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Policy Modelling for Ambitious Energy Efficiency Investment in the EU Residential Buildings

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Abstract: This paper presents the challenges of increasing the energy efficiency investments in European Union (EU) residential buildings in the context of achieving climate neutrality by 2050. The paper presents the results of the PRIMES buildings model in key energy policy applications to support cost-effective and fair policy making in buildings across Europe. The model covers, in detail, the building sector for all the EU Member States (MS), segmenting the buildings into many categories. The approach proposed includes non-market barriers in conventional microeconomic modelling, which combined with idiosyncratic preferences can capture poor energy efficiency choices and still represent rational behaviours. The model includes a detailed portrayal of policies specific to the sector, comprising economic and regulatory policies as well as institutional measures. The results of the model show that the removal of non-market barriers is of great importance in reducing energy consumption and increasing both the pace and the depth of renovation investment. However, the institutional measures alone are not enough to induce energy efficiency improvement to the scale required to achieve the climate neutrality objectives. Economic (i.e., subsidies) or regulatory measures (i.e., energy performance standards) are also required to decrease emissions and energy consumption in buildings and the paper compares different configurations thereof. The optimum policy mix obviously derives from a compromise among various aims including the cost-effectiveness of the policy budget and the distributional impacts across building and consumer types.

Keywords: modelling the building sector; energy efficiency policy; energy poverty; EU policy

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1. Introduction

The EU has signed the Paris Agreement, in which the signing parties agree to pursue efforts to limit the global average temperature increase to well below 2 °C compared to pre-industrial levels (and make best efforts in limiting the increase to 1.5 °C); this implies that all energy demand and supply sectors need to undergo a substantial transformation to achieve decarbonisation through strong energy efficiency improvements and a switch towards low- and zero-carbon technologies. The building sector is the highest energy consumer in the EU [1], but also has a large energy savings potential. Particularly in the residential sector, the exploitation of this potential depends on the investment decisions of individual consumers, featuring a large variety of socio-economic conditions and idiosyncratic preferences. They also decide under uncertainty and incomplete information as well as cash flow constraints. Therefore, conventional optimisation approaches are poor representations of reality, and thus approaches based on a representative decision maker fail to accurately model the potential for restructuring in the residential sector. Payback or net present value (NPV) approaches depend on the choice of discount rates for investment decisions; the literature [2–4] has found that discount rates tend to vary considerably across individuals and income classes. However, discount rates are subjective in reality. Thus, conventional approaches fail to understand why individuals often do not invest in energy efficiency although this investment is seemingly profitable based on pure techno-economic analysis, something termed as the "energy efficiency gap" or the "energy paradox", as stated in the literature [2–7]. The highly subjective discount rates may be due to market and non-market barriers and are heavily influenced by the income and fund-raising conditions of households.

This paper aims to propose a modelling approach of energy efficiency investment decisions in the EU residential sector, aiming at capturing idiosyncratic behaviours in the presence of market and non-market barriers. The impacts of alternative policies aiming at removing the barriers and inciting strong energy efficiency can be explored through a comprehensive model-based scenario assessment. The approach combines modelling of microeconomic decisions of individuals with a representation of (market and non-market) barriers, policy instruments, behavioural features varying by consumer category, and technical characteristics varying by building category. The approach aims at embedding the engineering features in a structural microeconomic modelling of decisions of households segmented in classes as much as the data allow for. The modelling approach also includes a representation of idiosyncratic behaviours within each class of consumers.

The research postulates that the market and non-market barriers play a major role in understanding the eventual lack of energy efficiency investment and the poor response of consumers to energy efficiency policies, which is currently observed in many EU countries supporting the idea of an "energy efficiency gap" in the sector.

The research also postulates that, because of the high heterogeneity of building types and consumer categories in the residential sector, high-resolution segmentation is necessary to project energy efficiency behaviours in the residential sector reliably and coherently and to assess the effectiveness of bottom-up policy measures aiming at removing market and non-market barriers and inciting energy efficiency investment. The concern is that in the context of deep decarbonisation and strong efficiency ambition, neglecting the particularities of income classes could have serious adverse social impacts and cause exclusion from energy services and advanced energy technologies (energy and technology poverty, respectively). Therefore, the social and distributional impacts of market policies should be explicitly included in the modelling and the policy assessment, which may suggest differentiating policy measures by income class and building type.

For this purpose, we used the PRIMES-Buildings Model (PRIMES-BuiMo), which is the detailed buildings module of the PRIMES energy system model. The model covers, in detail, the residential and services sector for each EU-28 country separately, segmenting the buildings into many categories. The model also represents various consumer behaviours differentiated, amongst others, by income class. A detailed portrayal of policies specific to the building sector is included, comprising economic policies and measures, regulatory instruments, tax and subsidies, energy and carbon performance standards, and policies removing barriers and improving the consumers' perception of the benefits from energy efficiency. Particularly for the residential sector, which is the focus of the current paper, the model represents several market and non-market barriers explicitly, to improve the representation of the so-called "energy efficiency gap".

In the literature, there have been many studies either assessing the existing policies (e.g., [8,9]) or offering a strategy for European buildings energy demand (e.g., [10–12]). These studies focused on the potential policies to reduce energy demand in buildings, and did not assess the preferable level of energy efficiency from an economic perspective.

A cross-country comparison regarding the effectiveness of energy policy instruments on energy efficiency in buildings is rather scarce in the literature [13]. Schild et al. [14] compared the regulatory standards of new residential buildings. Filippini et al. [15] and Ó Broin et al. [16] analysed and compared the effectiveness of energy policies on energy efficiency in residential buildings across different countries. Both studies focused on the predominant energy efficiency measures that have been adopted by the EU MS, namely, legislative measures (i.e., energy performance standards) and financial incentives (e.g., subsidies and tax deductions). Informative measures have also been examined in the analyses, but they have been found not to have a significant impact on fostering energy efficiency improvements.

All of the studies above-mentioned examine the effectiveness of energy efficiency policies in the EU as a whole or on a MS level in terms of energy consumption and/or CO_2 emissions reduction, in the context of the ambitious climate and energy targets that the EU have set over the years. Regarding the social impacts that the energy efficiency policies have in the different consumer categories, the literature usually includes country specific case studies. The focus of these studies has mainly been on the implications that the energy efficiency policies have on energy poverty [17–19]. The studies point to the fact that social groups suffering most from energy poverty such as low-income households experience more barriers in undertaking energy efficiency investments (such as building retrofits), thus energy efficiency policies that do not tackle these factors (i.e., not targeted energy efficiency policies) may exacerbate the inequalities between consumer categories. In other words, these studies have identified the social implications of known energy efficiency policies in different MS, without examining pathways that could probably alleviate the inequalities.

According to the literature [20,21], energy efficiency policies specifically targeting low-income households have positive social impacts and are able to deliver the multiple benefits of energy efficiency. Ugarte et al. [20] reported, however, that there were only a limited number of such policies in EU MS. The situation is similar in the U.S., according to Xu and Chen [21], which points to the fact that energy efficiency programs that are available to all income groups may cause a further breach of energy justice because they tend to benefit higher-income populations disproportionately.

Drawing from the literature above-mentioned, the current paper aims at quantifying the impacts that current and alternative future energy efficiency policies in the European residential sector would have on the energy consumption and CO_2 emissions of the EU. The coverage of the model, which examines each of the MS separately, allows for an in-depth analysis to that end, taking into account the specificities of each MS, in terms of building stock characteristics, energy consumption behaviours, and other factors that affect decisions regarding energy efficiency investments. Most importantly, the high resolution segmentation of the model allows for the examination of the distributional impacts that alternative energy efficiency policies or configurations thereof may have on different consumer categories. As the transition to climate neutrality will require the restructuring of the building sector, such considerations are important for policy makers in order to ensure a fair and cost-effective transition.

2. The PRIMES Buildings Model

The PRIMES-BuiMo projects into the future energy demand in the building sector. It focuses on the dynamic simulation of the renovation decisions and the choice of the degree of energy depth of building renovation as well as on the choice of technology type to cover the energy end-uses.

The design follows the methodology of hybrid energy-economy models commonly used in the literature to explore energy system restructuring induced by energy and climate policies [22–27]. In this sense, the model combines the detailed representation of economic behaviours with engineering aspects and technical constraints as embedded features of the integrated model-based decision framework.

2.1. Rationale

The building sector in the EU accounted for over one third of the total final energy consumption in 2020, according to Eurostat [1]. The largest part of energy consumption is used for space heating and cooling [28,29]. Energy demand for space heating and cooling depends on the thermal performance of the building shell and the efficiency of the equipment used for heating and cooling. Thus, the improvement in the insulation level of the building shell, combined with the shift towards more efficient equipment for heating and cooling (H&C), are options enabling the transition towards zero energy and/or zero carbon footprint building stock in the future [30].

The high inertia of the residential building stock (as demonstrated by the low demolition and construction rates in several EU countries [31,32]) indicates that the key to energy efficiency in the sector lies in the renovation of old buildings. The majority of the current EU building stock was built long before energy performance standards even existed [33]. Therefore, there exists a huge energy savings potential to tap through the deep renovation of the existing building shell.

Despite the widely recognised benefits of energy efficiency (i.e., in terms of energy savings, cost reduction, job creation, etc.), the large potential of energy efficiency in buildings remains significantly unexploited in the EU MS. For some authors, the limited amount of energy efficiency investments in buildings is the seemingly irrational behaviour of consumers. The approach proposed in the modelling is to postulate rational behaviours, as in standard microeconomic theory, but introduce barriers, which combined with idiosyncratic preferences, can capture poor energy efficiency choices. In other words, the seemingly irrational behaviour of consumers may be well explained through the concept of barriers to energy efficiency. Barriers can be split into market and non-market barriers [7]. Market barriers relate to "true" costs (that are actually paid by consumers, termed hidden up-front investment costs) and issues related to the access to capital resources [5,7,34–37]. Non-market barriers refer to elements that do not have a direct payable or "true" cost and are often termed as "perceived costs" [36]. The non-market barriers can broadly be split in three groups: (a) (lack of) information and knowledge [38,39]; (b) (technical and regulatory) uncertainty [5,36,40] and (c) economic factors related to individuals (e.g., high opportunity cost of equity and debt) (see Table 1).

Table 1. Taxonomy of market and non-market barriers to energy efficiency for buildings in the residential sector.

