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Modeling policies for the EU building stock decarbonization at sub-national resolution

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ABSTRACT

Understanding how the energy needs of different sectors will evolve in the future is key to informing climate policy design. For the buildings sector, this involves considering heterogeneity in technological, socioeconomic and climatic conditions. This paper develops a building energy sectoral model for Europe that considers technology adoption dynamics at the subnational scale, with high ($0.5^\circ \times 0.5^\circ$) resolution. The model focuses on energy efficiency by considering building renovation, space heating, space cooling, and their interplay. Wide-scale renovation waves in Europe are simulated, understanding where more household renovation efforts should be expected, and where policy support will be most needed in the following decades. Space cooling energy demand increase is expected, along with a substantial reduction of space heating energy demand and a general electrification of end-uses. This study implies that energy renovation investments in EU27 in the 2020–2050 period need to increase by roughly 18%, with respect to historical data, to significantly reduce energy demand and emissions. Spatial clustering of renovation activities, which this work uncovers with unprecedented detail across the EU both between and within countries, should be anticipated and explicitly accounted for in the design of European-level policy instruments. To increase renovation rates through subsidies, public government support should roughly match private investments, especially in those regions where the conditions of the building stock, construction costs and energy expenditures might not motivate households to renovate. This is a significant departure from the last decade during which private investments have been about 20 times higher than public ones, and a targeted use of EU funds and Emission Trading Systems revenues should be considered to address this gap.

1. Introduction

The building sector accounts for 31% of global CO_2 emissions, 82% of which is due to energy use in buildings and the remaining 18% to embodied emissions [1]. At the EU level, the Energy Performance of Building Directive (EPBD) [2] has set ambitious goals for the Member States building stocks. The final objective is to reach a fully decarbonized building stock by 2050 by reducing the energy use of existing buildings through renovation, and by considering zero-emission buildings as the new standard for newly built structures. It is therefore of fundamental importance to understand how operational energy demand [1] will evolve in the next decades. This will enable current policies to be properly adjusted and decision makers to be informed on the most efficient measures to reduce energy impacts of the building sector.

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[1] It is considered here that the operational energy is the one derived from using a building after its construction or renovation: it is composed of space cooling and heating, and usage of appliances and devices. On the other hand, embodied energy is the energy needed to build or renovate a building, and therefore depends on the energy intensity of materials and construction processes. Embodied energy and its associated emissions are not the focus of this study, but they are considered extensively in the literature [3–5].

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When considering future energy demand, three main drivers can be identified: climatic conditions, improvements in energy efficiency for appliances and buildings, and electrification of end uses. Global warming will decrease space heating needs and increase space cooling needs. How this will affect energy consumption is the object of many studies [6–8], that deal in particular with the estimation of households' Air Conditioners (AC) adoption and consumption. These variables are understood to depend on both past and present climate and on households' socioeconomic conditions. Particularly in modeling approaches, a popular formulation to account for AC is the econometric one first introduced by [9], using city-level and country-level AC adoption data to highlight the effect of both income and temperatures on AC adoption and energy consumption.

While energy needs might change, in response to changes in climate and in energy behavior of households [10], energy efficiency is generally seen as one of the most immediate and cost-efficient ways to moderate energy demand [2,11]. Energy efficiency measures in the building context involve both appliance efficiency and building envelope insulation. The energy efficiency of appliances such as heat pumps and ACs has been rising considerably in the last decades, with the average seasonal energy efficiency ratio increasing by 50% in the last 20 years globally [12]. The same can be observed for building insulation, specifically for the thermal transmittance (known as the U-value $[W/(m^2K)]$ of a surface) of different construction components and its variation through different building vintages [13,14]. Overall, in between 2000 and 2015 the average EU-27 U-value has gone down from 2.04 to 1.18 $W/(m^2K)$, generating substantial energy savings across the whole Union. The character of these technological innovations and adoptions has clear spatial differences in Europe, and also within single countries.

This has been investigated more in recent years through the application of Machine Learning approaches and more granular building data availability [15–17]. Data availability has shaped the research in this field. Datasets constructed bottom-up, as the aggregation of authoritative and open datasets, have reached building-level resolution [18], but their coverage for key attributes such as type of building and height is incomplete for many world regions. On the other hand, products generated with top-down approaches using remote sensing have been able to extend this coverage to virtually all areas in the EU and globally, but with a resolution which is often coarser and not building-level for all attributes [19].

This has, in turn, motivated initial investigations of how building conditions spatial distribution can inform retrofit strategies within single countries [15], and data-driven approaches to improve the definition of building archetypes [20,21], which are a fundamental building unit in many building sectoral models [7,8]. For the most part, however, these efforts have remained confined to the national scale, which strongly limits the generalization of results in spatial terms, especially when using aggregated bottom-up datasets, and reduces the capacity to assess cross-border policies, such as in the case of the EU. The question of how to model energy demand and energy efficiency spatial distribution at large scale and at high resolution therefore remains relevant [22,23]. In particular, there are no studies that consider how building policies and incentives can be applied in the whole EU level in the following decades, at the same time taking into account the significant differences found within each country's climate, building stock and socioeconomic characteristics. This strongly limits the policy strategies that the EU can define, and fails to highlight the spatial hotspots where the policy action of the EU is most urgently needed.

Spatial heterogeneity is a key feature also when considering the growth and electrification of specific end uses. Indeed, space cooling is expected to change the spatial and temporal features of energy use in buildings, and the attractiveness of certain thermal properties of the built environment. Compared to heating energy uses, it marks a shift toward the electrification of energy carriers. Electrification is also seen as the main process that will help decarbonize building energy demand [24], marking a paradigm shift in which electricity is expected to become the main energy carrier globally. However, as a consequence of this, the energy system is increasingly dependent on variable renewable energy production and exposed to its intrinsic variability [25]. To properly plan electricity production and transmission capacity expansion in the next decades, it is therefore fundamental to understand where and when energy consumption will take place.

The effect of sub-national resolution in energy modeling has been explored from the production side [26], while on the demand side, there have been efforts in downscaling already existing projections [27]. More effort is needed to analyse the effect of different scenario assumptions on sub-national energy distribution.

As also mentioned before, understanding the spatial dimension of energy demand and energy efficiency gains is necessary to understand where policies should be enforced, and also how much this will cost for the private sector and governments. For example, it has been shown for France that designing a retrofit strategy while accounting for the local building conditions can improve by a 30% the energy savings per m^2, compared to a strategy where only country-level information is used [15]. Spatial heterogeneity is equally important for modeling energy policies for countries such as the Southern European ones, where thermal comfort needs and energy consumption habits vary significantly at the sub-national scale [28]: representing them as a single-point country would lead to inefficient choices of renovation strategy.

A wide range of incentive schemes is currently in place in different EU countries, going from energy efficiency grants in Germany, to tax deductions in Italy, Energy Saving Certificates in France and energy taxes in Sweden and the Netherlands [29]. Their impact on energy savings, on a large scale, can be partly inferred from the available EU official data [30], while their efficacy is a matter of current debate [31]. Also, the distributional effects of these policies are very different and not adequately considered in the policy design. Many barriers to investment, from split incentives to credit constraints [32], when interacting with policies such as tax credits, have been seen to produce inequitable outcomes [33,34]. Acknowledging the distributional implications of these measures is fundamental to achieve a just transition, combining high well-being with low energy demand needs and taking into consideration all relevant dimensions such as energy poverty, quality of life, and health implications of energy demand consumption [35–37]. While this study does not include all of these aspects, it provides a crucial first step in identifying where efforts should be directed to improve the conditions of the building stock.

Given the knowledge gaps considered above, the following set of research questions should be timely addressed to inform EU policy-making:

- How can energy demand projections and policies for the building sector decarbonization be modeled at sub-national resolution for the EU?
- How will the spatial distribution of energy demand and investments evolve in the future across EU regions?
- What are the levels of investments and public support required to pursue ambitious EU-wide renovation strategies over the coming decades?

To answer such questions, this work considers the dimensions of climate, energy efficiency and electrification in building energy modeling by producing subnational energy demand projections at a spatial resolution unprecedented in multi-national building sectoral models. It goes beyond the typical approach for modeling space cooling, by employing a Machine Learning model to estimate cooling electricity use at a granular spatial resolution presented in [6]. It also comprehensively accounts for building conditions heterogeneity at the subnational level, drawing on state-of-the-art built-up surface data published in [19,38], and its future evolution according to optimal investment principles.

This represents a novel contribution in the literature of building energy sectoral models where large-scale analyses are limited in spatial resolution by the use of selected building archetypes with ex-

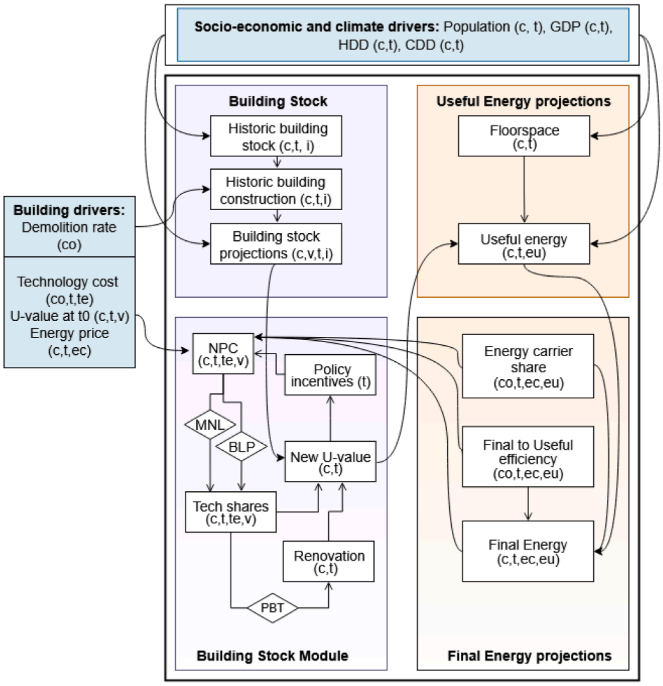

Fig. 1. EDGE-EU model schematic representation. This scheme is an updated version of the one originally published in [39]. The indices c, co, t, te, v, i, ec, eu, respectively, denote cell, country, time, technology, vintage, type of building (residential or commercial), energy carrier and end use. Blue boxes represent the inputs, purple boxes the modules for the building stock, the orange boxed the modules for energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ogenously defined characteristics [7,8], and limited internal dynamics driven mostly by exogenous assumptions. It also introduces a cost-efficient approach to renovation investments spatial allocation at the EU scale, as well as an analysis of the results of different renovation wave scenarios in Europe, quantifying both private investments and public costs while revealing their impact on energy consumption distribution, all elements that expand the state-of-the-art in the building sectoral models literature.

Finally, through a set of scenarios, it explores different policy pathways and their compliance with the objectives of the EPBD, in particular the 22% decrease in energy demand by 2030 relative to 2020 levels and the full decarbonization of the sector by 2050. Thanks to these updates, the model allows to better understand the future geography of building energy consumption at the European scale.

This paper is organized as follows: in the Methodology, the main updates of the model are presented, along with the new data sources employed; in the Scenarios, the considered scenario framework are presented; in the Results, main energy, renovation and cost variables are presented. In the Discussion and Research Needs, results are commented on and compared with the current literature, with a mention to the future works that can be further developed, starting from this study. In the Conclusions the main takeaways of this study and the policy message that can be derived from it are briefly reported.

