Energy Policies for Eco-Friendly Households in Luxembourg: 
a Study Based on the LuxHEI Model

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Abstract
In the Grand Duchy of Luxembourg, the residential building sector is a major energy consumer and greenhouse gases emitter that plays a key role in achieving the country’s environmental objectives. The purpose of this work is to assess the effectiveness of the most important policy instruments in decreasing the final energy consumption and direct CO2 emissions of Luxembourgish households. To this end, we developed the LuxHEI model, which is an enhanced and upgraded version of the well-known French simulation model Res-IRF. This variant has also been adjusted to the particular problems of a small country with growing economy and a quickly increasing population. The LuxHEI model goes beyond standard energy-economy models by incorporating global warming as a decision-making factor. The model outcomes reveal that in 2060, and compared with the no-policy baseline scenario, the most aspirational policy mix enables energy savings of 42% and emission reductions of 60%. However, in none of the projections, the residential building sector meets the national energy and climate targets on time. From the results we can draw the following policy implications: for a significant improvement of the sector’s energy efficiency and sufficiency, the implementation of a remediation duty for existing buildings and the tightening of the performance standards for new constructions, together with the application of a national carbon tax, are crucial.

Keywords Climate targets · Energy-economic policy modeling · Energy efficiency · Emission mitigation · Residential building sector

JEL Classification C10 · C63 · D10 · Q4

1 Introduction
Despite the fact that residential building sector has been known for a long time to hold a large and cost-effective energy- and emission-saving potential [1, 2], only a fraction of it is currently exploited [3]. Yet, with today’s efforts to mitigate the devastating consequences of human-made climate change [4] being largely insufficient to meet the vital goals of the Paris Agreement [5], the further exhaustion of this key GHG-emitting sector’s potential is now more important than ever. In order for this to be realized, the application of energy policies that aim at increasing energy efficiency and sufficiency is considered to be crucial [6].

In this light, the current study aims at evaluating the effectiveness of the most important policy instruments in making Luxembourgish households more eco-friendly, that is, reduce final space heating energy consumption and direct CO2 emissions. More precisely, we analyze the following: (1) the ranking of the policy instruments in terms of environmental and economic effectiveness when applied individually; (2) the ways in which the instruments generate savings; (3) how the instruments’ effectiveness is affected when applied concurrently; and (4) whether or not the national energy and climate objectives are achievable in the country’s residential building sector.

Although there exists a rich literature on the assessment of various energy policy instruments,1 the one that specifically analyzes their environmental and economic

1Just to mention a few: [7–18].
effectiveness, when being applied (individually or in combination) to promote energy efficiency in the residential building sector, is relatively scarce. Additionally, the latter analysis has, to our best knowledge, so far not been performed for Luxembourg; yet the impacts of policy tools can strongly differ among countries [19]. To fill this gap, we built on the work of [20–22] and design a significantly enhanced Luxembourgish version LuxHEI (Luxembourgish Households’ Energy Indicators model) of the French hybrid energy-economy model Res-IRF (Residential module of IMACLIM-R). Indeed, the Res-IRF model is unique in its kind, that is, we are not aware of any other model that is able to perform a similar analysis. What makes our project all the more important for Luxembourg’s political decision-makers is the fact that the country has committed itself to meet ambitious energy and climate targets over the next decades, while at the same time being expected to face both good economic development and the largest population growth rate (the population is projected to double until 2060) among all EU Member States [23].

The Res-IRF model is basically designed as a bottom-up model: technologically powerful but microeconomically rather limited [24]. Since the model’s microeconomic weakness is, however, largely compensated by incorporating several “barriers” to energy efficiency, it is considered a hybrid energy-economy model [24]. Indeed, engineering bottom-up models typically tend to follow the assumption of neoclassical economics, that is, consumers behave efficiently when making energy conservation investments. As this hypothesis requires a correct modeling of the costs and the decision-making behavior, [21] modeled the impacts of “market barriers” like hidden-costs and consumer heterogeneity. Besides that, the real world decision-making has been found to not always coincide with the neoclassical viewpoint, that is, not all capital expenditures with positive net present value are realized. This phenomenon is often referred to as the energy efficiency gap or paradox, for which several explanations exist in the literature: [3, 25–31]. For neoclassical economists, on the one hand, such suboptimal decisions result from an imperfect market structure; in a perfect market, consumers would still act rationally [32]. To include this “market failure,” the model takes into consideration asymmetric information, learning-by-using, and the principal-agent problem. For behavioral economists, on the other hand, “behavioral failures” are to be blamed for suboptimal consumer investments [32]. This explains why the model also relies on restricted consumer awareness. Finally, in order to reduce overestimations of the sector’s energy saving potential, the rebound effect is considered in the simulation.

The most important innovative feature of the LuxHEI model is probably the fact that it encodes climate change as a decision-making influence factor. More specifically, we assume that the significant consequences of global warming imply, firstly, that the percentage of the existing building stock that is renovated annually increases over time (from 1 to 3%) and, secondly, that the market becomes more heterogeneous. This allows us to go beyond standard models, which are often based on financial considerations only. Yet, models that do not take sufficient account of the effects of climate change have reduced informative value and misinform policy-makers. In other words, climate change improves the modeling of the decision-making behavior and thus further compensates for the microeconomic weakness of bottom-up models. The LuxHEI model also changes various other modeling methods of the Res-IRF model or adapts them to the available national data and the peculiarities of a small country with growing economy and quickly increasing population. We encoded, for example, the special national situation in all calibration procedures, parameterizations, and evaluated policy instruments.2 Beyond that, we included more sustainable energy efficiency classes (zero energy buildings (ZEB) and positive energy buildings (PEB)), energy carriers (pellets and solar), and heating systems (heat pumps). As to the carriers considered in the LuxHEI model, some of them are now authorized only in higher energy efficiency classes and some carrier switches became prohibited. The discrepancy that exists between the Luxembourgish households’ conventional and effective energy needs for heating was incorporated through an adjustment factor, which we determined empirically—for each energy efficiency class and each carrier. Furthermore, when an owner retrofits its dwelling, the tenant or potential buyer profits from reduced heating energy costs. The LuxHEI model encodes the corresponding green value, that is, the percentage of the energy costs savings that the owner can expect recovering through the monthly rent or the sales price. In addition, we encoded a dynamic evolution of the new constructions’ building types and changed the inclusion of discount rates. The preceding innovations are improvements that further adjust the LuxHEI model to reality.

Regarding our main findings, we get that (1) the highest environmental and economic effectiveness is achieved by the building codes, followed by the national carbon tax and the remediation duty; (2) while subsidy schemes and regulatory policies have a stronger impact on energy efficiency than on energy sufficiency, it is the other way around for taxes; (3) when the policies are applied concurrently, their individual effects are summed, so that the greatest savings are realized by the policy package with the

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2We wish to emphasize that the LuxHEI model allows to perform the present study for any other country, as long as there exists sufficient data to complete the necessary calibration and parameterization procedures.
largest number of instruments; and (4) even in the projection with the highest environmental effectiveness, the residential building stock can only meet Luxembourg’s energy and climate targets with delay.

The article is structured as follows. Section 2 describes how the final energy consumption of Luxembourgish households is encoded in the LuxHEI model. In Section 3, we outline the modeling of the existing building stock’s transformation. Section 4 completes the explanation of the model by elucidating the dynamics of the new building stock. In Section 5, we depict the policy instruments that are analyzed and explain how they are modeled. Section 6 presents and discusses the results of our simulations. In a final section, we draw conclusions and make policy recommendations.

2 The LuxHEI Model (I): Energy Consumption

Our objective is to study, between 2014 and 2060, the impact of various policy tools on the space heating final energy consumption $E_{\text{fin}}$ of Luxembourgish households.\(^3\)

2.1 Final Energy Consumption

The final energy consumption $E_{\text{fin}}(t)$ in the year $t$ (in kWh) is given by:

$$E_{\text{fin}}(t) = S(t) \frac{E_{\text{con}}(t)}{S(t)} - E_{\text{con}}(t),$$

(1)

where $S(t)$ denotes the total residential building stock (in m\(^2\)), $E_{\text{con}}(t)$ is the theoretically/Conventionally needed final energy (in kWh/m\(^2\)), and where $E_{\text{fin}}(t)/E_{\text{con}}(t)$ is the quotient of the effective and the conventional needs (dimensionless).

We attribute an energy efficiency class to each dwelling. For existing dwellings, we use classes $i \in \mathcal{I} = \{1, \ldots, B, A\}$, where $A$ is the most efficient and $I$ the least efficient of the 9 classes in $\mathcal{I}$. For new buildings we consider only 4 classes $j \in \mathcal{J} = \{B, A, ZEB, PEB\}$. Besides that, we introduce 32 additional categories: (1) we distinguish between owner-occupied individual houses and flats and tenant-occupied individual houses and flats, which defines the 4 categories $D \in \mathcal{D} = \{O-H, O-F, T-H, T-F\}$; and (2) we consider the 8 energy carriers heating oil, gas, electricity, pellets, oil combined with a solar thermal system, gas with solar, electricity with solar, and pellets with solar, which gives the 8 categories $e \in \mathcal{E} = \{F, G, E, P, F+s, G+s, E+s, P+s\}$. Altogether, we thus obtain for each $k \in \mathcal{I} \cup \mathcal{J}$, a $4 \times 8$ matrix of categories $D, e$. Note that here each class $k$ is defined by an overall primary

\(^3\) Starting from the situation on 31 December of our initial year $t = 2013$, we compute the situation on 31 December of the year $t + 1 = 2014$, from this, the situation in 2015, and so on, up to 2060.

energy demand that we can transform for each type $e$ of carrier into a conventional final energy $\rho_{k,e}$ needed for heating per square meter (and year).\(^4\)

Consequently, when denoting the residential building stock in $k, D, e$ by $S_{k,D,e}(t)$ and the factor $E_{\text{fin},k,e}(t)/E_{\text{con},k,e}(t)$ in $k, e$ by $F_{k,e}(t)$, we get that the final space heating energy of Eq. 1 is actually computed by:

$$E_{\text{fin}}(t) = \sum_{k \in \mathcal{I} \cup \mathcal{J}} \sum_{D \in \mathcal{D}} \sum_{e \in \mathcal{E}} S_{k,D,e}(t) \rho_{k,e} F_{k,e}(t),$$

(2)

where the dimensionless factor $F_{k,e}(t)$ is the adjustment factor and where the conventional energies $\rho_{k,e}$ ($k \in \{ZEB, PEB\}$ and $e = E + s$) are the sums of the buildings’ theoretical energy consumption $\rho_{k,e}^{\text{con}}$ and the opposite $\rho_{k,e}^{\text{pro}} < 0$ of their theoretical energy production. We highlight that for $k \in \{ZEB, PEB\}$, $D \in \mathcal{D}$ and for $e = E + s$, the terms $S_{k,D,e}(t) \rho_{k,e} F_{k,e}(t)$ in Eq. 2 must be interpreted as $S_{k,D,e}(t) \left(\rho_{k,e}^{\text{con}} F_{k,e}(t) + \rho_{k,e}^{\text{pro}}\right)$. In this case, we must hence rewrite Eq. 2 as:

$$E_{\text{fin}}(t) = \sum_{k \in \mathcal{I} \cup \mathcal{J}} \sum_{D \in \mathcal{D}} \sum_{e \in \mathcal{E}} S_{k,D,e}(t) \left(\rho_{k,e}^{\text{con}} F_{k,e}(t) + \rho_{k,e}^{\text{pro}}\right).$$

2.2 Adjustment Factor

We model the adjustment factor\(^5\) as a logistic function:

$$F_{k,e}(t) = a + \frac{b}{1 + \exp(c \rho_{k,e} P_e(t) - d)}(a, b, c, d \text{ constant}).$$

(3)

The references for the price $P_e(t)$ of the carrier $e$ in the year $t$ (expressed in per kWh) are the energy price projections in [34] and [35]. The modeling of the adjustment factor by such a logistic function was suggested in [36] and used in [21].

Equation (3) captures the impact of energy efficiency measures and energy price variations on energy sufficiency; known as prebound or rebound effect [37]. The concept behind this effect is that while households in dwellings with a low energy performance (high $\rho_{k,e}$) tend to consume less energy than the conventional energy $\rho_{k,e}$ (prebound effect, $F_{k,e}(t) < 1$), the exact opposite occurs in buildings with a

\(^4\) A detailed description of the determination of the conventional unit space heating energies can be found in [33].

\(^5\) This factor takes into account the discrepancy that exists between the effective and the conventional energy needs. Additional information about the origin of this discrepancy, as well as a detailed explanation of the adjustment factor’s calibration, can be found in [33].
high energy performance (low $\rho_{k,e}$): the measured energy consumption of these households is close to or even exceeds $\rho_{k,e}$ (rebound effect, $F_{k,e}(t) > 1$). The user behavior is similar when $P_e(t)$ passes from high values to low ones. The best modeling choice for $F_{k,e}(t)$ is therefore a decreasing logistic function ($c > 0$) in $\rho_{k,e} P_e(t)$.

We wish to highlight that the adjustment factor depends on:

$$\rho_{k,e} P_e(t) = \left(\rho_{k,e}^{\text{cov}} + \rho_{k,e}^{\text{pro}}\right) P_e(t),$$

and not on $\rho_{k,e}^{\text{cov}} P_e(t)$ alone. This is because the households are assumed to adjust their behavior to the net amount of money they make from their own energy production and not to the money that they spend for heating. Furthermore, using the latter sum of money would mean that the factor $F_{k,e}(t)$ is the same in the classes $A$, ZEB and PEB, since these classes have the same insulation and thus the same theoretical energy consumption. Our hypothesis rather implies that the adjustment factor increases when passing from $A$ to ZEB and from there to PEB.

3 The LuxHEI Model (II): Dynamics of the Existing Building Stock

Note that we study separately the building stock that existed at the end of 2013 (EBS) and the building stock that was newly constructed as of 2014 (NBS).