Market Barriers	**Non-Market Barriers**
Hidden up-front investment costs	Information and knowledge
Renovation Measures Related to construction: - Multi-storey buildings: additional costs for renovating due to, e.g., avoiding disturbances to neighbouring flats, complicated waste removal; possibly requirement for internal insulation work - Very old house renovation: unknown additional costs due to the unknown status of the structure - Urban (town centre): higher costs due to historic buildings, with renovation constraints - Remotely located buildings: includes additional costs of material transportation Not related to construction: - Loss of useful floor surface of the apartment (when applying internal renovation often in apartments) - Lock-in effect: from aesthetic renovation Heating and Cooling Equipment - Pipes, chimney availability when fuel switching, terminal units - Storage place for biomass and oil products - Back Up system for Heat pump technologies (especially in colder countries) and solar thermal boilers	- Lack of access to information or low accuracy of available information - Lack of incentives to gather information owing to the costs (time and money) associated with it - Lack of knowledge or capacity to evaluate information and draw correct conclusions (e.g., energy experts) - Asymmetric information (sellers vs. buyers)
	Uncertainty
	- Uncertainty about future energy prices and technology costs - Uncertainty about future consumption due to unknown technical specifications of new technologies - Uncertainty surrounding energy savings due to consumer's behaviour (e.g., rebound effect) - Consumers tend to be risk-averse; high discount rates for energy investment decisions
	Economic related to the individual
Lack of access to capital	- Lack of economies of scale - Lack of purchasing power to achieve the lowest possible costs of renovation - Poor fundraising possibilities - High opportunity cost of cash flow
- Investment in energy efficiency measures are capital intensive and have long payback periods - Low income houses are mostly affected by funding scarcity	

The effect of these barriers on the individual's decisions for energy efficiency depends on the specific attributes of the individual preferences. To capture consumer heterogeneity, it is important to segment the representation into several classes of consumers, as many as the data availability allows for. In this way, properly assessing the impacts of energy policies and measures for consumer classes may improve their effectiveness by addressing the specificities of each class.

Despite the high resolution of building segmentation in PRIMES-BuiMo, the consumer behaviours within each class of households are still not homogeneous. Idiosyncratic behaviours persist within each class, and thus the modelling approach also has to capture this heterogeneity. For this purpose, the model applies a discrete choice theory formulation within every consumer and building.

2.2. The Mathematical Framework of PRIMES-BuiMo

This section presents the modelling steps of PRIMES-BuiMo. All relevant equations in the model that represent each modelling step are explained in detail in Fotiou et al. [41].

The first modelling step is the estimation of the aggregate demand for energy services, that is, the desired useful energy demand for the specific uses covered in the model (i.e., space heating, air cooling, water heating, and cooking). The demand for energy services is a logistic function of the income and demographic growth and the unit cost of energy for households.

The building shell covers part of the total desired useful energy via thermal insulation. The heating equipment has to cover the remaining desired useful energy through energy consumption. To account for the useful energy remaining after the contribution of the building shell, which may also undergo renovation endogenously (i.e., to minimize the thermal losses of the building envelope), we followed the bottom-up engineering methodology of EN 13790:2008 [42]. The methodology considers the U-values of buildings (representing the thermal performance of the building shell), external temperatures, and internal thermostat settings.

The renovation choice module operates after the determination of total desired useful energy and after projecting the building stock into the future. For this purpose, the model uses a dynamic econometric equation to derive the annual growth rate of new buildings, to replace demolished buildings, based on an exogenous rate of demolition, and to increase the stock of buildings, which tends dynamically to an optimal stock at a certain pace. The renovation module applies to the stock of old buildings dynamically and calculates the level, rate, and depth of renovation up to 2050 and 2070. At this modelling stage, the characteristics of the building shell (thermal performance of the building envelope, useful energy demand for the specific end-uses, etc.) are known over the entire projection horizon. New constructions have applied the building codes, and parts of old buildings have been renovated.

The model then formulates the problem of how to meet the remaining useful energy using the heating and cooling equipment and the use of energy purchased from markets or self-produced (e.g., renewables) (see Figure 1). The model formulates the choices separately by type of energy use.

To represent the alternative options regarding the depth of energy efficiency investment and timeliness of the refurbishment of buildings (including the nested decision of heating technology) in the model, the modelling forms dynamic strategies, which are organised as dynamic trees (and are denoted by i or ii). Following a dynamic programming methodology, the model evaluates the net intertemporal economic benefit of each dynamic strategy and ranks the strategies for each building class in descending order. For the evaluation of the net benefit of each dynamic strategy, the model considers the intertemporal net present value of expenditure and monetary benefits ($v_{h,i}$) over a long period. Expenditure corresponds to investment in renovation, the purchase of equipment and its maintenance, while such expenditure may be required more than once over the projection horizon. A sequence of such expenditure is the main feature distinguishing a strategy from other strategies. The monetary benefits stemming from the expenditure are the annual energy cost savings due to energy efficiency enabled by the renovation and the eventual choice of efficient heating systems. The present value calculation uses a subjective discount rate (δ_h) that differs by income class and reflects the subjective cost of equity, the cost of debt, and risk premium factors [5], as in Equation (1). The monetary benefits do not only include the reduced energy bill of the household, but also other indirect benefits justified subjectively or objectively as a result of the improved efficiency. Indirect benefits may stem from the improved energetic quality of the building, which adds value to the real estate market, while they can also relate to the avoidance of penalties, which thanks to the renovation, the characteristics of the building comply with standards and regulations facilitating renting and selling actions. Subsidies to energy savings are also included in the modelling where applicable. In this way, the model captures the effects of regulatory policies as an indirect incentive for renovation and efficiency improvement. The monetary benefits added to the savings of energy bills may act as the shadow dual variable of an efficiency target or an efficiency performance standard. Other possibilities are to represent the market clearing price of cap and trade certificate systems (i.e., the so-called white certificates), or the implicit subsidy due to a policy obliging utilities to perform energy savings at the premises of their customers. In all cases, the monetary benefits are measured in € per energy saved.

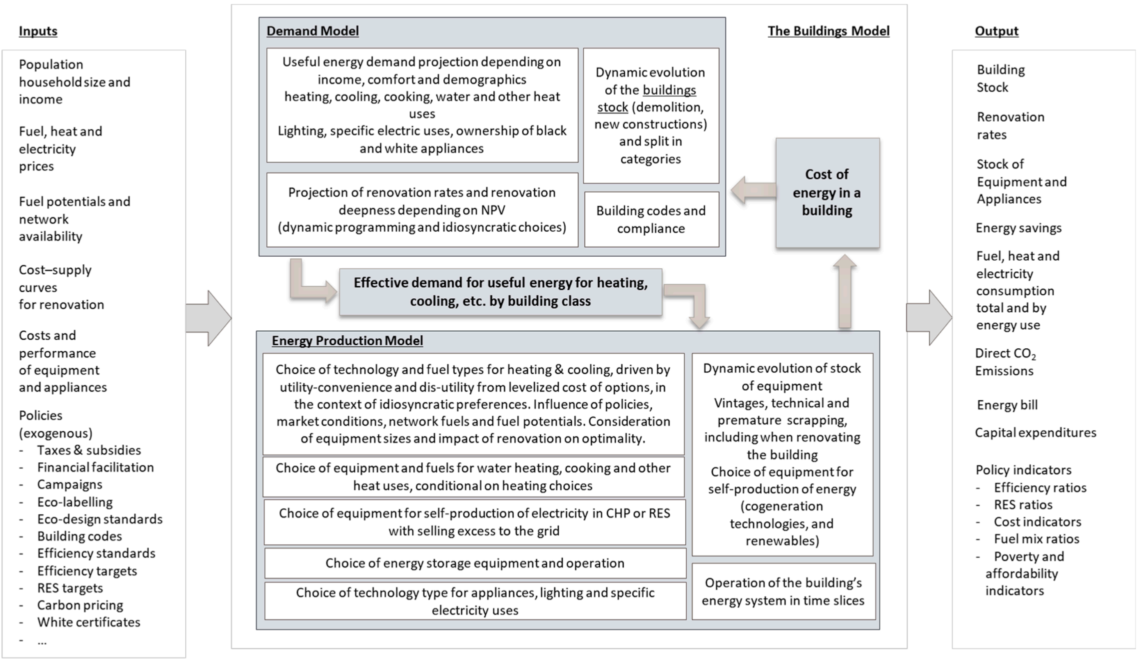


Figure 1. Flowchart of the PRIMES-BuiMo model [41].

The formulations of costs and benefits also include additional cost parameters and factors monetised to represent the market and non-market barriers. These factors may change in scenarios that apply specific policy measures targeting the removal of market and non-market barriers.

$$v_{h,i} = \sum_{t=\tau}^{T} \frac{-I_{t,h,i} - C_{t,h,i} + \sum_{tt>t}(S_{t,tt,h,i})}{(1+\delta_h)^t} \tag{1}$$

In Equation (1), $I_{t,h,i}$ represents the investment expenses for energy efficiency (i.e., insulation or the heating and cooling equipment) and includes the construction costs and all kinds of indirect hidden costs and investment subsidies; $C_{t,h,i}$ represents the annual costs of heating and cooling that would have been incurring without the implementation of investment; and $S_{t,tt,h,i}$ represents the cost savings derived from the implementation of the investment (see also Appendix C for the nomenclature).

The modelling uses the ranking of dynamic strategies for each building class as a basis to form a complex strategy for the representative consumer of the class. Complex means that it is a combination of several pure strategies taken among the highest positions of the ranking with probabilities applying to pure strategies. The probabilities derive from a Gumbel distribution [43–46], drawing on discrete choice theory, as in Equation (2). In this way, the model captures the idiosyncratic behaviours of individual consumers (both across and within the building classes) and heterogeneous building characteristics. Such a strategy is a mix of the best dynamic strategies for each class weighted by the respective frequencies.

$$f_{h,i} = \frac{e^{v_{h,i}}}{\sum_{ii} e^{v_{h,ii}}} \tag{2}$$

A non-linear function Φ is specified to represent the renovation investment possibility frontier (i.e., the locus of efficient combinations of investment expenditures in renovation and energy savings enabled by the improvement of the building shell). The function is specific to each building class to reflect the construction conditions and possibilities from a technical perspective. The numerical information to estimate the functions have been drawn from the "ENTRANZE project" [47], which provides the investment expenditure for interventions on the building shell of increasing deepness. The "ENTRANZE project" differentiates the expenses only by building type (i.e., multi-family households and single-family households). Engineering estimations enable the expansion of the numerical estimations to other categories by considering their specificities.