2. Methodology

The analysis conducted in this paper is based on an updated and spatially downscaled version of the Energy Demand GEnerator (EDGE) model, first introduced in [40] and later modified by [39], of which a short introduction is given in this paragraph. EDGE is a bottom-up model used to produce long-term building energy projections, with a 5-year temporal resolution, written in R. The model is designed to run up to 2100, but in this study, due to its policy-oriented focus, only the period 2020–2050 has been considered in the results. It is designed to be multi-regional, and it has country-level and sub-national resolution only for Europe. It considers multiple energy carriers and end-uses, and it is, for the most part, statistically-based, except for the Building Stock Module (BSM) introduced in [39]. More specifically, the BSM represents the evolution of the building stock by considering construction, demolition, and renovation rates, and by defining the optimal U-value and insulation thickness for new and renovated building surfaces. Net Present Cost (NPC) is calculated based on projected energy expenditures and future U-values. This formulation can be expressed concisely as:

$$NPC_{te} = Cost_{te} + Exp_{te} =$$
$$Cost_{te} + PWF\sum_{eu} UE_{eu'}\sum_{ec}\frac{Price_{ec}Share_{ec,eu}}{\eta_{ec,eu}}$$
$$\forall te \in [Window, OpaqueSurfaces] \qquad (1)$$

where the Present Worth Factor (PWF) accounts for the effect of the discount rate, UE is the Useful Energy of different enduses *eu*, Price is the price of different energy carriers *ec*, Share represents how much each energy carrier *ec* contributes to each enduse *eu*, and η is the energy efficiency of each enduse *eu* for each energy carrier *ec*. The NPC is computed within each region for different technologies, and it is used to compute the PayBack Time (PBT) of each renovation investment. If the PBT is below a given threshold (which is exogenously set and constant at 30 years, in this study), renovation interventions are implemented.

The share of each technological solution in each renovation is computed considering a multinomial logit (MNL) equation that depends on the NPC of each technology. Energy prices are the same as those used in the previous work where the model has been coupled with the Integrated Assessment Model WITCH [41]. It is important to note that regional differences in prices are significant, but they all follow similar temporal trends. In particular, fossil fuel carriers' prices increase throughout the simulation, while electricity ones reach a peak in 2040 and start to decrease afterwards. More information on this can be found in the Supplementary Materials.

All these elements are also shown in the scheme in Fig. 1, which describes the main variables and relations that constitute the model in the current version. This framework, therefore, does not consider building archetypes with exogenously defined U-values, as most building energy models do [7,8], but rather it looks at average building characteristics and lets the optimization module define the future insulation values. This approach is particularly innovative because it endogenously captures building-specific retrofit potentials, rather than imposing predefined scenarios. Thanks to this design choice, the model can be integrated with datasets at high spatial resolution, as is explained in the following sections. For further details and assumptions, refer to the previous publications [39–41]. Given the focus on Europe, this version of the model is referred to as EDGE-EU.

2.1. Downscaling

Estimation and projections of building energy demand at the subnational scale are usually performed for single countries [42], while more rarely data has been available to do this modeling exercise for broader scopes [15,18]. In EDGE, the absence of strict dependencies on the concept of building archetypes gives freedom to the developer in changing the spatial scale at which the model operates. For this version, it has been decided to bring it to a 0.5° × 0.5° resolution for the EU area, to maintain ease of integration with other data sources operating at this resolution [6,43]. In the following, it is shown how the model dynamics is brought to the cell level.

First, built-up surfaces and heights data derived from [19,38] are used to downscale country-level useful floorspace per capita, both for

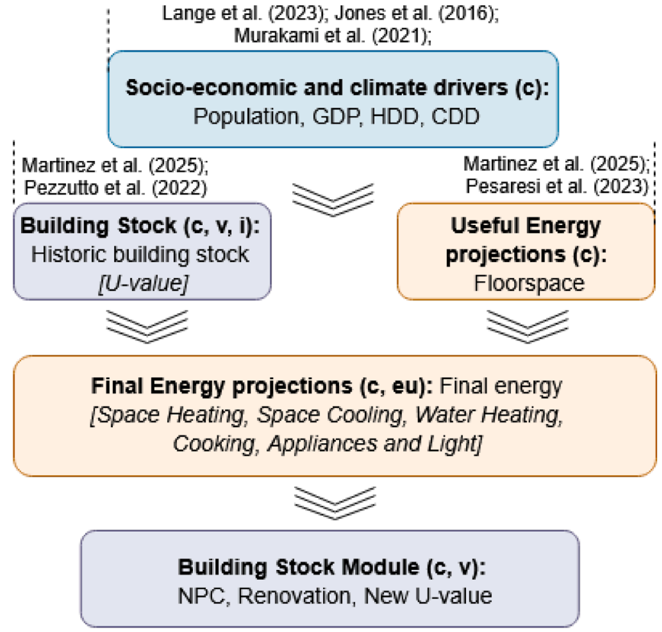

Fig. 2. Downscaling pipeline applied to EDGE-EU. The boxes refer to the modules shown in the model scheme in 1. Socio-economic and climate drivers, Building stock, and Useful Energy projections downscaling have been performed independently from one another, using the sources cited above the corresponding modules, and just for the variables mentioned. The dimensions that have been downscaled are indicated by the letters, where the legend follows the one in Fig. 1. Specifically, this means, for example, that the Useful Energy projections variable Floorspace has been only downscaled spatially (**c** represents the different cells in the model), while the Historic building stock has been downscaled also taking into consideration the vintage distribution **v** and the type of building distribution **i**.

residential and commercial buildings. These sources, recently developed, have been built by combining cadastral and satellite data. They have information at the building level at an unprecedented coverage for attributes such as construction epoch and type of building (residential/commercial). To the authors' knowledge, this is the first time that these datasets are being used for EU-scale energy demand policy analysis.

The downscaling equation for floorspace is straightforward, under the assumption that gross floorspace values are a valid proxy for useful floorspace :

$$m^2_{pc,useful,i,c} = \left(\frac{m^2_{useful,i,co}}{m^2_{gross,i,co}} m^2_{gross,i,c}\right)\frac{1}{pop_c}$$
$$\forall i \in type, \forall c \in co, \forall co \in EU27 \qquad (2)$$

with m^2_{pc} useful floorspace per capita, m^2 total useful or gross floorspace, i type of buildings (residential/commercial), c the considered cell and co the full country to which the cell belongs. The same equation is applied for demolitions and new constructions, so as to have properly downscaled building stock projections.

Another fundamental downscaling part is the U-value downscaling, made possible by the information on building vintages at high resolution provided by [19] for vintages from 1980 to the present day, and the data on country-level U-values from [14]. This process boils down to assigning the proportions of the vintages, as provided by the datasets, to each 0.5° × 0.5° resolution cell, for both commercial and residential buildings. In formulas:

$$m^2_{pc,useful,i,c} = \begin{cases} vs_{i,co} m^2_{pc,useful,i,c} & \text{if y} < 1980 \quad [14] \\ vs_{i,c} m^2_{pc,useful,i,c} & \text{if y} > 1980 \quad [19] \end{cases}$$
$$\forall i \in type, \forall c \in co, \forall co \in EU27 \qquad (3)$$

where $vs_{i,co}$ and $vs_{i,c}$ represent the vintage shares at the country and cell level, respectively, for building type i. Interestingly, the vintage distribution variation within countries can be substantial, as can be observed by the average vintage maps presented in the Supplementary Materials.

Once floorspace and insulation are downscaled at the cell level, all the model sources are updated to match the same resolution. This means using databases with $0.5° \times 0.5°$ resolution (or higher) for GDP [44], population [45], humidity and temperature [43], from which Heating Degree Days (HDD) and Cooling Degree Days (CDD) are computed.

In the other cases, concerning Final Energy projections, specific downscaling procedures are adopted based on the already existing expressions used to project the national-level variables into the future, and using the variables disaggregated in the previous steps. In particular, for all the end-uses, energy demand minus space cooling (space heating, cooking, water heating, lights, and appliances) the following cell weights have been derived:

$$CK_{c,t} = CK_{co,t} \frac{pop_{c,t}}{\sum_c pop_{c',t}}$$
$$\forall c \in co, \forall co \in EU27 \qquad (4)$$

$$AL_{c,t} = AL_{co,t} \frac{pop_{c,t}}{\sum_c pop_{c',t}}$$
$$\forall c \in co, \forall co \in EU27 \qquad (5)$$

$$SH_{c,t} = SH_{co,t} \frac{HDD_{c,t} m^2_{c,t} Uvalue_{c,t}}{\sum_c HDD_{c',t} m^2_{c',t} Uvalue_{c',t}}$$
$$c \in co, \forall co \in EU27 \qquad (6)$$

$$WH_{c,t} = WH_{co,t} * \frac{\phi^{WH}_{1,c,t}\left(1 + exp\left(\frac{\phi^{WH}_{2,c,t} - GDP_{c,t}}{\phi^{WH}_{3,c,t}}\right)\right)^{-1}}{\sum_c \phi^{WH}_{1,c',t}\left(1 + exp\left(\frac{\phi^{WH}_{2,c',t} - GDP_{c',t}}{\phi^{WH}_{3,c',t}}\right)\right)^{-1}}$$
$$\forall c \in co, \forall co \in EU27 \qquad (7)$$

with SH Space Heating, WH Water heating, CK Cooking, AL Appliances and Lights, ϕ^{WH}_1, ϕ^{WH}_2 and ϕ^{WH}_3 WH-specific parameters.

Appliances' efficiencies and electricity prices are not downscaled as it has been considered that the spatial subnational variation of these variables is not easily retrievable with the current data and not significant enough as to justify a downscaling procedure. Energy carriers' shares are also not downscaled, but in this case, doing so in future works will be considered, as spatial variations for these entities can be relevant and retrievable from existing data [46]. A general pipeline of the disaggregation process can be found in Fig. 2. This procedure, although conceptually simple, has the advantage of considering different end uses separately within the downscaling, differently from most procedures in literature that use population, GDP, and night-time lights as general proxies for buildings' energy demand [46,47].

All downscaling procedures are performed by maintaining input data coherence between the previous country-level version of the model and the current one. The downscaling exercise also gives access to new metrics that can be considered in the analysis of results. Specifically, a metric of energy demand distribution polarization is derived to visualize the evolution of the energy intensity distribution at the EU-27 level. To do so, the ratio between final energy and floorspace in each cell is considered. Then, the ratio between the 90% percentile of this distribution and the median is computed for each scenario. This metric represents how much the bulk of the energy density points is distant from the top 10%, and therefore how much the distribution is polarizing between low energy density and high energy density areas. In the Results, it will be shown how this metric changes across different scenarios.

2.2. New space cooling module

Given the new model resolution, and to improve the representation of space cooling, the Random Forest (RF) model developed in [6] is used to produce predictions of AC adoption and consumption, starting from EDGE-EU input data. In the original paper, this model was already used for building space cooling demand projections globally, but the connection with broader building sector dynamics was missing. By embedding it within the EDGE-EU model, the original paper's limitations are also addressed. To the authors' knowledge, it is the first time that a building sectoral model at the continental scale employs a machine learning module to build part of its projections.

The RF model was already designed to be trained on $0.5^\circ \times 0.5^\circ$ resolved data; therefore, no scale adjustment has been necessary. It must be noted that the addition of this module strengthens the bottom-up foundation of EDGE-EU. Indeed, the study adopted for calibration [6] is based on multi-country household survey data, and not just on average city-level AC adoption rates. This constitutes a notable advancement compared to the previous model formulation described in [48]. However, the RF model has been developed for residential-only AC consumption. Therefore, as done in the previous EDGE version, an estimation for space cooling in commercial buildings was required. This is defined as the country-level total residential space cooling demand, rescaled on the 2016 values for commercial space cooling demand reported in [49] for EU27 countries. The subnational downscaling of commercial space cooling is performed considering the distribution of non-residential buildings given by [38].

