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Household budget restrictions as reason for staged retrofits: A case study in Spain

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ABSTRACT

Staged retrofits were introduced in the energy performance of buildings directive, but they remain underexplored in the literature. This paper addresses households' budget restrictions as a reason for implementing staged retrofits based on a data-driven analysis of owner-occupied single-family houses in Spain. The research question is as follows: What is the impact of households' budget restrictions on modelling the optimal timing of staged retrofits and their resulting CO_2 emissions? This study combines two methods: the statistical matching of European Union statistics on income and living conditions and household budget survey data and the staged retrofit mixed-integer linear optimisation model. This paper concludes that without any financial measure designed to accelerate building stock decarbonisation, a building renovation roadmap, from the first optimisation year until the last measure, may consume a total of 17 years. Various energy policy instruments addressing building stock's techno-socioeconomic heterogeneities, such as innovative financing and incentive schemes, are needed to reduce the CO_2 emissions of buildings significantly and rapidly. Furthermore, the use of metrics representing CO_2 emissions with time (e.g. cumulative CO_2 emissions) is recommended for building renovation passports. Such a metric will enable the monitoring of buildings' decarbonisation and better frame EU Member States' policy strategies.

1. Introduction

In 2020, most of the household energy consumption of European Union (EU) members (EU-27) was allocated to space and hot-water heating, which accounted for 85% of their total energy consumption. Specifically, space heating accounted for 64%, hot-water heating for 15% and cooking for 6%. The remaining 15% was attributed to electricity usage, which consisted of lighting (14%), space cooling (0.4%) and other end uses (such as household devices; 1%) (Eurostat, 2020). These statistics indicate the significant challenge of decarbonising the space heating sector, especially considering that 32% of EU households' final energy consumption is covered by natural gas (Eurostat, 2020). This challenge has become even more urgent due to the Russian invasion of Ukraine, which started in 2022 and has emphasised the need to decarbonise the EU's heating systems to ensure energy supply security.

In this context, building renovation has been discussed as a strategy for reducing the fuel dependence of Member States. However, only 11% of the building stock undergoes yearly renovation activities; the annual renovation rate is 1%, with the deep renovation rate (aimed at reducing energy consumption by at least 60%) being only 0.2% (European Commission, 2019. The European Green Deal strategy for renovating EU buildings, known as the Renovation Wave, focuses exclusively on the building sector and aims to double the annual building renovation rate by 2030. The Renovation Wave strategy also targets a 60% reduction in buildings' CO_2 emissions, a 14% decrease in buildings' final energy consumption and an 18% decrease in buildings' energy consumption for heating and cooling by 2030 compared with 1990 levels (BPIE, 2020; European Commission, 2020). The impacts and effectiveness of renovation measures on buildings' heating demand and CO_2 emissions constitute an important research area (Jakučionytė-Skodienė and Liobikienė, 2023) and are the main focus of the present paper.

The main legislative instrument regulating building stock decarbonisation is the energy performance of buildings directive (EPBD), which introduced building renovation passports (BRPs) in 2018 (European Parliament, 2018). BRPs are roadmaps for incrementally improving the energy efficiency and the CO_2 emissions of buildings (Fabbri et al., 2016). Additionally, BRPs can address the information gap between the different stakeholders involved in building-related

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activities, such as building owners, public authorities, financing institutions, mortgage creditors, investors and insurers, construction companies and real estate companies. By improving building documentation and information, BRPs enable a comprehensive assessment of overall building quality, energy efficiency and CO_2 emissions (Sesana and Salvalai, 2018).

The staged renovation approach outlined in BRPs is an alternative to the traditional single-stage approach, where all renovation measures are completed simultaneously to minimise heat losses and optimise heating system operation. While recognising that the staged approach may not be the technically ideal solution, policymakers have acknowledged its prevalence based on evidence from real-life renovation practices (Cischinsky and Diefenbach, 2018; Fehlhaber, 2017). The staged approach involves implementing renovation measures gradually, considering factors such as the number of stages, the measures and lock-in effects per stage and the stage sequence Avoiding lock-in effect is especially relevant to maximise the energy saving potential when implementing a certain measure.

This paper elucidates the role of staged retrofits in decarbonising building heating systems, which has received limited research focus. The central question is as follows: What is the impact of households' budget restrictions on the optimal timing of staged retrofits and the resulting energy demand and CO_2 emissions? To answer this question, this study builds upon previous work and provides a detailed assessment of a Spanish case study. The main workflow consists of integrating data-driven budget restrictions derived from statistically matched EU statistics on income and living conditions (EU-SILC) and household budget survey (HBS) (Maia et al., 2023a, b)into a mixed-integer linear programming model (Maia et al., 2021). The main objective is to obtain indications about the time dimension of staged retrofits as time plays a key role on the achievement of the decarbonisation goals. The main contribution of the present paper is to use data-driven budget restrictions and to provide more precise time estimation about staged retrofits. It distinguishes the present paper from several studies that do not consider budget restrictions or use arbitrary assumptions for budget restrictions in renovation activities (Jafari and Valentin, 2017; Wang et al., 2014; Wu et al., 2017). Furthermore, this paper introduces new aspects to the discussion on staged retrofits modelling, such as the rebound effect and the impact of climate change.

The term "staged renovation" is used to be in line with the policy instruments terminology introduced by the EPBD. Other literatures refer to this renovation approach by "phased renovation" as explained in section 2. Section 2 presents a literature review on (1) reasons for and barriers to deep renovations, (2) EU surveys as data sources for household budget restrictions, (3) staged retrofits as a renovation approach and (4) current state of policy incentives for renovation activities. Section 3 presents the adopted methods and data also briefly explaining how to derive data-driven budget restrictions through statistical matching and calculate optimal timing using the staged retrofit optimisation model. Section 4 presents the results and discussions, including the limitations encountered. Finally, Section 5 presents the main conclusions.

2. Literature review

Renovation activities encompass an intricate multidisciplinary domain, requiring a comprehensive understanding of techno-socioeconomic aspects. These aspects involve bridging the gap between energy and CO_2 emission modelling, the technical specificities of practical renovation activities, socioeconomic data analyses and the policy framework supporting the actions necessary to achieve the goals set by the EU Commission. This chapter presents a holistic overview of studies focusing on the following: reasons for and barriers to perform deep renovation activities (Section 2.1), EU survey data providing techno-socioeconomic information (Section 2.2), staged renovations within the framework of BRPs (Section 2.3) and the current state of policy incentives for renovation activities (Section 2.4).

2.1. Reasons for and barriers to carry out deep renovation activities

Buildings' retrofits present various potentials like increased energy efficiency, mitigated carbon emissions, improved non-energy benefits (such as comfort and indoor air quality), and alleviation of energy poverty (through lower energy bills) among others. Especially after the Russian invasion of Ukraine, which started in 2022, the importance of retrofits to assure EU fuel independency became even more clear: the energy savings generated through deep renovation reduce the energy consumption decreasing the energy import necessity.

However, in the past years the EU-Member States have failed to achieve their own deep renovation targets as mentioned in Chapter 1 above. Given the low rates of building renovation, addressing these challenges calls for novel, innovative practices to encouraging building renovation activities that significantly increase energy efficiency while reducing CO_2 emissions. Such energy-saving building renovation activities are called retrofits. The primary distinction between a renovation and a retrofit lies in the higher initial investment required by the latter, which is due to its focus on achieving higher energy efficiency.

The decisions of households to retrofit depends on diverse personal, socioeconomic, geographical and cultural characteristics (Ipsos, 2018). A study on regional differences in renovation activities concluded that people living in urban areas prefer spending subsidies on new houses, whereas people living in deprived regions use subsidies to insulate their houses (Frantál and Dvořák, 2022).

Previous research has identified various obstacles to building renovation activities. These include technical challenges, such as a lack of skilled craftspeople or knowledge required for renovations (Fabbri, 2017). Additionally, renovation activities are hampered by acceptance issues, such as mistrust or scepticism toward new technologies or improvement measures (Filippidou et al., 2017). Given the different interests among involved parties, legal considerations also play a role, such as the landlord–tenant dilemma when splitting the capital costs (Ástmarsson et al., 2013; März et al., 2022). Economic factors, such as building owners' budget restrictions or their ability to invest in energy-saving measures, are also barriers. Furthermore, the lack of advantageous financing and incentive schemes is a financial challenge (Bertoldi et al., 2021). These barriers are not necessarily independent or isolated, and building owners have complex reasons for refusing to undertake retrofits (Tugran et al., 2021). Additionally, renovating a building element or replacing a component does not always guarantee an improvement in energy efficiency (Friege and Chappin, 2014), which depends on the capital invested in high building energy efficiency and climate-neutral standards.