Regarding the EBS, for each $i \in I$, $D \in D$ and $e_i \in E$ (subscript $i$ added to avoid possible subsequent ambiguity), we must compute the existing building stock $S_{i,D,e_i}(\tau)$ in $\tau = t + 1$ from the known entries $S_{i,D,e_i}(t)$ of a $9 \times 4 \times 8$ matrix. For this purpose, we use:

$$S_{i,D,e_i}(\tau) = (1 - \gamma_{i,D,e_i}(t))S_{i,D,e_i}(t) - \sum_{f > i} \text{TRANS}_{i,f ; D,e_i}(\tau) + \sum_{h > i} \text{TRANS}_{h,i ; D,e_i}(\tau), \quad (4)$$

where $\gamma_{i,D,e_i}(t)$ is the demolition rate of the stock $S_{i,D,e_i}(t)$. The second and third terms are the renovations/transitions in $\tau$ from class $i$ to a higher efficiency class $f$ and from a lower class $h$ to the class $i$, respectively. For example, to get the existing stock in class $i = F$ in 2017, we start from the existing stock in class $F$ in 2016 that was not destroyed. From this stock, we deduct the buildings in the energy class $F$ that were upgraded to any higher energy class in 2017 and add the buildings that were upgraded to the energy class $F$ in 2017.

The next equation explains the computation of the second term of Eq. (4) (the third term is calculated analogously):

$$p \text{TRANS}_{i,f ; D,e_i}(\tau) = (1 - \gamma_{i,D,e_i}(t))S_{i,D,e_i}(t) X_{i,D,e_i}(\tau) \frac{\rho_{k,e}^{\text{cov}} P_e(t)}{(\rho_{k,e}^{\text{cov}} + \rho_{k,e}^{\text{pro}}) P_e(t)} \quad (5)$$

To find the transitions/retrofits from the initial class $i$ to any higher final class $f$, the model thus computes the fraction $X_{i,D,e_i}(\tau)$ of the undamaged stock in $i$ that is retrofitted in $\tau$ (proportion of retrofits in class $i$) before the fraction $\frac{\rho_{k,e}^{\text{cov}} P_e(t)}{(\rho_{k,e}^{\text{cov}} + \rho_{k,e}^{\text{pro}}) P_e(t)}$ of the latter that is retrofitted to $f$ in $\tau$ (proportion of retrofits to class $f$). We explain in Section 3.5 how the demolition rate $\gamma_{i,D,e_i}(t)$ is computed from the time-invariant average demolition rate $\gamma$ in the whole stock $S(t)$.

3.1 Distributions of Retrofits

Without Climate Change The distribution $PR_{i,f ; D,e_i}(\tau)$ in the year $\tau$ of decided retrofits in a class $i$ over all higher classes $f$ is given by:

$$PR_{i,f ; D,e_i}(\tau) = \frac{LCC_{i,f,D,e_i}(\tau)^{\nu}}{\sum_{h \geq i} LCC_{i,h,D,e_i}(\tau)^{\nu}}. \quad (6)$$

Indeed, when a retrofit from $i$ was decided, the number of retrofits from $i$ to $f$ is roughly proportional to the inverse of the life cycle costs $LCC_{i,f,D,e_i}(\tau)$ of such a renovation. Hence, the percentage $PR_{i,f ; D,e_i}(\tau)$ is obtained by Eq. (6) with $\nu = 1$. In this case, the observed percentages in the initial year, however, do not correspond well with the computed ones. While the accordance becomes better for higher values of $\nu$, the best one is obtained for $\nu = 7$. This technique was first introduced by [38] to model consumer heterogeneity, which corresponds to one of the abovementioned market barriers. More specifically, values of $\nu$ close to 1 reflect preference heterogeneity: the choice of different investment options is relatively even. In contrast, higher values of $\nu$, such as $\nu = 7$, reflect a more homogeneous investment behavior: the retrofitting option with the lowest life cycle costs $LCC_{i,h,D,e_i}(\tau)$ is selected by most consumers.

Climate Change Up to here, the model is based on typical price-demand relationships and ignores possible shocks that could suspend this rule. Yet, in view of current climate trends [4], it is likely that over the next decades, the effects of climate change will steadily become more perceptible for society. Additionally, not only will the Luxembourghish population’s educational level keep raising [39] but also is the country projected to face both economic growth and increasing disposable household incomes [23]. Consequently, as environmental awareness is an increasing function of the experience of global warming impacts
and the educational level [41, 42], the latter can be expected to increase over the modeling period. Moreover, we know from [43] that the inhabitants of a territory with economic growth, an above-average income per capita and bad environmental quality, have great willingness to invest in environmental improvement measures. This tendency is further strengthened by self-serving reasons [43], for instance, an improvement of the insulation of a dwelling to decrease suffering from heat rather than to protect the climate. Against this backdrop, we suppose that Luxembourgish households will progressively accept spending more money for a retrofitting to a low energy class and a nonfossil carrier—even if this decision is not optimal from a financial viewpoint. In this case, the market will become more heterogeneous, that is, the parameter \( \nu \) decreases over time. A detailed description of the modelling method of the dynamic parameter \( \nu \) can be found in Appendix A1.

Life Cycle Costs

Coming back to the life cycle costs \( LCC_{i,f,D,ei}(\tau) \) in Eq. 6, they are the sum of the investment/retrofitting costs \( INVC_{i,f}(\tau) \), the energy operating costs \( ENERC_{i,f,D,ei}(\tau) \), and the intangible costs \( IC_{i,f}(\tau) \):

\[
LCC_{i,f,D,ei}(\tau) = INVC_{i,f}(\tau) + ENERC_{i,f,D,ei}(\tau) + IC_{i,f}(\tau).
\]

The model assumes that first the decision to renovate from \( i \) to \( f \) is made and that only then the decision to switch from the initial carrier \( e_i \) to a final one is taken. Therefore, the energy operating costs \( ENERC_{i,f,D,ei}(\tau) \) are based on the initial carrier \( e_i \); below, we explain their dependence on \( i \in I \) and \( D \in D \). The remainder of this subsection more precisely depicts the three terms in Eq. 7.

1. **Investment Costs**

The evolution of the investment costs \( INVC_{i,f}(\tau) \) is modeled by:

\[
INVC_{i,f}(\tau) = INVC_{i,f}(0) \left( \alpha + (1 - \alpha)(1 - l)^{\log_2\frac{C_f(\tau)}{C_f(0)}} \right).
\]

(8)

A large spectrum of measures can be taken to retrofit a building from an energy class \( i \) to a higher class \( f \). The initial retrofitting costs \( INVC_{i,f}(0) \) of Table 1 are hence average costs, which include costs ranging from small improvements of the envelope and the heating system to significant ones.6

The idea of equation (8) is that the retrofitting costs \( INVC_{i,f}(0) \) in the year 0 have decreased in the year \( \tau \) due to the experience \( C_f(\tau) \) accumulated in \( \tau \) through realized retrofits to the class \( f \). The term \( INVC_{i,f}(0)\alpha \) is the percentage \( \alpha \) of the initial retrofitting costs that cannot be decreased by experience (see Table 4 for the precise value of \( \alpha \)). The reduction of the remaining costs \( INVC_{i,f}(0)(1 - \alpha) \) is modeled through the multiplication by the exponential function \((1 - l)^{\log_2\frac{C_f(\tau)}{C_f(0)}}\). Here, the constant \( l \) (see Table 4) is a market failure called the learning-by-doing rate and the accumulated experience \( C_f(\tau) \) is calculated from \( C_f(t) \) by:

\[
C_f(\tau) = C_f(t) + \sum_{i < f D,ei} TRANS_{i,f ; D,ei}(t)
\]

(9)

and

\[
C_f(0) = 15 \times 1% \times S_f(0)
\]

(10)

where the experience \( C_f(0) \) in 2013 was accumulated through retrofits between 1998 and 2012. For \( C_f(\tau) = 2^\lambda C_f(0) \), we find that:

\[
(1 - l)^{\log_2\frac{C_f(\tau)}{C_f(0)}} = (1 - l)^n,
\]

(11)

which means that for each doubling of the experience, the price \( INVC_{i,f}(0)(1 - \alpha) \) is multiplied by \( 1 - l \), that is, it decreases by \( l \).

2. **Energy Operating Costs**

   **Step 1: Approximate energy costs**

The energy operating costs (in per \( m^2 \)) over the average lifetime \( N \) (see Table 4) of a retrofit are the sums:

\[
ENERC_{f,e_i}(\tau) = \sum_{t=1}^{N} P_e(\tau + t) \rho_{f,e_i},
\]

(12)

where the energy price \( P_e(\tau + t) \) of carrier \( e \) (in per kWh) again follows the projections of [34] and [35]. The terms of the sums in Eq. 12 are costs, denoted by \( C_t \), that are paid over the \( N \) years of the lifetime. To cover the retrofitting cost, the decision maker may use money from an interest-bearing investment with interest rate \( r_D \) and therefore bases her decision on the net present value of the periodic cash flows \( C_t \). Besides that, the model considers the prices \( P_e(\tau + t) \) as constant over lifetime and replaces them by \( P_e(\tau) \). The reason for this is a market failure: similar to the findings in [44], we assume that uncertainty about the energy price evolution leads people to drop a part of the information at disposal when making decisions about energy conservation.

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6The matrix of initial investment costs respects similar rules to those used in [21] and was determined after concertation with experts from renovation companies.
investments. By implication, the model calculates the energy operating costs as follows:

$$E N E R C_{f,D,e_i}(\tau) = \sum_{t=1}^{N} \left( 1 + r_D \right)^{-t} - r_D^{-t} \left( P_{e_i}(\tau) \left( \rho_{i,e_i} - \rho_{f,e_i} \right) \sum_{t=1}^{T} \left( 1 + r_D \right)^{-t} \right) G, \quad (13)$$

This modeling allows to account for the landlord-tenant dilemma (or principal-agent problem), which constitutes an important market failure to energy renovation in the residential sector of the European Union [45]. Actually, this dilemma occurs if tenants and landlords have split incentives, for example, if tenants wish to reduce their energy bill through energy efficiency measures but owners are reticent to come up for the costs (as they have no direct return on the investment) [46, 47]. As a result, when it comes to energy efficiency investments, non-occupying homeowners require a higher profitability than occupying homeowners. In order to model the lower (higher) number of renovations in the categories T-H and T-F (O-H and O-F), we assign different interest rates to these four decision situations $D$:

$$r_{T-H} = 0.10, \quad r_{T-F} = 0.07, \quad r_{O-H} = 0.30 \quad \text{and} \quad r_{O-F} = 0.25. \quad (3)$$

The lower (higher) rates for tenant-occupied (owner-occupied) dwellings produce higher (lower) net present values or energy operating costs. The model therefore yields lower (higher) numbers of renovations in the categories T-H and T-F [O-H and O-F].

**Step 2: Energy costs with green value**

In Luxembourg, owners sell their dwellings after an average period $T$ of 9 years. When an owner retrofits (we assume that he renovates right after he bought the habitation), the potential tenant and the future buyer have the advantage of reduced energy costs. On that account, we include the green value $G$ (see Table 4), which corresponds to the percentage of the energy cost savings that the owner recovers through monthly rents or an increased sales price. For occupying owners $D$, we therefore replace the approximate energy costs of Eq. 13 by the energy costs:

$$E N E R C_{i,f,D,e_i}(\tau) =$$

$$P_{e_i}(\tau) \rho_{f,e_i} \sum_{t=1}^{T} \left( 1 + r_D \right)^{-t}$$

$$- \left( \sum_{t=T+1}^{N} \left( 1 + r_D \right)^{-t} \right) G, \quad (14)$$

where the last term is the percentage of the energy cost savings of the new owner, which $D$ recovers when selling her dwelling. If $D$ is a non-occupying owner, she can furthermore recover the same percentage through the rents that the tenant pays during the first $T$ years:

$$E N E R C_{i,f,D,e_i}(\tau) =$$

$$P_{e_i}(\tau) \left( \rho_{f,e_i} - \rho_{e_i} \right) \sum_{t=1}^{T} \left( 1 + r_D \right)^{-t}$$

$$- \left( \sum_{t=T+1}^{N} \left( 1 + r_D \right)^{-t} \right) G, \quad (15)$$

where $r_{D'}$ is the owner interest rate that corresponds to the tenant interest rate $r_D$ (for example, if $D = T-H$, then $D' = O-H$, since the buyer tries to reduce the increase of the sales price).

**Intangible Costs**

When the calculation of the proportions $P R_{i,f:D,e_i}(\tau)$ is based only on the two former costs, that is,
\( IVC_{i,f}(\tau) \) and \( ENREC_{i,f,D,e_i}(\tau) \), the computed proportions in the year 0 do not coincide with the observed proportions. To counter this gap, \cite{21} uses intangible costs \( I_{C,i,f}(\tau) \), split into hidden intangible costs \( HIC_{i,f}(\tau) \) (market barrier) and intangible costs \( IIC_{i,f}(\tau) \) due to imperfect information. Given that hidden costs can, on the one side, hardly be changed, they are calculated as a constant percentage \( \beta \) (see Table 4) of the initial intangible costs: \( HIC_{i,f}(\tau) = I_{C,i,f}(0) \beta \). On the other side, imperfect information gets smaller with growing accumulated experience \( C_f(\tau) \) \cite{3, 51}, so that the costs \( IIC_{i,f}(\tau) \) decrease and eventually tend to disappear completely. We model the evolution of these costs by:

\[
IIC_{i,f}(\tau) = I_{C,i,f}(0) \frac{1}{1 + c \exp \left( d \frac{C_f(\tau)}{C_f(0)} \right)} \quad (c, d > 0),
\]

where the decreasing logistic function of the relative accumulated experience \( \frac{C_f(\tau)}{C_f(0)} \) takes the value \( 1 - \beta \) for \( \tau = 0 \). Equation 16 can be compared with the learning-by-doing rate \( \mu \): recall that when the initial accumulated experience \( \psi f \) doubles, the initial value \( 1 - \beta \) is multiplied by a factor \( 1 - \mu \). The percentage \( \mu \) can be compared with the learning-by-doing rate \( \mu \): recall that when the initial accumulated experience doubles, the initial value \( 1 - \alpha \) is multiplied by \( 1 - \beta \) (see Eq. 11). In this sense, the percentage \( \mu \) (see Table 4) can actually be interpreted as the information acceleration rate, which is related to the asymmetric information that causes the market failure; the learning-by-doing rate can be interpreted analogously. We obtain that way the system of equations:

\[
\frac{1}{1 + c \exp(d)} = 1 - \beta \quad \text{and} \quad \frac{1}{1 + c \exp(2d)} = (1 - \beta)(1 - \mu),
\]

where

\[
c = \frac{(1 - \mu)^2}{(\mu + (1 - \mu)\beta)(1 - \beta)} > 0 \quad \text{and} \quad d = \ln \left( \frac{\mu}{(1 - \mu)\beta} + 1 \right) > 0.
\]

Here, the constant \( c \) determines the proportion \( \frac{1}{1 + c} \) that corresponds to \( C_f(\tau) = 0 \) and the constant \( d \) is responsible for the steepness of the sigmoid curve. Equation 17 shows that if the information acceleration rate \( \mu \) increases, the values of \( \frac{1}{1 + c} \) and \( d \) increase; just the way it should be. Equation 16 can be used once the initial intangible costs are known. However, because they are intangible, the initial costs \( I_{C,i,f}(0) \) cannot be observed but must be calculated. A detailed presentation of the calibration procedure can be found in Appendix A1.