The adopted space cooling downscaling procedure allows for a reliable spatial attribution of space cooling energy demand, considering different sectors, while keeping data coherence with the most updated sources for this end-use in Europe.

To insert this module within the already existing EDGE-EU model, a soft coupling is defined in order to estimate the impacts of renovations on space cooling energy demand. In particular, it is assumed that the unmodified results given by this module are to be matched with the run of EDGE-EU in the Reference scenario, which is defined in the following sections. Therefore, in all the other runs, space cooling is rescaled by considering the formula of space cooling final energy demand previously in use in the model [39], so as to obtain the following expression:

$$FE_{c,t}^{SC,scen} = FE^{SC,ref}\frac{Uvalue_{c,t}^{scen}}{Uvalue_{c,t}^{ref}}\frac{\eta_{co}^{ref}}{\eta_{co}^{scen}} \qquad \forall i \in type, \forall c \in co, \forall co \in EU27 \tag{8}$$

where η_{scen} and η_{ref} are the efficiencies in the current scenario and in the Reference one, and analogously for $Uvalue_{scen}$ and $Uvalue_{ref}$.

Especially for insulation, this relation might neglect the phenomenon of buildings overheating [50,51], occurring with too low insulation values and high outdoor temperatures. It must also be noted that ventilation, shading, external shell light coloring, and more generally other measures that define the optimal design choices for buildings in warmer climates, are not considered in this model, but could partly prevent overheating if implemented [50]. In the Results, the overheating risk and the choice of not modeling overheating prevention will be commented upon, while a more detailed analysis on it can be found in the Supplementary Materials.

2.3. Building stock module update

The BSM, which has been defined in the previous versions of EDGE [39], is only partially modified so as to be able to set a renovation rate target at the country and EU27 level, while keeping optimally spatially distributed renovation rates at the cell level. This procedure is based on an incentive scheme, defined as a uniform cost reduction on windows and opaque surfaces, with variable and fixed costs. Importantly, policies are defined at the country level and apply the same incentive for all types of surfaces. The incentive level of the policy is defined according to an optimization routine to reach the desired renovation rate target, up to a given error margin. To limit execution time, the maximum number of iterations of the routine has been set to 100. As presented in the results, this leads to a mean error on the average renovation rate equal to 2%, which, for the sake of the analysis, is acceptable.

Although the runtimes have increased substantially, this development allows for a well-defined time series of incentive levels required to reach ambitious renovation levels at the country and EU27 scale. In order to calibrate the model renovation rates to measured historical renovation rates, it is assumed that all renovations in EDGE-EU can be considered as either medium or deep [30].[2] However, it must be noted that according to the considered source, medium and deep renovations make up only 16% of the total energy reductions due to renovations. The remaining part is mostly due to light renovations, which EDGE-EU does not consider. The effects of this limitation in renovation options are commented upon in the Discussion.

Once incentives and renovation rates are properly defined, and since investments are given, it is also possible to compute the yearly private investments and the public investments and costs, which are given by the sum of policy costs and of the investments for public buildings renovations.[3] To estimate the amount of surfaces undergoing renovation, a conversion from floorspace quantities to opaque surfaces and window surfaces is necessary. To do this, the available data for vertical and horizontal surfaces in [14] is downscaled to the cell level. Multiplying this for the cost data gives the total private investments [4]

$$\begin{aligned} Investment^{Private} = \sum_{v,s,i} m_{v',s',i'}^{2,ren} R_{s',i'} O_{co,i'} Policy_{co} \; * \\ \sum_{te} Cost_{co,s',te'} Share_{s',te'} \end{aligned} \tag{9}$$

and the total policy costs

$$\begin{aligned} Cost^{Public} = \sum_{v,s,i} m_{v',s',i'}^{2,ren} R_{s',i'} Policy_{co} \sum_{te} Share_{s',te'} \; * \\ [(1 - Cost_{co,s',te'})O_{co,i'} + Cost_{co,s',te'}(1 - O_{co,i'})] \end{aligned} \tag{10}$$

where $m_{v',s'}^{2,ren}$ is the floorspace undergoing renovation for each vintage v and type of surface s, $R_{s'}$ is the conversion ratio from floorspace to each surface s, $O_{co,i'}$ is the share of private buildings for each type of building and country, $Policy_{co}$ is the level of Policy applied, $Cost_{co,s',te'}$ the cost of renovation for a unit of surface s with technology te, and $Share_{s',te'}$ the relative weight of each technology te for surface s within the renovation.

The functioning of the Building Stock Module described so far indicates that each country allocates optimally in space and building vintages the investments, by gradually changing the incentive. It is important to stress that the spatial resolution given by the downscaling is key to providing each country a wide space of solutions. It can indeed be shown that if investments are computed in the aggregate version of the model, using a space of solution limited to only the different building vintages within each country, the results drastically change. This will be commented on in the Discussion and also more broadly in the Supplementary Materials.

Further development has also changed the definition of the technology mix to be considered for the renovation and new construction

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[2] According to the classification in [30], medium renovations are the ones that achieve in between 30% and 60% energy reduction, and deep renovation the ones that achieve more than 60% reduction.

[3] Private investments are those that are recovered by private owners within a fixed payback period. Also, for brevity, in the following it is referred to public costs to identify both public investments and costs, since the latter make up the largest share in the total of the two.

[4] To improve formulas' readability, from now on the indexes for time (t), cells (c), and country (co) will be omitted. With this, it is meant that, where not explicitly mentioned, all variables are to be interpreted as cell-level variables, and that for all formulas the $\forall t \in time, \forall c \in co, \forall co \in EU27$ condition holds.

Table 1
Scenario assumptions for Reference, HistRenRate and LED scenarios.

Scenario	Insulation	Electrification	Floorspace	Efficiencies
Reference	No incentive on renovations, MNL approach for new constructions	40% SH and WH and 50% cooking electrified by 2080	No cap (Mild growth)	SH and WH efficiency tend to 3, SC efficiency to 7 by 2100
HistRenRate	Country specific historical renovation rate (EU average 1.67%), MNL approach for new constructions	40% of SH and WH and 50% cooking electrified by 2080	No cap (Mild growth)	SH and WH efficiency tend to 3, SC efficiency to 7 by 2100
LED	High renovation rate (2%), BLP approach for new constructions	80% of SH and WH and 100% cooking electrified by 2080	40 m^2_{pc} cap by 2050 (Mild degrowth)	SH and WH efficiency tend to 4.2, SC efficiency to 11 by 2100

decisions. In particular, to allow more renovations to happen, the Payback Time is defined for each renovation decision in a separate process for each technology in a first stage, in order to exclude those technologies with too high costs to be implemented. In a second stage, only the remaining (if any) technologies are considered to compute the U-value decrease associated with the renovation decisions.

As regards new constructions, an option is introduced (used in one of the scenarios introduced in the following section) to detach new constructions' U-values from NPC considerations. Indeed, a factor that strongly limits U-value decrease in EU27 within this model is the NPC principle that leads to higher U-values than the ones expected to achieve the EPBD directive goals on energy efficiency [2,39]. This is due to the fact that, starting from the NPC value for each investment option, the *MultiNomial Logit* (MNL) approach is used to determine the share of each technology following Economical Optimality considerations, and this procedure favours higher NPC options and ignores low NPC options, although they might be economically viable nevertheless. For renovations, this limit is overcome by introducing the policy incentives, therefore lowering all NPCs, while for new constructions a *Best Local Practice* (BLP) approach is considered. This consists of making the new constructions U-values adopt the lowest U-values available within each cell. In other words, when using this option, locally, the new constructions' U-values follow the renovation ones. The two options are exemplified in the following formula:

$$Uvalue_{NC,t} = \begin{cases} \sum_{te} Uvalue_{te'} \dfrac{e^{-\lambda NPC_{te',t-1}}}{\sum_{te'} e^{-\lambda NPC_{te'',t-1}}} \text{(MNL)} \\ min(Uvalue_{Ren,t-1}) \qquad \text{(BLP)} \end{cases} \tag{11}$$

where $Uvalue_{NC,t}$ and $Uvalue_{Ren,t-1}$ represent the existing buildings Uvalues at time t and t-1, $Uvalue_{te}$ are the insulation levels of the different technological solutions available for renovations and new constructions, and λ is the logit parameter, determining the sensitivity of markets to differences in NPC [39].

2.4. Calibration

Model calibration has been performed in different phases, and it concerns mostly energy and insulation. For energy variables, the considerations in the previous paper using the EDGE model still hold [39]: the energy demand projections are calibrated to meet the 2015 energy demand data from the IEA [52]. Where necessary, end-use and region-specific adjustments were made in order to ensure this matching between historical values and projections, and after 2015, the difference to the projection from the functional relationship is phased out over time.

Historical U-values are taken from up-to-date sources [14], and in order to calibrate the construction values with the historical trends, the discount rate ρ has been calibrated. To do this, U-values historical data for 2010 and 2020 are used to adjust country-level ρ values in order to have the Building Stock Module reproduce the historical trends. However, it must be noted that U-values evolution in between these two periods has been so strong that many of the EU-27 countries have reached the lower boundary (3%)[5] of the calibration procedure for ρ. As an example, France, Spain and Poland reach the 3% rate while Germany stabilizes at 3.9%, Italy at 5% and Denmark at 5.9%. For these three countries whose calibration reached the lower bound, the error on new buildings' U-value is on average 0.22 $W/(m^2K)$, while for the whole EU the calibration error amounts to 0.15. While significant, it is a necessary compromise to maintain both consistency with the literature on the topic and with the historical data.

As concerns the other main variables of this model version, renovation rates are target variables and therefore are directly calibrated to historical data in one scenario, specifically, as explained in the next section. Investments, on the other hand, are linked to the renovation rates, materials, construction costs, and the inner dynamics of the Building Stock Module. Comparing this metric with existing records is not straightforward because of the specific definitions of what constitutes a renovation intervention within the EDGE-EU model, and therefore, it has been decided to avoid an explicit calibration of this variable. However, it is discussed in the results how well it matches the historical values, depending on the scenario chosen for the renovation rate, in order to validate the model.

2.5. Spatial heterogeneity analysis

Given the model complexity, this section describes the methodology used to identify which input variables best explain the spatial heterogeneity that is seen in the model's outputs by applying an interpretable Machine Learning approach, following [54]. In particular, a new Random Forest model is fitted with all the per-cell model inputs as predictors[6] and two model outputs as targets: the focus here is on the percentage change in Final Energy demand per m^2 between 2020 and 2050, and the Total Investments per m^2 over the same period. In other terms, the RF model is used to emulate the building sectoral model [55,56] to better understand its behaviour. The model is validated internally using out-of-bag R^2. As previously done in IAM emulation studies [56], SHapely Additive exPlanation (SHAP) values [57] are used to decompose each cell's predicted output into additive contributions from individual features: grounded in cooperative game theory, they provide locally consistent, observation-level attributions that reveal how the relative importance of drivers varies across cells, directly capturing the spatial heterogeneity in the model's behaviour. The resulting feature importance analysis then supports the interpretation of the spatial patterns observed in the results.