The house ownership status is a significant socioeconomic characteristic in retrofitting projects. It plays a crucial role in determining various aspects of a project, as it indicates the parties involved in the decision-making process, those responsible for making investments and the specific budget constraints of project implementation. Additionally, the house ownership status helps identify the primary interests and motivations of the individuals or entities engaged in the retrofitting process. In owner-occupied households, the homeowners make technical and economic decisions themselves, whereas in multi-family houses, obtaining a common agreement between several parties is an important challenge (Ebrahimigharehbaghi et al., 2019).

Hence, differentiating the three key parties in building retrofits, namely, decision-makers, investors and beneficiaries, is crucial. The investor bears the financial responsibility for the retrofitting of the building, whereas the beneficiary—typically the owner or tenant—directly uses the building. At times, the decision-maker may also be the investor and beneficiary, such as in the case of an owner-occupied single-family house. In such cases, the owner invests in retrofits and directly reaps their benefits, such as reduced energy costs and improved comfort. However, for rentals, the decision-maker and beneficiary may not be the same individual or entity. In the context of rented apartments, the decision-maker could be the building owner, who may be a private person, a private company or a public authority, and the beneficiary is the building user or renter. Similarly, in a rented office, the direct beneficiary is the workers, the decision-maker is the company renting the building and the investor is the building owner (e.g. a real estate company). Building owners are classified as follows: (1) private individuals or companies, such as real estate firms, and (2) public entities or housing associations. Building ownership is categorised as follows (iBROAD, 2020):

- Owner-occupied buildings: The building user and owner are the same party, which may include public authorities in the case of non-residential buildings. A private owner-occupied property can be either fully owned (no outstanding loans or mortgages on the principal residence) or owned with an ongoing mortgage.
- Privately rented buildings: Tenants pay rent to landlords at market prices, and landlords, who may be private persons or companies, operate their buildings for commercial purposes.
- Socially rented buildings: Tenants pay a subsidised rent (reduced or zero) to landlords, who are typically public entities or housing associations.

The present paper contributes to the literature by elucidating the economic aspects of retrofitting activities that are particularly linked to household budget restrictions. Household survey microdata are assessed and an optimisation model is used to quantify the time dimension of renovation activities. Given these considerations, this paper focuses on owner-occupied single-family residential buildings.

2.2. EU surveys as data sources for household budget restrictions

The EU-SILC and HBS datasets are crucial data sources widely used in various fields of research. The EU-SILC survey is designed to collect timely, comparable microdata on income, poverty, social exclusion and living conditions (Eurostat and Commission, 2021a). It has been a well-established annual survey in EU countries since 2004. The survey encompasses cross-sectional and longitudinal data providing valuable insights into different aspects of households' well-being. The dataset is organised into separate files, each containing information at the household inhabitant and household levels. They offer data on more than 100 variables, which are categorised into four main groups: household register, personal register, household data and personal data. These variables cover a wide range of socioeconomic factors, enabling researchers and policymakers to gain a comprehensive understanding of living conditions and societal dynamics. The EU-SILC microdata are anonymised (individual and household identifiers are removed) to ensure privacy and confidentiality. The number of observations available in the dataset varies depending on the specific country and year under consideration. Overall, the EU-SILC dataset is a valuable resource for conducting in-depth analyses and drawing evidence-based conclusions to address the social and economic challenges in the EU. The HBS is a national survey that focuses on households' expenditure on goods and services, thus also providing information about the socioeconomic and living conditions of households (Eurostat and Commission, 2021b). HBS results are primarily used to compile weightings for important macroeconomic indicators, including the consumer price indices used to measure national inflation and accounts. The survey is performed every five years, and the dataset is organised into separate files containing household-level information. Some variables are covered by both datasets, whereas others are exclusively covered by either dataset. Therefore, some researchers have performed statistical matching to impute some variables from one dataset (EU-SILC) to the other (HBS). The authors developed and demonstrated a method for statistically matching the two datasets via logistic regression; they introduced the novel approach of incorporating EU-SILC data into the HBS dataset for a quantitative analysis of household budget constraints per house ownership status and dwelling type (Maia et al., 2023a, b). The same paper reviewed various studies involving statistical matching and found that most researchers impute data from HBS to EU-SILC, which is the opposite of their developed workflow (Donatiello et al., 2016; Serafino and Tonkin, 2017).

In the present study, after an assessment of datasets from 10 countries, Spain's data were considered the most reliable for use due to their completeness and large number of so their outcomes were used in this paper. A recent literature review identified a study about household budget restrictions and transport poverty using Spain's HBS data (Alonso-Epelde et al., 2023) which confirmed the usefulness of HBS for studying household budget restrictions and the usability of Spain's HBS data.

2.3. Staged retrofits in BRP context

The concept of long-term, step-by-step renovation was introduced in the energy performance of buildings directive (EPBD) in 2018 (EPBD recast 2018/844/EU) as part of the BRPs. A BRP is a building document that is also called a building roadmap and provides tailored advice on how to improve the building's energy efficiency gradually. Since the approach was proposed, the terminology has evolved, and the term 'staged' currently refers to gradual, stepwise renovation. The ongoing proposal for an EPBD recast suggests a more robust and specific definition: '*staged deep renovation* means a deep renovation carried out in several steps, following the steps set out in a renovation passport following Article 10′ (European Parliament, 2023).

Some authors use different terms to refer to the same practices in the process of implementing renovation measures within the same building. The concept of retrofit measure 'sequencing' was used by an author in adopting a decision-support system model to determine the order and ranking of retrofitting measures for non-residential buildings (Ibn-Mohammed, 2014). The term 'sequencing' was also used to examine and understand the intricacies of retrofits (Murto et al., 2019). Other authors introduced the term 'phasing' to delineate the time dimension of retrofit measure sequences (Merlet et al., 2022).

Another term used is 'serial renovation', denoting a series of renovation activities done to scale up different buildings, such as those in a building portfolio, as used to investigate the viability of serial renovation using air heat pumps in multi-family houses Ochs et al., 2022).

Fig. 1 explores possible roadmaps according to the numbers of stages. The technical specifications required to avoid lock-in effects are taken into account, especially in regard to the measures combined in a step. Six renovation measures are considered: insulating the upper ceiling (or roof), insulating the facade (or external wall), replacing the windows, insulating the cellar ceiling (or floor), replacing the heating system and installing a renewable energy system. A roadmap with five or more steps is technically possible but has high interruption/cancellation risks; a maximum of four steps is ideal. The staged retrofit model used in the present paper defines the optimal retrofit sequence by calculating the timing of performing each stage. The model assumes a three-stage building roadmap, which is considered a reasonable, realistic practice.

Certain projects in Europe have already embraced the concept of building passports to promote awareness of a building's energy performance and encourage staged deep renovations. In Germany, the State of Baden-Württemberg launched the *sanierungsfahrplan* (iSFP) in 2015 as an energy audit instrument, which has also been adapted into the Austrian building certification scheme *klima aktiv*. France's *passeport efficacité énergétique* (P2E) offers solutions to achieve low-energy or nearly zero-emission buildings (P2E, 2018). In Flanders, Belgium, the *de woningpas* serves as a digital tool for storing building-related information and automated renovation details (Flanders, 2017). Although a national initiative regarding BRPs in Spain was not found in this literature review, a past study concluded that BRPs have considerable potential in Spain, especially if the urban scale were considered, thus reducing