### 3.2 Further Description of the Transformations of the Existing Building Stock

We now rewrite Eq. 5 by incorporating the carrier switch that we mentioned below Eq. 7, that is, we must compute the transitions from \( i \) to \( f \) and \( e_i \) to \( e_f \). Therefore, we calculate the total proportions \( PR_{T,i,f} : e_i,e_f : D \), which corresponds to the product of the proportion \( PR_{i,f} : D,e_i \) of retrofits from \( i \) to \( f \) and the conditional proportion \( PRS_{e_i,e_f} : D|_{i,f} \) of switches from \( e_i \) to \( e_f \).

We thus determine the transitions:

\[
TRANS_{i,f} : e_i,e_f : D(\tau) = (1 - \gamma_{i,D,e_i}(\tau)) S_{i,D,e_i}(\tau)
\]

\[
Xi,D,ei(\tau) \sum_{f > i} TRANS_{i,f} : e_i,e_f : D(\tau) S_{i,D,e_i}(\tau)
\]

\[
PR_{i,f} : D,e_i(\tau) \sum_{f > i} PRS_{e_i,e_f} : D|_{i,f}(\tau)
\]

where \( f > i \), and the transitions:

\[
TRANS_{\psi,i} : e_{\psi},e_i : D(\tau) = (1 - \gamma_{\psi,D,e_{\psi}(\tau)} S_{\psi,D,e_{\psi}(\tau)} X_{\psi,D,e_{\psi}(\tau)} PR_{\psi,i} : D,e_{\psi}(\tau) PRS_{e_{\psi},e_i} : D|_{\psi,i}(\tau),
\]

where \( \psi < i \). To obtain the number of transitions (or the corresponding number of square meters) that is needed in Eq. (4), we sum the transitions in (18) over all \( f > i \) and all \( e_f \), and we sum the transitions in (19) over all \( \psi < i \) and all \( e_{\psi} \). While the first sum is:

\[
\sum_{f > i} TRANS_{i,f} : D,e_i(\tau) = (1 - \gamma_{i,D,e_i}(\tau)) S_{i,D,e_i}(\tau)
\]

\[
Xi,D,ei(\tau) \sum_{f > i} PR_{i,f} : D,e_i(\tau) \sum_{f > i} PRS_{e_i,e_f} : D|_{i,f}(\tau)
\]

\[
= (1 - \gamma_{i,D,e_i}(\tau)) S_{i,D,e_i}(\tau)
\]

\[
Xi,D,ei(\tau),
\]

\[\text{ Springer}\]
the second sum is equal to:
\[
\sum_{\phi<i}^{\phi} \text{TRANS}_{\phi,i} D,e_{\phi}(\tau) = \sum_{\phi<i}^{\phi} (1 - \gamma_{\phi,D,e_{\phi}}(t)) S_{\phi,D,e_{\phi}}(\tau) X_{\phi,D,e_{\phi}}(\tau) \text{PR}_{\phi,i} D,e_{\phi}(\tau) \text{PRS}_{e_{\phi},e_{\phi}} D|_{\phi,i}(\tau),
\]
and really depends on the proportions PR and PRS.

### 3.3 Distributions of Carrier Switches

**Homogeneous Market** We calculate the (conditional) proportions \( PRS_{e_{i},e_{f}} : D|i,f(\tau) \) of switches from \( e_{i} \) to \( e_{f} \) analogously to the proportions \( PR_{i,f} : D,e_{i}(\tau) \) of retrofits from \( i \) to \( f \):

\[
PRS_{e_{i},e_{f}} : D|i,f(\tau) = \frac{LCCS_{f,D,e_{i},e_{f}}(\tau)}{\sum_{e_{\phi}}^{e_{\phi}} LCCS_{f,D,e_{\phi},e_{\phi}}(\tau)}. \tag{22}
\]

Here, \( \nu(\tau) \) is the dynamic heterogeneity parameter of Eq. 32 and

\[
LCCS_{f,D,e_{i},e_{f}}(\tau) = SWIC_{e_{i},e_{f}} + P_{e_{f}}(\tau) \rho_{f,e_{f}} \sum_{t=1}^{M} (1 + r_{D})^{-1}. \tag{23}
\]

The life cycle costs of a switch from \( e_{i} \) to \( e_{f} \) in Eq. 23 are similar to the life cycle costs of a retrofit from \( i \) to \( f \) in Eq. 7. While the switching costs\(^{10}\) \( SWIC_{e_{i},e_{f}} \) of Eq. 23 include costs arising, for example, from oil tank removal, drilling for geothermal probes or laying a gas pipe as well as services provided by electricians or masons, the analogous investment costs \( INVC_{i,f} \) of Eq. 7 include the heater and heater installation costs. The second term of (23) can be compared with the term \( ENERCI_{i,f,D,e_{i}} \) of (7), except that in the present situation the final carrier is known and we can thus compute the energy costs using this carrier (which is more natural). Unlike the lifetime of a retrofit, which is \( N \) years, the lifetime of a carrier switch is \( M \) years (see Table 4). Moreover, we do not use a green value in Eq. 23 because the carrier is switched in a fixed efficiency class.

As opposed to (7), (23) does also not contain intangible costs because in Luxembourg, the observations needed for the calibration of the initial intangible costs are unavailable. Lastly, the switching costs are considered as constant, that is, no learning effect is included; also due to infeasibility.

As illustrated in Table 2, the final carriers “pellets” (P), “pellets combined with a solar thermal system” (P + s), “electricity” (E), and “electricity with solar” (E + s) can be chosen only in higher energy efficiency classes.

Firstly, we mentioned earlier that each energy efficiency class is initially defined in primary energy \( Q_{pri} \) and then transformed in the model for each type of carrier into final energy \( Q_{fin} \). Based on the data of the [52], we find that the final energy of almost all Luxembourgish dwellings is lower than 643 kWh/m\(^2\)/year. This means that if a person who renovates chooses the final carrier P or P + s, the primary energy \( Q_{pri} = 0.07 Q_{fin} \) is lower than 45, which, however, means that the dwelling has the energy efficiency class A. In other words, a person who renovates to the final class \( f \equiv A \) (see Table 2). Secondly, given the bad overall efficiency of electric heaters and the resulting environmental disadvantages, the Luxembourgish government wants to push back these heating systems and promotes the use of heat pumps instead. Hence, in our model, if \( e_{f} = E \) or \( e_{f} = E + s \), the heating system used is a heat pump. Yet, for technical reasons, heat pumps are solely adapted for space heating in the energy classes B, A, ZEB, and PEB [53]. This is why carrier switches to \( e_{f} \in \{E, E+s\} \) are only permitted if \( f > C \) (see Table 2).

---

\(^{10}\)These costs were determined after concertation with experts from renovation companies.
In contrast to the above, the heating system of an initial carrier \(e_i \in \{E, E + s\}\) is an electric heater. As these systems consist mostly of direct-heating electric radiators and not of central heating systems (as do all other carriers in the model), switching from such an \(e_i\) to any other carrier is very expensive. Finally, because carrier switches are related to retrofits to higher energy classes, households who already used “solar” do usually not switch to a carrier without “solar.” For this reason, carrier switches from \(e_i \in \{F + s, G + s, E + s, P + s\}\) to \(e_f \in \{F, G, E, P\}\) are not allowed (see Table 2).

**Heterogeneous Marked** If we calculate the percentages \(P R S_{e_i, e_f; D | i, A}(\tau)\) using the homogeneous market behavior defined by the heterogeneity parameter \(\nu(\tau)\), then the numbers of houses using \(E, E + s, P\) or \(P + s\) are rather low in 2060. This insufficiency of the model comes from the values of \(\nu(\tau)\), which range from 7 to 3.25, that is, when the life cycle costs double the percentage of switching decisions decreases from 100% to a percentage between approximately 1% and 10%. The values of \(\nu(\tau)\) can of course decrease in specific subpopulations, for example, switches in the class \(A\) to one of the carriers \(E, E + s, P\) or \(P + s\) reflect a very good environmental consciousness, which in turn decreases the effect of costs on the switching decision. In order to remedy for the mentioned insufficiency of the model, we decrease \(\nu(\tau)\) in the calculation of the proportions \(P R S_{e_i, e_f; D | i, A}(\tau)\). A complete illustration of this decrease can be found in Appendix A1.

### 3.4 Fraction of Retròfitted Buildings

**Without Climate Change** The proportion \(X_{i,D,ei}(\tau)\) of retrofits of class \(i\) dwellings is correlated to the profitability of the corresponding investment. The net present value \(NPV_{i,D,ei}(\tau)\) of such a retrofit is the difference between the lifetime energy costs in the class \(i\) (when no retrofit is made) and the weighted average lifetime costs of a retrofit from \(i\) to any higher class \(f\):

\[
NPV_{i,D,ei}(\tau) = ENERCI_{i,D,ei}(\tau) - \sum_{f>i} PR_{i,f:D,ei}(\tau) LCC_{i,f,D,ei}(\tau).
\]

The precise relation between \(NPV_{i,D,ei}(\tau)\) and \(X_{i,D,ei}(\tau)\) is defined by a logistic function: 11

\[
X_{i,D,ei}(\tau) = \frac{1}{1 + a \exp(-b \ NPV_{i,D,ei}(\tau))} \quad (a, b > 0).
\]  

This models that if the net present value begins to increase, it is not yet really attractive and the proportion of retrofits increases only slowly and that, on the contrary, if the profit of a retrofit becomes more and more attractive the proportion increases quicker.

Equation

\[
\sum_{i,D,ei} \frac{S_{i,D,ei}(0)}{1 + a \exp(-b \ NPV_{i,D,ei}(1))} = 0.01 S(0)
\]

asks for the retrofitted surface in the first year to be 1% of the surface of the existing building stock in the initial year. The constants \(a\) and \(b\) are the positive solutions of this equation for which the percentage \(\frac{1}{1+a}\) of retrofits for zero-profitability is minimal. Given that this calibration problem is an optimization problem under constraint, we solve it numerically using Lagrange multipliers.

**With Climate Change** The percentage of the existing stock \(S(t)\) that is renovated in the next year will increase over time. 12 This percentage \(p(\tau)\) is modeled as an increasing logistic function, 13 and by applying the same procedure as for \(\nu(\tau)\) (see Appendix A1), we get:

\[
p(\tau) = 0.01 \left(0.85 \frac{2.30}{1 + \exp(-0.124 \tau + 2.66)}\right).
\]

In this modeling alternative, \(a\) and \(b\) in Eq. 24 depend on \(\tau\): \(a = a_\tau\) and \(b = b_\tau\). Their calculation uses the time-dependent constraint:

\[
\sum_{i,D,ei} \frac{S_{i,D,ei}(t)}{1 + a_\tau \exp(-b_\tau \ NPV_{i,D,ei}(\tau))} (p(\tau) - 0.01) S(t) + \sum_{i,D,ei} \frac{S_{i,D,ei}(t)}{1 + a \exp(-b \ NPV_{i,D,ei}(\tau))}.
\]

In this formula, the sum at the left-hand side is the total surface that is renovated in the year \(\tau\) after consideration of the economic and the climatic issues encoded in the LuxHEI model. The percentage \(p(\tau)\) in the right-hand side increases from the current 1 to 3% due to (essentially) climatic reasons. Since we subtract in the term \((p(\tau) - 0.01) S(t)\) the approximate total surface 0.01 \(S(t)\) that is renovated in \(\tau\) for economic reasons, this term represents the total surface renovated in \(\tau\) for climatic reasons. Adding the last term of the right-hand side means replacing the approximate \((0.01 S(t))\) by the true total surface renovated in \(\tau\) for economic reasons.

11 For the reasons already set out in the paragraph “Climate change” of Subsection 3.1.

12 The asymptotic values are 0.85% (in the year 0, the value of \(p\) was 1% in Luxembourg) and 3.15% (newer versions of [21] use the value \(p = 3\%\) constantly, from the initial to the final year).
3.5 Demolition Rates

The demolition rate \( \gamma_{I,D,e_i}(t) \) in the stock \( S_{I,D,e_i}(t) \) remains to be calculated. We regard the demolition rate \( \gamma \) in the whole stock \( S(t) \) as time independent: \( \gamma \) is equal to the demolition rate 0.35%, which we observed for \( S(0) \). Furthermore, the calculation of \( \gamma_{I,D,e_i}(t) \) is based on the suggestion of [54] to first demolish the low energy classes.