3. Scenarios

The space of solutions is explored by combining multiple dimensions that lead to alternative, coherent scenarios with distinct narratives and

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[5] This lower limit has been defined in the previous paper on the EDGE model [39]: it is therefore a model assumption derived from the literature on discount rates for mitigation on short time horizons [53].

[6] For time-varying variables, the only 2020 values are considered as input for this RF.

relations with historical energy demand trends and policies. In the results, the Reference scenario, the Historical Renovation Rate (HistRenRate) scenario, and the Low Energy Demand (LED) scenario are considered. All scenarios are based on the SSP2-RCP4.5, with different targets and assumptions, and consider the years between 2020 and 2050. In all scenarios, it is assumed that technology costs slowly decrease in time, as in the previous versions of the model.

The Reference scenario is used to observe how building owners would behave in the absence of incentives. No renovation rate target is set, and assumptions regarding electrification and appliances' efficiency trends follow the historical ones along the SSP2 narrative. This scenario is expected to underperform with respect to the historical energy demand decrease trend in Europe, given the absence of incentives.

In the HistRenRate scenario, each country's historical renovation rate is targeted by considering only medium and deep renovations from [30], but while keeping all the other assumptions the same. In this case, the historical differences between countries are highlighted as the model simulation progresses in time, and at the same time it is expected to match the historical energy demand trend at the EU scale.

In the Low Energy Demand scenario, a higher renovation rate has to be matched by all countries. Furthermore, more aggressive electrification and efficiency growth are used, as well as the BLP approach for new constructions. A cap on floorspace per capita is also included, which is a policy measure usually coded as demand-side that implies households' behavioural changes instead of technological development, following the scenario description for LED scenarios in [58].

Low Energy Demand scenarios generally aim at improving end-use efficiency while promoting high wellbeing [36]. Strong electrification and efficiency growth, either defined exogenously (as in the case of appliance efficiency trends) or partially endogenously (using the BLP approach for new buildings' insulation levels and the target renovation rates), are necessary factors to comply to this narrative. At the same time, the floorspace cap at 40 m^2_{pc} that is used is well above the 30 m^2 considered in the most ambitious low energy demand scenarios [58], and a factor of four higher than the minimum decent living standards [59]. The combination of these elements therefore leads to a scenario that achieves strong efficiency gains while at the same time guaranteeing high service levels. Finally, it is also designed so as to address the requisites of the EPBD, in particular a reduction of 20–22% in energy consumption for the building stock by 2030 and a full decarbonization of the sector by 2050.

In this way, even though EDGE-EU's focus is on renovations, the simulations cover a comprehensive set of policy packages that consider the whole building sector.

A detailed description of the scenarios can be found in Table 1.

4. Results

In this section, the results for the three scenarios for the 2020–2050 period are presented, analyzing three main aspects: renovations, energy, and investments.

4.1. Renovations

In Fig. 3 the renovation rates along the three scenarios are shown, and how the two renovation options (corresponding to the two types of surfaces) contribute to determining the total renovation rate. Starting from the Reference, most interventions are on Opaque Surfaces, and that the total rate decreases after 2030. This is a sign that most of the cost-effective renovations are completed in the first years of the simulation, but at the same time, new renovation opportunities are generated in the following years, partially because of decreasing technology costs and increasing energy prices.

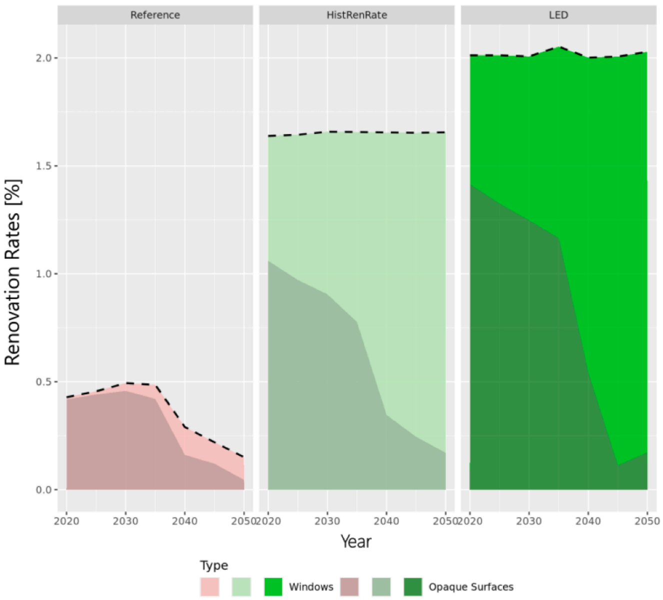

Fig. 3. Renovation rate for the three scenarios, where the relative share of different renovated surfaces is shown with different shadings.

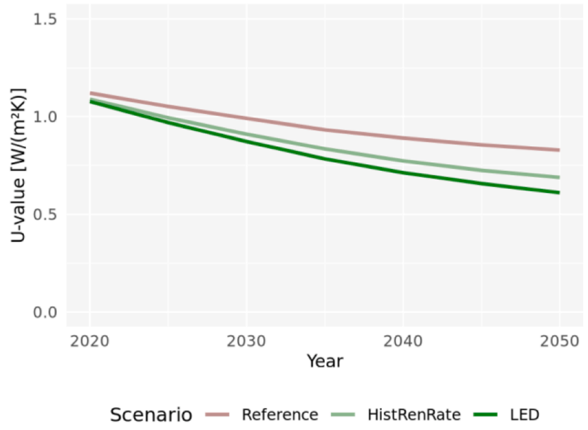

Fig. 4. U-value trend determined by renovations and new constructions along the three scenarios.

This picture changes in the HistRenRate and LED scenarios, where the renovation rate to be reached is set. Here the share of Windows renovations in the total increases considerably, becoming the aim of the majority of renovation investment decisions by 2040. All these renovations, along with New Constructions, produce the decreasing trends in average EU-27 U-values that can be observed in Fig. 4. As expected, the strongest reduction is observed for the LED scenario. However, in all the scenarios, the reduction trend tends to flatten as 2050 is reached. This is due to the diminishing returns for renovations in an already very efficient building stock towards the end of the simulation. The effect of this is also observed in the following section on Investments and Costs.

To better understand how these average values and renovation investments are distributed among the 2847 cells that compose the EU-27 area in this model, the Figs. 5 and 6 can be considered. If the annual average renovated floorspace shown in Fig. 5 is examined, substantial spatial heterogeneity emerges in the Reference scenario. Renovation activity is very limited in some countries (Poland, Netherlands, Portugal, Bulgaria), present only in specific sub-national areas in others (North of Spain and Finland, Germany), and widespread across the entire territory in a third group (France, Italy, Greece, Ireland). This highlights not only the different techno-economic conditions of the countries (different energy and material prices, different energy mixes), but also the great variety of the building stock conditions and of the climatic conditions it experiences, also within single countries. When a constant renovation

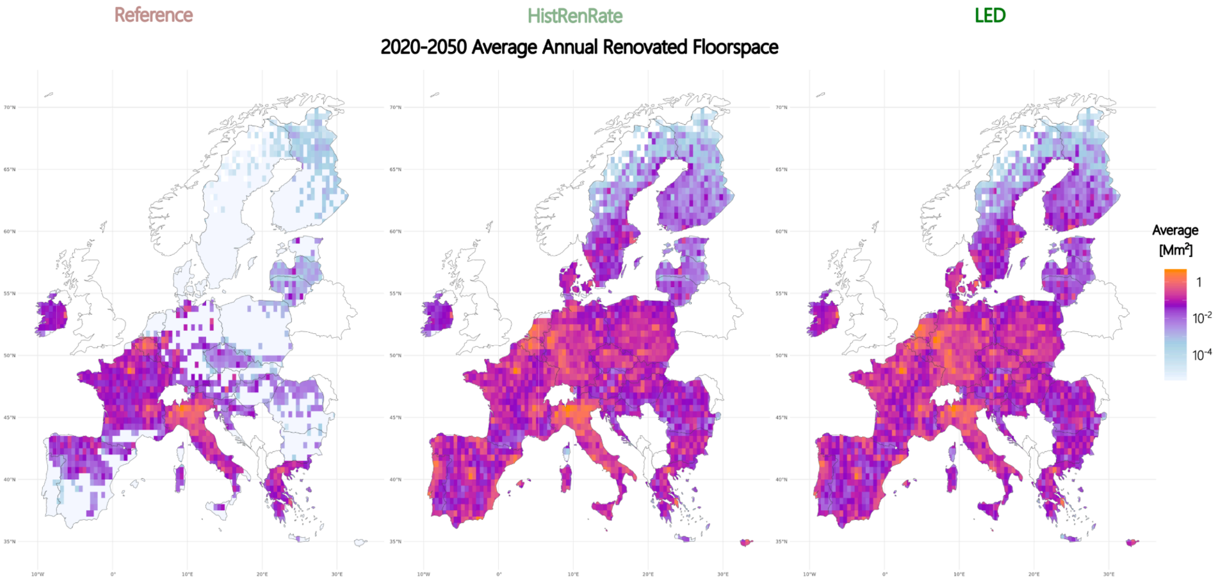

Fig. 5. Average renovated floorspace at the cell level in between 2020 and 2050, for the three scenarios.

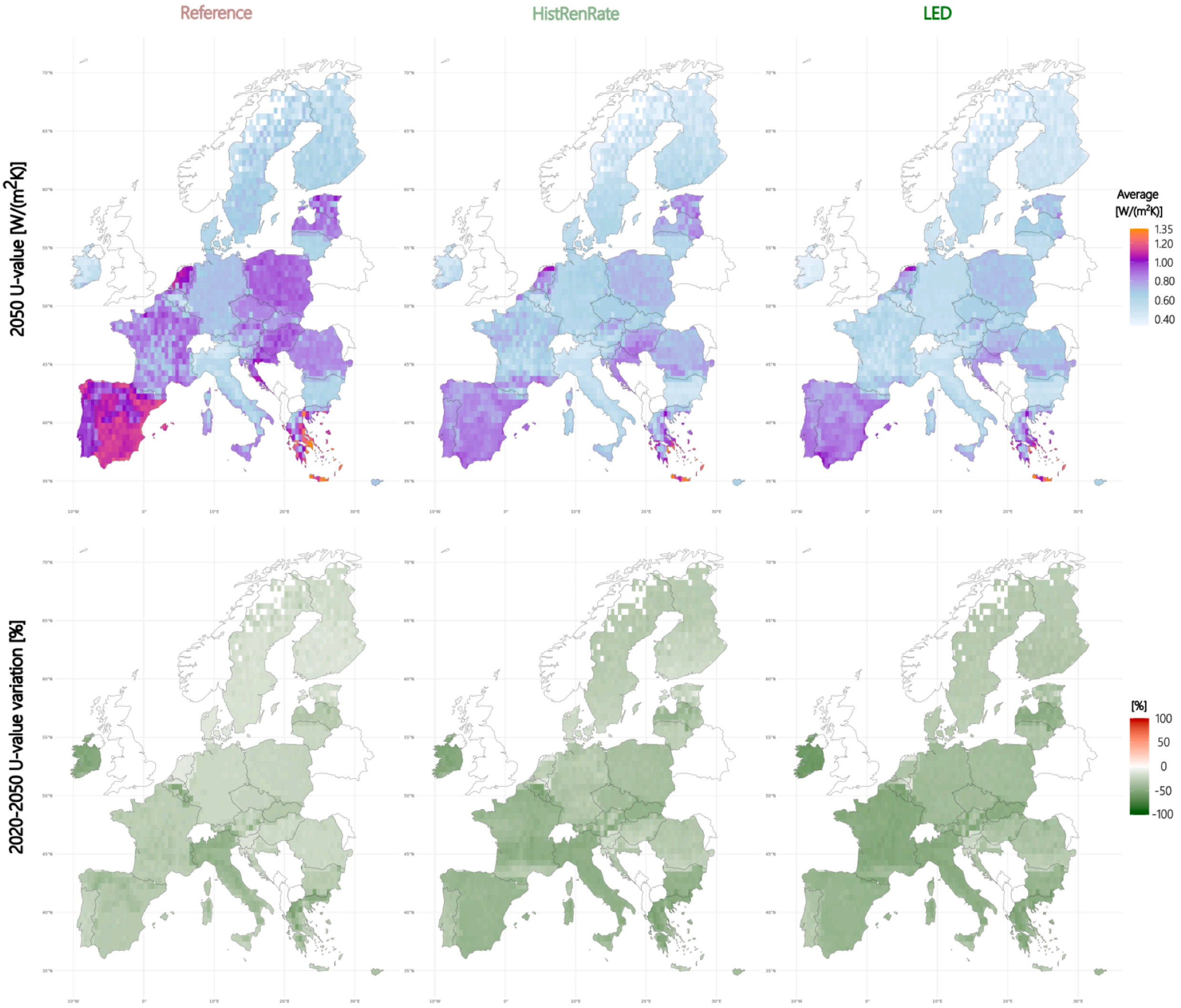

Fig. 6. Top: Building stock U-value in 2050 at the cell level, for the three scenarios. Bottom: Percentage decrease for U-value at the cell level, from 2020 to 2050.

rate target is set as in HistRenRate and LED scenarios, the differences between countries are inevitably reduced, while the within-country differences partly remain.