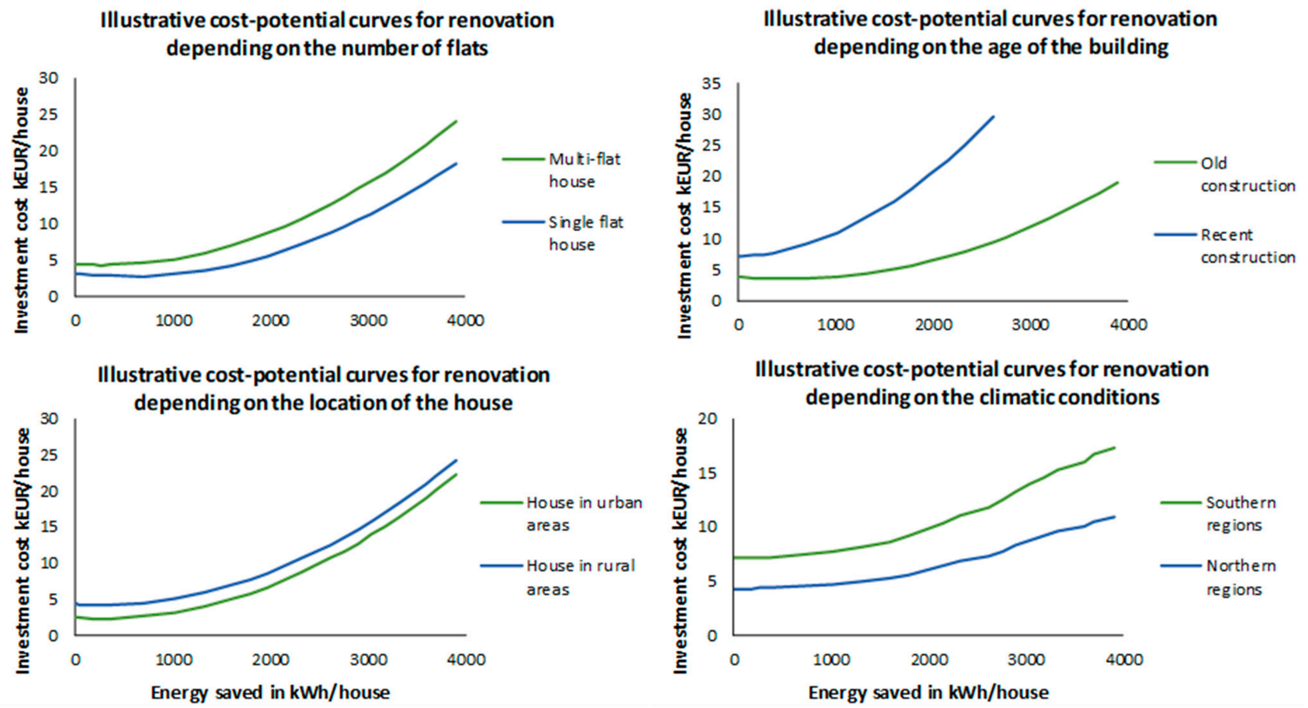
The functions Φ monotonically increase and feature increasing marginal investment costs. The variable $Q_{tt,h,j}$ represents the volume of energy savings derived from investment $I_{tt,h,j}$, with j representing the energy-oriented depth of intervention. A strategy i consists of undertaking investment at times tt of depth j and the corresponding avoided expenses are $S_{tt,t,h,i}$. The non-linear cost-potential function Φ is then:

$$I_{t,h,j} = \Phi\left(Q_{tt,h,j}\right) \tag{3}$$

Figure 2 shows illustrative representations of the non-linear cost potential function Φ with specific shapes by type of building. The aged buildings have poor insulation, resulting in high energy consumption (i.e., in kWh/household), and have a higher energy savings potential compared to the newer constructions. The most recent constructions have high thermal performance as they follow the building codes implemented in EU countries. In such cases, the unit costs of renovation to further improve insulation are higher than for aged buildings (for the same incremental energy saving amount). Renovation of recent constructions may also imply high hidden costs (e.g., the need for a scaffold).

Deep renovation is more expensive for multi-flat buildings compared to individual houses per unit of energy savings, as insulation works may be easier for the latter. Additionally, hidden costs apply for multi-flat buildings due to the complicated waste removal or avoiding disturbances to neighbouring flats. Finally, renovation of buildings located in rural or remotely located areas is more expensive (per unit of energy savings) compared to urban areas due to the transport costs for labour, machinery, and materials.

Based on the complex renovation strategy by class, the model calculates useful energy demand that has to be met by the purchase of energy carriers. The various equipment types consume final energy, the purchasing of which is also derived from the dynamic complex strategy that concerns the choice of the heating system and is determined after the complex strategy on renovation. The heating system strategy is conditional on the timing and the depth of the renovation strategy. Similarly, the dynamic strategies for water heating and cooking are conditional on the heating system strategy. Keeping track of capital turnover as vintages, the model also determines the fuel mix for the various equipment and their operation, thus deriving the energy consumption by fuel/energy form, associated CO_2 emissions, operating costs, and investment expenditures.


Illustrative cost-potential curves for renovation depending on the number of flats

Illustrative cost-potential curves for renovation depending on the age of the building

Illustrative cost-potential curves for renovation depending on the location of the house

Illustrative cost-potential curves for renovation depending on the climatic conditions

Figure 2. Cost–potential curves relating unit investment cost of house renovation with saved energy potential.

The module of specific electricity uses first determines the energy service—the number of lighting devices, and black and white appliances by building category—and then chooses the type of technology to purchase to replace obsolete stock and meet the desired level of energy use. The choices depend on the relative efficiencies and costs of competing options. The turnover of the stock of appliances is dynamic and endogenous. Eco-design regulations influence the types of technologies that the market offers to consumers. Labelling and other policies are represented in the model and facilitate the uptake of highly efficient, yet more expensive, technology types through reducing the uncertainty and lack of information factors.

2.3. The Dataset

PRIMES-BuiMo covers each of the EU28 MS individually. The model runs in 5-year time steps from 2005 to 2070; projections are from 2020 onwards, while past years 2005 to 2015 are calibrated to EUROSTAT statistics for energy consumption by fuel for the residential and services sectors [1]. The model has been coded in the GAMS modelling language and can run independently as a stand-alone model or fully integrated within the PRIMES fully-fledged energy system model [48].

PRIMES-BuiMo includes a detailed database of many building classes and explicit energy-related technologies distinguished by type and vintage.

The households' database consists of 270 building classes for each MS, which are split by [41]: type of building; age of construction; spatial allocation; and income class.

The classification of households in income classes is based on data from the EUROSTAT EU-SILC database, and the ranges of each class are country specific. The purchasing power standard (PPS) ranges for different income classes and for different regions in the EU (Table 2). To derive the PPS ranges for each income class for the whole projection period, we assumed that they increased by the same percentage as GDP in the country.

The income classes use different discount rates in their investment decisions. Subjective discount rates represent different availability of financial resources and preferences over time; usually, the highest income class has the lowest discount rate, and the lowest income class has the highest discount rate [5]. In the current model version, discount rates range between 10 and 15% for the residential sector and are in line with the lower end of the statistically estimated discount rates for households [4,49,50].

Table 2. PPS ranges of the differentiated income classes in regions in the EU.

	PPS Ranges (Year 2010)							
	Centre\West		**South**		**North**		**East**	
	Lower	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**
Low Income		19,556		16,656		17,111		8126
Medium Income	19,556	32,720	16,656	28,663	17,111	26,223	8126	13,698
High Income	32,720		28,663		26,223		13,698	

In PRIMES-BuiMo, the services sector is divided into the following sectors and subsectors [41]: trade, and further commercial buildings, warehouses, cold storages; market services, and further private offices and other buildings in market services, hotels, and restaurants; and non-market services, and further public offices, hospitals and health institutions, schools, and educational buildings. The buildings are also split by their age of construction such as in the residential sector.

The database for both sectors is integrated in the modelling framework and has been constructed using data from a variety of databases, reports, and studies that had to be reconciled to construct a consistent dataset [29,42,51–58]. In Appendix A, there is an extended list of all the databases (and the respective references) that have been combined and elaborated to build the database for PRIMES-BuiMo building stock.

The model includes over 50 different types of technology equipment for space heating, air cooling, water heating, and cooking (e.g., conventional and condensing boilers, heat pump technologies, wood pellets boilers, etc.). Each equipment type is further split into four efficiency categories ranging from currently available technology to best not available technology (BNAT), being in-line with the efficiency classification of the eco-design directive [59]. The data and assumptions for the technical-economic characteristics of equipment technologies (efficiency rate, technical and economic lifetime, investment cost, operation and maintenance costs, and other variable non-fuel costs) draw on a large number of sources (see Appendix B). Most technology assumptions were derived from a recent study, which reported on extensive consultation with industrial stakeholders and included consistent estimations and projections for the technical-economic characteristics of energy-related technologies in buildings [60].

2.4. Representation of Policies

Several policy instruments can be implemented to mitigate or remove the various market and non-market barriers and facilitate energy efficiency investment. The instruments range from institutional and regulatory, which should act as facilitators of investment, but not as direct incentives, through hard regulatory instruments up to financial incentives.

PRIMES-BuiMo can simulate a wide variety of policies and measures that are considered as policy options for the building sector. As the model is currently applied to the EU MS, the focus lies on policies implemented in the EU and is consistent with the EU energy and climate policy framework. However, the model could also be adapted for other measures and countries/regions.

PRIMES-BuiMo can simulate alternative economic policies and measures such as:

- Energy-related excise taxes and VAT applicable to all fuels defined according to the DG TAXUD datasets. Currently, the PRIMES-BuiMo database incorporates the energy taxation directive [61] and the current levels of taxation for each fuel, according to its use, across all the EU MS [62];
- Special energy taxes to incite energy savings or mixed energy and carbon tax schemes;

- Carbon pricing, as a means to reduce CO_2 emissions, is implemented in the model in different forms: direct CO_2 tax; emissions allowance cost when subject to the EU Emission Trading System (ETS), carbon value for sectors applicable, for example, to sectors not included in the EU ETS aiming to act as a shadow price of a carbon emission cap. The carbon tax and the EU ETS imply tax payments to the state by the emitting consumer, whereas the carbon value, by definition, does not entail payments. However, it serves to convey price signals favouring low emitting options and energy savings;
- Subsidies or financing rebates: these are represented explicitly or implicitly in the modelling. Subsidies and financing rebates can be directly monetised (explicit representation), while implicit representation concerns the elimination or reduction in hidden and perceived costs;
- Energy savings or efficiency value acting as a virtual subsidy (or penalty) measured as €/toe of energy savings (or energy consumption, respectively). In this way, energy saving investment becomes more profitable for decision makers. The energy efficiency value can represent the market clearing price of white certificates, the marginal cost of policies obliging utilities to perform energy savings at the premises of their customers, otherwise, they are subject to a penalty, shadow cost—dual variable of energy performance standards represented as energy consumption caps, etc.

The model also includes regulatory instruments such as:

- Building energy codes: the building codes are represented explicitly in the model at a MS level, based on country and European legislation [63]; building specifications follow engineering-based calculations for the determination of energy requirements. Due to the different levels of compliance to building codes, the model includes parameters to represent non perfect compliance to building codes, as in [64].
- Minimum energy efficiency standards for the building shell, which may support certificates that are necessary for renting or selling a property; and
- Minimum energy performance standards (MEP) for equipment and appliances, which are based on the implemented regulations of the Eco-Design Directive [59].