The total destruction in \( t \) in the category \( D, e \) is:

\[
T_{ot,D,e}(t) = 0.0035 \times S_{D,e}(t) = 0.0035 \times \sum_{i} S_{I,D,e}(t).
\]

The inclusion of the suggestion to begin demolishing this surface in the worst energy class is modeled as follows: if in the category \( D, e \) the percentage \( \frac{S_{I,D,e}(t)}{S_{I,D,e}(0)} \) of class \( I \) dwellings in the year 0 that do still exist in the year \( t \), is still high (already low), we demolish much (we do not demolish much) of the total destruction \( T_{ot,D,e}(t) \) in the class \( I \). Here, the demolition in \( I \) is taken to be: \(^{14}\)

\[
D_{I,D,e}(t) = T_{ot,D,e}(t) \times \frac{S_{I,D,e}(t)}{S_{I,D,e}(0)}.
\]  

(25)

The remainder of the total destruction is demolished in the next class:

\[
D_{H,D,e}(t) = T_{ot,D,e}(t) - D_{I,D,e}(t).
\]  

(26)

If in some year, the class \( I \) has been completely destroyed we destroy first in \( H \), then in \( G \), and so on. Equations (25) and (26) can thus be written, respectively, as:

\[
D_{I,D,e}(t) = \frac{T_{ot,D,e}(t)}{S_{I,D,e}(0)} S_{I,D,e}(t) = \gamma_{I,D,e}(t) S_{I,D,e}(t),
\]  

(27)

and

\[
D_{H,D,e}(t) = \frac{T_{ot,D,e}(t) - D_{I,D,e}(t)}{S_{H,D,e}(t)} S_{H,D,e}(t) = \gamma_{H,D,e}(t) S_{H,D,e}(t).
\]  

(28)

which allows to calculate \( \gamma_{I,D,e}(t) \) and \( \gamma_{H,D,e}(t) \).

4 The LuxHEI Model (III): New Building Stock Dynamics

Section 3 dealt with the building stock that existed in 2013 (EBS), its transformation, and the associated demolitions: we calculated the evolution over time of the surface \( S_{i,D,e_i} \) of the EBS in all \( 9 \times 4 \times 8 \) categories \( i, D, e_i \).

Hereinafter, we study the building stock growth or new building stock (NBS). Therefore, we will calculate for all \( 4 \times 4 \times 8 \) categories \( j, D, e_j \) the temporal development of the surface \( S_{j,D,e_j} \) (or the number \( H_{j,D,e_j} \) of new houses constructed in 2014 or later (in the case of new buildings \( j \in \{ B, A, ZEB, PEB \} \)).

The total housing needs:

\[
H = \frac{L}{L_{PH}}
\]

are the quotient of the “population” and the “average population per house” (for example, if \( L = 500,000 \) and \( L_{PH} = 4 \) the total housing needs are 125,000). The evolution over time of \( L \) is obtained exogenously using the findings of [23]. The data of [55] suggest that the number \( L_{PH} \) of people per house decreases over time. In the model, the decrease of \( L_{PH} \) is bounded by a minimal number\(^{15}\) and is calculated endogenously.

We denote the number of new constructions in 2014, 2015, etc., up to \( \tau \) (\( \tau = t + 1, t \geq 0 \)) by \( \mathcal{H}(\tau) \). The difference \( (\Delta \mathcal{H})(\tau) = \mathcal{H}(\tau) - \mathcal{H}(t) \) is thus the number of new constructions in the year \( \tau \). Yet, this number is also the difference:

\[
(\Delta \mathcal{H})(\tau) = H(\tau) - \left( \frac{1}{S_{PH}} \sum_{i,D,e_i} S_{i,D,e_i}(\tau) + \mathcal{H}(t) \right)
\]  

(29)

between the housing needs \( H(\tau) \) in \( \tau \) and the sum of the number of dwellings from 2013 and earlier that still exist in \( \tau \) and the number of new dwellings constructed in 2014, 2015, up to \( t \). The fact that Eq. (29) is expressed in (number of) houses and the existing stock \( \sum_{i,D,e_i} S_{i,D,e_i}(\tau) \) is expressed in squared meters explains why the latter must be divided by the average surface \( S_{PH} \) of a house that existed in 2013. The surface \( (\Delta S)(\tau) \) of the new constructions \( (\Delta \mathcal{H})(\tau) \) naturally depends on the surface per house:

\[
(\Delta S)(\tau) = S_{PH}(Y(\tau))(\Delta \mathcal{H})(\tau),
\]

where the surface \( S_{PH}(Y(\tau)) \) is an increasing function of the disposable income per capita, with the value of \( Y(\tau) \) for the years \( \tau \) up to 2060 coming from the projections of [23]. Actually, the surface \( S_{PH} \) is modeled by incorporating a maximal surface per house and by assuming that the annual increase of \( S_{PH} \) shrinks as the surface gets closer to this limit; the modeling of the evolution over time of \( L_{PH} \) is very similar. Since the data of [56] yields that the surface \( \sum = S_{PH} \) increases by 20% if the income doubles,\(^{16}\) we have:

\[
\sum_{\tau} = \sum_{t} \left( 1 + \frac{\Delta Y}{Y} \times 20\% \right).
\]  

(30)

Although \( \sum \) is in fact bounded by a limit or maximal surface \( \sum_{\max} \), Eq. (30) produces an increasingly higher

\(^{13}\)Which is set equal to 2.

\(^{16}\)The percentage 20% is only valid in the categories O-H and T-H; for O-F and T-F, it is only 1%.
surface over time. To rather model that $\sum_{\tau}$ increases by lower percentages than 20% when it comes closer to $\sum_{\tau}$, the quotient $\sum_{t=0}^{\tau} \sum_{D_{E}} \frac{S}{\sum_{\tau}}$ is included into (30):

$$SPH(Y(\tau)) = \sum_{\tau} \left( 1 + \frac{\Delta Y}{Y} \times \frac{\sum_{\tau} - \sum_{0} \times 20\%}{\sum_{\tau}} \right).$$

Similar to $S(\tau)$ in the EBS, we distribute $S(\tau)$ in the NBS among the categories $j, D, e_j$. More specifically, the surface of new constructions in the category $j, e_j$ is given by:

$$(\Delta S)_{j, D, e_j}(\tau) = PRN_{j, e_j}(\tau)(\Delta S)(\tau),$$

and the proportion $PRN_{j, e_j}(\tau)$ of new constructions in $j, e_j$ is calculated exactly as the proportions in Eqs. (6) and (22):

$$PRN_{j, e_j}(\tau) = \frac{LCN_{j, e_j}(\tau)}{\sum_{k, e_k} LCN_{k, e_k}(\tau)},$$

where

$$LCN_{j, e_j}(\tau) = INV_C N_{j, e_j}(\tau) + ENER_C N_{j, e_j}(\tau) + ICN_{j, e_j}(\tau).$$

As depicted in Table 3, the carrier $e_j$ is $E + s$ for $j \in \{ZEB, PEB\}$. Indeed, a ZEB [PEB] is a house with a neutral (positive) annual energy balance, that is, it produces as much (more) energy as the household consumes over a year. With this being achieved by perfect insulation and an efficient heating system, we suppose households living in such buildings to have high environmental awareness: they desire sustainable heating and want to maximize the energy production from renewable energies. Therefore, the model only allows solar thermal heating combined with a heat pump that works mainly with electricity from the in-house photovoltaic system.\footnote{The initial construction costs $INV_C N_{j, e_j}(0)$ were again determined after concertation with experts from renovation companies and do only contain direct building costs, that is, no land costs are included.}

However, unlike the proportions in Eqs. (6) and (22), the share $PRN_{j, e_j}(\tau)$ does not depend on the category $D$. The reason for this is that while the dependence on $D$ in (6) and (22) comes from the different discount rates used for the different categories $D$, these discount rates are not needed in the case of new dwellings. On this account, the actually searched surface $(\Delta S)_{j, D, e_j}(\tau)$ is thus simply given by:

$$(\Delta S)_{j, D, e_j}(\tau) = PR_D(\tau)PRN_{j, e_j}(\tau)(\Delta S)(\tau),$$

where $PR_D(\tau)$ is the proportion of $D$-dwellings (for example, owner-occupied houses when $D = O-H$) in the new constructions in the year $\tau$. As $D = P \cap T$, with $P \in \{O, T\}$ and $T \in \{H, F\}$, we have:

$$PR_D(\tau) = PR_T(\tau)PR_{P\cap T}(\tau),$$

where the percentage $PR_{P\cap T}(\tau)$ was observed in the year $\tau = 1$ and we use that value. Concerning the two shares $PR_T(\tau)$, they are known once we found the percentage $PR_E(\tau)$ of flats in the new constructions in $\tau$. Notice that we consider the fact the latter percentage increases over time. A complete description of this modeling method can be found in Appendix A1.

## 5 Description of the Energy Policy Tools

As the building sector is accountable for about half of the EU’s energy needs and greenhouse gas (GHG) emissions\footnote{Since 2013, the Luxembourgish state offers PRIME-House capital grants to promote household investments in}, it is considered essential to meet large energy and climate objectives (for example, the EU’s 20-20-20 strategy or the Paris Agreement) and so is the residential building sector\footnote{For this reason, Luxembourg’s policy-makers also devote particular importance to this sector: since the 1990s, the government promotes energy conservation in the building stock through the application of various policy instruments. More precisely, energy policy tools of direct nature (regulatory instruments) and indirect nature (communication or financial instruments) were implemented to address the barriers that hinder the full exploitation of the sector’s significant energy conservation potential: often referred to as the energy efficiency gap or paradox. In this light, the LuxHEI model aims at evaluating the effects of currently applied and possible future financial and regulatory instruments. A detailed synopsis of the considered instruments and their modeling is provided in this section.}. For this reason, Luxembourg’s policy-makers also devote particular importance to this sector: since the 1990s, the government promotes energy conservation in the building stock through the application of various policy instruments. More precisely, energy policy tools of direct nature (regulatory instruments) and indirect nature (communication or financial instruments) were implemented to address the barriers that hinder the full exploitation of the sector’s significant energy conservation potential: often referred to as the energy efficiency gap or paradox. In this light, the LuxHEI model aims at evaluating the effects of currently applied and possible future financial and regulatory instruments. A detailed synopsis of the considered instruments and their modeling is provided in this section.

### 5.1 Existing Instruments: Initial and Extended Forms

#### 5.1.1 Capital Grants

Since 2013, the Luxembourgish state offers PRIME-House capital grants to promote household investments in
insulation measures on existing dwellings, green building, and sustainable heating systems.\textsuperscript{18}

Here, the subsidy ($S_1$) granted for insulation measures in an existing dwelling increases with both the quantity of insulation material used (including windows) and its quality. As information about material properties is not captured by the model, we use available data of \textsuperscript{[53]}\textsuperscript{19} and compute that for a retrofit from $i$ to $f$, 15\% of the average capital expenditures for insulation measures are covered by the subsidy (up to 2026).\textsuperscript{20}

Between 2013 and 2016, state aids were also granted for all new energy class $B$ and $A$ constructions (for example, the maximal grant for a new single-family house of class $A$ was 24,000 in 2014). Yet, with the introduction in 2016 of the Luxembourgish environmental certification system LENOZ, the regulations of this policy changed. In fact, the new scheme determines a building’s sustainability no longer exclusively by its energy class but also through its geographical location and factors of economic and social nature. To benefit from the grant, new constructions must now obtain a certain amount of points in the LENOZ evaluation. Since such specifications are not tangible for the model, we build on the assertions of consultants from Myenergy and assume that between the beginning of 2017 and the end of 2020, 35\% of new energy class A dwellings, 50\% of new ZEB, and 65\% of new PEB remain eligible for this second type of PRIME-House grant ($S_2$).

Besides that, until the end of 2024, the Luxembourgish state also offers grants for solar thermal plants, pellet heating systems, and heat pumps (varying between 2500 and 8000). An additional subsidy (of 1000) is accorded whenever the two latter systems are combined with a solar thermal plant. As the overall costs of a heating system replacement are split into system and installation costs (included in the investment costs $INVC_{i,f}(\tau)$) and ancillary costs induced by the carrier swap (included in the switching costs $SWIC_{e_i,e_f}$), this last type of grant ($\sum_3$) is split ($S_3 = S_3^a + S_3^b$, $S_3^a$ and $S_3^b$ are fixed percentages of $S_3$):

\[
INVC_{i,f}(\tau) = INVC_{i,f}(\tau) - (S_1(\tau) + S_2^a(\tau)),
\]

\[
SWIC_{e_i,e_f}(\tau) = SWIC_{e_i,e_f} - S_2^b(\tau),
\]

\[
INVCN_{j,e_j}(\tau) = INVCN_{j,e_j}(\tau) - (S_2(\tau) + S_3(\tau)).
\]

Based on the findings of \textsuperscript{[59]}, we take into account that probably not all eligible households actually use the capital grants, mainly because of imperfect information. Due to the substantial efforts of the Luxembourgish government to promote the PRIME-House grants, we, however, suppose the utilization rates to be slightly higher than those in France \textsuperscript{[59]}: in Luxembourg, on average, 75\% of retrofits and 90\% of new constructions apply the instrument.

Furthermore, an extended version of the policy is modeled. This means that at the end of the instruments’ initial application period, the model prolongs the grants for 15 additional years and considers their application as mandatory: as in \textsuperscript{[20, 21]}, all eligible households apply the instrument.

### 5.1.2 Subsidized Loans

With the launch of the Luxembourgish climate bank in 2017, households became eligible for a retrofitting credit at reduced interest or even zero-interest rate. Under the interest-free loan, recipients can take out a credit of up to 50,000, repayable (without interests) within 15 years, and further get a capital grant of 10\% of the loan. On the contrary, under the loan at a reduced interest rate, the credit is limited to a maximum of 100,000, repayable within 15 years, and the state grants a 1.5\% subsidy on the interest rate of the bank.

To encode both retrofitting credits, we again refer to \textsuperscript{[59]} and consider that not all households borrow money to pay a retrofit. Similarly to the situation observed in France, we assume the proportion $P$ of retrofitting households taking out a loan to be 30\%, whether or not the policy tool is applied. For this proportion $P$, the investment costs $INVC_{i,f}(\tau)$ are then increased by the accrued interests under an averaged fixed interest rate\textsuperscript{21}. Only if the government applies the interest-free or reduced interest loan, the increased investment costs $INVC_{i,f}(\tau)$ of the proportion $P$ are decreased by the saved interests. Furthermore, the instruments’ effectiveness is improved by limiting their duration of application \textsuperscript{[19]}: as for capital grants, the subsidized loans are available until 2026.