Given the uneven distribution of renovation efforts, the resulting U-values distributions are correspondingly diverse, reflecting also the different historical conditions of the national and regional building stocks of EU-27 countries. The top graphs in Fig. 6 show the insulation values at the end of the simulation for the considered countries. These range from the high values (1.3 - 1.4 $W/(m^2K)$) in Spain and coastal areas of Greece to the very low ones in the Alpine area and Northern Europe (0.3 - 0.4 $W/(m^2K)$). Within-country differences driven by initial building stock conditions and climate are also evident in Italy, Spain, France, Austria, Greece, and Romania. Compared to the results obtained on the renovation rate, the differences in this case tend to remain relevant in all scenarios, although with varying magnitudes.

This is due to two separate dynamics at play: with low rates, in the Reference scenario, renovations focus exclusively on the most cost-efficient areas of the countries, driving therefore the spatial differences between different regions at sub-national resolution; with high rates, in the HistRenRate and LED scenarios, renovations are carried out more uniformly within countries. However, they are also influenced by the climate driver, which is affecting households' energy expenditures, which results in higher U-values in warmer areas and lower U-values in the colder areas within the same country. Furthermore, in the LED scenarios some countries reach saturation at low U-values, as is the case for Italy, Germany, and Finland, Due to the already good insulation levels that these countries showed in 2020 at the beginning of the simulation. In the next section, how these trends influence EU-27 final energy demand in time and space will be analyzed.

4.2. Energy use

Total energy demand decreases gradually along all scenarios, with the LED scenario displaying the most substantial reduction, as depicted in Fig. 8. This can be attributed mostly to the decrease in space heating final energy, while the remaining end uses have a lower impact. Building space cooling faces a relative increase in all scenarios, especially in the Reference scenario, where it grows to almost 1 EJ in total. In 2050, in the LED scenario, it amounts to 0.70 EJ, 1/3 of total space heating demand (2.11 EJ). Overall, the contribution of space heating and cooling to total energy demand declines in all scenarios, reflecting a shift in the end-use composition. Note, however, that this relies on the assumption that energy end-uses are not targeted by strong demand-reduction policies — and thus outside the scope of this analysis — remain unchanged across scenarios. Final energy distribution in 2020 reflects population concentrations in major urban centers, as shown in the first map on the left in Fig. 8. Fig. 8 furthermore shows the percentage variation between 2020 and 2050 at the cell level, underscoring how even in the Reference scenario, the combined effect of renovations and decrease of space heating needs is enough to compensate the effect of increased space cooling needs everywhere in Europe: no region witnesses an increase in total consumption. The spatial distribution of energy reductions largely reflects the U-value decrease observed in Fig. 6, with some exceptions such as the Île-de-France region, where the decrease is less strong. As discussed below, this is due to the strong space cooling demand increase projected in that area in the next decades. In the high renovation rate scenarios like LED, it is also clearly seen that most of the total final energy decrease is increasingly focused in Central and Northern Europe, mostly because of the marginal impact of space cooling and the sensible decrease in space heating needs in these areas (see Fig. 7).

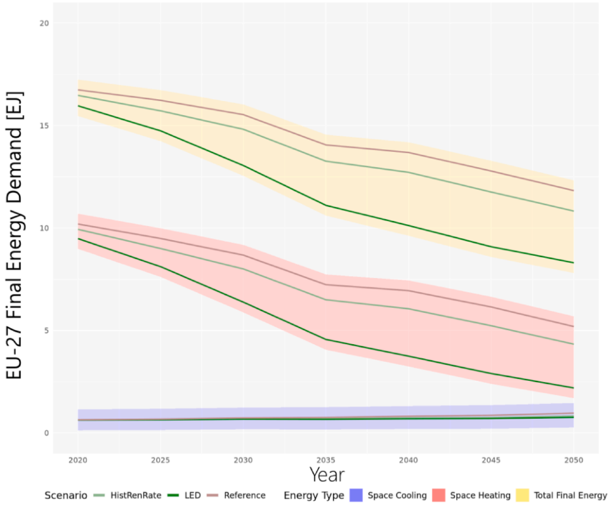

Fig. 7. EU-27 total final energy consumption, and space heating & cooling final energy consumption along the three different scenarios.

The results for space heating and cooling shown in Fig. 8 reinforce the prior findings. Notably, they reveal that while space heating decrease is quite homogeneous even within single countries, space cooling exhibits much more diversified trends, reflecting the sensitivity of this end-use on not only shifts in temperatures, but also on variations in income, urbanization, and humidity. This leads to a spatial concentration of space cooling in Central and Southern Europe urban conglomerates, most notably the Île-de-France region mentioned earlier, but also the Po Valley in Italy, Madrid and Barcelona in Spain, as can be seen in Fig. 8. Growth of space cooling is also quite different from country to country: in Southern Europe, potential growth is limited by the already high historical level of adoption and use of Air Conditioners, and in some cases like Greece the strong decrease in U-values leads in many areas to a marked decrease in cooling energy demand. On the other hand, in France, Germany, and Benelux, the increase is substantial, although in many areas space cooling remains at very low values in absolute terms. Finally, the rest of Europe shows mixed results, with countries having different space cooling growth rates depending on the specific region considered. The EU-27 energy and renovation results discussed above are presented in numerical form in Table 2 for the three scenarios, giving a synthetic overview of the study's findings. For more detailed country-level results, see the Supplementary Materials.

Space cooling and insulation improvements interaction

It is important to note that renovation decisions, especially in Central and Northern Europe, are typically driven by high space heating, but they also affect space cooling. Therefore, in many European regions, a decrease in space cooling energy demand growth is due to insulation investments targeting space heating, a beneficial secondary effect that should not be overlooked.

Next to this secondary effect of heating-driven renovations on space cooling demand, the risk of overheating already raised in the Methodology can be commented on. From the literature, computed U-value thresholds, below which buildings overheat significantly during the warm season, vary from 0.12 in Northern European countries to 0.64 $W/(m^2K)$ in Southern European ones, under current climate CDD values [60]. As shown in the Supplementary Results, one zone in Southern Europe (Malta) might eventually exceed this threshold in 2050 in the LED scenario. Thus, according to this, overheating might happen in only relatively contained areas, and only in the most ambitious renovation scenario. For this reason, and for the relatively low weight that space cooling has in the total energy accounting of most European countries, it has been decided to ignore the modeling of overheating prevention, leaving these considerations to be tackled in a future development phase of the model.

Future trends of energy demand spatial distribution

In order to better understand the future trends of energy demand from a spatial point of view, energy demand distribution polarization

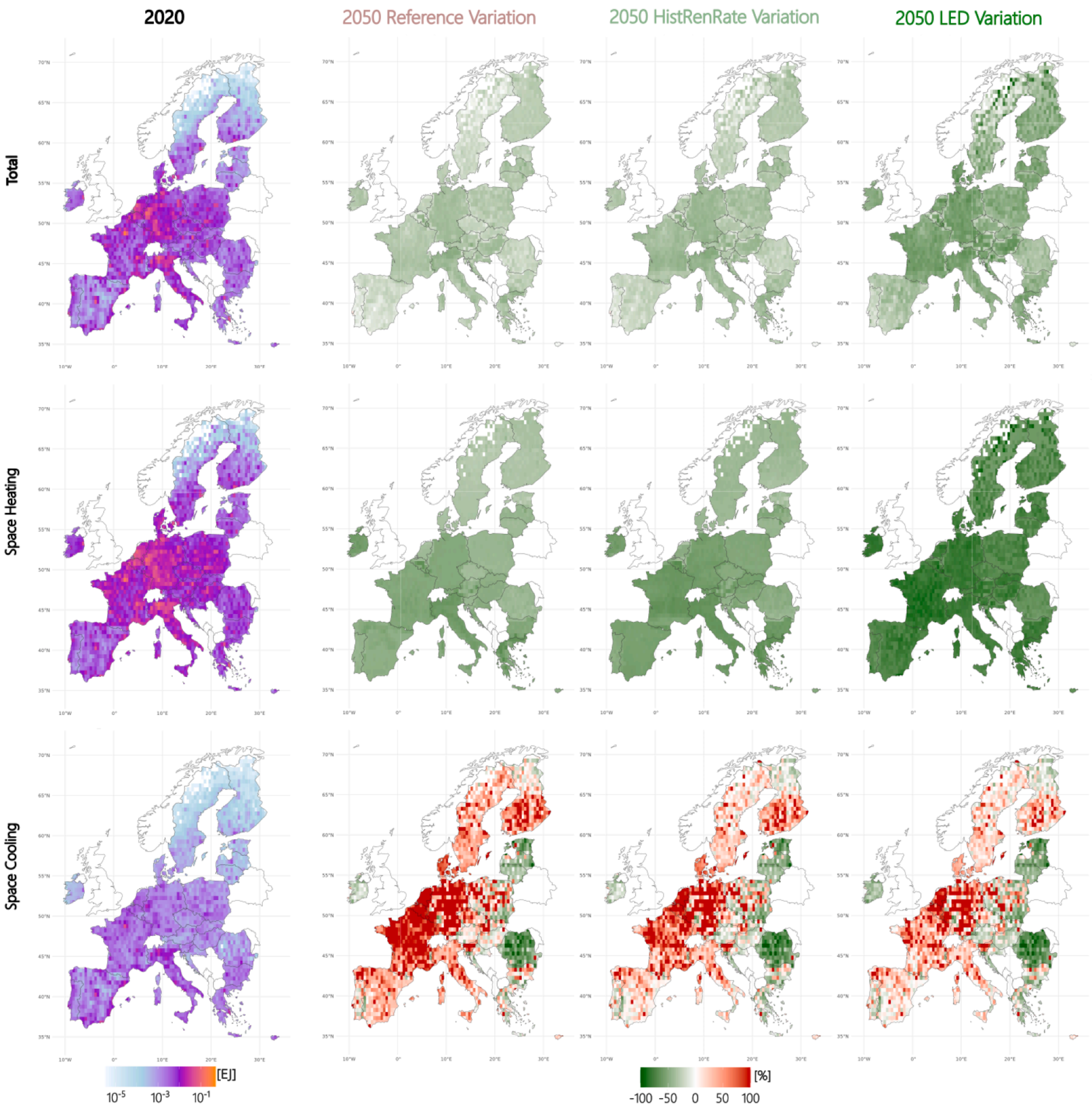

Fig. 8. Total (top), space heating (middle) and space cooling (bottom) final energy demand in EU-27. First on the left, absolute consumption in 2020, followed by the maps of percentage variation from 2020 to 2050 for Reference, HistRenRate, LED scenarios.