The model also represents information and education policies as well as research and innovation instruments that implicitly support the assumed learning performance for specific technologies. The model also includes energy labelling, serving to improve the perception of the decision-makers towards technology performance (by modifying perceived costs).

The high resolution segmentation of the model allows one to perform analyses examining the application of policy instruments under different regimes, namely, by applying the policy instruments uniformly to all building and consumer classes, or differentiating the intensity of the policy instrument according to the consumers' attributes.

This paper examines two active policy options to drive the deep renovation of buildings, as much as needed to meet a certain energy savings target. In the first option, the policy instruments are subsidies directly transferred to households and represent the direct monetary benefit added to saving energy bills. In the second option, the policy instruments are energy performance standards, which apply a cap on energy consumption, for example, by square meter of the building. The marginal cost for complying to the energy performance standard is a measure of the magnitude of price-oriented measures to obtain a similar energy saving as the application of the regulations based on standards. In other words, the energy performance standard conveys a shadow value of potential energy savings to the decision maker. This establishes a duality between the level of the standard and the subsidy rate.

The methodology applied for the model-based analysis in this paper follows the steps stated below.

In the subsidisation policy, a subsidy rate, defined as €/kWh of energy saved is considered as a control variable. We applied the subsidy uniformly to all classes of consumers and buildings and we varied the rate until we obtained the desired total energy savings.

The iterations apply to all time periods until 2050 sequentially, as the model handles renovation dynamically.

The subsidy is applied annually and increases the net present value of strategies that involve higher energy savings because the monetary value of savings, denoted by $S_{tt,t,h,i}$, becomes higher. As the more energy saving intense strategies are more valuable, in terms of $v_{h,i}$ as in Equation (1), the probability $f_{h,i}$ of selecting these strategies increases. Consequently, the volume of savings (i.e., $Q_{tt,h,j}$) increases, but at the same time, investment costs increase through the function Φ as in Equation (3). The shape of this function differs by building type, while the consumers' view of capital costs differs by type of consumer. Therefore, a uniformly defined subsidy implies different renovation investment, energy savings and expenses by household. Thus, unequal distribution effects occur from a uniform application of subsidies across the classes.

In theory, when allocating the overall effort to a number of individual activities with different cost curves, the maximum cost-efficiency, expressed by minimising the total cost of the overall effort, is achieved when all individual activities produce amounts at which marginal cost are the same in all activities. Based on this, maximum cost-efficiency, in terms of minimising subsidy expenses per unit of total energy savings, is achieved if the price-oriented policy instrument applies uniformly to all classes of buildings and consumers.

Differentiating the subsidy rate by consumer and building class would weaken policy effectiveness, measured as total energy savings per unit of expenses for subsidies, but at the same time, it could alleviate the adverse social effects of the policy.

It is difficult to define an "objective" rule on how much subsidy rates should be differentiated across the consumer classes. In our model-based analysis, we defined an arbitrary differentiation scheme for subsidies that only regarded income differences for implementation. We also measured the social implications as the ratio of energy bill remaining after energy savings over income. We assumed a differentiation of subsidy rates to obtain almost the same shares of the energy bills in consumer income, after renovation. We determined the differentiation of subsidy rates iteratively. The cost of energy purchases as a percentage of household income was also used to analyse the threat of energy poverty. Low-income households may cut energy purchasing expenses to accommodate other expenses within a limited family budget. In this way, they may be deprived of essential energy services. Similarly, a poor subsidy to energy savings may maintain energy expenses over income at a non-affordable level. Combining the energy-saving goal with energy poverty policies implies setting the subsidy rate at a level that renders energy expenses relative to income below an energy poverty threshold.

Opting to regulate an energy performance standard, instead of a subsidy, requires us to first define the level of the standard. Not complying with the standard implies that the owner will have to undertake renovation investment.

For our analysis, we first determined, through iterations, the level of the standard, so that if applied in a uniform manner to all building and consumer classes, it would lead to the desired overall energy savings. When standards are applied uniformly across building classes, all classes would have to meet the same energy performance standard. As they have different features, the buildings will implement different renovation schemes and bear different costs to comply with the same level of the standard. In the context of the modelling, it is logical that the level of the standard applied uniformly should lead to a different marginal cost per unit of energy saved than the cost determined by the application of the uniform subsidy rate, although both led to the same overall energy savings.

It follows that uniformly applying the standard does not correspond to the maximum cost-effectiveness from the perspective of energy saving policy because the flat standard implies different marginal compliance costs across the classes of consumers and buildings. In addition, the uniform standard implies adverse social effects, probably more pronounced than the flat subsidy. Therefore, a policy that considers addressing the adverse distributional impacts implies differentiating the level of the standard across consumer and building classes.

It follows from duality that differentiated standards that correspond to marginal compliance cost equalisation would lead exactly to the same allocation as driven by the uniform subsidy rate. This allocation may be undesirable from the perspective of social implications. Therefore, a social indicator should additionally intervene to drive the differentiation of standards by class. The choice of the non-uniform levels of the standard needs to derive from a combination of policy goals, in a manner that attributes weights to criteria, notably regarding the effectiveness of energy savings and social implications.

To model the policy case based on standards, we measured the social implications as the ratio of annual equivalent capital expenses for renovation over income. We used capital costs over income as an indicator, instead of energy bill over income, because the standards call upon investment in renovation, which is the cause of the affordability burden for social classes.

Regulating house investment using standards cannot accommodate the social implications as it is infeasible to differentiate the stringency of the standard based on social criteria. Low-income households with difficulties in affording the costs of compliance with a strict energy performance standard will invest in renovation inadequately and will continue living in an inferior building from a technology perspective. This situation is described as "technology poverty", which may also lead to the deprivation of essential energy services. Standard-oriented regulatory policies alone cannot address technology poverty as it is impractical to add social criteria in the attribute-related regulation of buildings. It is then imperative to apply hybrid policies that combine subsidies and standards. This was explored in this paper.

Both policy options (i.e., the subsidy and the standards) are public interventions into the market and their efficiency may be lower than the policy makers would have expected when shaping the policy. The degree of inefficiency in implementation depends on the nature of the policy instrument. However, the modelling does not include these inefficiencies.

Policies based on subsidies present inefficiencies due to the misuse of the revenue generated by the subsidy. The misuse leads to lower energy savings than expected as a result of either money leaks or an overpricing of materials or services.

Another reaction that causes lower energy savings than expected is the so-called rebound effect [65–67]. The improvement in energy performance of the building shell implies a decrease in the energy bill, which, in turn, allows for an increase in energy consumption while staying within the budget limits. The model considers the rebound effect through elasticity values that apply to the determination of useful demand for heating.

Policies based on standards present various drawbacks regarding the effectiveness and adverse effects. If the level of the standard is too strict for a consumer, the probability of non-compliance increases, and the enforcement becomes more difficult for social reasons. Setting weak standards may not be enough to drive towards the policy goals. It is not only more difficult to fix an adequate level of the standard, compared to a subsidy rate, but it is also difficult to modify the standard often to correct mistakes. The literature mentions several other drawbacks that relate to technology lock-in.

3. Illustrative Model Application

The purpose of the model application in this paper was to evaluate the effectiveness of specific policies aimed at saving energy in the residential buildings, mainly as a result of renovating the housing stock deeply from an energy perspective. The model-based analysis covered the period until 2050 and was carried out for each MS of the EU. The comments and figures included below refer to the EU as a whole.

3.1. Description of Scenarios

We designed three scenarios (see Table 3) differentiated regarding the policy measures intended to incite energy efficiency investment for the refurbishment of the building envelope. We also defined two variants of the scenario achieving the most ambitious energy-saving targets by applying alternative policy means, aiming to influence the behaviours by either making investment more attractive (price measures) or partly mandatory (regulation measures). We investigated the importance of complementing by specific policies that help to perceive the benefits of building refurbishment as adding value on top of energy bill reduction.

Table 3. Summary of the scenario design.

Scenario Name	Modelling Options
Reference scenario	- Refurbishment rates are higher than historical trends until 2020, but revert to historical trends after 2020. - For new constructions, the building codes reflect moderate ambition on energy performance.
Enabling Conditions scenario	- Refurbishment rates are significantly higher than historical trends until 2030, due to the obligations imposed by legislation, but are slowing down after 2030. - Refurbishment rates are higher than historical trends in the period 2030–2050 due to the removal of distortions and non-market barriers thanks to institutional and informational measures that continue after 2030. - Appliance technologies improve the above trends assumed for the reference scenario and the costs of the not yet fully mature technology decrease due to market diffusion. - For new constructions, the building codes also reflect high ambition in energy performance in the period until 2050.
Climate Neutrality scenario	All modelling assumptions of the *Enabling Conditions* scenario apply. Additional assumptions: Price-oriented measures: - Subsidy level for all building classes of 0.075 € per kWh saved due to building refurbishment. - Subsidy level differentiate by consumer and building class so as to reduce the energy bill, remaining after refurbishment, as % of private income. Energy performance standards: - Same energy performance standard for all building classes, set to around 45 kWh/m^2. - Energy performance standards differentiated by consumer building class to reduce annual equivalent capital cost of refurbishment as % of private income.

We started by designing a *Reference* scenario that includes the policy package adopted for the 2020 EU climate and energy targets and by assumption, does not include any new policy in the period after 2020. The 2020 EU climate and energy framework set three key targets for the year 2020: (a) at least 20% reduction in GHG emissions (wrt. 1990 levels); (b) at least 20% share for renewable energy in gross final energy consumption; and (c) at least 20% improvement in energy efficiency. The Energy Efficiency Directive, as it was in the legislation prior to the 2018 reform, applied only in the period until 2020. Its implementation acted towards inciting renovation of the building envelope and the replacement of the heating and cooling equipment by more efficient technologies, but only until 2020. In addition, we assumed that the measures and the general policy context in this scenario were not sufficient to remove the barriers to energy efficiency. Thus, the *Reference* scenario foresees that individuals perceive high technical and economic uncertainties and hesitate to invest in energy efficiency, while the high opportunity costs of investment funding drive subjective discount rates too high.

The second scenario (*Enabling Conditions* scenario) includes the same policies as the *Reference* scenario until 2020, the policy interventions to achieve the 2030 EU climate and energy targets for the period 2021–2030 and does not include new policies after 2030. The 2030 EU climate and energy framework set three key targets for the year 2030: (a) at least 40% reduction in GHG emissions (from 1990 levels); (b) at least 32% share for renewable energy in gross final energy consumption; and (c) at least 32.5% lower primary and final energy consumption compared to a projection performed in 2007. The policy package of the *Enabling Conditions* scenario is as proposed by the European Commission in the "Clean Energy for All Europeans" communication [68]. The scenario incorporates throughout the projection horizon adequate institutional and informational measures to remove the non-market barriers to investment in deep refurbishment of the building envelope. The measures tackle technical uncertainty, lack of information, inability to access funding, and other institutional issues. Such measures may include education and information campaigns, an appropriate adaptation of building regulations, certification, guarantees, third party financing systems, the obligation of energy companies to assist energy saving investment in the premises of the customers, and others. We considered that the institutional and informational measures constituted conditions enabling consumers using reasonable discount rates in the assessment of investment decisions in energy efficiency while minimising hidden and perceived costs.