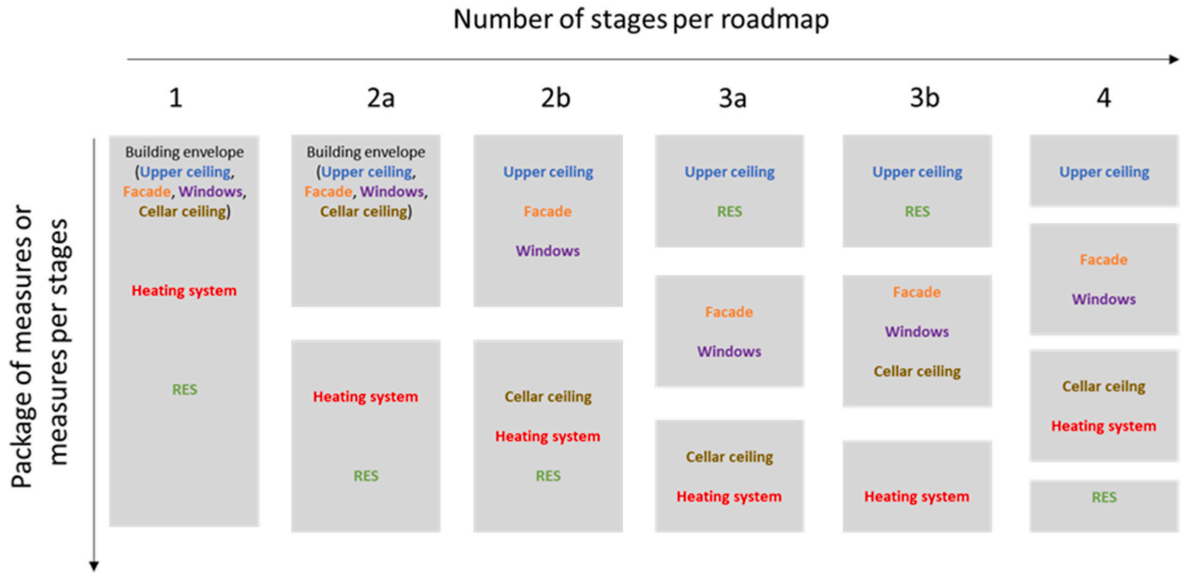

Fig. 1. Deterministic matrix of roadmaps with different numbers of stages and measure combinations to avoid lock-in effects per stage (for one building). Source: Maia et al., 2023a, b.

transaction costs in some cases (Villarejo et al., 2021). Nevertheless, Spain was used in a cross-country comparison of the climate optimality of staged renovation activities between Germany, Sweden and Spain (Maia et al., 2023a, b).

Besides the abovementioned country-specific initiatives, several EU-funded research projects have explored BRPs and their potential. The Alliance for Deep Renovation in Buildings (ALDREN) project supports deep renovation investments and proposed an EU-wide building assessment framework that incorporates sustainability metrics in certification schemes and decision-support protocols and tools (Aldren, 2018).

The Individual Building Renovation Roadmap (iBRoad) project developed two tools: the building logbook and the roadmap assistant. The building logbook centralises essential information about a building, from its administrative details to its characteristics, whereas the roadmap assistant facilitates the creation of a staged renovation plan considering the occupants' needs and circumstances (I. Maia et al., 2020; Monteiro and Fragoso, 2018). The iBRoad2EPC project extends the usability of these tools by exploring their convergence with energy performance certificates, which are important instruments for assessing and comparing buildings' energy performance (iBRoad2EPC, 2022).

2.4. Current state of policy incentives for renovation activities

Although the policymakers have made an effort to increase the deep renovation rates through funding and financing programs, unfortunately, these mechanisms had only limited diffusion as concluded by (Conforto and Hummel, 2022) and as shown by the deep renovation rates presented in chapter 1.

In the past, many studies have dedicated attention to the topic of financing building renovations, and some of these are presented next. A country-by-country overview of the most important public schemes identified across the EU various private, public financial and fiscal mechanisms for energy renovations in buildings (Bertoldi et al., 2019). A few years later, the same authors collected EU data about financial and fiscal instruments applied by municipalities to encourage renovations in residential, commercial and public buildings across European regions and municipalities (Economidou et al., 2021). After these deep-dive studies and the review of ongoing financing practices, the authors presented innovative instruments for energy renovations of residential buildings to encourage the increase of deep renovation rates through new financing instruments and schemes (Bertoldi et al., 2021). Other authors studied financing interventions from different stakeholders' perspectives: demand-side (such as subsidised loans to homeowners) and supply-side (sales and service offer from companies). The authors concluded that one-off payment grants and tax incentives are more widely used by homeowners and inadequate attention is paid by the policymakers concerning supply-side policies (Kerr and Winskel, 2020).

The COVID-19 pandemic period made the low renovation rates evident and helped reinforce the argumentation that most renovations are not sufficiently energy efficient and do not achieve climate neutrality standards. Although existing, financing schemes and funding programmes were not properly uptaken by the market and, consequently not widespread.

2021 was a political game changer as clear goals were set to achieve Europe's climate neutrality until 2050. The European Green Deal represents a stronger commitment to strengthen EU-Member States' support mechanisms, especially from the financial point of view. The European Investment Bank (EIB), the European Structural and Investment Funds (ESIF) and the European Fund for Strategic Investment (EFSI) are exemplary funding streams to finance buildings' renovation. According to the EU Commission Website, more specific financial instruments will be developed between 2021 and 2027 under the InvestEU. The same website shows increased transparency about existing actions by providing a list of national programs that target building retrofits, their current rules and support measures. Alternative to public funds, private and green banks also finance retrofitting, however with a stronger homeowners' financial participation need as reported (GFI, 2020). Finally, from the perspective of financial investments' availability, one can say that the current situation is more favourable and promising to considerably boost retrofitting activities than it was in the past.

In this favourable context, where an increased amount of retrofit funds and destinated investment help to overcome an important barrier, complimentary champagnes and actions should not be forgotten. Active communication and clarification champagnes should bring information to the homeowners about the existence and conditions of these incentives. Furthermore, a well-established support structure should exist (ie. One-stop-shops). In a literature paper, the authors present six key retrofit design features: the *source of capital*; the *financial instrument(s)*; the *project performance* requirements; the *point of sale*; the nature of the *security (ie. repayment)*; and the *channel* and *customer journey*. The paper concludes that finance alone is not a driver for retrofitting and a holistic view leads to successful retrofits when these key features are included (Brown et al., 2019).

3. Methods and data

This chapter presents the methods and data used in this study being divided into three sections. Data-driven budget restrictions of different household types: owner-occupied or rented single- and multi-family houses derived through statistical matching (Section 3.1). These restrictions were utilised as input data into the staged retrofit optimisation model (Section 3.2), which was used to calculate the optimal timing of each stage. The Spanish reference building stock (single-family houses) is described in Section 3.3, particularly their technical characteristics, retrofitting costs, energy efficiency standards and household budget restrictions. Fig. 2 presents an overview of the method used in this study and the data flow between the different methods (M1 and M2).

3.1. Statistical matching for defining data-driven household budget restrictions

Assessing retrofitting activities has the challenge that the data is available from different sources. The technical approach focuses on characteristics like geometry, energy efficiency standards, construction period, etc. Without considering the socioeconomic aspects of the households. On the other hand, many socioeconomic studies use the EU-SILC (explained in section 2.2) indicators like “household type” and “ownership status” to assess sociodemographic and living conditions. In these studies, detailed quantitative information about household expenditures is not required, which is on the hand crucial to define the data-driven budget restrictions (and available in the HBS surveys).

Statistical matching is a statistically proven method to combine different data sources and set up a database. A workflow was developed to statistically match both data sources EU-SILC and HBS to obtain combined information about the *household type* (ie. single-family or multi-family houses), *ownership status* (owned or rented) and *budget restrictions* (numerical indication). With that, the data-driven household budget restrictions were defined and used as input into the staged retrofit optimisation model (explained in section 3.1) that requires techno-socioeconomic data as input.

The detailed *statistical matching* via *logistic regression method* was developed by the same authors as the present paper and is explained in the journal publication “Integration of datasets to provide insights about households' natural gas expenditure as trigger to building stock decarbonisation” (Maia et al., 2023a, b). The whole statistical matching workflow consists of four stages starting from *data preparation* (selecting data from different EU countries, merging files, analysing data gaps, excluding observations, etc); *dataset comparison* (identifying common variables, harmonising the data, comparing variables distribution, selecting a country dataset); *modelling* (setting the model, setting the programming code in R and generating the synthetic data) *and results (*assessing the results and verifying their plausibility*).* The *modelling* stage consisted of imputing the variable ‘dwelling type’ from EU-SILC into HBS, a parametric modelling workflow developed, implemented and tested using a logistic regression model to carry out the analysis (Equation (1)). According to the literature and expert knowledge of statistics, trustful prediction models have an accuracy higher than 70% (considered a plausible threshold value). The developed model presents an accuracy of 77% according to the R program indicators. After the validation, the results were considered plausible and were used as input into the optimisation model as presented in section 3.3.3.

