Optimizing the Retrofitting Paths for Vulnerable Residential Buildings in Spain: Modeling Shallow Renovations for Net-Zero 2050

Abstract

This paper uses openMASTER, an open-source model of the entire Spanish energy system [1], to analyze how home energy renovations could be carried out based on cost savings. We add renovation to the model as an endogenous investment and study what the optimization says about how much to renovate and whether the pace of renovation or its cost is the limiting factor.

Almost half of Spanish dwellings (45%) were built before any thermal regulation (pre-1980) and require up to ten times more heating than recent ones [1]. The draft National Building Renovation Plan (PNRE) sets a renovation path, but the current pace lags behind [2]. We divide dwellings into four efficiency levels set by Spanish regulation (*Very Low, Low, Medium, High*) and let the model decide when and where to renovate. We call a building vulnerable when its efficiency level is *Very Low* or *Low*; the model does not yet disaggregate households by income. We take the renovation costs from the shallow renovation studies of Fundación Naturgy (the technical report and the VAREX 2022 and 2024 evaluations) [3], [4], [5]. Besides, the PNRE renovation rates are used as the maximum number of renovations that the construction sector can deliver. The model uses energy service demand (for this specific case, the heat a home needs).

By 2050, the model makes 16.6 million renovation steps, and no *Very Low Efficiency (VLE)* dwelling remains after 2035. The heating service demand falls 36% in 2050 against a case without renovation, and residential emissions in 2030–2050 fall 56%. Each euro invested in renovation (8.6 G€ in total over the whole modeling period, discounted to its first year) returns 4.3 € in avoided energy system costs. Renovation would stop only at a cost 8 to 39 times the package costs, so the pace of renovation, not its cost, is the limit.

1. Introduction

Renovating old homes is beneficial for the Spanish energy system, as it yields cost savings. The renovation pace is limited by the speed of renovation, not its cost. This paper explores this result with a modeling exercise. It adds energy renovation to an open-source model of the whole energy system, so that the model decides when, where and how much to renovate by comparing the cost of renovating with the cost of supplying energy. Here a vulnerable building is one with a low efficiency level (*Very Low* or *Low*); the model does not yet disaggregate households by income (Section 1.3).

1.1 Context

Buildings account for around 30% of global final energy demand, and homes make up about 70% of that [6]. Space and water heating are about 70% of the energy that homes use in advanced economies [6]. In the European Union (EU), households used 26.0% of final energy in 2024, 77.1% of it for heating [7]. The European stock is old and renews slowly: 85% of EU buildings date from before 2000, and the energy renovation rate is only about 1% a year, with deep renovations at 0.2% [8], [9]. Better-insulated homes could also help people in energy poverty to live in comfort [4].

Spain follows a similar pattern. Housing uses 17.9% of national final energy and emits 5.2% of greenhouse gases (2023 data) [10]. Heating is 36.3% of household energy use and hot water 22.1% [11]. Most dwellings predate the first thermal regulation, NBE-CT-79, which applied from 1980 [12]: 45.2% of residential buildings were built before 1980 [1]. The gap between old and new is large. A dwelling built after 2019 needs 88% to 93% less heating than one built before 1980 [1] (Annex A). Low-income households live more often in the older stock: 72% of households in the five lowest income deciles lived in buildings over 25 years old in 2019 [4].

Spanish policy expects renovation to close this gap. The draft National Building Renovation Plan (PNRE) expects 17.8 million dwelling renovations in 2020–2050 and cuts the average primary energy

use of the residential stock from 51.2 to 22 kWh/m^2·year [2]. It classifies renovations as light (saving below 30%), medium (30–60%) or deep (above 60%), and 14.4 million of the 17.8 million (81%) are light. Low-cost interventions of this kind are what the Naturgy Foundation has applied in vulnerable households since 2018 [3], [4].