The third scenario (*Climate Neutrality* scenario) includes the same policies as the *Enabling Conditions* scenario throughout the projection period. In contrast to the *Enabling Conditions* scenario, the *Climate Neutrality* scenario also includes active incentives in the period 2030–2050 to drive deep renovation of buildings and energy consumption reduction as much as needed so that the building sector contributes to making the entire energy system reach climate neutrality by 2050.

The model-based analysis splits the *Climate Neutrality* scenario into two scenario variants. One variant uses a policy based on subsidies to make refurbishment investment attractive. The other variant, in contrast, employs regulation based on energy performance standards, in order to oblige consumers saving energy by means of refurbishment investment. The two variants further consider whether to apply the same magnitude of the policy measure to all consumer and building classes, or to vary the magnitude of the measure across the classes.

Apart from active incentives to drive the deep renovation of buildings, the *Climate Neutrality* scenario assumes specific policies to accelerate the electrification of H&C in the residential sector, considering that in the context of climate neutrality the electricity grid will be carbon-neutral. These policies may include recognising and rewarding the contribution of heat pumps in the calculation of the overall RES performance indicator, or giving specific incentives to invest in heat pumps due to their high coefficient of performance (COP) and associated energy savings.

3.2. Results and Discussions

3.2.1. Model Results for the Entire Residential Sector

Due to limited policy ambition and the lack of measures supporting energy efficiency, the *Reference* scenario exhibited the highest energy consumption (Figure 3) and the highest CO_2 emissions (Figure 4) throughout the projection period. Final energy consumption remains broadly constant over the period 2015–2050 due to the low refurbishment rates of buildings and the limited improvement in the energy efficiency of the equipment. Old buildings lacking renovation continue to require large amounts of energy for heating and maintain conventional heating equipment. In contrast, new buildings that are highly insulated and driven by stringent building codes opt for modern heating equipment such as the heat pumps, which are economically appropriate for well-insulated buildings.

The average annual refurbishment rate of houses in the *Reference* scenario is close to historical trends (i.e., about 0.8% per year). The depth of renovation is also shallow, consisting mostly of replacing windows. The average annual refurbishment rate increased only in the period 2016–2020 (reaching 1.7% per year), driven by the Energy Efficiency Directive applicable in this period.

The differences in final energy projections of the policy scenarios from the *Reference* scenario, shown in Figure 3, are indicative of the amount of energy savings primarily due to the renovation of houses.

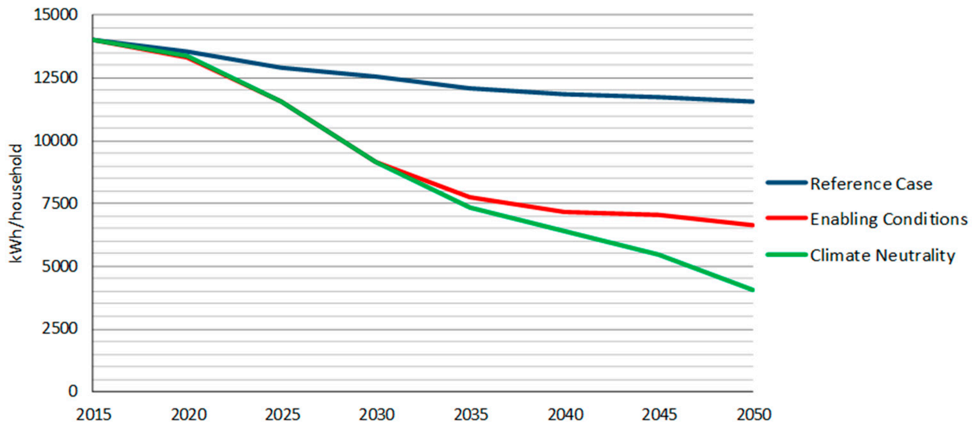


Figure 3. Final energy for the heating and cooling of houses.

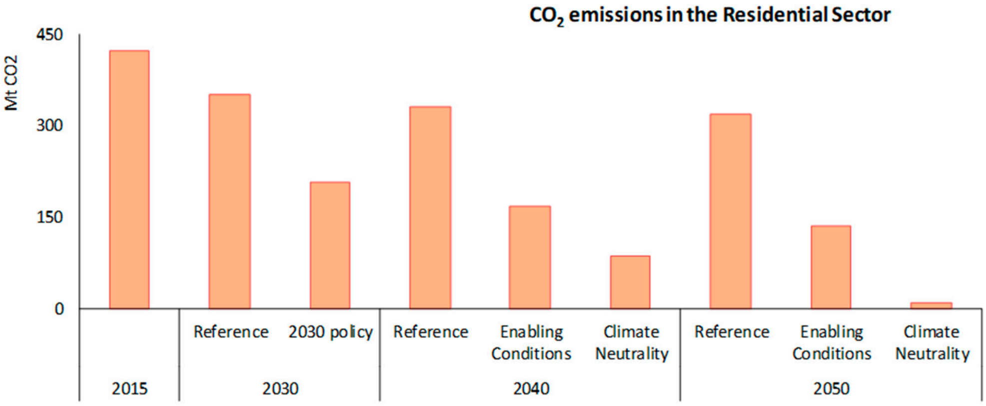


Figure 4. CO_2 emissions in the residential sector in the EU over 2015–2050.

The 2030 Energy and Climate policy package included in the *Enabling Conditions* scenario drives the increase in the average annual refurbishment rate in the period 2021–2030 compared to the *Reference* scenario, which reaches 2.1% per year. The model results show that the institutional-informational measures that apply in the *Enabling Conditions* scenario after 2030 are able to drive a substantial increase in the average annual refurbishment rate and energy depth of renovation, compared to the *Reference* scenario. In particular, the refurbishment rate reaches 1.5% per year during the period 2031–2050 (well above the average rate in the *Reference* scenario, which is 0.8% per year). Additionally, the renovations are deeper and more intensive than in the *Reference* scenario throughout the projection period. Consequently, useful energy for heating and cooling decreases by 32% in 2030 and by 50% in 2050, compared to the corresponding energy consumption before the energy upgrading interventions.

In the *Enabling Conditions* scenario, electrification is higher than in the *Reference* scenario in the medium- and the long-term, as a result of the synergy between highly insulated houses and the economic appropriateness of heat pumps for well-insulated buildings. Electricity share in total final energy demand of households reaches 40% in 2030 and 56% in 2050 in the *Enabling Conditions* scenario, far above the shares in the *Reference* scenario that are 28% and 34% in the respective years. Deep renovation is thus accompanied by a significant shift towards heat pumps. Electrification of heating based on heat-pumps is beneficial to achieving energy efficiency, renewables, and carbon emission targets.

In summary, the removal of non-market barriers, as in the *Enabling Conditions* scenario in the period 2030–2050, brings multiple benefits by pushing renovation rates upwards, increasing the energy depth of the renovation investment, facilitating market diffusion of heat pumps and indirectly serving several goals of the energy and climate package of the EU. The enabling conditions also act in conformity with social goals, as acting in the support of low-income families allows them to mitigate energy poverty threats. As the institutional measures are of negligible costs, the benefits are by far greater than the costs, thus rendering the removal of non-market barriers to renovation an undisputable no-regrets policy measure.

The combination of institutional and incentivisation policies in the *Climate Neutrality* scenario leads, in the period 2030–2050, to significantly higher and deeper energy refurbishment of the building envelope compared to all other scenarios. The refurbishment rate reaches 1.7% on average per year and delivers a 59% decrease in useful energy consumption for heating and cooling.

The strong policies included in the *Climate Neutrality* scenario not only imply deep renovation of old constructions, but also a wide diffusion of heat pumps. The remaining use of fuels is small and the corresponding carbon emissions are abated by greening gas distribution using hydrogen, biogas, and synthetic methane, produced in a climate-neutral manner. The blending of green gas fuels in the gas distribution network starts in 2035, and the green gas quantities will progressively increase their share in the network over the years, leaving only ~15%vol fossil gas in the gas distribution network in 2050. As hydrogen and synthetic methane are electricity-intensive, minimising the amounts needed to achieve almost zero carbon emissions is a goal per se, important to maintain total volume of electricity, hence the total volume of renewables, within reasonable limits. To this end, both large and deep renovation as well as the renovation-pushed large diffusion of heat pumps are particularly helpful. The changes combined maximise efficiency and thus minimise recourse to green gas, as a last resort option in achieving the zero emissions.

Table 4 summarises the fuel mix as projected using the model for the three scenarios.

Table 4. Final energy demand by fuel in the residential sector in the EU.

EU28	**2015**	**2030**		**2050**		
Final Energy Demand (in Mtoe)		Reference	2030 Policy ("Clean Energy for All Europeans" Policy)	Reference	Enabling Conditions	Climate Neutrality
Residential sector	300	289	220	294	186	142
by fuel						
Solids	10	5	1	3	0	0
Liquids	38	24	4	18	1	0
Gas	113	110	80	107	51	28
of which						
Biogas	-	-	-	-	-	5
Hydrogen	-	-	-	-	-	5
Clean gas	-	-	-	-	-	14
Renewables	43	46	32	41	19	14
Electricity	72	81	87	100	104	91
Distributed heat	24	23	16	24	12	8

3.2.2. Model Results by Building Class in the Residential Sector

For presentation easiness, we aggregated the numerous building classes of the PRIMES-BuiMo into six "typical" classes in such a manner that the aggregated classes had the largest gap among each other regarding the renovation difficulty when taking into account both building and consumer attributes. We mainly used household income and the age of the building to perform the aggregation. The aggregated classes were as follows:

1. Old constructions of low-income households (OLD-LOW);
2. Old constructions of medium-income households (OLD-MEDIUM);
3. Old constructions of high-income households (OLD-HIGH);
4. Recent constructions of low-income households (RECENT-LOW);
5. Recent constructions of medium-income households (RECENT-MEDIUM); and
6. Recent constructions of high-income households (RECENT-HIGH).