Equation (1) shows the logistic function that generated the forecasted values based on the probability (*p*) that an observation *i* with *x* characteristics has *Z*.

$$p(Zi) = \frac{exp^{ß_0+ß_1*x_1+ß_2*x_2+ß_3*x_3+\ldots ß_6*x_6+e}}{1+exp^{ß_0+ß_1*x_1+ß_2*x_2+ß_3*x_3+\ldots ß_6*x_6+e}} \quad \text{Equation 1}$$

where p is the probability of a house to be classified as dwelling type 1 (single-family house) or 0 (multi-family house). Four socioeconomic parameters are represented by the matching variables x_1 to x_6: ***marital status***, x_1 = never married and x_2 = separated/widowed; ***degree of urbanisation,*** x_3 = intermediate urbanised area and x_4 = sparsely urbanised area; ***status of employment***, x_5 = employer; and ***ownership status,*** x_6 = rented. e is the regression residual. The regression coefficients (β0, β1, …, β6) were calculated using logistic regression modelling in the statistical computing software/environment R.

3.2. Staged retrofit optimisation model to calculate the optimal timing

The retrofitting model embodies the perspective of homeowners and is based on three key principles. An economic premise initially holds: homeowners allocate a portion of their income to cover energy-related costs, encompassing the initial investment for retrofitting, ongoing energy expenses and maintenance charges, as outlined in prior studies (Less and Walker, 2014; Verbeeck and Hens, 2005). The second principle pertains to energy-related expenses or expenses associated with the retrofit and those currently installed systems; the former denotes costs linked to enhancing energy efficiency, whereas the latter refers to routine expenditures, often designated for maintenance. The maintenance activities are represented in the model by the variable building material ageing. The third principle revolves around the remaining value of the initial investment. The staged retrofit optimisation model is in detail explained, developed, improved and tested in the publication “New step-by-step retrofitting model for delivering optimum timing” (I. Maia et al., 2021).

The primary goal of the staged optimisation is to calculate the optimal timing when each stage is performed. For optimal timing, the net-present-value (NPV) is maximised. Therefore, the optimisation process consists of, first, calculating the NPV (Equation (2)) over the period and; second, calculating the time in a mixed-integer optimisation (Equation (3)).

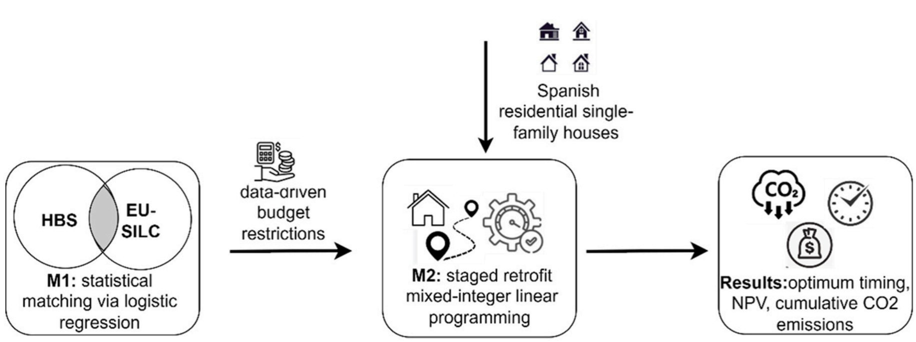

Fig. 2. Inputting of outcomes from statistical matching (M1), namely, data-driven budget restrictions, into staged retrofit mixed-integer linear programming model (M2) for a case study of Spanish single-family houses.

The NPV of household income relates to energy assets, considering accumulated income and deducting energy-related expenses, within a specific optimisation timeframe.

$$NPV = \sum_{t}^{T} \frac{CF_t}{(1+r)^t} + \frac{L_T}{(1+r)^{tp}}, \quad \text{Equation 2}$$

L is the residual value of the retrofitting measures in year t (euro), r is the interest rate (%), tp is the depreciation time (yr) and T is the optimisation period (yr).

The mixed-integer optimisation calculates the maximised NPV by defining when each stage should be performed. Equation (3) shows the objective function indicating the optimal timing when the NPV is maximised per stage. The binary decision variables **x, y** and **z** represent each stage and its corresponding year, tx, ty and tz.

$$\max \text{NPV} = f\{t_x, t_y, t_z, x, y, z\} = NPV_{t_x} * x + NPV_{t_y} * y + NPV_{t_z} * z \quad \text{Equation 3}$$

$s.t.$

$x \in \{0, 1\}$

$y \in \{0, 1\}$

$z \in \{0, 1\}$

$x_t + y_t + z_t \leq 3$

$t \in T$

$\sum_{t}^{T} x \leq 1$

$\sum_{t}^{T} y \leq 1$

$\sum_{t}^{T} z \leq 1$

$t_x + t_y + t_z \leq T$

There are different optimisation conditions (described in s.t.): over the optimisation period (T), a stage can only be performed once; in a specific year t, more than one stage can be performed (meaning a maximum of three stages performed); and each stage has an optimal timing (t_x, t_y and t_z) that can also be the same for different stages, but cannot exceed the optimisation period (T).

The model consists of a mixed-integer linear programming code implemented in Python using Gurobi as the solver. Fig. 3 shows an overview of this model, which consists of the input data (described on the left-side), the core programming code and the background databases (including country-specific ones) and the output data (described on the right-side). Four indicators represent the optimal time at which each stage should be performed in terms of economic feasibility (net present value [NPV]), climate friendliness (cumulative CO_2 emissions) and energy efficiency (roadmap duration and optimal timing).

The input data for the model are as follows:

1. **Renovation cycles**: The model determines the optimal timing (t_{op}) of each renovation cycle within the specified period. It decides whether a step should be performed and in which year it should be performed.
2. **Retrofitting measures and their initial investments (IC):** The staged approach involves one or more retrofitting measures, or a package of measures, based on building roadmaps.
3. **Building material lifetime database (tL):** This database aligns with relevant literature (BBSR, 2017; Pfeiffer et al., 2010) and contains the lifetimes of building materials and heating technologies. The model automatically assigns a lifetime to each building element using this database, which is also accessible online.
4. **Material ageing rate (m):** The material ageing rate is assumed to be 6.5 based on literature sources (Hansen, 2010; Kockat, 2011).
5. **Heating and cooling system technologies**: The model considers the currently installed heating and cooling systems and those specified in each building roadmap. The energy carrier prices for the specified heating technologies are automatically retrieved from the heating and cooling system technologies database.
6. **Energy prices and heating technology prices (EC):** The prices and price development of energy and heating technologies were determined based on previous studies, which mainly used different modelling scenarios (Capros et al., 2018; European Commission, 2019; Grave et al., 2016).
7. **Optimisation period (T):** The model's optimisation period spans 30 years, from 2020 to 2050.
8. **Depreciation time (tp):** The depreciation time considered for assets is 30 years.
9. **Annually allocated energy-related asset (A):** Initially, the model calculates a constant annual allocated income of 3000 euros for all cases, accumulated over the 30-year optimisation

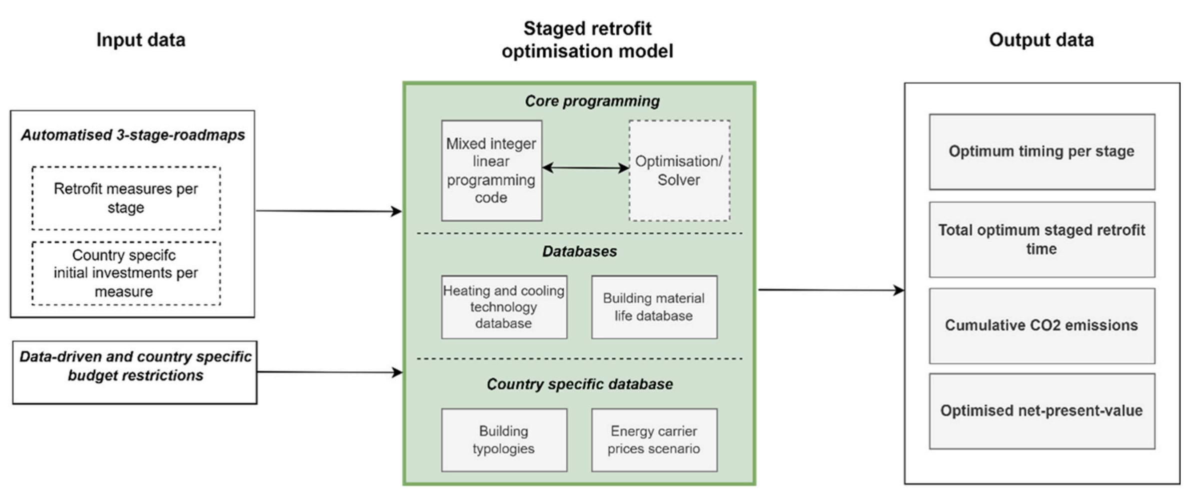

Fig. 3. Optimisation model overview to assess optimal timing, economic feasibility and cumulative CO_2 emissions of staged retrofits at building stock level. Source (Maia et al., 2023a, b).

period. This income is derived from 10% of the disposable income (INC), which is assumed to be 30,000 euros based on a review of studies on European households' disposable income (del Pero et al., 2016; European Commission, 2019). The sensitivity analysis considers worst- and best-case scenarios of 900 and 6000 euros annually, respectively.