1.2 Literature review

Models of the building stock and of the energy system. Two kinds of model look at renovation, and they answer different questions. The PNRE builds its path with ModESTo, a simplified model of the building stock developed by IETcc-CSIC [2]. ModESTo describes each building: it starts from cadastral and INE data, assigns 14 residential and 29 tertiary building prototypes, defines their envelope, heating systems and use profiles, and simulates them with OpenStudio to obtain primary energy use and CO_2 emissions. It is a model of the architecture of the stock, and it shows what renovation does to a building.

openMASTER examines the same renovation from the energy system perspective [13]. It covers the whole Spanish energy sector (power, heat, transport, industry and homes) in one optimization, so renovation competes with every other way of meeting demand. This has three key advantages. First, the model prices renovation against the alternative of supplying heat: it renovates only where the energy-system savings exceed the investment. Second, it captures the effects outside the building, such as less gas use, smaller heat pump capacity and lower CO_2 costs for the whole system. Third, it is open source, so anyone can check and reuse the result. A building model such as ModESTo gives more detail on the building itself. A system model gives the cost, the timing and the interactions across sectors.

Energy service demand. openMASTER does not work with energy or fuel demand. It works with energy service demand: the heat, cold, light or cooking that people need. In the comparison of [13], it is the only open-source strategic planning model (against EnergyScope, oemof and OSeMOSYS) that defines all exogenous demand as energy services and represents behavioral measures endogenously and linearly. This matters for renovation, because insulation and a heat pump deliver the same service (a warm home) with different energy uses. Roy et al. [14] make the same point: they define heating demand as the service of thermal comfort, which insulation can deliver as well as a heating system. They report that in buildings demand-side solutions save 10% to 94% of energy, emissions and lifetime cost for the same service, and they note that models lack cost estimates for these solutions [14].

Demand side in openMASTER. In the public model [15], the efficiency of the dwellings is fixed by construction year (before and after 2001, with shares from the 2011 census [16]) and no demand shift measure exists in the residential sector. The model can choose how to supply the heat, but it cannot invest in reducing the heat needed. Its predecessor MASTER has been used in Spain for more than a decade, including studies of energy efficiency and of energy poverty [13], [17].

Energy poverty in models. Rios-Ocampo et al. [18] review 26 long-term energy models and find none with an explicit energy justice analysis. They recommend disaggregating the residential sector by income, building type, household composition, energy efficiency and climate. We build on this framework, and a forthcoming working paper extends openMASTER with vulnerability indicators [19]. Income is hard to include: the energy needed for a decent life depends on how income is distributed [20], and mitigation scenarios embed large inequalities [21]. Other works cover social renovation [22], energy poverty interventions [23], terminology [24], household vulnerability [25], the Social Climate Fund [26] and energy justice [27].

Evidence on shallow renovation. The main evidence comes from the Naturgy Foundation. Its 2022 study simulated a low-cost package (wall insulation, window replacement, solar protection) in a nine-dwelling block in four cities. It estimated EUR 5,600–8,000 per dwelling in the least favorable case, about 25% of the cost of a conventional renovation [3]. Real cases show a gap between theory and practice: in 54 Catalan households studied by the VAREX-2024 project, hidden energy poverty fell from 89% to 79%, but consumption rose, a possible rebound effect [4]. Besides, in 416 Spanish vulnerable households of VAREX-2024 it fell from 71.7% to 68.3%[28]. This evidence gives us real costs and savings for calibration, and it supports defining four efficiency levels aligned with the Spanish building regulation [12].

1.3 Contribution

Three gaps remain. Long-term planning models usually take building efficiency as given [13]. Cost data for demand-side options only recently exist in comparable form [14]. And the Naturgy and VAREX evidence [3], [4], [28] has not been used to let a national optimization model decide how much to renovate. This paper is a modeling exercise focused on the renovation of dwellings. Even so, we implement it in a model that interacts with all energy sectors at national level, which differs from what the PNRE presents with ModESTo. It makes three contributions:

1. **Model.** This is the first implementation of demand shift measures in the public openMASTER [13], [15]. We replace two efficiency levels with four, defined from Spanish regulation, and let the model invest in moving dwellings between levels at a cost, with a reduction in the energy service demand.