For the *Climate Neutrality* scenario variant that applies the energy efficiency subsidy uniformly to all categories of buildings, the model calculates that at minimum, the subsidy should be 0.075 €/kWh-saved. This is a relatively high subsidy compared to 0.080 €/kWh-fuel, that is, the average fuel price for heating and cooling in 2015 in the EU. Seen from another angle, this level of subsidy is not that high when including carbon pricing in the fuel price of fossil fuels. The scenario projects carbon prices of the EU ETS to reach high levels, above 100 €/t CO_2 in the long-term, notably after 2040. Such carbon pricing would increase fuel prices up to 0.25 €/kWh-fuel for residential heating uses, and then the subsidy representing roughly 30% of the fuel price inclusive of carbon pricing is relatively low; despite this, it can drive energy demand down substantially.

The subsidy calculated for the *Climate Neutrality* scenario leads to substantial energy savings and the entire stock becomes close to the energy for heating and cooling, as low as 45 kWh/m^2 on average. This level of energy performance, being substantially lower than the current levels, is still higher but reasonably close to the specification of passive houses or low energy demand buildings, according to the definitions of [69].

It is remarkable that the institutional measures alone, as included in the *Enabling Conditions* scenarios, are substantial drivers of renovation for both low-income and high-income consumers. The effects of the subsidy on energy efficiency inducement after having implemented the institutional measures is a magnitude lower than the effect of the institutional measures taken alone (depicted by comparing *Enabling Conditions* to *the Reference* case projection).

Noticeable differences exist among the categories of consumers and houses regarding the energy performance of buildings after renovation after having applied a flat subsidy to all categories. The level of income influences the level of energy requirements, prior to renovation, and at the same time, the propensity to undertake refurbishment investment. The age of the building influences the volume of final energy prior to renovation as recent constructions apply stricter building codes than old ones, which implies that the remaining energy saving potential for recent constructions is lower than for old ones and the marginal costs of renovation are higher. A high potential of energy to save implies large benefits from a reduction in energy bills, and if at the same time income is high, capital funding burden is probably manageable. The opposite holds for low income and low energy depending cases, while mixed situations exist in other cases. A flat subsidy unlocks energy savings potential differently in each case. The subsidy makes a reduction in energy bills more attractive, but at the same time facilitates capital funding, which is particularly important for low-income classes. The net effect of these factors are depicted in Table 5. Low-income consumers perform lower energy savings for the same subsidy than high-income ones in all categories of buildings.

Table 5. Energy consumption for heating and cooling after renovation, avg. in kWh/sqm of the house and in % diff. from the current average level.

2050	Reference Scenario		Enabling Conditions		Climate Neutrality	
OLD-LOW	93	−2%	51	−46%	45	−53%
OLD-MEDIUM	96	−4%	47	−53%	44	−56%
OLD-HIGH	127	−7%	54	−61%	52	−63%
RECENT-LOW	44	−3%	36	−21%	32	−29%
RECENT-MEDIUM	46	−3%	34	−28%	31	−35%
RECENT-HIGH	67	−2%	41	−40%	38	−45%
Total Stock	74	−8%	43	−46%	40	−51%

The model results show a similar pattern across classes for the energy-oriented deepness of the renovation. The subsidy drives a significant increase in the energy-oriented depth of renovation compared to the institutional measures. The share of deep interventions in total houses renovated almost doubles in the *Climate Neutrality* scenario compared to the *Enabling Conditions* scenario (see Table 6). This holds true in all cases of income classes and building types. It is a remarkable result, which indicates that the subsidy is an important tool in delivering maximum energy efficiency, whereas the institutional measures are important to make people undertake renovations without, however, ensuring adequate depth of the renovation. The shift towards greater depth of the renovation is more pronounced for low-income consumers than for high-income ones. In other words, it is more likely that the removal of non-market barriers suffices to incite high-income consumers to undertake fairly deep renovations, but not for low-income consumers, who require a monetary incentive in addition to institutional measures to shift to a deeper renovation. The differential effects by income classes also hold true within the category of recent constructions as well as evidently in more aged houses.

Table 6. Summary of model results for house renovation split by renovation depth level and house or consumer category.

EU28	**Average Annual Refurbishment Rate 2031–2050**				**Investment for Renovation (avg. in €/house)**				**Average Energy Savings Form Refurbishment (Depth)**			
House Classes	**All**	**Light**	**Medium**	**Deep**	**All**	**Light**	**Medium**	**Deep**	**All**	**Light**	**Medium**	**Deep**
	Reference Scenario				Reference Scenario				Reference Scenario			
OLD-LOW	0.94%	0.83%	0.11%	0.00%	7629	7192	10,835	14,246	18.8%	14.2%	53.4%	79.1%
OLD-MEDIUM	1.21%	0.99%	0.21%	0.00%	7981	7346	10,912	14,318	20.6%	13.7%	53.5%	79.1%
OLD-HIGH	1.24%	0.92%	0.32%	0.00%	8349	7369	11,109	14,688	24.7%	14.4%	53.9%	79.6%
RECENT-LOW	0.64%	0.57%	0.07%	0.00%	6239	5748	10,089	14,743	30.1%	26.6%	39.4%	63.9%
RECENT-MEDIUM	0.80%	0.67%	0.13%	0.00%	6605	5933	10,201	14,784	28.6%	25.4%	39.9%	64.1%
RECENT-HIGH	0.76%	0.60%	0.16%	0.00%	6738	5861	10,125	14,776	29.5%	30.0%	44.3%	67.3%
	Enabling Conditions				Enabling Conditions				Enabling Conditions			
OLD-LOW	1.69%	0.16%	1.03%	0.50%	12,029	7271	11,638	14,353	59.3%	14.2%	65.2%	79.3%
OLD-MEDIUM	1.96%	0.19%	1.17%	0.61%	12,118	7420	11,682	14,439	60.5%	13.8%	64.8%	79.3%
OLD-HIGH	1.82%	0.11%	1.01%	0.70%	12,768	7392	11,919	14,811	65.0%	14.5%	65.3%	79.9%
RECENT-LOW	0.94%	0.31%	0.47%	0.16%	9758	5645	10,739	14,737	41.0%	26.7%	46.5%	64.3%
RECENT-MEDIUM	1.47%	0.44%	0.76%	0.28%	10,104	5824	10,836	14,797	41.2%	25.4%	46.9%	64.4%
RECENT-HIGH	1.53%	0.36%	0.78%	0.40%	10,845	5754	10,985	15,159	44.1%	27.9%	49.5%	66.7%
	Climate Neutrality				Climate Neutrality				Climate Neutrality			
OLD-LOW	2.14%	0.08%	1.14%	0.92%	12,755	7271	11,751	14,453	69.2%	14.3%	66.3%	79.2%
OLD-MEDIUM	2.17%	0.09%	1.15%	0.92%	12,743	7407	11,781	14,504	68.3%	13.8%	65.7%	79.2%
OLD-HIGH	1.94%	0.05%	0.94%	0.95%	13,290	7363	12,015	14,867	70.7%	14.5%	66.2%	79.7%
RECENT-LOW	1.23%	0.23%	0.64%	0.36%	11,078	5627	10,973	14,708	46.0%	26.7%	48.7%	64.2%
RECENT-MEDIUM	1.71%	0.34%	0.88%	0.50%	11,053	5798	10,962	14,772	45.1%	25.4%	48.2%	64.3%
RECENT-HIGH	1.71%	0.27%	0.83%	0.60%	11,650	5731	11,074	15,136	47.6%	28.0%	50.6%	66.7%

The uniform subsidy policy maintains and even slightly accentuates the social differences represented by energy costs relative to income. The subsidisation policy, enabling an increase in renovation, improves the affordability of energy expenses by reducing the energy consumption significantly and rather uniformly for all consumers. However, the differences in energy bills as a percentage of income that existed prior to renovation continue to prevail and even increase in magnitude, albeit slightly. Prior to renovation, low-income consumers had to use 2.5 times larger part of their income to purchase energy per unit of income compared to high-income consumers, but after the renovation, they will have to use almost three times a larger part of their income. The uniform subsidy corresponds to the maximum cost-effectiveness of the policy as it minimises the total subsidy budget per unit of energy saved and reduces the energy bills for all consumers, but increases the social differences among income classes.

As expected, the differentiated subsidy rates drive differentiation of renovation intensity, energy savings, and capital expenses by consumer category. Low-income consumers invest more in renovation than under the uniform subsidy regime, hence further reducing energy consumption, and at the same time, require larger funding. Assuming that the non-market barriers have been removed thanks to institutional measures, raising higher funding would be less of a problem. However, capital funding easiness deserves consideration from a policy implementation perspective and is a prerequisite for facilitating low-income classes to trade-off energy fuel expenses, which diminish due to high subsidies, for additional capital funding. In contrast, high-income classes would be less exposed to such challenging issues under a differentiated subsidy regime. They would receive a lower subsidy than under the uniform subsidy policy, hence they would undertake lower investment and save lower amounts of energy, but the changes in the ratio of energy bill over income and for fund-raising are minor. Regarding the group of recently constructed houses, as they are better insulated, the differential effects of the two subsidy allocations are smaller than for the older constructions. In other words, the implementation burden of differentiations probably pays off mainly in the case of old buildings. Figure 5 presents the two subsidy regimes comparatively.

Looking at the policy effected via energy performance standards (see Figure 6) that make renovation mandatory, we considered capital funding as the main scarce resource that the policy chooses to tackle to alleviate distributional impacts When the standards are applied uniformly to income classes, low-income classes need to spend a substantial share of their income as a capital cost to finance the renovation investment to comply with the standard. This share is more than three times higher than for high-income classes. Despite the high investment effort, the energy efficiency gain does not allow low-income consumers to reduce energy bills per unit of income so as to get closer to the economics of the high-income classes. The ratio of the energy bill to income after the renovation, as induced by the standard, continues to be almost three times higher than for high-income classes, a difference that also prevailed prior to renovation. Therefore, applying uniform standards (per age category of buildings) does have adverse social implications. As long as fund-raising continues bothering low-income consumers, the social implications are negative with respect to both capital and cash flow indicators.

In the differentiated standards case, relaxing the standard for low-income consumers, allows them to mitigate the fund-raising burden at the expense of performing less renovation and lower energy savings compared to the case of the uniform standard. The reduction in the ratio of capital costs to income was significant in the case of the differentiated standards, a result that indicates the degree of difficulty in alleviating the social effects when applying a policy based on standards, as in reality, they cannot be differentiated by income level. We tested applying uniform standards to both old and recent constructions and found small differences regarding the challenges of low-income households. In contrast, increasing the level of the standard for high-income consumers to compensate for the reduction in low-income ones causes minor disturbance to the economics of the former. The incremental renovation undertaking driven by the more stringent standard is small in magnitude and the income effects due to capital raising are negligible.