10. **Loan (l):** Although the model regards incentives and loans as input data, this study does not take loans into account.
11 Interest rate (r): The model calculates an estimated interest rate, initially set to 3% and later to 8%.
12 **Number of stages (i):** The model generates a roadmap with three stages (i = 3). Step 3 allocates the active system (heating and cooling technologies) measure if it is foreseen in the roadmap. This approach enables an analysis of the effects of 'dependency' or 'no dependency' between the sequence of measures and the impacts on the energy efficiency and CO_2 emission reduction of including Step 3.
13. **Automated three-stage roadmaps:** This is a new calculation module that automatically computes roadmaps and offers two possible combinations of measures per stage.
14. **Country-specific initial investments**: The calculated roadmaps consider country-specific measurement costs, including installation, material and labour costs.
15. **Data-driven budget restrictions**: Data-driven household budget restrictions are classified by dwelling type and ownership status.
16. **Country-specific building typologies**: The building typologies for Spain are defined considering the building characteristics per construction period.

3.3. *Definition of Spanish reference building stock*

3.3.1. *Technical characteristics of reference buildings*

Table 1 shows the input parameters per building element of the reference single-family houses in Spain (continental climate) according to the reference typologies described by the EU-funded TABULA and EPISCOPE projects. The characteristics of the Spanish buildings, which are described using their typology-specific element surface areas and envelope qualities, are divided into six construction periods. In all buildings, a gas boiler (η = 0.85) for space heating and domestic hot water is considered. The described building geometries differ significantly between construction periods, and buildings with better energy efficiency have been constructed since 1980.

3.3.2. *Retrofit standards and investment capital*

Fig. 4 shows specific global costs of the sixteen combinations of energy different measures per construction period (represented by ID 1 to 16). It shows that ID 2, namely, 15 cm of external wall and floor insulation, 20 cm of roof insulation and a window U-value of 0.95 W/m^2K, is the cost-optimal variant in all construction periods. Then, these retrofit measures and respective investment capital were utilised as input data into the staged retrofit optimisation model.

3.3.3. *Household budget restrictions*

According to previous studies, owner-occupied single-family houses account for 32% of Spain's building stock; only 40% of these households can afford retrofits without government incentives. Then, the annual budgets of 36,000 to 50,000 euros/year were used as input data, where a fixed rate of 10% was considered as budget restrictions.

4. Results

The presented results were used to evaluate the buildings' decarbonisation roadmap and the economic feasibility of staged retrofits for owner-occupied single-family houses in Spain using the following indicators: roadmap time (total time between the first optimisation year and the year of the last stage), cumulative CO_2 emissions (representing the time dimension of CO_2 emission reduction) and NPV (indicating economic feasibility). Furthermore, this section discusses this study's limitations.

4.1. *Roadmap time versus NPV*

The Spanish reference buildings have diverse geometries and thus surface areas between construction periods, as shown in Table 1. Due to the heterogeneity of the building stock and the lack of any trend regarding building standards norms, the results are interpreted per construction period. The total roadmap time is the period between the first optimisation year (2020) and the year when the last stage is performed. The roadmap time indirectly represents the building's age (and thus energy efficiency standards) and geometry. Given the same annual budget, older, larger, and lower-efficiency buildings will need more time to complete the roadmap than smaller or younger buildings. The NPV represents the relation between annual income, capital investments and energy costs.

Fig. 5 shows the total roadmap time versus the NPV; the total roadmap time generally decreases with the annual income. Except 1937–1959, all construction periods have positive NPVs, showing the economic feasibility of the cost-optimal retrofitting measures. The NPVs are positive because Spanish buildings generally have lower energy demand (compared with German and Austrian buildings) due to climate conditions. This reduces energy costs and increases NPVs. The NPVs in this analysis vary between −11,000 and 12,000 euros. The construction period of 1937–1959 presents a negative NPV because it has the most economically unfeasible buildings, namely, those with high energy demand (reflecting low-energy efficiency standards) and large geometric sizes (and thus higher initial investments).

The effect of the annual income on economic feasibility is highly relevant in 1901–1936, in which retrofit activities are not economically feasible for lower-annual-income households.

4.2. *Roadmap time versus cumulative CO_2 emissions*

Fig. 6 shows the total roadmap time versus the cumulative CO_2 emissions. The specific cumulative CO_2 emissions vary between 252 and 715 $kgCO_2/m^2$, depending on the annual income and the construction

Table 1
Geometric characteristics and energy efficiency standards per element of reference buildings in Spain. Source: (EPISCOPE, 2016).

Building element	Construction year	until 1900	1901–1936	1937–1959	1960–1979	1980–2006	after 2007
	Ref.floor area [m2]	55	202	350	171	163	119
Roof 1	Surface area [m2]	50	87	166	64	132	68
	U-value [W/(m2K)]	2.1	3.1	2.7	4.2	0.6	0.5
Wall 1	Surface area [m2]	66	258	464	312	234	176
	U-value [W/(m2K)]	0.2	2.9	2.6	1.3	0.6	0.5
Floor 1	Surface area [m2]	50	87	146	90	107	68
	U-value [W/(m2K)]	2.4	0.9	1.8	0.9	0.9	1.3
Window 1	Surface area [m2]	4	29	44	13	66	20
	U-value [W/(m2K)]	5.0	4.6	4.6	4.6	3.1	3.1

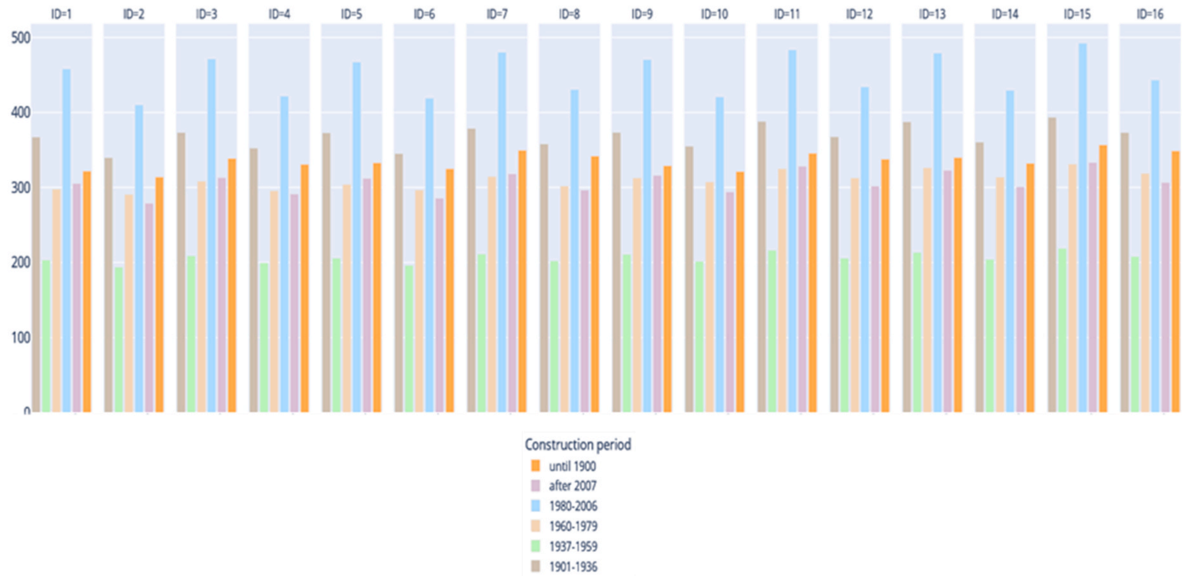

Fig. 4. Specific global costs per energy efficiency measure variant (ID 1 to 16) per construction period. ID 2 is the cost-optimal variant (lowest global costs) in all construction periods.