2. **Parameterization with real data.** Renovation costs come from the Naturgy Foundation and VAREX studies [3], [28], the heating service demand of each level from IDAE [29], and the stock from URBAN3R [1]. The stock data is cadastral data, like those of the PNRE [2], so the novelty is coupling them with real renovation data.

3. **Policy-relevant analysis with a different use of the PNRE.** The PNRE presents its renovation rates as political goals. We use them as industry limits: the maximum number of renovations the construction sector can carry out each year. With this reading the model shows the return of renovation, the effect of the pace and the cost at which renovation stops.

Section 2 describes the Spanish context, Section 3 the methodology, Section 4 the data and settings, Section 5 the results, Section 6 the discussion and limitations, and Section 7 the conclusions. Vulnerable refers here to the building, not to the household. We call a building vulnerable when it has a low efficiency level (*Very Low* or *Low*). This is a first proxy: low-income households live more often in the older stock (Section 1.1), but the model does not yet disaggregate households by income. It does not classify households or compute energy poverty indicators. A later version will include income in the vulnerability levels of households (Section 6.3).

2. The Spanish context

2.1 History of the thermal standards

Spanish thermal regulation for new dwellings has three generations, and they define the four efficiency levels of this paper. Dwellings built before 1980 had no thermal requirement (*Very Low*). The NBE-CT-79 standard became mandatory for new buildings three months after its publication on 22 October 1979 [12], [30], so it marks dwellings built from 1980 (*Low*). The CTE DB-HE of 2006 and its 2013 revision set the *Medium* level, and the DB-HE 2019 sets the *High* level (Table 1).

Standard	Applies from	What it limits	Level in this paper
Before NBE-CT-79	—	No thermal requirement	Very Low (before 1980)
NBE-CT-79 (RD 2429/1979) [12]	1980	Heat-transfer coefficients by element and climate zone	Low (1980–2006)
CTE DB-HE 2006 (RD 314/2006) [31]	Sep 2006	Envelope quality, demand limit, renewable contribution	Medium (2007–2019)
CTE DB-HE 2013 (FOM/1635/2013) [32]	Mar 2014	Adds a limit on non-renewable primary energy	Medium (2007–2019)

CTE DB-HE 2019 (RD 732/2019) [33]	Sep 2020	Primary energy limits (nearly-zero-energy), solar control, air renewal	High (after 2019)

TABLE 1, SPANISH BUILDING REGULATIONS AND THE EFFICIENCY LEVELS OF THIS PAPER.

Each generation regulates different things, not only stricter values [34], so we cannot rank the limits on one scale. We do not derive the consumption of each level from the standards. The energy reduction of each renovation step comes from the measures of the Naturgy Foundation and VAREX (Section 3). The cutoff dates are approximate, because a dwelling finished soon after a date was often licensed under the previous rule.

2.2 The residential stock

The model starts in 2020 with 18.54 million homes (viviendas principales), consistent with the 19.17 million of the Ministry of Transport in 2023 [35]. We distribute them with the shares of the URBAN3R cadastral data [1], by climate zone (Atlantic, Continental, Mediterranean), building type (multi-dwelling block or single-family house) and efficiency level (Figure 1). Figure 1 shows the shares and the totals of the 2023 stock (19.17 million dwellings); the model applies the same shares to the 2020 stock.