Table 2
2020–2050 values and variations of U-value, total final energy and space heating and cooling energy for EU-27 in the Reference, HistRenRate and LED scenarios.

Variable	2020	2050 Ref. Abs.	2050 HRR Abs.	2050 LED Abs.	2050 Ref. Var.	2050 HRR Var.	2050 LED Var.
U-value $[W/(m^2K)]$	1.13	0.83	0.69	0.62	−26.5%	-38.9%	−45.
Total final energy [EJ]	16.7	11.8	10.8	8.16	−29.4%	−35.5%	−51.3%
SH final energy [EJ]	10.20	5.18	4.34	2.11	−49.2%	−57.4%	−79.3%
SC final energy [EJ]	0.64	0.96	0.79	0.70	49.4%	22.6%	9.2%

has also been analyzed. The results indicate that the considered polarization metric rises from 3 in 2020 to 3.3 in 2050 under the Reference scenario and 3.5 under the HistRenRate scenario. The LED scenario shows a lower increase in the polarization, up to 3.2 in 2050. This underscores that renovations alone tend to increase energy density polarization, whereas a comprehensive and ambitious policy approach, such as the one in the LED scenario, can partially mitigate this effect. The mechanism underlying the increase in energy density polarization induced by the renovations is as follows: within most countries, the areas with higher energy intensity, older building stock, and higher energy expenses, generally colder regions, only partially overlap. As a result, the main drivers of renovations within individual countries redirect the investments disproportionately towards areas with already lower than average energy intensity, therefore exacerbating the polarization of the energy density distribution. Although this effect does not pose significant issues for households within the context of an overall decrease

Table 3

2020 and 2050 energy mix by energy carrier shares across the three considered scenarios, and emissions reductions of equivalent CO_2 between 2020 and 2050.

	2020	2050		
		Reference	HistRenRate	LED
Electricity Share	38.2	56.1	57.9	84.2
Gas Share	29.6	22.8	22.1	7.1
Other Carriers Share	32.2	21.1	20.0	8.7
Emissions Reduction		−53.6	−59.0	−74.4

in building stock energy demand, it may present non-trivial challenges for capacity expansion planning of the energy system. For more results related to this point, see the Supplementary Materials.

Energy mix and emissions

Next, the analysis considers the energy carrier shares that determine the energy mix in the different scenarios, as well as the associated emissions.[7] From the results in Table 3, the energy mix changes between the Reference and HistRenRate scenarios are modest, and only due to the stronger reduction in space heating in the latter, that decreases the share of fossil fuels in the mix. In the LED scenario, the differences are more marked, due mainly to the more aggressive assumptions on electrification and to the reductions in space heating demand. This type of energy mix translates to a −74.4% reduction in total emissions from 2020 to 2050. Although complete decarbonization has not been reached, results point to a substantial decrease in emissions.

4.3. Investments

When considering different policy mixes, an important dimension of analysis is how each intervention affects private owners' expenditures and the public budget. Building energy-related renovations are expensive, compared to other measures [11,62], but are nevertheless necessary in a complete mix, also for their co-benefits on quality of life and broader low-energy demand strategies [63], and for their interconnection with non-energy-related building renovations. In this section, the investments for the three scenarios are quantified, and it is shown how investments change when the target renovation rate changes. The bottom-left plot in Fig. 9 shows that in the Reference scenario, there are limited public finance needs, and that private investments follow the trend of the renovation rate previously shown in Fig. 3: investments increase until 2035, after which they start to decrease. In the other two scenarios, public support start in 2020 from a higher level than in the Reference scenario, and grows slowly during the following decades. After 2040, it represents the largest share of the total investments.

Interestingly, for both HistRenRate and LED scenario, total investments tend to decrease from 2035 to 2045, while increasing strongly again from 2045 to 2050: in the first decade, this derives from the effect of construction costs, decreasing due to exogenous assumptions, while in the last 5 years the increase is given by the increasing ambition of renovations, which target very low U-values requiring expensive investment solutions. Overall, average annual private investments range from 68 to 224 b€, and public policy support from 5 to 204 b€,[8] for a total investment need ranging from 73 to 428 b€.[9] Importantly, in the LED scenario, the total investment increase is limited by the constraint on floorspace, which limits the total amount of renovated surfaces. It is useful to look at how the distribution of these investment needs, both at the national and subnational levels. From the maps in Fig. 9, it can be seen that annual average investment per unit of floorspace follow quite diverse spatial distributions. More specifically, a combination of high energy prices, materials costs and energy intensity leads to substantial private investments per unit of GDP for Italy, Ireland, Greece, and Belgium, among others. Moreover, while policies are more homogeneously distributed, the results underscore that most of the countries with high private investments have, at the same time, lower-than-average policy costs. The clearest examples of this phenomenon are Italy and Ireland, while on the other hand, Slovakia stands out for very high public investments and costs and lower than average private investments. It must also be noted that for Northern European countries, where the share of public residential buildings is considerable, and for many post-communist countries, where the majority of commercial buildings are state or city property, public investments are inflated by the role of the public as building owner (see Supplementary Material for the data used on building ownership).

For what concerns within-country investment distributions, these again follow quite closely the renovation data from Fig. 5. This distribution of investments hints at the fact that renovation needs might impact territories very differently, and weigh differently if the local amount of floorspace and the local share of GDP involved are considered. In other words, limited regions may require, under these assumptions, a very high amount of private and public investments to satisfy optimal renovation intervention allocation, within each country. Considering the plots in Fig. 9, indeed, it is generally seen that, relatively to the country they belong to, regions such as the Northern part of Spain and the Alpine region show higher private investments per unit of floorspace. At the same time, these regions are in many cases rural, sparsely populated, and poorer [64], and therefore harder to target with renovation policies. However, it can also be noticed that for high renovation rates in the LED scenario, these spatial differences are relatively less important and, at least within countries, there is a more uniform distribution of private investments per unit of floor space. Similar reasoning can be done for policy costs, where spatial differences are relevant but not for all countries: Greece and Italy, which have a high level of private investment, are complemented by low and spatially homogeneous policy costs.

In order to better identify hotspot regions, the country average private investments per unit of floorspace and per unit of GDP, between 2020 and 2050, are computed: all cells that report values 30% higher than the national average on both these metrics are considered as a hotspot cell. In Fig. 9, the areas where most of these cells are found for the LED scenario are delimited with dashed lines, complementing the analysis reported above.[10] A full list of hotspot cells can be found in the Supplementary Materials. Besides the hotspots phenomenon concerning the feasibility of renovations in high-intensity intervention areas, it must also be remembered that in this work and generally in building energy sectoral models [8,11] there is no income and social heterogeneity within each unit region (cells, in this work). This, in turn, does not allow for a proper analysis of the distributional effects of policies [32], and this point will be further commented on in the Limitations and future work section of this paper.

Exploring the investment–energy efficiency tradeoff

To conclude this section, and in light of the evidence presented so far, one may ask: how can an appropriate renovation rate target be

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[7] To evaluate emissions, a coupling with an energy system model has been necessary. The emission factors used for electricity are computed using a no-policy run of PyPSA-EUR for the period 2030–2050 [61], backcasted to 2020. For more information on country-level emission factors, please refer to the Supplementary Materials. In this way, a conservative production-side scenario is used in order to focus on the demand-side scenarios and their efficacy.

[8] As indicated in the Methods, public costs also include public investments in publicly owned buildings, amounting to ∼ 13% of the total values reported here.

[9] All prices are reported in USD2025 (the model currency reference is USD2005), taking into consideration exchange rates and inflation.

[10] Running the same analysis for total investments and public support, instead of only private ones, leads to the same spatial distribution.

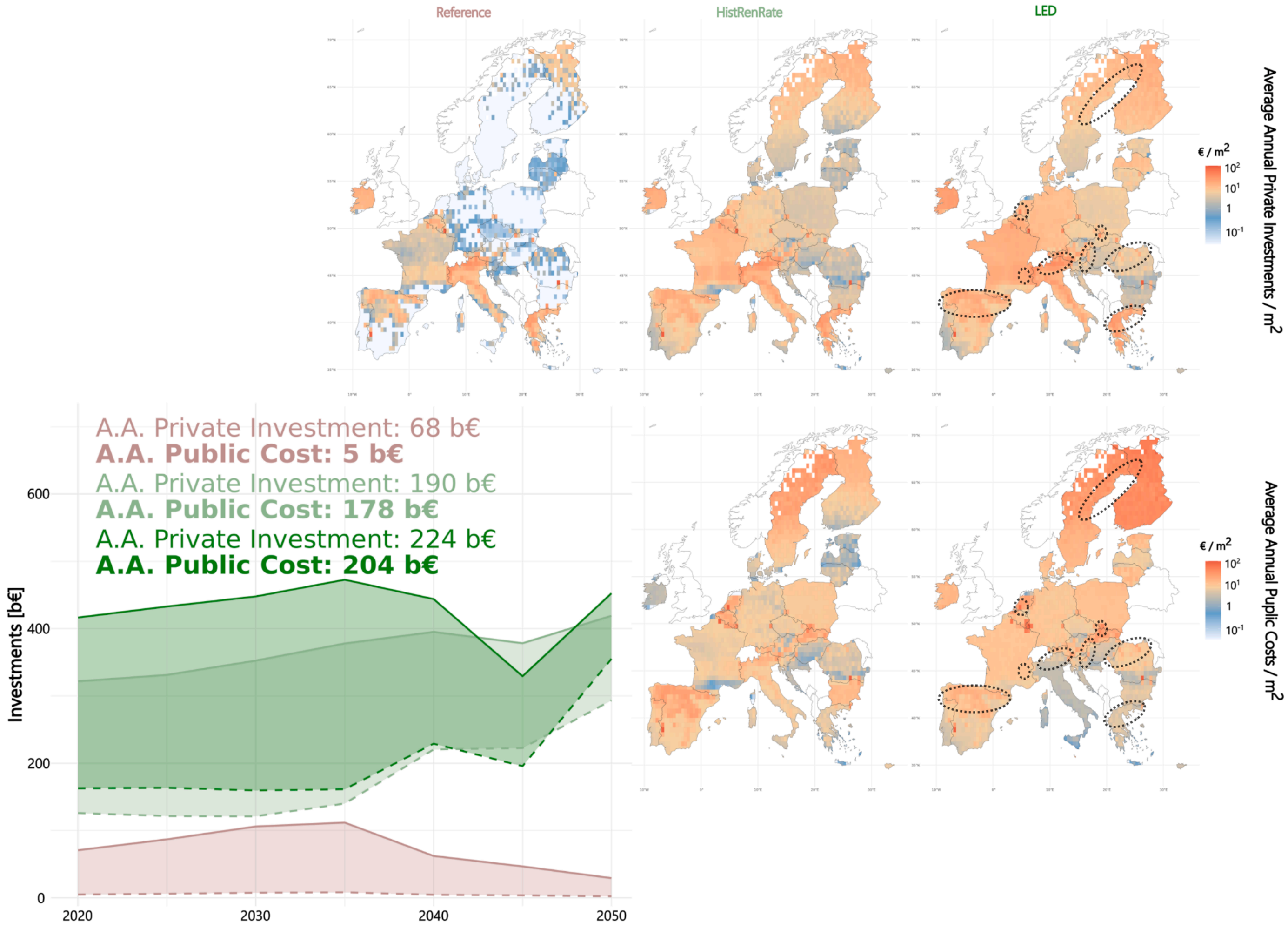

Fig. 9. Average Annual (A.A.) Private Investments and Public Costs per local floorspace, along the three scenarios between 2020 and 2050 (public cost in the Reference scenario is here not shown). In the inset in the bottom-left corner, the Annual Average Private Investments and Public Costs are also reported along the three scenarios between 2020 and 2050, and the annual averages in numbers. Areas delimited by dashed lines are the hotspot identified for their high investment density, both in terms of m^2 and local GDP, for the LED scenario.

identified, one that delivers substantial energy savings without imposing excessive burden on households or the public budget? While this ultimately remains a political decision, some insight can be gained by examining the plot in Fig. 10. Here, the three scenarios considered so far are put aside, and explore renovation rates between 0.33% (the Reference scenario) and 3.5%, to understand how renovation investments and energy decreases vary in a broader set of scenarios. This analysis is limited to investments and energy, in particular to annual average total investments, and annual average energy decrease divided by the annual average total investment: in other words, the average energy efficiency gain of renovation per unit of investment.