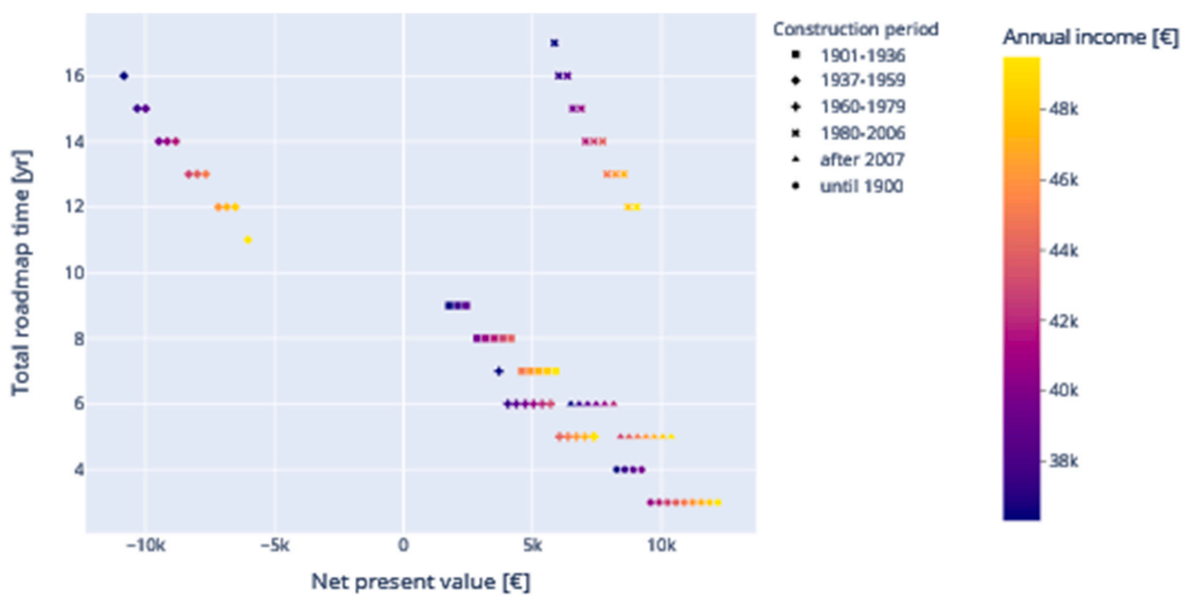

Fig. 5. Total roadmap time and NPV from optimisation model for Spanish reference buildings at annual household budgets of 36,000–50,000 euros.

period. The construction period after 2007 has the lowest cumulative CO_2 emissions and shortest roadmap time, whereas 1901–1936 has the highest cumulative CO_2 emissions for lower-annual-income households. Some construction periods require a higher budget than others to achieve the same cumulative CO_2 emissions. For example: for a cumulative CO_2 emission of approximately 600 $kgCO_2/m^2$, the construction period 1937–1959 requires an annual budget of 3760 euros; 1980–2006, 4310 euros; 1901–1936, 4360 euros.

4.3. NPV versus cumulative CO_2 emissions

Fig. 7 is a plot of economic feasibility versus climate friendliness. At the assumed annual budgets of 36,000–50,000 euros, only 1937–1959 presents a negative NPV. These results highlight the climate friendliness between households by showing that higher-annual-income households have lower specific cumulative CO_2 emissions. However, this scenario should be avoided in real life.

4.4. Discussions and limitations

Staged retrofits were introduced into policy instruments (EPBD) in 2018, and different studies have shown that this deep renovation practice is widely performed in real buildings. Although many studies focus on the single-stage approach, this is not the most performed renovation approach in real-life scenarios while evidence from real-life practices show that staged retrofits are commonly performed. Nevertheless, retrofits still present low rates, although they are important to assure energy security and decarbonise the buildings.

Due to the high risks of lock-in effects and interruption, staged retrofits have been insufficiently covered in the literature, specifically their modelling approaches and detailed examples of completed staged retrofits. Therefore, one limitation of the present study is result validation, which is

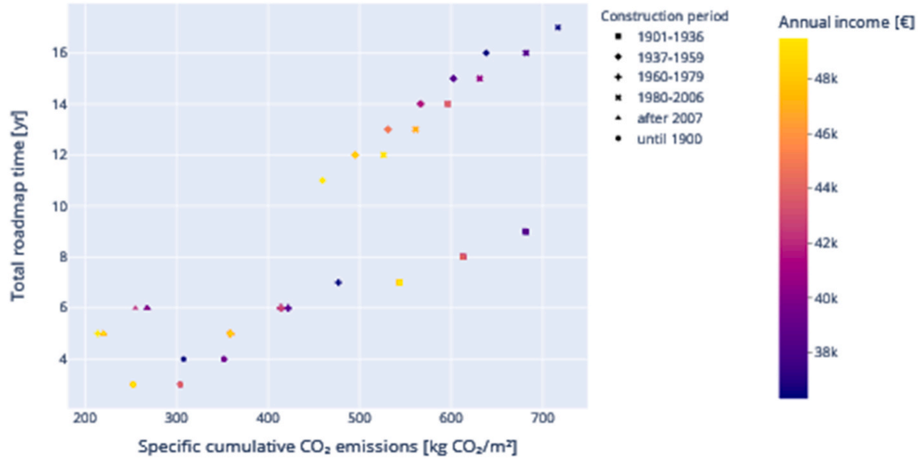

Fig. 6. Total roadmap time and specific cumulative CO_2 emissions from optimisation model for Spanish reference buildings at annual household budgets of 36,000–50,000 euros.

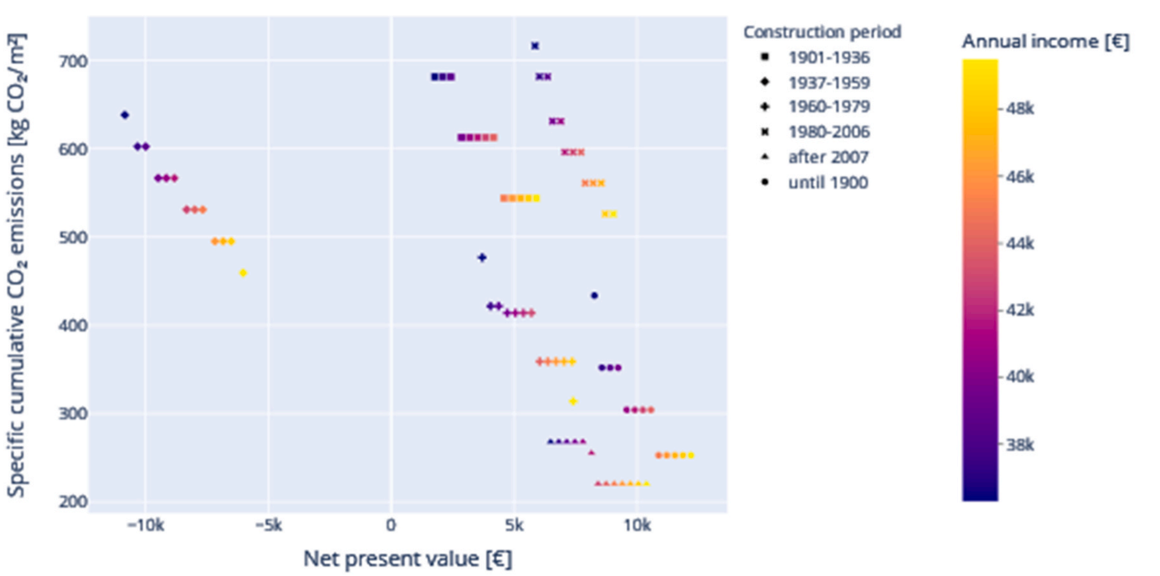

Fig. 7. NPV and specific cumulative CO_2 emissions from optimisation model for Spanish reference buildings at annual household budgets of 36,000–50,000 euros.

due to the small number of studies exploring this topic. Germany has documentation on staged retrofit practices (Cischinsky and Diefenbach, 2018), but it does not include the time the measures were implemented.

A novelty of the present work is the development of deterministic roadmaps (Fig. 1) based on the technical specifications of implementation, which are intended to generate roadmaps with low lock-in risks. The automated three-stage roadmap covers a wider range of possibilities; nevertheless, other technical and even individual aspects involved in generating roadmaps should be further explored in the literature.