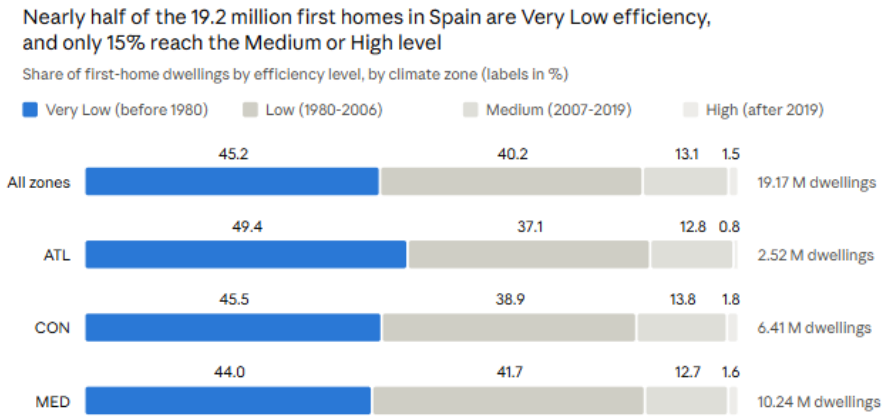


FIGURE 1, SHARE OF FIRST-HOME DWELLINGS BY EFFICIENCY LEVEL AND CLIMATE ZONE. SOURCE: OWN ELABORATION BASED ON URBAN3R DATA [1] (SHARES) AND MINISTRY OF TRANSPORT DATA [35] (TOTAL DWELLINGS)

The *Very Low* level holds 45.2% of the dwellings, between 44% and 49% in every zone. *Very Low* and *Low* together hold 85.4% (15.8 million dwellings), so nearly all the stock can move up at least one level. The Mediterranean zone has 53.4% of the dwellings, the Continental zone 33.4% and the Atlantic zone 13.1%. Building type matters as much as age. Blocks are 71.5% of the stock, but a *Very Low* house needs about four times the heating of a *Very Low* dwelling in a block (12,486 against 3,178 kWh per year in the Continental zone) [1]. The renovation potential per dwelling is therefore concentrated in houses.

2.3 Renovation policy and energy poverty

Three instruments plan renovation. The PNIEC update of 2024 plans 1,377,300 dwellings renovated in 2021–2030 (about 0.14 million a year), prioritizing the envelope [36]. The ENPE 2026–2030 plans pilot express interventions in the homes of severely vulnerable consumers (Measure 7), aid lines reserved for vulnerable households (Measure 8) and social energy-saving certificates (Measure 10) [37]. The draft PNRE plans 17.8 million renovations in 2020–2050, about 0.6 million a year, 81% of them light [2]. The express interventions of ENPE Measure 7 are of the kind that the Naturgy Foundation has applied since 2018 and that provide the renovation costs of this paper [3].

The ENPE adopts the definition of energy poverty of Directive (EU) 2023/1791, in which the efficiency of the dwelling is part of the definition [37]. This links the renovation levels of this paper to energy poverty. Official monitoring uses four indicators, among them hidden energy poverty (9.3% of

households) [37], [36]. The VAREX studies measure it against the energy a household requires, which separates a real saving from under-consumption [4], [28].

3. Methodology

3.1 The demand side of openMASTER

openMASTER [13], [15] minimizes the total discounted cost of the energy system with a dynamic, bottom-up linear program written in Pyomo. Demand is exogenous and expressed as energy services. For the residential sector, the demand for a service (for example space heating) in a year is the product of three terms: the number of dwellings in a *macro-data* segment (*sMD*), the share of those dwellings in a *service-demand* category (*sSD*) given by the *Demand Characterization* (*DC*), and the energy service demanded per dwelling in that category, the *Activity Factor* (*AF*). The model then chooses the technologies and fuels that supply the service at the lowest cost.

Two types of demand-side measure change this demand. *Behavioral Measures* act on the *AF*, and *Demand Shift Measures* act on the *DC*. The public model [15] has no *Demand Shift Measure* in the residential sector. We use it to represent renovation: a dwelling moves to a more efficient category in exchange for a cost, and the optimizer decides when and where.