Comparable with the extended version of the PRIME-House grants, we encode a complementary scenario where both instruments’ period of application is prolonged until 2041 (+15 years) and where for the reduced interest loan the 1.5\% subsidy is increased to 2.0\%.

### 5.1.3 Energy Tax

Since the European Commission implemented the EU Energy Taxation Directive (ETD) \textsuperscript{[60]} in 2003, minimum tax rates are imposed on energy products in the Member

\textsuperscript{18}Instruments that were already applied in 2013 are considered in the calibrations of the model.

\textsuperscript{19}Myenergy is the main national structure to promote the transition to sustainable energy.

\textsuperscript{20}Note that this modeling choice reflects reality as the level of subsidies increases, as it should, with the quality of the final energy class $f$, that is, the number or grade of the undertaken actions.

\textsuperscript{21}This rate corresponds to the mean of the fixed rates that Luxembourgish banks charged on mortgage loans between 2009 and 2017.
States. Within this framework, the Luxembourgish government taxes the use of electricity and fuels like oil, gas, and coal (if they are not used to produce electricity). Here, the tax rates depend on the energy source (the carrier), the sector of application, and the volume of the annual consumption. Based on the data of the [52], we find that carriers used for space heating in the residential sector are taxed between 1.5 \$/t CO\textsubscript{2} and 5 \$/t CO\textsubscript{2}. In this first form of the policy tool, we consider the energy tax as time-independent and encode the instrument by adding the amount of the tax (converted into per kWh) to the energy price \( P_{r}(t) \) of the corresponding carrier \( e \).

An enhanced energy tax is also included in our model: following the objective of the [61] to raise the taxes on energy products, we increase the initial level of taxation by 100\% every 10 years. The first increase is implemented in 2025, the last in 2055.

5.1.4 Energy Performance Requirements for New Buildings

In Luxembourg, the energy efficiency of new residential buildings is prescribed by law since November 2007. This initial building code dictated that as of 1 January 2008, all new constructions needed to have at least the energy efficiency energy class \( D \). The standard was then increased to energy class \( B \) [A] in 1 July 2012 (1 January 2015). This is why in the proportion \( PRN_{j,e}(\tau) \) of new constructions, \( j \in \{B, A, \text{ZEB, PEB}\} \) in 2014 (\( j \in \{A, \text{ZEB, PEB}\} \) as of 2015).

Once again, an extra scenario in which building codes are further tightened is included: as of 1 January 2030 (2045), the standard ZEB [PEB] becomes mandatory for new constructions.

5.2 Possible Future Instruments

This subsection discusses policies that we believe the most interesting for Luxembourg.

5.2.1 Remediation Duty for Existing Buildings

As most Member States, Luxembourg does not specify minimum energy efficiency standards for existing residential buildings [62]. The only obligation with regard to existing dwellings is to respect minimum material standards when retrofitting. However, in Luxembourg’s neighboring countries (Germany and France), stricter requirements on the existing building stock do exist. In Germany, partial renovation is, for example, mandatory after the acquisition of an existing building: if a dwelling was bought or inherited after 1 February 2002, the new owners must either insulate the roof or the top floor ceiling. As regards France, the National Assembly adopted on 26 May 2015 a bill which stipulates that every dwelling must be retrofitted until 2025 if its overall primary energy consumption is above 330kWh/m\textsuperscript{2}/year; in the LuxHEI model, this corresponds to a house of energy efficiency class \( G \). The bill also dictates that as of 2030, all dwellings must be retrofitted before they can be listed for rent or sale.

In light of the energy saving and CO\textsubscript{2} mitigation potential of the existing building stock [63, 64] and the rules deployed in two of Luxembourg’s three bordering countries, we included a remediation duty in the LuxHEI model: as of 2022 (considered as the closest possible year for implementation), all residential buildings that are listed for rent or sale must be retrofitted to an overall primary energy class above \( H \). To ensure effectiveness of this tool, the regulation is gradually tightened by one energy class every five years: buildings whose inhabitants switch must at least reach class \( F \) as of 2027, \( E \) as of 2032, and \( D \) [C] as of 2037 (2042).

To model this policy, we begin by considering that without remediation duty, a fraction \( \xi \) of the proportion \( X_{i,D,ei}(\tau) \) of retrofits of class \( i \) dwellings is induced by an inhabitant switch. On the contrary, whenever the instrument is applied, all inhabitant switches are followed by a retrofit. To avoid double counting when the remediation duty is in force, the fraction \( \xi X_{i,D,ei}(\tau) \) must be subtracted from \( X_{i,D,ei}(\tau) \) and Eq. (5) of the model must thus be changed to:

\[
\text{TRANS}_{i,f:D,ei}(\tau) = (1 - \gamma_{i,D,ei}(t)) S_{i,D,ei}(\tau) \left( Z_{i,D,ei}(\tau) \right) + \left( X_{i,D,ei}(\tau) (1 - \xi) \right) P R_{i,f:D,ei}(\tau),
\]

for all \( i < i_{\text{min}} \) and all \( f \geq i_{\text{min}} \). The percentage \( Z_{i,D,ei}(\tau)^{22} \) is the proportion of owner-occupied or rented dwellings that change occupancy in the year \( \tau \) and the class \( i_{\text{min}} \) is the required lowest efficiency class. More specifically, if \( i < i_{\text{min}} \) and \( f < i_{\text{min}} \), we set \( P R_{i,f:D,ei}(\tau) = 0 \) and if \( i \geq i_{\text{min}} \), then \( f > i_{\text{min}} \) and so we leave the original formula unchanged.

5.2.2 Carbon Tax

In 2005, the world’s first and largest international emissions trading system, the European Union Emissions Trading System (EU ETS), was implemented to reduce greenhouse gas (GHG) emissions in the EU. Yet, this system covers only about 45\% of the EU’s GHG emissions, since it does not cap the volume of gases emitted by the agriculture, residential, and transportation sectors. Instead, binding national targets are fixed for these three sectors through the Effort Sharing Decision (ESD).

\[^{22}\text{The data of [65] shows that } Z_{i,D,ei}(\tau) \text{ is 1.3\% (6\%) for owner-occupied (rented) dwellings.}\]
To meet these targets in a cost-effective way, a carbon tax is often recommended by environmental economists [66–68]. As several attempts to introduce an EU-wide carbon tax failed, we consider in our model a national carbon tax that applies a uniform price to emissions from all sources and sectors [69, 70]. For this purpose, we set the initial level of the tax equal to the price of the EU ETS allowances [71], and increase the level over time to enhance the reduction of CO2 emissions progressively [72]. More precisely, the tax is based on the predicted annual price increase of EU ETS certificates [34]. The carbon tax (in the residential sector) will thus increase from 15 /t CO2 in the starting year 2020 of the policy tool to 33 /t CO2 in 2030 and 89 /t CO2 in 2050. In the second half of the century, carbon emissions are projected to decrease [73, 74] and the level of the tax is estimated to decline [75]. We therefore assume that the carbon tax comes down to 80 /t CO2 (72 /t CO2) in 2055 (2060).

The modeling of the carbon tax is similar to the encoding of the energy tax: the price of the tax (in per kWh) is added to the energy price $P_e(t)$ of the corresponding carrier e.

6 Results and Discussion

We now evaluate the policy tools of Section 5 in a similar manner as in [19, 20, 76, 77] and [17]. To this end, different model scenarios are generated: firstly, the model is run without any instrument (this baseline scenario serves as a benchmark for the following evaluation); secondly, each instrument is put in force individually (the original and extended forms of the existing policy tools are examined); and, thirdly, various bundles of instruments are studied (the bundle of all existing initial tools, the bundle of all existing extended tools, and the bundle of all existing and possible future tools). After each run, the scenario is assessed with regard to its environmental and economic effectiveness and its potential to help in achieving the Luxembourgish energy and emission targets are determined. Actually, in order to contribute to the EU’s 20-20-20 strategy, Luxembourg must decrease by 20% its final energy consumption (in comparison with the 2007 level) as well as its CO2 emissions from sectors outside the EU ETS (in comparison with the 2005 levels). In the period 2021–2030, emission cuts of even 40% must be achieved (relative to the 2005 levels). Although the national targets are not limited to a single sector, the second part of our assessment is interesting since the building sector offers one of the greatest potentials to decrease energy consumption and CO2 emissions [78, 79], and this at comparatively low costs [80, 81].

A detailed overview of the parameters that were not yet specified but used in the model runs can be found in the table below (Table 4).

### 6.1 Baseline Projection

The model projects for 2060 a total final energy consumption of 4122 GWh (−9% compared with that in 2014) and total CO2 emissions of 734,600 t CO2 (−20% compared with that in 2014) (see Appendix A1, Table 5). At the end of the model’s projection period, the (aggregated) new building stock (NBS) corresponds to 66% of the total building stock. This major growth of the residential building stock is due to the projected increase of the Luxembourgish population: based on the 3% GDP growth scenario of [23] and the baseline population projections of Eurostat, we can assert that Luxembourg will face the largest population growth rate (approximately 98% between 2014 and 2060) among all EU Member States. On this basis, savings in energy consumption and CO2 emissions can only be achieved through changes in the sector’s energy efficiency or energy sufficiency. As concerns the gains in energy efficiency, they are mainly realized via a transformation of the existing building stock (EBS), that is, by means of demolitions and retrofits, and the construction of a highly efficient NBS. More precisely, in 2060, the final energy consumption per square meter has fallen by 61% (in comparison with 2014) (Table 5), 69% of the total dwellings have at least the energy class B (compared with 7% in 2014), and 32% of the households make use of solar thermal energy to support their

| Parameter | Signification | Setting | Literary basis |
|-----------|---------------|---------|----------------|
| $\alpha$ | Percentage of the initial retrofitting costs that cannot be decreased by experience | 20% | [21] |
| $l$ | Learning-by-doing rate | 10% | [21, 82] |
| $N$ | Average lifetime of a retrofit | 35 years | [83] |
| $\gamma$ | Green value | 33% | [84] |
| $\beta$ | Constant percentage of the initial intangible costs | 20% | [21] |
| $\mu$ | Information acceleration rate | 25% | [21] |
| $M$ | Average lifetime of a carrier switch | 20 years | [83] |
heating system (Figs. 1 and 2). Such large energy efficiency increases are, however, followed by a significant rebound effect: by the end of the projection period, the adjustment factor increased by 38% (Table 6). This is due to the fact that all along the modeling period, the continuously increasing share of dwellings with a low $\rho_{k,e}$ compensates the natural raise of the energy price $P_e(t)$, thus generating a shrinking of the adjustment factor’s independent variable $\rho_{k,e}P_e(t)$ and hence a higher overall factor $F(t)$. Concerning the country’s energy objectives, none of them can be achieved in the residential building sector (Table 8): the 2020 levels of final energy consumption (CO2 emissions) are 29% (7%) higher than the 2007 levels (2005 levels) and the 2030 emissions are projected to decrease only by 4% instead of 40% (compared with 2005).

Notice that ignoring the effects of climate change, the green value, and the dynamic evolution of the new constructions’ building type changes the outcomes of the baseline scenario for the worse. Actually, compared with the baseline projection that contains all new features (see above), we end up with a total final energy consumption that is 8% higher (4478 GWh) and total CO2 emissions that are increased by 10% (805,600 t CO2). This is inter alia due to the fact that at the end of the projection period, the total number of retrofits has decreased by 50% (compared with the projection with all new features), only 0.2% (0.0%) of the total building stock correspond to ZEB [PEB] (compared to 0.8% (0.5%)), and just 27% make use of solar thermal energy to support their heating system (compared with 32%).

6.2 Evaluation of the Individual Energy Policy Tools

In the following evaluation, the effects of the 10 single-instrument scenarios (see above) are compared with those of the baseline scenario. The ranking 1–10 means “most effective—least effective” and the description of the results starts at “rank 10” and ends with “rank 1.”

6.2.1 Places 10 to 7: Subsidy Schemes

No significant variations (about 1% at most) from the baseline are observed in the initial and extended forms of the subsidized loan and capital grant scenarios.

From an ecological and economic viewpoint, the initial subsidized loan scenario is the least effective. Compared with the baseline projection, virtually no reduction effects can be observed: additional energy and emission savings of 0.01% (Appendix A1, Table 5) are realized, for a benefit to cost ratio of 101 /kWh saved (Table 7).

In the enhanced version of the subsidized loan scenario, while energy and emission savings increase slightly (−0.02%; Table 5), cost-effectiveness deteriorates (+26%; Table 8).

A bit better results are achieved in the scenario with the initial form of the capital grants: energy savings (−0.17%) and emission reductions (−0.47%) can be observed in 2060 (Table 5), for a benefit to cost ratio of 74 /kWh saved (Table 7). Although the instrument induces gains in energy efficiency (−0.21% of conventional energy consumption in 2060), a decrease of the adjustment factor is observed (−0.05% in 2060) (Table 6). This small prebound effect is mainly due to the somewhat greater use of electricity, an energy carrier with a comparatively high energy price. Compared with the baseline scenario, a small decrease in accumulated retrofits is also observed at the end of the projection period (−0.05%; Table 6). This is due to the fact that capital grants boost the number of retrofits during their application period so that fewer lucrative retrofitting options remain after that period.

Although the environmental effectiveness of capital grants more than doubles in the enhanced scenario (Table 5), its cost-effectiveness changes for the worse (+40%; Table 7).