As shown in the previous sections of the analysis, increasing the renovation rate leads to diminishing returns of the energy efficiency investments due to the already good condition of the building stock targeted by interventions and by the higher costs of high insulation renovation options. Fig. 10 indeed shows that the relationship between investments and the renovation rate is non-linear, and that two segments can be identified qualitatively: below 1.875%, investments increase linearly and more gradually; after 1.875%, the increase becomes more than linear.

These patterns are also evident, in reciprocal terms, in the energy decrease per unit investment trends, shown by the purple line: at low renovation rates, substantial energy reductions are achieved at a relatively contained cost, but as the rate increases, the marginal gains decrease rapidly. At a 1% renovation rate, investing one cost unit leads to less than one-third the energy decrease that would have been obtained at a 0.33% renovation rate. This further means that, after 1.875%, for each unit of investment, the marginal energy efficiency gains decrease much faster than before, and more than linearly. For this reason, the results underscore that the 2% renovation rate assumed in the LED scenario might be a good candidate for a cost-effective renovation policy, from a purely techno-economic point of view, combining a substantial energy decrease with a relatively constrained marginal investment.

4.4. *Sensitivity analysis*

After the main outcomes of the model, the results of a sensitivity analysis (see more in Supplementary Materials) on materials costs, discounting rate ρ, and multinomial logit Lambda is briefly commented to understand their impact on total energy, insulation, and investments. The analysis has been performed in the Reference scenario. The choice of these variables for the sensitivity analysis follows the importance that they have in defining the outcome of the dynamical process represented by the Building Stock Module. Also, they are at least partially exogenously defined, and there is significant uncertainty on their values [53,65]. Finally, as variables, they are not part of a specific scenario and policy narrative, which makes the evaluation of their influence on results particularly important. In short, variations on materials costs have

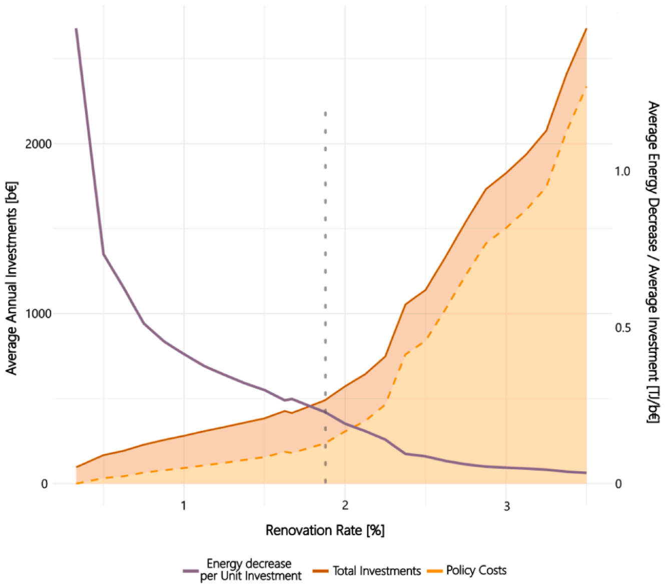

Fig. 10. On the left axis, orange plot: average annual private investments (darker color) plus policy costs (brighter color) [b€] versus target renovation rate. On the right axis, in violet: absolute value of the average annual energy decrease over average annual investments [TJ/b€] versus target renovation rate. The vertical dashed line represents the change point in the plot's trends.

a significant impact on total investments, as expected, and much less on final energy and U-values.

Lambda and ρ variations, instead, have a contained effect on the output variables.

The same results are observed also when applying this sensitivity analysis approach to the renovation rate sweeps performed in the previous subsection that lead to the identification of the 1.875% turning point. In particular, in this case, only a sensitivity analysis on Materials Costs and Lambda has been performed, since the discount rate is the subject of the sweep. The analysis plots that can be observed in the Supplementary Materials confirm a substantial increase in total investments as the Materials Costs increase, but the shape of the curve does not drastically change: in other words, the 1.875% rate is confirmed as a stable result within the settings of this study.

Spatial heterogeneity analysis

In addition to the sensitivity analysis, as mentioned in the Methodology, a spatial heterogeneity analysis is performed on two of the main outputs of the model to better understand the spatial differences observed in the Results. Final energy and investments results are considered for the LED scenario. The choice of this scenario, in place of the Reference one used in the Sensitivity analysis, is dictated by the fact that in the Reference scenario many cells do not undergo renovations, strongly limiting the number of samples (which are the cells, in this case) on which the RF can be run. The computed R^2, which is used to assess the quality of the RF simulator, amounts to 0.79 for the final energy output, and to 0.71 for the investments. Considering the model performance, the analysis will be limited to the features with the highest SHAP average absolute values.

The analysis, shown in Fig. 11, shows first of all the importance of the spatial heterogeneity of space heating in determining the significant differences in total energy decrease from 2020 to 2050. This variable also captures indirectly the influence of the local building stock conditions and U-values, since they are used to downscale space heating as defined in Eq. (6). The second-most important variable for space heating is GDP_{pc}: this variable is key especially for space cooling growth and the increases in appliances and lighting energy demand.

As concerns investments, the effect of climate and space heating can be noticed again through the HDD variable, and most importantly the materials costs variable is found to be the most significant one on average, as suggested also in the previous sensitivity analysis. Also, the electricity and gas prices are found to be relevant, but not as much as the other drivers mentioned.

In general, in this spatial analysis, it can be seen that in most EU countries, and especially in Southern Europe, the effect of spatial heterogeneity within single countries is very strong for the most influential input variables, while it is less relevant in Central-Eastern Europe. This further justifies the sub-national approach employed in this study.

5. Discussion

5.1. Comparison with other work

5.1.1. Comparison with historical data

While to the best of the authors' knowledge no other model with sub-national resolution and allocation of investments exists for EU-27, some comparison can be done especially for the Investment and Energy results with other EU-27 studies and reports. First, the seminal European Commission study [30] on building energy renovations states that the annual average investments (combining residential and commercial sectors) in energy-related renovations in between 2012 and 2016 have amounted to 362 b€. This is comparable to the 368 b€ obtained by the HistRenRate scenario, while the LED scenario outputs 18% higher total investments (428 b€). As mentioned in Section 3, the HistRenRate is specifically targeting the renovation rate of medium and deep renovations reported in the European Commission study. Accordingly, an almost exact match is observed between renovation rates and associated investments in the results, and those in [30].

A plausible explanation for the higher values reported by the HistRenRate scenario, which is unexpected considering that this a simulation of an optimal allocation of investments, is the absence of explicit modeling of Light and below-Threshold energy-related renovations in this study, which make up the bulk of energy-related renovations in the other study, and therefore the absence of low-cost renovation options in EDGE-EU. A more in-depth discussion of these aspects is presented in the following section on the limitations and future work. The agreement between the historical data and the HistRenRate scenario is also clear if the energy savings per unit of investment are considered: the scenario achieves a -1.1% decrease of final energy per year, which is quite close the -1% decrease reported by Commission study.

The picture is very different if instead the shares that the private and public sectors have in these total investments are taken into consideration. As for total renovations, a JRC report from 2019 [66] finds a total of 18.6 b€ used every year by the public through a variety of policies. This is roughly 1/10 of the total subsidies found in the HistRenRate and LED scenario. In other words, while the current ratio of private investments over public costs in energy renovations is roughly 20, the model finds instead that they should have a similar weight, that is, a ratio of 1.05 in the HistRenRate and 1.1 in the LED scenarios. Part of this gap can be motivated by the use in the model of an expensive type of policy: that is, homogeneous subsidies within each country. The allocation of the incentive does not therefore consider that many households, as in the Reference sector, would renovate also in the absence of the policy [67]. It also assumes that the public sector performs as the private sector in satisfying the required renovation rate within each cell, while it can be expected that the private sector to actually overperform in reality.

5.1.2. Comparison with other models

When considering other EU-27 studies on investments projections, using sectoral models, significant discrepancies are observed again. In [11], a study evaluating the cost and benefits of a wider set of policy mixes for the residential sector only, considering also constraints to renovations, renovations investments reach at most an annual average of

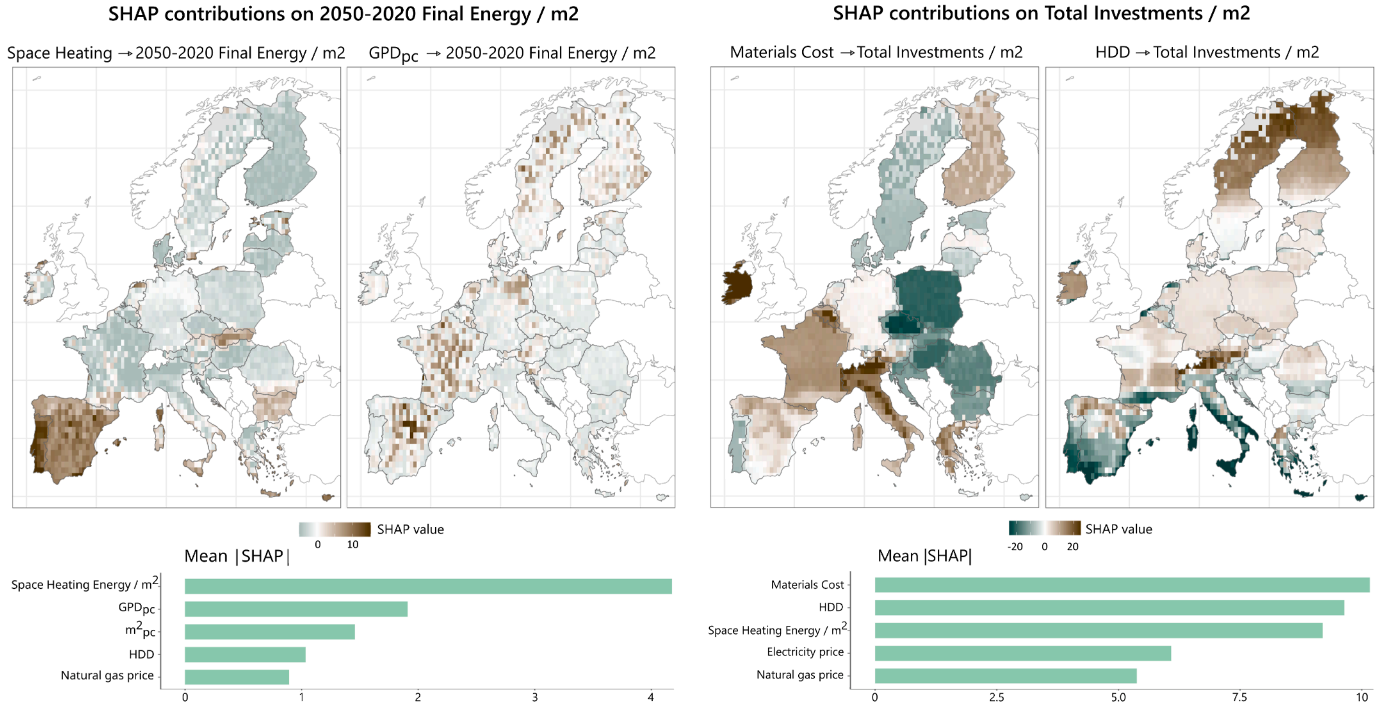

Fig. 11. SHAP analysis of the most important drivers for the percentage variation of Final Energy per m^2 in between 2050 and 2020 and the Total Investments per m^2 in between 2020 and 2050. The SHAP values of the top two drivers for each output variable are shown in the geospatial plots on top, while on the bottom the average absolute SHAP value for the 5 highest contributions to each output variable is reported.