A remarkable policy dilemma is put forward when comparing the two policy approaches. The trade-off is between the share of variable costs in total income, derived from fuel purchasing, and the share of fixed costs in income, corresponding to renovation investment. It turns out that the subsidy policy with differentiated rates by income classes led to a reduction in the variable costs at the expense of increasing the fixed costs, whereas the policy based on standards led to the opposite, leading to lower fixed costs to the detriment of variable expenses. The trade-off derives from the choice of the measurement of the social implication as guidance to differentiate the allocation and alleviate the burden for low-income classes. Using the variable cost indicator for the social policy gives priority to tackling energy poverty, whereas opting for the fixed cost indicator puts forward the aim of ensuring adequate renovation levels, a choice that envisages “technology” poverty as a priority.

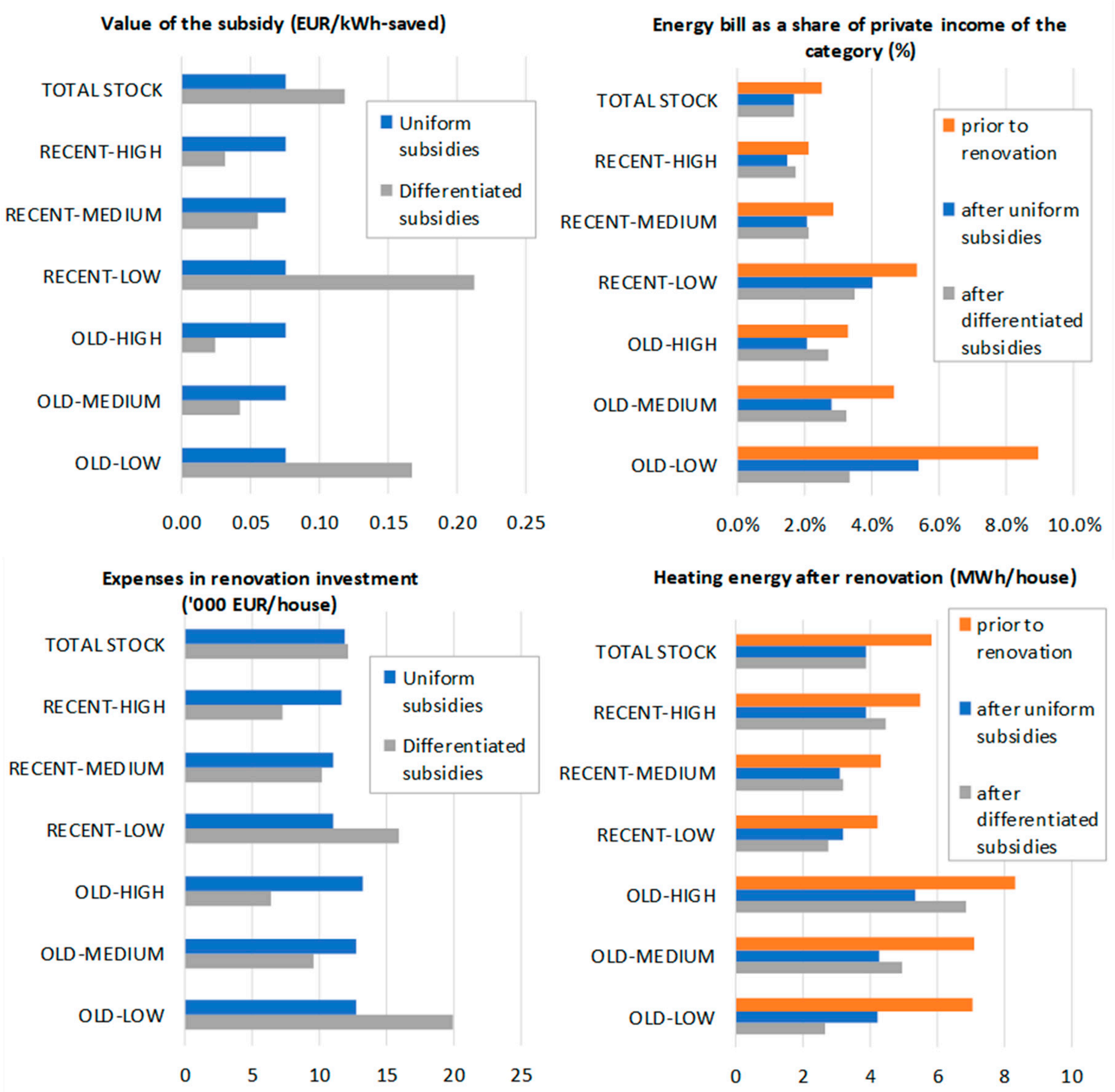


Figure 5. Model results for the subsidy policy case.

Table 7 summarises the information to assess the cost-effectiveness of the efficiency promoting policy options. We measured cost-effectiveness, in the usual manner, as the ratio of total expenses directly entailed by the policy to the resulting energy saving amounts. The calculation is straightforward in the case of the policy based on subsidies for which the budget of the policy is directly the multiplication of subsidy rates by the amount of energy savings. To make the same calculation for the policy based on standards, we first determined the subsidy rate that corresponds as a shadow value to the upper limit on energy consumption by category represented by the respective level of the standard. The shadow subsidy rates are shown in the table.

The results clearly show that the policy based on uniform subsidies performed considerably better with respect to the cost-effectiveness than the policy using differentiated subsidies. The ratio (i.e., unit cost, for the public, of energy saved) for the latter policy was 1.6 times higher than for the former. This is a significant loss of effectiveness at the expense of alleviating social implications.

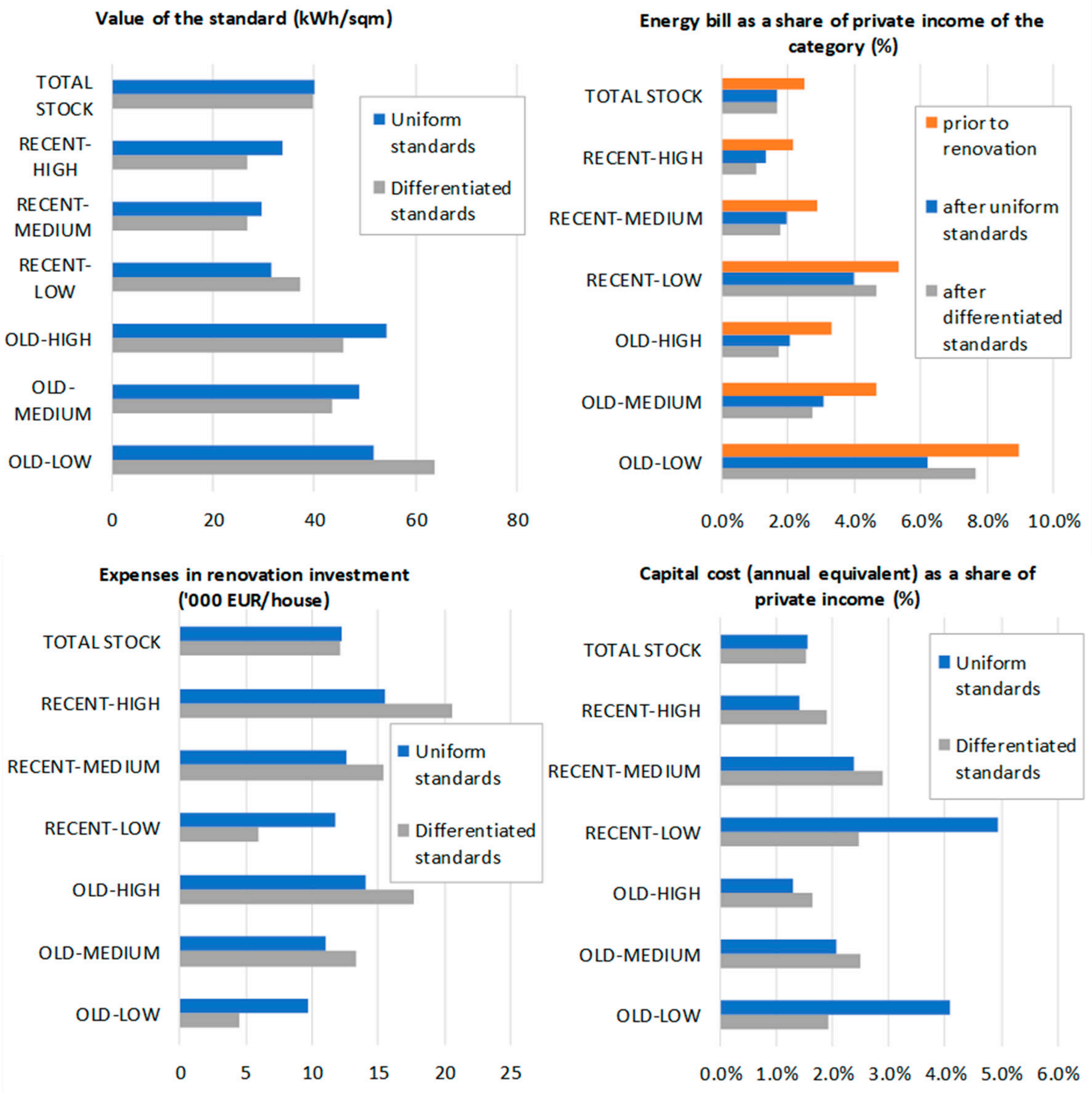


Figure 6. Model results for the standards' policy case.

The policy based on uniform standards applies equal standards only on the same class of building age, and the differentiation only concerns income classes in the corresponding policy variant. The uniform standards do imply different marginal compliance costs, but the differences compared to the case of uniform subsidies are small because the differences are due to building characteristics (as it is logical for technical reasons), rather than to economic features of the consumer. This explains why the inefficiency cost of uniform standards is small in comparison to uniform subsidies.

The differentiated standards aim at alleviating the burden of capital costs, which is relevant for low-income classes, and to this end, it modifies the standards substantially based on social criteria and ignores the marginal cost structures associated with building characteristics. This drives significant deviation from optimality of the policy budget allocation. In fact, the unit cost, for the public, of energy saved is in the case of differentiated standards 1.45 times higher than for the case of uniform standards. This latter policy case puts emphasis on reducing the capital costs for low-income households while at the same time improves the cost-effectiveness, albeit slightly, when compared to the policy based on differentiated subsidies. This is because the relative efficiency of renovation investment driven by the subsidy is slightly higher for high-income consumers than for low-income ones, for various reasons. Without having such intention, the policy focusing on reducing capital costs to alleviate social implications exploits, at the same time, the high energy saving potential of high-income classes in a more efficient manner than the policy focusing on reducing fuel costs for social reasons.

Table 7. Comparison of policy options from the perspective of cost-effectiveness of the policy.