6.2.2 Places 6 and 5: Energy Taxes

Next ranks the initial (extended) form of the energy tax scenario: state revenues of 14 (8 )/kWh saved (Table 7) come along with a decreased total final energy consumption (−0.34% [−1.61%]) and decreased total CO2 emissions (−0.37% [−1.77%]) (Table 5) in 2060. On the contrary, to the initial and extended forms of the capital grant scenario, the savings rather come from a better energy sufficiency (adjustment factor in 2060: −0.17% [−0.81%]) than from gains in energy efficiency (conventional energy consumption in 2060: −0.02% [−0.08%]) (Table 6). The prebound effect induced by the increased price $P_e(t)$ of most carriers $e$ (largely) offsets the rebound effect caused by the slightly more efficient building stock. At the end of the projection, no substantial deviation from the baseline can be observed in the total number of retrofitted dwellings and in the performance of the total final building stock (Tables 6, Figs. 1 and 2).

6.2.3 Places 4 and 3: Remediation Duty and Carbon Tax

Significant savings are reached under the remediation duty and the carbon tax. Compared with the baseline, the remediation duty (carbon tax) reduces the final energy consumption by 4.58% (5.38%) and the carbon dioxide emissions by 5.28% (6.04%) (Appendix A1, Table 5). Although both possi-
ble future instruments result in comparable savings, the way in which they are achieved is different.

Among all 10 single-instrument scenarios, the remediation duty generates naturally the largest increase in energy efficiency (conventional energy consumption in 2060: $-8.01\%$) but also the second-highest rebound effect (adjustment factor in 2060: $+1.17\%$). Similar to the phenomenon observed in the capital grant scenarios, annual demolitions and retrofits shrink the number of buildings that are affected by the remediation duty. Relative to the baseline, a visibly higher share of solar energy is achieved by the policy tool, and while it decreases the share of energy efficiency classes below $E$, an increase in the share of the classes $E$, $D$, and $C$ is observed (Figs. 1 and 2). From a governmental perspective, the scenario generates no direct expenses or revenues (Table 7).

In contrast to this but comparable to the effects already observed in the energy tax scenarios, the carbon tax generates state revenues of 10 /kWh saved (Table 7) and realizes its savings (conventional energy consumption in 2060: $-0.35\%$) less through performance improvements but rather through a more conscious heating behavior, implying the strongest decrease of the adjustment factor ($-3.00\%$ in 2060) (Table 6). Moreover, no significant variations from the baseline are observed in the quantity of retrofits as well as in the share of energy classes and carriers in the total final building stock (Table 6, Figs. 1 and 2).

6.2.4 Places 2 and 1: Performance Requirements

In the initial form of the scenario with energy performance requirements for new buildings, energy conservation (total final energy consumption in 2060: $-2.06\%$) is below the savings of the remediation duty and the carbon tax scenarios (Table 5). The scenario’s emission mitigations (total CO$_2$ emissions in 2060: $-10.04\%$) are, however, well above those of the two previous scenarios, so that the mean value of energy and emission savings becomes the second-highest among all 10 single-instrument scenarios (Table 5). In this case, energy conservation is achieved through the joint decrease of the 2060 conventional energy consumption ($-0.86\%$) and the adjustment factor ($-2.03\%$) (Table 6). The regulation implies that as of 2015 only 3 performance classes are allowed for new buildings (A, ZEB and PEB); a large majority goes for energy efficiency class A: 62.7% of the buildings in the total stock of 2060 have class A, compared with 3% with class ZEB or PEB (Table 1). In comparison with the baseline, there is also a trend for more solar thermal energy (34.2% of the total final building stock) (Table 2).

By far, the best environmental effectiveness is reached in the extended form of this policy tool: not only does the instrument realize major energy savings (final energy consumption in 2060: $-32.87\%$) but also does it achieve massive carbon dioxide reductions (total CO$_2$ emissions in 2060: $-48.62\%$) (Table 5). These major savings particularly stem from a much more efficient NBS, which induces the largest decrease of the total conventional energy consumption in 2060 ($-27.53\%$; Table 6). The share of dwellings in the total final stock with an energy efficiency class above $B$ is equal in the initial and extended forms of the building code but a clearly higher share of ZEB (12.6%) and PEB (26.7%) exists in the latter form (Figs. 1 and 2). Note that although the NBS increases continuously, the greater construction of PEB (as of 2030) results in a strong decrease of the NBS’ final energy consumption, induced by the new buildings’ energy production. Remarkable is also that in 2060 more than half of the total building stock uses solar thermal energy to support their heating system (Fig. 2). These large performance improvements are followed by a comparably large rebound effect: with a raise of 3.60% in 2060, the highest increase of the adjustment factor is observed in this scenario (Table 6). Besides that, no direct state revenues or expenses are generated by the policy tool (Table 7).

While none of the single-instrument scenarios achieves the country’s energy and climate objectives in time, the extended form of the energy performance requirements for new buildings is the only tool that accomplishes the 2020 energy targets as well as the 2030 emission goals (not in time but) in the course of the projection period (Table 8). The latter goal ($-40\%$ of total CO$_2$ emissions compared with 2005) is fulfilled in 2050, and the energy target ($-20\%$ of total final energy consumption compared with 2007) is realized in 2055.

6.3 Evaluation of Combined Energy Policy Tools

In the previous section, we observed that the 10 single-policy instruments have different ecological and financial impacts. To accumulate the advantages of these instruments, policy-makers typically combine the tools in packages and apply them simultaneously. In addition to the standard evaluation of the scenarios’ effectiveness (see above), we now evaluate whether or not instruments generate synergistic effects when applied concurrently. Therefore, 3 multiple-instrument scenarios are run: the first (second) consists of the existing instruments in their initial (extended) form and the third corresponds to the second, except that we consider the initial form of the energy tax and include the two possible future instruments.

6.3.1 Bundle 1

From an environmental viewpoint, running the model with the policy mix that is currently applied by the Luxembourgish state results in a decrease of the total final
6.3.2 Bundle 2

Further improvements in environmental and economic effectiveness are achieved in the second policy package scenario: compared with the 2060 baseline levels, energy savings of 34.60% and carbon dioxide reductions of 50.71% (Table 5) are realized.

Environmentally, similar to bundle 1, the savings of bundle 2 are almost identical to the aggregated decreases of the corresponding single-instrument scenarios (Table 5). The presence of capital grants, subsidized loans, and the energy tax in the package leads to a greater energy efficiency than in the extended building code scenario (total conventional energy consumption in 2060: −28.13%; Table 6) and to a lower rebound effect (adjustment factor in 2060: +2.90%; Table 6).

Compared with bundle 1, the balance of state revenues and expenses more than quadruples. Due to the much larger energy savings in bundle 2, the scenario yet generates a benefit to cost ratio of 2 /kWh saved (Table 7), which means that the economic effectiveness is further increased.

In bundle 2, even though the energy and emission targets are not achieved in time, they are all achieved within the projection period (Table 8): the 2020 energy objective is realized in 2054, and the 2020 (2030) emission goal in 2037 (2044).

6.3.3 Bundle 3

The highest and most cost-effective energy and emission savings are realized in the multiple-instrument scenario of bundle 3: for state expenses of less than 1 /kWh saved (Table 7), the 2060 final energy consumption decreases by 42.37% and the CO₂ emissions by 59.53% (Table 5).

Despite the very large performance improvement of the total building stock (total conventional energy consumption in 2060: −36.32%; Table 6), the scenario projects a relatively low rebound effect (adjustment factor in 2060: +2.40%; Table 6). This is mostly due to the carbon tax, an instrument that realizes most of its savings through a better energy sufficiency. Moreover, the higher quantity of accumulated annual retrofits in 2060 (about +39%; Table 6) is due to the incorporation of the remediation duty. This instrument, together with the performance requirements for new constructions, is primarily responsible for the share of efficient energy classes and carriers in the total building stock of 2060, which is the highest among all 10 scenarios (Figs. 1 and 2).

Similar to bundle 2, all national energy and emission targets are reached belatedly (Table 8): while a decrease of the final energy consumption by 20% is reached in 2048, emissions mitigation of 20% (30%) is realized in 2034 (2040).

7 Conclusion

With a focus on the Grand Duchy of Luxembourg, the present chapter evaluates the influence of energy policy tools on final energy consumption and direct CO₂ emissions in the residential building sector. For this purpose, we develop an advanced version LuxHEI of the French hybrid energy-economy model Res-IRF [21], which we also customized to the truly specific characteristics of Luxembourg. The LuxHEI model is an energy policy model that is based on economic principles and that takes into account, for instance, global warming, the green value, sustainable energy efficiency classes, and energy carriers, as well as a limited availability of carriers. Based on our model’s results, four principal conclusions can be drawn. Firstly, we observe that building codes generate the largest energy conservation and mitigation of carbon diox-

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24We again wish to point out that whenever the data is sufficient to realize the above calibrations and parameterizations, then the LuxHEI model also allows to perform the present study for any other country.
ide emissions, without requiring direct government spending. Secondly, environmental effectiveness is achieved differently depending on the instrument type: while subsidy schemes and regulations mainly affect the building stock’s energy efficiency, taxes usually induce a more conscious heating behavior. Thirdly, when used simultaneously, policy tools neither counteract nor generate direct synergistic effects but their individual impacts are more or less added up. Therefore, the policy package with the greatest number of instruments (bundle 3) also generates the largest effects. Fourthly, in none of the evaluated policy scenarios, the national energy and emission targets are achieved on time.

Although we encoded quite a few new features (for example, more sophisticated behavioral factors) to increase our dynamic simulation model’s level of realism, it remains a stylized illustration of the real world. This means that modeling assumptions (for example, about households’ decision-making behavior and the evolution of the new dwellings’ surface or building type) and parameterization hypotheses (for example, about climate change or population growth) are still subject to uncertainty. Changing these suppositions likely affects the scenarios’ outcomes to a certain extent. As concerns the barriers to energy efficiency, not all of them are fully integrable in a model (especially those of behavioral nature) and the LuxHEI model’s projections may therefore be somewhat optimistic. Apart from this, we did not directly encode the impact of communicative policy tools which tend to nudge households to behave in a more environmentally conscious way. Even if the energy saving potential of such instruments is relatively small [6], their absence in the model may induce a bit too pessimistic results, thus counteracting the preceding limitation. We are hence confident that the model’s predictions are fairly accurate.

The policy recommendations that accompany our analysis are in compliance with other studies [19, 85, 86]. More specifically, in the case of Luxembourg, the policy advice can be phrased as follows. Because all instruments have their pros and cons, and induce higher overall effectiveness when applied concurrently, a suitable combination of energy policy tools is advisable for the Luxembourgish residential building sector. In this policy mix, regulatory instruments should play a central role as they have the potential to strongly decrease the sector’s energy consumption and CO₂ emissions at low governmental costs. Even though such standards are easier to enforce for new buildings [19], efforts should persist to ensure the implementation of the remediation duty for existing buildings. In addition, our simulations confirm that regulations do not encourage households to go beyond the standard’s requirements; the threshold of these two regulatory instruments should thus be raised regularly. With the two latter instruments being included into the national policy mix, the further presence of capital grants and subsidized loans is essential. These financial instruments allow low-income homes to meet the standard’s demands and incite households to go beyond the threshold. However, our results indicate that the design of these subsidy schemes is decisive for the tool’s cost-effectiveness: the instrument’s application period should be limited relative to the product’s market dynamics and eligible households should be specified. To curb the rebound effect that is induced by these four instruments, taxes should not be omitted in the country’s policy mix. Considering the overall effectiveness of evaluated tax instruments, we advise the government to focus on the implementation of a national carbon tax (and hereby set an important example for other EU Member States), and to maintain the energy tax rates at the required minimum level of the ETD. To reduce the adverse effects of such a taxation policy, that is, falling economic growth or competitiveness of heavy energy-using industries, the revenues of the tax should be used to promote energy conservation [87] (for example, by using the revenues to fund a part of the subsidy schemes).

Future research should focus on the setup of an alternative modeling method where one considers the dwellings’ thermal insulation class instead of their energy efficiency class and where one adds information about the buildings’ heating system into the model. That way, the determination of the building stock’s final space heating energy demand could be improved and dwellings that realize energy savings by solely replacing their heating system could be taken into account. Additionally, there is room for a better representation of households’ behavioral patterns, for example, the decision-making behavior and the adjustment factor could be developed by including additional socio-economic variables into the model. Such modifications should be realized once the needed data on Luxembourgish households are available.

Moreover, new studies could strengthen the modeling of climate change by slowly lowering the conventional unit energy needs of the classes considered.

Finally, learning-by-doing could increase the competitiveness of the currently available sustainable heating systems, which would of course have a positive impact on the problems investigated in the present paper. A similar but even more far-reaching step would be a technological change that leads to a new high-quality and competitive system. If we fix the classes that can be heated by the new technology and the degree of its competitiveness, we can try to include such a change in the model without explicitly defining the new system.
Appendix

A.1: The Impacts of Climate Change on the Heterogeneity Parameter $\nu$

Whenever the heterogeneity parameter $\nu$ increases, the price elasticity of demand (for us the elasticity of the number of retrofits) increases (in absolute value). Actually, we saw earlier (in Eq. (6)) that the number of retrofits from $i$ to $f$ is roughly proportional to the inverse of the life cycle costs $LCC_{i,f,D,ei}(\tau)$ of such a renovation raised to the power of $\nu$. This implies that if the life cycle costs $P$ of a retrofit increase by 100%, the number $Q$ of retrofits decreases by $(2^{-\nu} - 1) \times 100%$. The price elasticity at the initial price and initial number is thus:

$$\frac{\Delta Q/Q}{\Delta P/P} = \frac{(2^{-\nu} - 1) \times 100%}{100%}.$$ (31)

Based on our assumption that the market becomes more heterogeneous over time (due to the impacts of climate change), we model $\nu$ as a decreasing logistic function of time with asymptotic values 7.5 and 1:

$$\nu(t) = 1 + \frac{6.5}{1 + (ct - d)} \quad (c > 0).$$

While climate summit meetings target zero emissions around 2050 and a limitation of global warming to less than 2 °C by the end of this century [88, 89], the effects of climate change are expected to be seriously perceptible around 2030 [2]. For this reason, we set the inflection point of the sigmoid curve at the year 2040 $(t = 27)$, which connotes that $27c = d + \ln 0.5$. This condition and the information $\nu(0) = 7$ yield $d = 2.48$ and $c = 0.066$, so that:

$$\nu(t) = 1 + \frac{6.5}{1 + \exp(0.066t - 2.48)}.$$ (32)

In light of Eq. 32, the value of $\nu$ in 2060 is (a bit higher than) 3.25, that is, approximately 10% of the population maintain their renovation choice even when the costs double (see Eq. 31).