102 b€ and contribute substantially to achieve a 67% of energy saving by 2050. This is comparable to this study's LED scenario, where a 52% of energy savings is achieved for a total investment of 428 b€, respectively. Even more pronounced is the difference with the study in [62], where renovation investments account for at most 11 b€ annually, to achieve 35% of energy savings by 2050. The HistRenRate in this study reaches 36% energy savings, but with average total investments 33 times higher. It is to be noted that these two studies are based on models that differ quite significantly from EDGE-EU: more specifically, they are at the country-level and they account for differences at the sub-national level with building archetypes for specific climatic zones. This in turns changes especially the offer of sources for renovations investments and effectiveness that can be considered.

Turning to country-level studies and to models more comparable to EDGE-EU for what concerns the analysis of investments, the work on Portugal from [42] can be considered. In this study, climate change is not considered, and the Portuguese building stock is fixed through time, assuming therefore a one-shot renovation plan. Since the cooling needs increase in Portugal will be substantial in the following decades, only the effect of investments on space heating final energy are compared. In the study, the most costly scenario achieves a space heating decrease of 86% for a total investment of 119 b€, which leads to an energy efficiency gain per unit investment of 0.72%/b€. In the EDGE-EU LED scenario presented in this paper, Portugal achieves a 66% decrease in space heating demand with a cumulated total investment of 133 b€ over the period 2020–2050, therefore a ratio of 0.50%/b€. In this case, EDGE-EU shows lower but comparable energy efficiency gains per unit of investment. Given the similarities between this model and the one used by [42], the reasons for this discrepancy can be discussed more thoroughly. In particular, the Portuguese study considers four renovation options, as it distinguishes opaque surfaces into floors, windows, and roofs. As noted in that study, while wall renovations are generally cost-effective, floor ones are not, and roof renovations are by far the most cost-effective of all. EDGE-EU instead combines all these three elements in the opaque surfaces category, reducing the availability of cost-effective single renovation options that might be taken if this decomposition of building elements were present. This point, which is further considered in the next section on the limitations of this work, highlights why such similar models differ in the results, and suggests a way forward for future work on EDGE-EU.

Another useful comparison, as mentioned in the Methods, can be done by considering the model aggregate version's results. In this case, the reduction of cost-effective investment options is strong as each country can only decide to invest in different building vintages, without sub-national spatial resolution. For comparable total energy and emission reductions, the average total investment in the LED is 1282 b€, almost a threefold increase compared to the 428 b€ found in the disaggregated version and to the historical data[11] This clearly shows how much resolution and scale can matter in such applications.

5.2. Limitations and future work

This study, in line with the existing work using the EDGE model [39,40], carries significant uncertainties and simplifications due to the model's data sources, especially concerning different energy uses and building conditions. As concerns the latter, it is highlighted that, although the advance in the model spatial resolution through a sub-national downscaling of U-values based also on local building age is substantial, sub-national information on buildings in different climate zones are not used. This constitutes a strong limitation that is here acknowledged and that will be overcome in the following development phases of the model. The new space cooling model has a strong empirical foundation for what concerns residential space cooling [6]. It has been validated on household-level data covering 25 countries worldwide for a total of 673.000 samples. Commercial space cooling, however, in this study is still based on country-level data for EU, and it is downscaled using data on the broad category of non-residential buildings [19]. For this reason, it might suffer from an imprecise matching

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[11] The differences between the results of the two versions of the model are more thoroughly explained in the Supplementary Material.

between what is commonly intended as commercial floorspace and non-residential building floorspace. In the second category, industrial built-up surfaces and mixed-use buildings (which comprise both residential and commercial use) are included. This does not invalidate the process since it is considered that the non-residential data act only as a proxy for commercial buildings. However, it is expected that this methodology will tend to overrepresent space cooling demand in industrial areas, and for this reason a more precise spatial downscaling will be considered in the next phases of model development. Then, as observed also in an earlier publication on the EDGE model [39], when considering space cooling, the complex relation with building geometry and sunlight is ignored. In this version of the model, this is relevant for the rescaling of the space cooling module results outside of the Reference scenario, especially to evaluate the impact of renovations on it. As a further development, the model could be improved by including shading, coloring, and coating renovation options aiming at reducing the net solar intake, as done in studies tackling this issue specifically [50].

It is also acknowledged that in the current model, there are limited renovation options that could drive up the total investments. As observed in the previous section, having a broader representation of renovation options and also HVAC implementation costs would lead to optimal renovation allocation with lower total costs for both households and governments. At the same time, the lack of representation of investment barriers might overestimate the renovation potential of the private sector, leading to lower policy costs overall.

As evidenced in the Discussion, the model is also currently limited in its simulation of policies, since country-level homogeneous subsidies are the only available policy. Future work will be dedicated to introducing a broader set of policies, to represent also loans and sector- and location-specific interventions. Indeed, even if in the Results a criterion to identify hotspots is defined, and cell-level hotspots are listed in the Supplementary Materials, specific policy instruments for these high renovation intensity areas, besides subsidies, should be studied extensively in a separate dedicated work. In this way, it is also expected that it will be possible to design scenarios with results closer to the historical data on public support for energy-related renovations.

Finally, as highlighted in the Results, large scale building sectoral models currently do not fully take into account socioeconomic heterogeneity within the spatial units they use, in this case the $0.5^\circ \times 0.5^\circ$ cells. This is a significant limitation, as it does not allow for the consideration of the distributional effects of simulated policies. For this reason, the future works on the EDGE model will address this by introducing a within-cell income stratification to understand the effect of the modeled policies on key metrics such as energy poverty [11], both related to space cooling and to space heating needs, and to better evaluate socioeconomic barriers to renovation investments [34,68].

Notwithstanding these limitations, the EDGE-EU model can already be a useful tool at the European scale for designing energy policies under the constraints of climate change, especially to understand within-country differences for energy, building conditions and investment allocation. EDGE-EU can also enrich production-side energy system models and integrated assessment models by giving a high-resolution and detailed picture of future building energy consumption. In order to do that, a necessary development will be a temporal downscaling to hourly values.

6. Conclusions

Throughout this study, it has been highlighted how within-country spatial differences in building stock conditions, energy consumption, and climate can characterize an optimal evolution of the building stock towards the decarbonization aims that the European Union has defined through the Energy Performance of Buildings Directive. European Parliament and Council [2]. The downscaled version of the Energy Demand GEnerator model for Europe has been used to bring the dynamics of sectoral models to the sub-national cell level, making substantial use of spatially explicit modules and databases. Across the three considered scenarios, Reference, Historical Renovation Rate, and Low Energy Demand, the spatial distribution of renovation efforts and the importance of long-lasting insulation differences within single countries, which are also expected to be in place in 2050, have been observed.

For what concerns energy, space heating decrease will be substantial and relatively homogeneous in the whole Union, while space cooling trends will be much more diversified and linked to specific local conditions. A counterintuitive result comes from the considerations on energy density: optimally-allocated strong renovations may increase the current energy density polarization in the energy system. To compensate for this, strong appliance efficiency growth and other demand-side measures such as a cap on floorspace emerge as effective options in the Low Energy Demand scenario.

The emissions that originate in the building sector across the different scenarios confirm the need for a comprehensive policy mix that can support both the electrification of end uses and energy efficiency measures such as renovations. Indeed, the Low Energy Demand scenario coupled with a production-side energy system model under conservative assumptions achieves a 74% decrease in emissions and a 84% electrification of all enduses. Although it does not reach the full decarbonization of the building stock required by the EPBD directive by 2050, it contributes significantly to it by achieving a 31% decrease in energy demand already in 2030.

As for the quantified investment needs for the private and public sectors, it is found that their distribution is not homogeneous in the EU27, and hotspots can be identified both for private investments and for public policy costs. Finally, it is highlighted that by using uniform incentive-based policies only, public costs and private investments have a similar share in the total, when considering EU27 as a whole.

To summarize, this study suggests that a high renovation rate in line with low-energy demand scenarios (e.g. 2% per year), can be a feasible target for EU-level policy making, achieving substantial energy efficiency gains if properly coupled with a broader set of demand-side policies. However, this requires significant commitment in terms of public and private investments. In total, investments need to increase by $\sim 18\%$ compared to historical trends (going from the historical value of 362 b$ to 428 b$), under a spatially optimal allocation. Most importantly, the commitment of governments to support the renovations needs to significantly increase. Going beyond the 2% rate of the Low Energy Demand scenario means encountering quickly increasing investments and costs.

In achieving these ambitious goals under the conditions mentioned above, EU policies should anticipate and take into account investment hotspots and strong public intervention. Public investments would need to increase substantially, approximately 10 times compared to the current values, and match the private ones. This average increase also hides differences between countries, going from the Southern European ones where private investments would retain a higher share to the Central-Eastern European ones where public support would be more important.

In addition to this, support for private investments will be needed especially in those regions where the density of investments is high (both in terms of floorspace and GDP). Finally, since public expenditure capability might be a limit for many countries with substantial public investments and policy costs, the EU role in support of governments will be fundamental to reach the ambitious decarbonization objectives of the Union. As suggested in previous publications, a better utilization of the available EU Cohesion and European Regional Development Funds should be pursued [69], as well as a targeted use of Emission Trading Schemes 1 and 2 revenues for energy efficiency [70], in order to overcome the different fiscal limitations of the EU27 countries. All this would mean generally a fundamental change in current renovation policies at the EU level.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Grammarly in order to proofread the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

E. Cofler: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization; **F.P. Colelli:** Writing – review & editing, Supervision, Formal analysis, Conceptualization; **G. Falchetta:** Writing – review & editing, Software, Data curation, Conceptualization; **M. Tavoni:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Data availability

Data will be made available on request.

Declaration of competing interest

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Supplementary material

Supplementary material associated with this article can be found in the online version at 10.1016/j.enbuild.2026.117521.

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