Another novelty of the present work is the incorporation of data-driven budget restrictions into the optimisation model; this differs from common practice, which adopts arbitrary assumptions. From the statistical matching workflow, data from Spain was selected based on their completeness, sample amount and quality. The workflow compared ten different EU countries. From the building energy consumption perspective, due to its climate, Spain is not considered the main challenging EU country (when compared with countries in colder climate zones). However, in Spanish households, the socioeconomic characteristics (also represented by the budget restrictions) play a relevant role. The present paper calls for country-specific analysis due to different building stock, socioeconomic, and cultural (eg. scepticism, heritage) aspects. Some EU countries might have more challenges on the building side, while others on the socioeconomic or cultural side. This justifies the relevance of considering both techno and socioeconomic aspects when assessing building stock decarbonisation.

The optimisation model is capable of providing indications about rapid energy price shock, as generated by the Russia–Ukraine war. Such a situation will affect the sequence chosen by the model for each stage and the total time needed to complete a roadmap.

Previous studies have discussed optimisation model sensitivity analysis regarding energy prices, building owner budget restrictions and initial investment (I. Maia et al., 2021). However, further sensitivity analyses can include the calculated energy savings, final energy demand and their effect on the NPV. Furthermore, limitations exist regarding the energy demand calculation model because weather data that account for climate change scenarios were not used. It is expected that climate change affects buildings' energy demand by mainly decreasing space heating (Olonscheck et al., 2011) or even increasing space cooling (Frank, 2005). And not considering the trade-off between capital investment and future uncertainties is considered a limitation.

Another limitation is the lack of consideration for rebound effects after the first or second stage. The increased non-energy benefits through retrofits may generate less energy savings than expected because the building users adapt the consumption behaviour (Ferreira et al., 2017). This means that certain energy savings and CO_2 emissions may not be achieved, and the model should be further developed to internalise such non-energy benefits (such as increased comfort, indoor air quality, lighting, etc).

Other future model improvements should include the dynamic adjustment of a household's available budget based on its annual income. Households with lower annual incomes may have lower shares of income to invest than higher-income households, as shown by Spain's results. Finally, the model should include a final energy demand factor that corrects the energy expenditure according to the annual income.

5. Conclusion and policy implications

This paper mainly aims to assess the effects of staged retrofits and their time dimension, which are underexplored topics in the literature. The two main novelties of this work are its combination of technological and socioeconomic parameters in an optimisation model for staged retrofits and evidence-based model inputs in the form of household budget restrictions derived via statically matched EU datasets.

The study assesses the long-term climate friendliness and economic feasibility of retrofit measures in terms of using primarily the cumulative CO_2 emissions and NPV together with the total roadmap time. This assessment is relevant because its insights support accelerating building stock decarbonisation, which is significant for the achievement of climate goals.

In Spain, only 12% of houses are owner-occupied single-family houses. The annual income of this group exceeds 36,000 euros, and in most construction periods (except 1937–1959), staged retrofits are economically feasible. The calculated optimised roadmap time is an average is 12 years, depending on the annual income. The majority of households present budget restrictions and together with the heterogenous building stock characteristics, incentives targeted to end users are needed to accelerate real-life retrofits. Even households that can afford staged retrofits, as suggested by the data, will need incentives for faster decarbonisation. Other non-technical aspects play a role (e.g. legal decision-making rights, financing split between involved parties and psychological aspects related to the retrofit experience), especially in Spain, where 70% of households are multi-family houses. Then, for a more accurate policy design of retrofitting schemes, future work should consider households' socioeconomic characteristics (represented by budget restrictions, age, demography, etc.) together with the technical ones. We aim to do so, by extending the models' parameters and assumptions, for example by monetarizing non-energy benefits and by assessing different incentive scenarios (under the consideration of household budget restrictions).

CRediT authorship contribution statement

Iná E.N. Maia: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. **Daniel Harringer:** Software, Visualization. **Lukas Kranzl:** Funding acquisition, Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Aldren, 2018. Aldren Building Renovation Passport | ALDREN. https://aldren.eu/building-renovation-passport/.

Alonso-Epelde, E., García-Muros, X., González-Eguino, M., 2023. Transport poverty indicators: a new framework based on the household budget survey. Energy Pol. 181, 113692 https://doi.org/10.1016/J.ENPOL.2023.113692.

Ástmarsson, B., Jensen, P.A., Maslesa, E., 2013. Sustainable renovation of residential buildings and the landlord/tenant dilemma. Energy Pol. 63, 355–362. https://doi.org/10.1016/J.ENPOL.2013.08.046.

Bertoldi, P., Economidou, M., Palermo, V., Boza-Kiss, B., Todeschi, V., 2021. How to finance energy renovation of residential buildings: review of current and emerging financing instruments in the EU. Wiley Interdisciplinary Reviews: Energy Environ. 10 (1), e384. https://doi.org/10.1002/WENE.384.

Bertoldi, P., Economidou, M., Todeschi, V., 2019. Accelerating Energy Renovation Investments in Buildings - Publications Office of the EU. Joint Research Centre (European Commission). https://op.europa.eu/en/publication-detail/-/publication/540c01a3-fba1-11e9-8c1f-01aa75ed71a1/language-en.

BPIE, 2020. Renovation Wave - Briefing. https://www.bpie.eu/wp-content/uploads/2020/10/Renovation-Wave-briefing_04.pdf.

Brown, D., Sorrell, S., Kivimaa, P., 2019. Worth the risk? An evaluation of alternative finance mechanisms for residential retrofit. Energy Pol. 128, 418–430. https://doi.org/10.1016/J.ENPOL.2018.12.033.

Cischinsky, D.H., Diefenbach, D.N., 2018. Datenerhebung zu den energetischen Merkmalen und Modernisierungsraten im deutschen und hessischen Wohngebäudebestand, vol. 179. http://files/354/Cischinsky.

Conforto, G., Hummel, M., 2022. Financing Energy Efficiency in Buildings: an Overview of Current and Upcoming European Funding Programmes. https://www.academia.edu/86631810/Financing_energy_efficiency_in_buildings_an_overview_of_current_and_upcoming_European_funding_programmes.

Donatiello, G., D'Orazio, M., Frattarola, D., Rizzi, A., Scanu, M., Spaziani, M., 2016. The Statistical Matching of EU-SILC and HBS at ISTAT: where Do We Stand for the Production of Official Statistics, vol. 11. https://www.istat.it/it/files//2018/11/Scanu_original-paper.pdf.

Ebrahimigharehbaghi, S., Qian, Q.K., Meijer, F.M., Visscher, H.J., 2019. Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: what drives and hinders their decision-making? Energy Pol. 129, 546–561. https://doi.org/10.1016/J.ENPOL.2019.02.046.

Economidou, M., Della Valle, N., Melica, G., Valentini, O., Bertoldi, P., European Commission. Joint Research Centre, 2021. Financing Energy Renovations at Local and Regional Levels : European Status and Good Practices. https://op.europa.eu/en/publication-detail/-/publication/9c7ebaa2-436d-11ec-89db-01aa75ed71a1/language-en.

European Commission, 2019. Comprehensive study of building energy renovation activities and the uptake of nearly zero-energy buildings in the EU Final report. https://energy.ec.europa.eu/publications/comprehensive-study-building-energy-renovation-activities-and-uptake-nearly-zero-energy-buildings-eu_en#details.

European Commission, 2020. Renovation Wave. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

European Parliament, 2023. *Energy performance of Buildings Amendments Adopted by the European Parliament on 14 March 2023 on the Proposal for a Directive of the European Parliament and of the Council on the Energy Performance of Buildings (Recast) (COM (2021)0802 – C9-0469/2021 – 2021/0426(COD))*. 1–128.

Eurostat, 2020. Energy Consumption and Use by Households - Eurostat News. https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20200626-1.

Eurostat, Commission, E., 2021a. EU statistics on income and living conditions (EU-SILC) methodology – concepts and contents - statistics Explained. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=EU_statistics_on_income_and_living_conditions_(EU-SILC)_methodology_–_concepts_and_contents.

Eurostat, Commission, E., 2021b. Household Budget Survey - Access to Microdata - Eurostat. https://ec.europa.eu/eurostat/web/microdata/household-budget-survey.