A.2: Calibration of the Initial Intangible Costs

In order to calculate the initial intangible costs $IC_{i,f}(0)$ we consider for any $i < B$ the system

$$PR_{i,f}(0) = F_f(INVC_{i,h>i}(0), ENERC_{h>i}(0), IC_{i,h>i}(0)) \quad (i < f \leq A)$$ (33)

which is obtained from equation (6) and (7).

We derive the proportions $PR_{i,f}(0)$ from the analysis of 402 retrofitting operations undertaken in the Luxembourgish residential sector. As this sample does not allow for the proportions $PR_{i,f;D,ei}(0)$ to be observed, the initial energy costs must be independent of $D$ and $ei$. The sample is split into two building types: individual houses and flats. In order to eliminate $D$ from the energy costs $ENERC_{h,D,ei}(0)$, we use a weighted mean $r$ of the average discount rates of the building types. To eliminate the carrier, we calculate the proportions $PR_{ei}(0)$ from the available data and compute the energy costs in each efficiency class as weighted mean:

$$ENERC_{h}(0) = \sum_{ei} PR_{ei}(0) Pei(0) \delta_{h,ei} \sum_{t=1}^{N}(1 + r)^{-t}.$$ 

Notice that the sum of the proportions on the left-hand side of (33) is equal to 1, just as the sum of the functions on the right-hand side (see Eq. (6)). For this reason, the system in (33) reduces to the same system but with $f > i$ and $f < A$. As this entails that the new system consists of $8 - i$ equations (see possible values of $f$) and of $9 - i$ unknown intangible costs (see possible values of $h$), an additional equation must be added. To this end, we base on the fact that the percentage $\lambda$ of the average $LCC_{i,h>i}(0)$ that consists of the average $IC_{i,h>i}(0)$ can be defined by:

$$\sum_{h>i} PR_{i,h}(0) IC_{i,h}(0) = \lambda \sum_{h>i} PR_{i,h}(0) LCC_{i,h}(0),$$

in the same unknown intangible costs $IC_{i,h>i}(0)$. This constitutes the required additional equation, where the parameter $\lambda$ should of course have a low value. On this account, for any $i < B$, we search for the lowest value of $\lambda$ that solves the total system (new system and additional equation). This finishes the calibration of the initial intangible costs.

A.3: Decreasing the Heterogeneity Parameter $\nu$ in Certain Subpopulations

We justified above that (1) if $f \leq C$ only the carriers $F$, $F + s$, $G$ and $G + s$ are possible; (2) for $f = B$ the decider can choose $ef \in \{F, F + s, G, G + s, E, E + s\}$; and (3) for $f = A$ all eight carriers are possible final carriers. In the first case, the parameter $\nu(\tau)$ used in the calculation of the proportions $PRS$ is given by Eq. 32. Yet, in the final class $A [B]$, we choose $\nu(\tau) - 1$ [$(\nu(\tau) - 0.5$] and further reduce this parameter in a way that depends on the chosen carrier.

With a view of specifying a coherent way to further reduce $\nu$, we record numerically, on a scale from 0 to 5, the environmental awareness $\alpha$ of the deciders who switch in $A [B]$ to the carrier:

$$ef = F (F + s, G, G + s, E, E + s, P or P + s)$$

$$[ef = F (F + s, G, G + s, E or E + s)].$$
Respectively, we set:
\[ \alpha = 0.0 \ (0.4, 0.4, 0.8, 3.2, 3.6, 4.0 \text{ and } 4.4) \]
\[ [\alpha = 0.0 \ (0.2, 0.2, 0.4, 1.6 \text{ and } 1.8)]. \]

In the calculation of the proportions \( PRS_{e_i, e_f : D_i, A} (\tau) \), we thus replace \( \nu(\tau) \) by
\[ \nu_A(\alpha, \tau) = \nu(\tau) - 1 - \pi \alpha, \]
where the coefficient \( \pi \) is determined by the request that for the maximal awareness 5 the heterogeneity parameter is \( \nu_A(5, 47) = 1 \) in the year 47 (that is, in 2060). From this, we obtain:
\[ \nu_A(\alpha, \tau) = \nu(\tau) - 1 - 0.25 \alpha, \]
and for \( B \) we get
\[ \nu_B(\alpha, \tau) = \nu(\tau) - 0.5 - 0.35 \alpha. \]

Conclusively, we use Eq. 22 to find the proportions \( PRS \) in the classes \( f \leq C \). In \( f = A \) and \( f = B \), we use the same equation but replace \( \nu(\tau) \) by \( \nu_A(\alpha, \tau) \) and \( \nu_B(\alpha, \tau) \) and choose the value \( \alpha \) that corresponds in \( A \) and \( B \) to the final carriers \( e_f \) and \( e_h \). \(^\text{25}\)

A.4: Dynamic Building Types in New Constructions

The data of \([56]\) suggests that the percentage \( PR_F(\tau) \) of flats in the new constructions is an increasing logistic function of the relative growth:
\[ G(\tau) = \frac{H(\tau) - H(1960)}{H(1960)} \]

of the total building stock with respect to 1960:
\[ PR_F(\tau) = a + \frac{b}{1 + \exp(-c \ G(\tau) + d)} \quad (a, b, c, d > 0). \]

We have:
\[ \lim_{G \to +\infty} PR_F = a + b = 1, \]
and set
\[ \lim_{G \to -\infty} PR_F = a = 0. \]

This choice is justified as the linear regression that gives \( c = 0.54 \) and \( d = 0.42 \) is of good quality and the law
\[ PR_F(\tau) = \frac{1}{1 + \exp(-0.54 \ G(\tau) + 0.42)}, \]
leads to a good approximation of the observed value \( PR_F(1960) \).

A.5: Figures and Tables

Table 5 Final energy consumption and direct \( CO_2 \) emissions (total building stock)

| Scenario | Final energy consumption (kWh) | Final energy consumption per square meter (kWh/m²) | Direct \( CO_2 \) emissions (t CO\(_2\)) | Direct \( CO_2 \) emissions per square meter (t CO\(_2\)/m\(^2\)) |
|----------|-----------------------------|---------------------------------|----------------|---------------------------------|
|          | 2014 | 2030 | 2045 | 2060 | 2060 | 2030 | 2045 | 2060 | 2060 |
| Baseline | 4609715970 | 4387523790 | 412808610 | 60 | 60 | 0.36% | 0.42% | 0.47% | 0.011 |
|          | Deviation from the baseline: | Deviation from the baseline: | |
| Individual energy policy tools | | | | | | | | |
| 1. Existing instruments—initial form | | | | | | | | |
| Capital grants | -0.14% | -0.15% | -0.17% | 60 | -0.36% | -0.42% | -0.47% | 0.011 |
| Subsidized loans | -0.01% | -0.01% | -0.01% | 60 | -0.01% | -0.01% | -0.01% | 0.011 |
| Energy tax | -0.54% | -0.42% | -0.34% | 60 | -0.54% | -0.44% | -0.37% | 0.011 |
| Energy performance requirements | -0.49% | -1.08% | -2.06% | 59 | -3.66% | -6.39% | -10.04% | 0.010 |
| 2. Existing instruments—extended form | | | | | | | | |
| Capital grants | -0.19% | -0.34% | -0.37% | 60 | -0.64% | -0.96% | -1.05% | 0.011 |
| Subsidized loans | -0.01% | -0.02% | -0.02% | 60 | -0.01% | -0.05% | -0.02% | 0.011 |
| Energy tax | -1.06% | -1.23% | -1.61% | 59 | -1.06% | -1.30% | -1.77% | 0.010 |
| Energy performance requirements | -1.32% | -15.43% | -32.87% | 59 | -1.32% | -30.27% | -48.92% | 0.005 |
| 3. Possible future instruments | | | | | | | | |
| Remediation duty | -1.13% | -3.34% | -4.58% | 57 | -1.30% | -3.79% | -5.28% | 0.010 |
| Carbon tax | -3.71% | -5.67% | -5.38% | 57 | -3.79% | -6.06% | -6.04% | 0.010 |
| Combined energy policy tools | | | | | | | | |
| Bundle 1 | -1.09% | -1.56% | -2.45% | 58 | -4.33% | -6.97% | -10.53% | 0.010 |
| Bundle 2 | -2.43% | -16.87% | -34.60% | 59 | -5.46% | -21.99% | -50.71% | 0.005 |
| Bundle 3 | -6.64% | -24.58% | -42.37% | 55 | -9.92% | -30.47% | -50.53% | 0.004 |

\(^\text{25}\)This alternative modeling approach produces good (in particular not at all excessive) results.
### Table 6  Number of retrofits, Conventional energy consumption, and Adjustment factor (total building stock)

| Scenario                     | Number of retrofits | Conventional energy consumption (kWh) | Adjustment factor |
|------------------------------|---------------------|----------------------------------------|-------------------|
|                              | up to 2030 | up to 2045 | up to 2060 | 2030 | 2045 | 2060 | 2030 | 2045 | 2060 |
| Baseline                     | 46474    | 1138250  | 185755    | 5961251570 | 5392410660 | 4764806730 | 0.91   | 0.97   | 0.986 |

Deviation from the baseline:

| Individual energy policy tools | Capital grants | Subsidised loans | Energy tax | Energy performance requirements |
|--------------------------------|----------------|-----------------|------------|----------------------------------|
| 1. Existing instruments—initial form | 0.00% | 0.00% | -0.05% | -0.19% | -0.20% | -0.21% | -0.07% | -0.06% | -0.05% |
| 2. Existing instruments—extended form | 0.00% | 0.00% | 0.00% | -0.03% | -0.02% | -0.02% | 0.00% | 0.00% | 0.00% |
| 3. Possible future instruments | 0.00% | 0.00% | 0.00% | -0.03% | -0.01% | -0.01% | -0.22% | -0.22% | -0.17% |

### Table 7  Benefit to cost ratio (in €; from a governmental perspective)

| Scenario                     | Direct revenues | Direct expenses | Balance | Benefit to cost ratio (€/kWh saved) |
|------------------------------|-----------------|----------------|---------|-----------------------------------|
|                              | during instrument’s time period |                  |         |                                   |
| Baseline                     | 0.00            | 0.00           | 0.00    | 0.00                              |

**Individual energy policy tools**

1. Existing instruments—initial form

- Capital grants: 0.00
- Subsidised loans: 0.00
- Energy tax: 199761810.82
- Energy performance requirements: 0.00

2. Existing instruments—extended form

- Capital grants: 0.00
- Subsidised loans: 0.00
- Energy tax: 531075380.17
- Energy performance requirements: 0.00

3. Possible future instruments

- Remediation duty: 2251340323.00
- Carbon tax: 0.00

**Combined energy policy tools**

- Bundle 1: 189813712.28
- Bundle 2: 451734508.71
- Bundle 3: 1776990472.89
Table 8  Energy consumption (comp. to 2007), CO₂ emissions (comp. to 2005)

| Scenario               | Final energy consumption compared to 2007 | Direct CO₂ emissions compared to 2005 |
|------------------------|------------------------------------------|---------------------------------------|
|                        | 2020 Target: -20% | 2030 | 2060 | 2020 Target: -20% | 2030 Target: -40% | 2060 |
| Baseline               | 28.79% | 18.97% | 6.55% | 6.76% | -4.44% | -21.10% |
| Individual energy policy tools |                                 |                                        |
| 1. Existing instruments—initial form |                                        |                                        |
| Capital grants         | 28.68% | 18.81% | 6.37% | 6.46% | -4.80% | -21.47% |
| Subsidised loans       | 28.79% | 18.96% | 6.54% | 6.76% | -4.45% | -21.11% |
| Energy tax             | 27.80% | 18.33% | 6.19% | 5.96% | -4.96% | -21.39% |
| Energy performance requirements | 28.37% | 18.39% | 4.35% | 4.63% | -7.94% | -29.02% |
| 2. Existing instruments—extended form |                                        |                                        |
| Capital grants         | 28.66% | 18.75% | 6.16% | 6.44% | -5.05% | -21.93% |
| Subsidised loans       | 28.79% | 18.96% | 6.53% | 6.76% | -4.45% | -21.12% |
| Energy tax             | 27.80% | 17.71% | 4.84% | 5.96% | -5.46% | -22.49% |
| Energy performance requirements | 28.37% | 17.41% | -28.47% | 4.63% | -8.44% | -59.46% |
| 3. Possible future instruments |                                        |                                        |
| Remediation duty       | 28.79% | 17.63% | 1.67% | 6.70% | -5.68% | -25.26% |
| Carbon tax             | 28.79% | 14.56% | 0.82% | 6.70% | -8.06% | -25.86% |
| Combined energy policy tools |                                 |                                        |
| Bundle 1               | 27.37% | 17.68% | 3.94% | 3.75% | -8.58% | -29.41% |
| Bundle 2               | 27.35% | 16.09% | -30.32% | 3.73% | -9.66% | -61.11% |
| Bundle 3               | 27.35% | 11.07% | -38.60% | 3.73% | -13.92% | -68.07% |

Fig. 1  Number of dwellings per energy class (total building stock of 2060)
Fig. 2  Number of dwellings per energy carrier (total building stock of 2060)

