	842	848	788	739	667	602	540	474
		thousand	AP+	740	732	806	744	648	553	468	394	333
	Payment in regular certificates	million euro	AP	411	340	389	327	299	260	227	201	178
		million euro	AP-LTD	553	460	510	406	345	286	245	212	180
		million euro	AP+	487	446	1 530	1 238	967	733	528	384	285
	Payment in low-income certificates	million euro	AP	231	201	300	241	182	140	118	104	93
		million euro	AP-LTD	240	211	315	253	191	146	123	108	94
		million euro	AP+	306	302	1 208	771	524	374	263	189	142
	Proceeds	million euro	AP	105	206	418	431	448	477	512	554	600
		million euro	AP-LTD	105	202	400	402	410	429	454	485	521
		million euro	AP+	105	101	1 138	1 127	1 149	1 174	1 137	1 117	1 104
CAT	Proceeds	million euro	AP	0	660	2 019	2 309	2 671	2 950	3 245	3 615	4 205
		million euro	AP-LTD	0	649	1 933	2 157	2 443	2 648	2 866	3 149	3 624
		million euro	AP+	0	646	1 886	2 085	2 357	2 576	2 831	3 170	3 727