Fabbri, M., 2017. Understanding building renovation passports: customised solutions to boost deep renovation and increase comfort in a decarbonised Europe. ECEEE Summer Study Proceedings 1409–1417. In: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2017/6-buildings-policies-directives-and-programmes/understanding-building-renovation-passports-customised-solutions-to-boost-deep-renovation-and-increase-comfort-in-a-decarbonised.

Fabbri, M., de Groote, M., Oliver, R., 2016. Building renovation passports. customised roadmaps towards deep renovation and better homes. http://bpie.eu/wp-content/uploads/2017/01/Building-Passport-Report_2nd-edition.pdf.

Fehlhaber, D., 2017. PhD Dissertation: bewertung von Kosten und Risiken bei Sanierungsprojekten. 186. files/694/Bewertung von Kosten und Risiken bei Sanierungsprojekten.pdf.

Ferreira, M., Rodrigues, A., Höfler, K., Maydl, J., Venus, D., Sedlák, J., Struhala, K., Mørck, C., Østergaard, I., Thomsen, K.E., Rose, J., Jensen, S.Ø., Zagarella, F., Ferrari, S., Dalla Mora, T., Romagnoni, P., Kaan, H., Almeida, M., Brito, N., et al., 2017. Co-benefits of Energy Related Building Renovation-Demonstration of Their Impact on the Assessment of Energy Related Building Renovation (Annex 56) Energy in Buildings and Communities Programme Author of Parametric Calculations of Generic Buildings. www.iea-ebc.org.

Filippidou, F., Nieboer, N., Visscher, H., 2017. Are we moving fast enough? The energy renovation rate of the Dutch non-profit housing using the national energy labelling database. Energy Pol. 109, 488–498. https://doi.org/10.1016/j.enpol.2017.07.025.

Flanders, 2017. De Woningpas - Publieke Welkomspagina. https://woningpas.vlaanderen.be/.

Frank, T., 2005. Climate change impacts on building heating and cooling energy demand in Switzerland. Energy Build. 37 (11), 1175–1185. https://doi.org/10.1016/J.ENBUILD.2005.06.019.

Frantál, B., Dvořák, P., 2022. Reducing energy poverty in deprived regions or supporting new developments in metropolitan suburbs? Regional differences in the use of subsidies for home energy efficiency renovations. Energy Pol. 171, 113250 https://doi.org/10.1016/J.ENPOL.2022.113250.

Friege, J., Chappin, E., 2014. Modelling decisions on energy-efficient renovations: a review. Renew. Sustain. Energy Rev. 39, 196–208. https://doi.org/10.1016/j.rser.2014.07.091.

GFI, 2020. *Financing Energy Efficient Buildings: the Path to Retrofit at Scale A Report on Phase One of the Coalition for the Energy Efficiency of Buildings Financing energy Efficient Buildings Green Finance Institute*. 1–70. https://www.greenfinanceinstitute.co.uk/.

Ibn-Mohammed, T., 2014. Optimal Ranking and Sequencing of Non-domestic Building Energy Retrofit Options for Greenhouse Gas Emissions Reduction Taofeeq Ibn-Mohammed, p. 295.

iBROAD, 2020. Beyond the Single-Family House Potential Extension of iBRoad to Other Building Types Ifeu-Institute for Energy and Environmental Research. www.ibroad-project.eu.

iBRoad2EPC, 2022. Horizon 2020 iBRoad2EPC project. Integrating Building Renovation Passports into Energy Performance Certification schemes for a decarbonised building stock. https://ibroad2epc.eu/.

Ipsos, 2018. Uncover the Underlying Motivations and Barriers for Energy Efficient Renovations Report for European Climate. Foundation.

Jafari, A., Valentin, V., 2017. An optimization framework for building energy retrofits decision-making. Build. Environ. 115, 118–129. https://doi.org/10.1016/j.buildenv.2017.01.020.

Jakučionytė-Skodienė, M., Liobikienė, G., 2023. Changes in energy consumption and CO2 emissions in the Lithuanian household sector caused by environmental awareness and climate change policy. Energy Pol. 180, 113687 https://doi.org/10.1016/j.enpol.2023.113687.

Kerr, N., Winskel, M., 2020. Household investment in home energy retrofit: a review of the evidence on effective public policy design for privately owned homes. Renew. Sustain. Energy Rev. 123, 109778 https://doi.org/10.1016/J.RSER.2020.109778.

Maia, I.E.N., Harringer, D., Kranzl, L., 2023a. Staged renovation and the time-perspective: which other metric should be used to assess climate-optimality of renovation activities? Smart Energy 11, 100110. https://doi.org/10.1016/J.SEGY.2023.100110.

Maia, I.E.N., Moraes, R.M., Almeida, R.T., Kranzl, L., Müller, A., Schipfer, F., 2023b. Integration of datasets to provide insights about households' natural gas expenditure as trigger to building stock decarbonisation. Heliyon 9 (4), e14922. https://doi.org/10.1016/J.HELIYON.2023.E14922.

Maia, I., Kranzl, L., Monteiro, C.S., Volt, J., Fabbri, M., Mellwig, 2020. The iBRoad Tools Structure – iBRoad Project. https://ibroad-project.eu/news/the-ibroad-tools-structure-2/.

Maia, I., Kranzl, L., Müller, A., 2021. New step-by-step retrofitting model for delivering optimum timing. Appl. Energy 290, 116714. https://doi.org/10.1016/j.apenergy.2021.116714.

März, S., Stelk, I., Stelzer, F., 2022. Are tenants willing to pay for energy efficiency? Evidence from a small-scale spatial analysis in Germany. Energy Pol. 161 https://doi.org/10.1016/J.ENPOL.2021.112753.

Merlet, Y., Rouchier, S., Jay, A., Cellier, N., Woloszyn, M., 2022. Integration of phasing on multi-objective optimization of building stock energy retrofit. Energy Build. 257, 111776 https://doi.org/10.1016/j.enbuild.2021.111776.

Monteiro, C.S., Fragoso, R., 2018. The iBRoad Concept in Practice – EU H2020 iBRoad Project. https://ibroad-project.eu/news/the-ibroad-concept-in-practice/.

Murto, P., Jalas, M., Juntunen, J., Hyysalo, S., 2019. Devices and strategies: an analysis of managing complexity in energy retrofit projects. Renew. Sustain. Energy Rev. 114 https://doi.org/10.1016/J.RSER.2019.109294.

Ochs, F., Monteleone, W., Dermentzis, G., Siegele, D., Speer, C., 2022. Compact decentral facade-integrated air-to-air heat pumps for serial renovation of multi-apartment buildings. Energies 15 (13), 4679. https://doi.org/10.3390/EN15134679, 2022, Vol. 15, *Page 4679*.

Olonscheck, M., Holsten, A., Kropp, J.P., 2011. Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Pol. 39 (9), 4795–4806. https://doi.org/10.1016/J.ENPOL.2011.06.041.

P2E, E., 2018. Expérience P2E - mettre en oeuvre une démarche de rénovation énergétique qui s'appuie sur un Passeport Efficacité Energétique (P2E). In: Expérience P2E. http://www.experience-p2e.org/.

Serafino, P., Tonkin, R., 2017. Statistical Matching of European Union Statistics on Income and Living Conditions (EU-SILC) and the Household Budget Survey 2017 Edition. https://doi.org/10.2785/933460.

Sesana, M.M., Salvalai, G., 2018. A review on Building Renovation Passport: potentialities and barriers on current initiatives. Energy Build. 173, 195–205. https://doi.org/10.1016/J.ENBUILD.2018.05.027.

Tugran, T., Lakacova, Z., Bruggeman, V., McGuinn, J., 2021. Commission for the Environment, Climate Change and Energy Renovation Wave and Local and Regional Authorities: Policy and Tools to Build Capacity and Finance Projects ENVE, vol. 99. https://doi.org/10.2863/90699.

Villarejo, P., Gámez, R., Santamaría-López, Á., 2021. Building Renovation Passports in Spain: integrating exiting instruments for building conservation, renovation and heritage protection. Energy Pol. 157, 112506 https://doi.org/10.1016/J.ENPOL.2021.112506.

Wang, B., Xia, X., Zhang, J., 2014. A multi-objective optimization model for the life-cycle cost analysis and retrofitting planning of buildings. Energy Build. 77, 227–235. https://doi.org/10.1016/j.enbuild.2014.03.025.

Wu, R., Mavromatidis, G., Orehounig, K., Carmeliet, J., 2017. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. Appl. Energy 190, 634–649. https://doi.org/10.1016/J.APENERGY.2016.12.161.