		Customer and Building Categories						
Indicators	**Policy Cases**	**OLD-LOW**	**OLD-MEDIUM**	**OLD-HIGH**	**RECENT-LOW**	**RECENT-MEDIUM**	**RECENT-HIGH**	**TOTAL STOCK**
Policy budget (bn€)	Uniform subsidies	3.0	2.8	1.9	1.3	1.4	1.5	11.9
	Differentiated subsidies	10.6	1.2	0.3	5.4	1.0	0.4	18.9
	Uniform standards	1.4	1.8	2.1	1.7	2.2	3.0	12.2
	Differentiated standards	0.2	2.9	3.6	0.1	4.4	6.5	17.5
Energy after renovation (kWh/sqm)	Uniform subsidies	45	45	56	32	31	39	40
	Differentiated subsidies	26	54	74	27	33	46	40
	Uniform standards	52	49	54	31	29	33	40
	Differentiated standards	65	44	45	38	26	25	40
Ratio of cost-effectiveness of the policy (€ subsidy per kWh saved)	Uniform subsidies	0.075	0.075	0.075	0.075	0.075	0.075	0.075
	Differentiated subsidies	0.162	0.045	0.028	0.201	0.058	0.034	0.119
	Uniform standards	0.047	0.056	0.077	0.086	0.096	0.112	0.077
	Differentiated standards	0.013	0.075	0.103	0.012	0.156	0.175	0.111

4. Summary and Conclusions

The PRIMES-BuiMo was used in this paper to analyse policies inducing ambitious energy efficiency improvement in the EU residential sector, notably through the energy-oriented renovation of the building stock. The EU policy, recognising the fact that deep renovation of old buildings is a key pillar in reaching ambitious energy efficiency targets, has put major emphasis on inciting such investments through various policy instruments. The monitoring of the EU directives has already shown that all countries encounter serious difficulties in promoting strong renovation of the housing stock. Both the national reports and the academic literature have identified that several barriers and inefficiencies deform utility perceptions of consumers, making them behave in a seemingly irrational manner regarding renovation investment.

Modelling behaviours and non-market barriers are difficult in economic research for two main reasons. There is no established method concerning functional forms and parameters to represent seemingly irrational behaviours, and any such model may be subject to criticism for lack of empirical foundation. The model needs to segment the decision-makers in numerous classes to capture the heterogeneity of idiosyncrasies as their variety is large when seemingly irrational behaviours prevail in decisions. The PRIMES-BuiMo was designed in light of this research ambition.

The current paper exploits the model possibilities not only regarding the simulation of energy efficiency behaviours, but also for the assessment of the cost-effectiveness of alternative policy instruments. Any policy instrument is a means of market intervention and entails a cost to be borne by the state, and indirectly by society.

For analytical purposes, a scenario was designed that included only institutional and informational measures, which were assumed to remove non-market barriers to renovation decisions. Then, another scenario was designed that, in addition, includes actively incentivising policies such as price interventions, in the form of subsidies, and quantity interventions, in the form of energy performance standards. The second scenario also has an ambitious energy savings target for buildings, which is in-line with the objective for the energy system to be climate neutral by 2050. The study performed modelling experiments regarding the choice of policy instruments and their specification at an adequate level to meet the energy savings target. Scenario variants were thus quantified for the climate-neutrality goal and on that basis, the study evaluated the policy options comparatively.

The study performed modelling experiments for a variety of rules regarding the specification of the policy instruments, notably by differentiating subsidy rates, and alternatively, the level of the standards by consumer class and building type. The acceptability of the policy is obviously facilitated by varying the policy intensity by class of consumer, but the practical implementation and monitoring may be more difficult when the segmentation in consumer classes is high.

The performance in terms of energy efficiency improvement depends on the rate and the energy-oriented depth of the renovation of old buildings. Both are particularly low historically. The modelling represents the possible benefits of energy-oriented renovation (i.e., a reduction in energy bills and increase in the value of the house) as drivers. The non-market barriers are monetised by the model as if they increase the discount rates and costs. The price-oriented policy instruments increase the economic benefits of renovation investment, whereas the standards make a certain renovation investment imperative.

An important clear conclusion of the model application is that the removal of non-market barriers is of great importance in reducing energy consumption and increasing both the rate and the depth of renovation investment. A substantial part of the energy efficiency objective can be covered only by the institutional and informational measures, which turn out to be an undisputable no-regrets policy measure.

However, institutional measures alone are not enough to induce energy efficiency improvement to the scale required to achieve the climate-neutrality objective. The additional policies need to make economically attractive or mandatory renovation investments that otherwise would have not been decided by households due to their performance below their hurdle rates.

The results of the model show that the subsidy is an important tool for maximising energy efficiency gains, whereas the institutional measures are important to make people undertake renovations without, however, ensuring adequate depth of the renovation.

A policy that applies a uniform subsidy to all categories of households and buildings was found to correspond to the minimum total subsidy budget per unit of induced energy savings. Flat subsidisation does not serve social goals, although it helps reduce the energy bills for all consumer classes, it does not close the gap between low- and high-income groups.

The study employed the ratio of energy bills to income as an indicator to measure distributional implications of subsidisation policies and to guide differentiation of subsidy values by income class. The differentiation of subsidies weakens the cost-effectiveness of the subsidy budget. It is critical to ensure ease of fund-raising for low-income consumers, otherwise, the policy effectiveness would further worsen.

The regulation based on standards needs to consider the technical attributes of the building, notably the age of the building. Defined to equalise marginal compliance costs across building types, the policy leads to a pattern that corresponds to a similar cost-effectiveness performance as the policy based on uniform subsidies.

Not varying the level of standard by income class also implies similar adverse distributional effects as derived from uniform subsidies. However, it is impractical to establish different standards based on income attributes, for many reasons including monitoring difficulties. The policy based on subsidies is therefore more flexible than the standards in addressing distributional implications.

Despite the implementation difficulties, the study explored the differentiation of standards based on income criteria. Given that the imposition of a standard implies undertaking investment, the study employs the indicator of capital costs relative to income as guidance in differentiating the level of the standards.

The modelling experiments used a variable cost indicator (i.e., fuel costs) to differentiate subsidies and a capital cost indicator (i.e., capital costs for refurbishment) to differentiate the standards among income classes. Essentially, the first option puts a priority on tackling energy poverty, whereas the second option aims at increasing renovation to avoid "technology" poverty.

The optimum policy mix obviously derives from a compromise among various aims including the cost-effectiveness of the policy budget (direct or indirect) and the distributional impacts. For the latter, attention should be paid on the type of economic burden to tackle in a priority for low-income classes, notably, whether to improve energy bills or the fund-raising possibilities. This appreciation should guide the relative mix of subsidies and standards as well as the focus of the accompanying institutional policies.

An important limitation of the study is that the model-based quantifications have ignored the inefficiencies in the implementation of the various policy options. Policies based on subsidies are often inefficient due to the misuse of the revenue generated by the subsidy. Policies based on standards are inefficient when the degree of compliance is not satisfactory. Both options would, in reality, lead to lower energy efficiency gains than the analysis calculated using the model.

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Appendix A

Table A1. List of databases, projects, and reports we combined and elaborated to build the database for the PRIMES-BuiMo building stock and energy consumption for the years 2005 to 2015.

Name of Database/ Project/Report	Reference	Use
TABULA	TABULA, 2017	EN 13790:2008 for heating/cooling
BPIE	BPIE, 2011	U-values for the buildings stock
EU Building Stock Observatory	EU BSO	Number of buildings by type
		Surface of buildings by type
		U-values for the buildings stock
		Energy renovation rate
		Energy renovation deepness
EUROSTAT	Distribution of population by degree of urbanisation, dwelling type and income group [ilc_lvho01]	Split of buildings by category
	Average number of rooms per person by degree of urbanisation [ilc_lvho04d]	
	Demographic balance and crude rates [demo_gind]	
	Household characteristics by urbanisation degree [hbs_car_t315]	
	Living conditions - cities and greater cities [urb_clivcon]	
	Energy balances	Final energy consumption by fuel in the residential and services sector
	Disaggregated final energy consumption in households [nrg_d_hhq]	Final energy consumption by fuel and use in the residential sector
EPISCOPE projects	EPISCOPE, 2017	Split of buildings by category
Heat Roadmap Europe	Profile of heating and cooling demand in 2015	Final energy consumption by use in the services sector
The Housing statistics	Haffner, 2010	Average useful floor area per dwelling and per person
	S. Birchall, 2014	Energy needs and architectural features of the EU building stock

Appendix B

Table A2. List of databases, projects, and reports we combined and elaborated to build the database for the PRIMES-BuiMo stock, energy consumption, and technoeconomic characteristics of the equipment.

Name of Database/Project/Report	Reference	Use
ODYSEE-MURE	ODYSEE Database	Stock and energy consumption of electrical appliances
BRG Building Solutions	The European Heating Product Markets, 2018	Stock of appliances for heating and water heating
EurObserv'ER	Heat pumps barometer 2020	Stock of heat pumps
2050 Pathways for Domestic Heat—Final Report—DELTA Energy & Environment		Technoeconomic characteristics of technologies used for heating and cooling in the residential and services sector
Spon's Mechanical and Electrical Services Price Book 2015		
Updated Buildings Sector Appliance and Equipment Costs and Efficiencies—EIA		
IRENA-IEA-ETSAP Technology Brief 3: Heat Pumps		
Heat Pump Implementation Scenarios until 2030—ECOFYS		
Technology Roadmap—Energy Efficient Buildings: Heating and Cooling Equipment—IEA		
Eco-Design directive	EuP Lot 22 Domestic and Commercial Ovens	
	EuP lot 23 Domestic and Commercial Hobs and Grills	
	ENER Lot 20—Local Room Heating Products	
Online available brochures of manufacturers and retailers		
"Omnibus" Review Study on Cold Appliances, Washing Machines, Dish Washers, Washer-Driers. Lighting, Set-top Boxes and Pumps		Technoeconomic characteristics of appliances in the residential sector
Buildings Energy Data Book (2011)—U.S. Department of Energy		
ENTRANZE Project	Entranze, 2017	Technoeconomic on renovation in the residential and services sector
Eco-Design directive	EUP, 2017	Technoeconomic characteristics of technologies used for heating and cooling in the services sector

Appendix C

Table A3. Nomenclature of the PRIMES-BuiMo and scenario variables.

Nomenclature	
Sets	
t	Time (years) within a time horizon $\tau \leq t \leq T$
h	Building categories
i *or* ii	Discrete set of dynamic strategies
j	Deepness of energy efficiency investment in renovation
Variables	
$I_{t,h,i}$	Investment expenditures for renovation (i.e., investment costs, hidden costs and/or subsidies) (€/household)
$C_{t,h,i}$	Annual costs of renovation (i.e., variable fuel and non-fuel costs) (€/household)
$v_{h,i}$	Present value of cost streams to compare alternative renovation strategies (€/household)
$f_{h,i}$	Frequency of choice of renovation strategies i per building category h
$S_{t,tt,h,i}$	The cost savings deriving from the implementation of the energy efficiency investment
$Q_{tt,h,j}$	The volume of energy savings deriving from investment $I_{tt,h,j}$

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