References

1. European Commission (2010). Energy 2020: a strategy for competitive, sustainable and secure energy.
2. Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J. A., Clarke, L., Dahe, Q., Dasgupta, P., et al (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
3. Jaffe, A. B., & Stavins, R. N. (1994). The energy-efficiency gap. What does it mean?. Energy Policy, 22(10), 804–810.
4. Lindner, M., Maroschek, M., Netherer, S., Kremer, A., Barbati, A., Garcia-Gonzalo, J., Seidl, R., Delzon, S., Corona, P., Kolström, M., et al. (2010). Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. Forest Ecology and Management, 259(4), 698–709.
5. Olhoff, A., & Christensen, J. M. (2018). Emissions gap report 2018.
6. Gillingham, K., Keyes, A., Palmer, K. (2018). Advances in evaluating energy efficiency policies and programs. Annual Review of Resource Economics, 10, 511–532.
7. Weitzman, M. L. (1974). Prices vs. quantities. The Review of Economic Studies, 41(4), 477–491.
8. Pizer, W. A. (2002). Combining price and quantity controls to mitigate global climate change. Journal of Public Economics, 85(3), 409–434.
9. Lee, W.L., & Yik, F.WH. (2004). Regulatory and voluntary approaches for enhancing building energy efficiency. Progress in Energy and Combustion Science, 30(5), 477–499.
10. Bovenberg, A. L., Goulder, L. H., Gurney, D. J. (2005). Efficiency costs of meeting industry-distributional constraints under environmental permits and taxes. RAND Journal of Economics, 36(4), 951–971.
11. Boonekamp, Piet.G.M. (2006). Actual interaction effects between policy measures for energy efficiency: a qualitative matrix method and quantitative simulation results for households. Energy, 31(14), 2848–2873.
12. Geller, H., Harrington, P., Rosenfeld, A. H., Tanishima, S., Unander, F. (2006). Policies for increasing energy efficiency: Thirty years of experience in OECD countries. Energy Policy, 34(5), 556–573.
13. Böhringer, C., Koschel, H., Moslener, U. (2008). Efficiency losses from overlapping regulation of EU carbon emissions. Journal of Regulatory Economics, 33(3), 299–317.
14. Fankhauser, S., Hepburn, C., Park, J. (2010). Combining multiple climate policy instruments: How not to do it. Climate Change Economics, 1(03), 209–225.
15. Boeters, S., & Koornneef, J. (2011). Supply of renewable energy sources and the cost of EU climate policy. Energy Economics, 33(5), 1024–1034.
16. Flues, F., Löscher, A., Lutz, B. J., Schenker, O. (2014). Designing an EU energy and climate policy portfolio for 2030: Implications of overlapping regulation under different levels of electricity demand. Energy Policy, 75, 91–99.
17. Knobloch, F., Pollitt, H., Chewpreecha, U., Mercure, J.-F. (2019). Simulating the deep decarbonisation of residential heating for limiting global warming to 1.5 C. Energy Efficiency, 12(2), 521–550.
18. Bye, B., Fæhn, T., Rosnes, O. (2018). Residential energy efficiency policies: Costs, emissions and rebound effects. Energy, 143, 191–201.
19. Köppel, S., & Ürge-Vorsatz, D. (2007). Assessment of policy instruments for reducing greenhouse gas emissions from buildings. Report for the UNEP-Sustainable Buildings and Construction Initiative.
20. Giraudet, L.-G., Guivarch, C., Quirion, P. (2011). Comparing and combining energy saving policies: Will proposed residential sector
policies meet French official targets?. The Energy Journal, 32, 213–242.
21. Giraudet, L.-G., Guivarch, C., Quirion, P. (2012). Exploring the potential for energy conservation in French households through hybrid modeling. Energy Economics, 34(2), 426–445.
22. Giraudet, L.-G., Branger, F., Guivarch, C., Quirion, P. (2015). Global sensitivity analysis of an energy-economy model of the residential building sector. Environmental Modelling & Software, 70, 45–54.
23. Haas, T., & Peltier, F. (2017). Projections macroéconomiques et démographiques de long terme: 2017-2060.
24. Hourcade, J.-C., Jaccard, M., Bataille, C., Gherisi, F. (2006). Hybrid modeling: New answers to old challenges. Introduction to the special issue of "The Energy Journal". The Energy Journal, 27, 1–11.
25. Weber, L. (1997). Some reflections on barriers to the efficient use of energy. Energy Policy, 25(10), 833–835.
26. Sorrell, S., Schleich, J., Scott, S., O’Malley, E., Trace, F., Boede, U., Ostertag, K., Radgen, P. (2000). Reducing barriers to energy efficiency in public and private organizations.
27. Rohdin, P., & Thollander, P. (2006). Barriers to and driving forces for energy efficiency in the non-energy intensive manufacturing industry in Sweden. Energy, 31(12), 1836–1844.
28. Schleich, J., & Gruber, E. (2008). Beyond case studies: Barriers to energy efficiency in commerce and the services sector. Energy Economics, 30(2), 449–464.
29. Thollander, P., & Ottosson, M. (2008). An energy efficient Swedish pulp and paper industry—Exploring barriers to and driving forces for cost-effective energy efficiency investments. Energy Efficiency, 1(1), 21–34.
30. Fleiter, T., Worrell, E., Eichhammer, W. (2011). Barriers to energy efficiency in industrial bottom-up energy demand models—A review. Renewable and Sustainable Energy Reviews, 15(6), 3099–3111.
31. Trianni, A., & Cagno, E. (2012). Dealing with barriers to energy efficiency and SMEs: Some empirical evidences. Energy, 37(1), 494–504.
32. Gillingham, K., & Palmer, K. (2014). Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence. Review of Environmental Economics and Policy, 8(1), 18–38.
33. Poncin, S. (2019). Energy policies for eco-friendly households in Luxembourga study based on the LuxHEI model.
34. Capros, P., De Vita, A., Tasiós, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopoulos, D., Nakos, C., et al (2016). EU Reference Scenario 2016: Energy, transport and GHG emissions—Trends to 2050.
35. Birol, F. et al. (2010). World Energy Outlook 2010. International Energy Agency, (1), 1–738.
36. Cayre, E., Allibe, B., Laurent, M.-H., Osso, D. (2011). There are people in the house! How the results of purely technical analysis of residential energy consumption are misleading for energy policies. Proceedings of the ECEEE Summer Study, Paper 7-277, 1675–1683.
37. Sunikka-Blank, M., & Galvin, R. (2012). Introducing the prebound effect: The gap between performance and actual energy consumption. Building Research & Information, 40(3), 260–273.
38. Jaccard, M., & Dennis, M. (2006). Estimating home energy decision parameters for a hybrid energy-economy policy model. Environmental Modeling & Assessment, 11(2), 91–100.
39. Schofer, E., & Meyer, J. W. (2005). The worldwide expansion of higher education in the twentieth century. American Sociological Review, 70(6), 898–920.
40. Reynolds, T., W., Bostrom, A., Read, D., Morgan, M. G. (2010). Now what do people know about global climate change? Survey studies of educated laypeople. Risk Analysis: An International Journal, 30(10), 1520–1538.
41. Palmer, J. A., Suggate, J., Robottom, I., Hart, P. (1999). Significant life experiences and formative influences on the development of adults environmental awareness in the UK, Australia and Canada. Environmental Education Research, 5(2), 181–200.
42. Aminrad, Z., Zakaria, S.ZBS., Hadi, A. S. (2011). Influence of age and level of education on environmental awareness and attitude: case study on Iranian students in Malaysian Universities. The Social Sciences, 6(1), 15–19.
43. Huang, P., Zhang, X., Deng, X. (2006). Survey and analysis of public environmental awareness and performance in Ningbo, China: A case study on household electrical and electronic equipment. Journal of Cleaner Production, 14(18), 1635–1643.
44. Simon, H. A. (1955). A behavioral model of rational choice. The Quarterly Journal of Economics, 69(1), 99–118.
45. Åstmarsson, B., Jensen, P. A., Maslesa, E. (2013). Sustainable renovation of residential buildings and the landlord/tenant dilemma. Energy Policy, 63, 355–362.
46. Gillingham, K., Harding, M., Rapson, D. (2012). Split incentives in residential energy consumption. The Energy Journal, 33(2), 37–62.
47. Charlier, D. (2015). Energy efficiency investments in the context of split incentives among French households. Energy Policy, 87, 465–479.
48. Hausman, J. A. (1979). Individual discount rates and the purchase and utilization of energy-using durables. The Bell Journal of Economics, 10(1), 33–54.
49. Train, K. (1985). Discount rates in consumers’ energy-related decisions: A review of the literature. Energy, 10(12), 1243–1253.
50. Rivers, N., & Jaccard, M. (2005). Combining top-down and bottom-up approaches to energy-economy modeling using discrete choice methods. The Energy Journal, 26, 83–106.
51. Jaffe, A. B., Newell, R. G., Stavins, R. N. (2004). Economics of energy efficiency. Encyclopedia of Energy, 2, 79–90.
52. Ministry of the Economy of Luxembourg (2017). Energiepass-Datenbank des Wirtschaftsministeriums Luxemburg.
53. Myenergy Luxembourg (2018). Quelles aides financières pour votre projet de construction ou de rénovation.
54. Sartori, I., Wachenfeldt, B. J., Hestnes, A. G. (2009). Energy demand in the Norwegian building stock: Scenarios on potential reduction. Energy Policy, 37(5), 1614–1627.
55. STATEC (2011). Recensement de la Population.
56. BBSR (2016). Mietrecht und energetische Sanierung im Wohnungswesen.
57. Lechtenböhmer, S., & Schüring, A. (2011). The potential for energy conservation in French households through hybrid modeling. Energy Economics, 34(2), 426–445.
64. Tommerup, H., & Svendsen, S. (2006). Energy savings in Danish residential building stock. *Energy and Buildings, 38*(6), 618–626.
65. Eurostat (2017). European Union Statistics on Income and Living Conditions (EU-SILC).
66. Pearce, D. (1991). The role of carbon taxes in adjusting to global warming. *The Economic Journal, 101*(407), 938–948.
67. Gerlagh, R., & Van der Zwaan, B. (2006). Options and instruments for a deep cut in CO2 emissions: Carbon dioxide capture or renewables, taxes or subsidies?. *The Energy Journal, 27*(3), 25–48.
68. Ghalwash, T. (2007). Energy taxes as a signaling device: An empirical analysis of consumer preferences. *Energy Policy, 35*(1), 29–38.
69. Bruvoll, A., & Larsen, B. M. (2004). Greenhouse gas emissions in Norway: Do carbon taxes work?. *Energy Policy, 32*(4), 493–505. https://doi.org/10.1016/S0301-4215(03)00151-4.
70. Lin, B., & Li, X. (2011). The effect of carbon tax on per capita CO2 emissions. *Energy Policy, 39*(9), 5137–5146. https://doi.org/10.1016/j.enpol.2011.05.050.
71. Weisbach, D. A. (2012). Carbon taxation in the EU: Expanding the EU carbon price. *Journal of Environmental Law, 24*(2), 183–206. https://doi.org/10.1093/jel/eqr033.
72. Peck, S. C., & Teisberg, T. J. (1992). CETA: A model for carbon emissions trajectory assessment. *The Energy Journal, 13*, 55–77.
73. Chakravorty, U., Roumasset, J., Tse, K. (1997). Endogenous substitution among energy resources and global warming. *Journal of Political Economy, 105*(6), 1201–1234.
74. OECD, IEA, NEA, ITF (2015). Aligning policies for a low-carbon economy.
75. Vollebergh, H. (2014). Green tax reform: Energy tax challenges for the Netherlands.
76. Amstalden, R. W., Kost, M., Nathani, C., Imboden, D. M. (2007). Economic potential of energy-efficient retrofitting in the Swiss residential building sector: The effects of policy instruments and energy price expectations. *Energy Policy, 35*(3), 1819–1829.
77. McCormick, K., & Neij, L. (2009). Experience of policy instruments for energy efficiency in buildings in the Nordic countries.
78. Schulz and Mavroyiannis (2012). Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.
79. TIR Consulting Group LLC, & Grand Duchy of Luxembourg Working Group (2016). The Third Industrial Revolution Strategy Study for the Grand Duchy of Luxembourg.
80. Levine, M., ¨Urge-Vorsatz, D., Blok, K., Geng, L., Harvey, D., Lang, S., Levermore, G., Mongameli Mehlwana, A., Mirasgedis, S., Novikova, A., et al (2007). Residential and commercial buildings. *Climate Change, 20*, 1–17.
81. Schimschas, S., Blok, K., Boermans, T., Hermelink, A. (2011). Germany’s path towards nearly zero-energy buildingsEnabling the greenhouse gas mitigation potential in the building stock. *Energy Policy, 39*(6), 3346–3360.
82. Weiss, M., Junginger, M., Patel, M. K., Blok, K. (2010). A review of experience curve analyses for energy demand technologies. *Technological Forecasting and Social Change, 77*(3), 411–428.
83. Ministry of the Economy of Luxembourg, & Lichtmell, M. (2014). Berechnung kostenoptimaler Niveaus von Mindestanforderungen an die Gesamtenergieeffizienz fr neue und bestehende Wohn- und Nichtwohngebude.
84. Högberg, L. (2013). The impact of energy performance on single-family home selling prices in Sweden. *Journal of European Real Estate Research, 6*(3), 242–261.
85. Schaefer, C., Weber, C., Voss-Ulthombrock, H., Schuler, A., Oosterhuis, F., Nieuwlaar, E., Angioletti, R., Kjellsson, E., Leth-Petersen, S., Togeby, M., et al (2000). Effective policy instruments for energy efficiency in residential space heating: An international empirical analysis (EPISODE).
86. Weiss, J., Dunkelberg, E., Vogelpohl, T. (2012). Improving policy instruments to better tap into homeowner refurbishment potential: Lessons learned from a case study in Germany. *Energy Policy, 44*, 406–415.
87. Callan, T., Lyons, S., Scott, S., Tol, Richard S.J., Verde, S. (2009). The distributional implications of a carbon tax in Ireland. *Energy Policy, 37*(2), 407–412.
88. Falkner, R. (2016). The Paris Agreement and the new logic of international climate politics. *International Affairs, 92*(5), 1107–1125.
89. Schleussner, C.-F., Rogelj, J., Schaeffer, M., Lissner, T., Licker, R., Fischer, E. M., Knutti, R., Levermann, A., Frieler, K., Hare, W. (2016). Science and policy characteristics of the Paris Agreement temperature goal. *Nature Climate Change, 6*(9), 827.

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