3.2 Renovation as a demand shift measure

Segmentation. We segment the stock by climate zone (*Atlantic, Continental, Mediterranean*), building type (*block dwellings, BL, or single-family house, SH*) and efficiency level (*VLE, LE, ME, HE*, defined in Section 2.1). This gives six segments and four levels. Three renovation measures connect consecutive levels (Table 2). A dwelling can reach a level in one step only from the level directly below, so going from Very Low to High takes the three measures in sequence and pays the three costs.

Measure	From	To	Renovation package	Cost per dwelling	Model value (G€ per million dwellings)
Ins_VLE_to_LE	Very Low	Low	Package I: draught-proofing, Thermocover, glazing replacement	620 €	0.62
Ins_LE_to_ME	Low	Medium	Package II: glazing and joinery, roof	3,221 €	3.221
Ins_ME_to_HE	Medium	High	Package III: wall insulation	3,040 € (block 2,468, house 3,611)	3.04

TABLE 2, RENOVATION MEASURES, PACKAGES AND COSTS. PACKAGES BASED ON NATURGY FOUNDATION AND VAREX [3], [28]

Stock balance. Let *Q(l,m,y)* be the number of dwellings of level l in segment m in year y. The constraint *EQ_DCOth* gives:

$$Q(l,m,y) = Q(l,m,y-1) + DC(l,m)\,[MD(m,y) - MD(m,y-1)] + \sum_{in}[Up(d,m,y) - Up(d,m,y-1)] - \sum_{out}[Dn(d,m,y) - Dn(d,m,y-1)]$$

MD is the number of dwellings in the segment, *DC(l,m)* is the share of level l in segment m in the calibration year, and *Up* and *Dn* are the cumulative variables of the measures. The sum "*in*" covers the measure that ends at level l and the sum "*out*" the measure that starts at l. For example, *Medium* receives from *Ins_LE_to_ME* and gives to *Ins_ME_to_HE*, while *Very Low* only gives and *High* only receives. Two consequences matter. First, new dwellings enter with the same shares as the existing stock, so the change in the level mix over time comes from renovation. Second, because the variables are cumulative, the model pays for each dwelling once, in the period in which it moves.

Cost in the objective function. The objective, *vSysCost*, adds the investment and operating cost of the supply side, the emission cost, the terminal cost after 2050 and the cost of the demand shift measures. The renovation cost enters through *vDMCost*, the discounted investment of measure *d* in year *y*:

$$vDMCost(d,y) = \frac{1}{(1+r)^{\Delta(ord(y)-1)}} \cdot pDMCost(d,y) \cdot \sum_{m} [Up(d,m,y) - Up(d,m,y-1)]$$

Here, *r* is the discount rate, *Δ* the length of the period in years and *ord(y)* the position of the year in the horizon, so all costs are discounted to 2020. The increment of *Up* is the number of dwellings renovated in the period, and *pDMCost* is the cost per million dwellings, so the term is an investment in G€. The optimizer thus compares the cost of renovating a dwelling with the cost of supplying its energy services, now and in the future, and renovates where the saving exceeds the investment. The terminal cost represents the system after 2050: it is the perpetuity of the costs of the last year, which grow at 1% a year and are discounted at 8%. It stops the model from leaving equipment unrenewed at the end of the horizon.

3.3 Energy service demand per dwelling at each level

The *AF* of each level sets the energy service demand of a dwelling. For heating and cooling, the demand of each level comes from the IDAE records of consumption by use [29], which fit the efficiency levels better than the alternatives. We use URBAN3R [1] only for the distribution of dwellings by zone, type and level. The other services (domestic hot water, lighting, appliances, cooking) come from the original model. Table A1 in Annex A gives the heating service demand of a dwelling at each level.

The reductions of the model (24–43% for *Low*, 46–63% for *Medium* and 88–93% for *High*, against *Very Low*) come from IDAE, while the costs come from the VAREX packages [3], [28]. The savings and the cost of a step are therefore not derived from the same intervention. The reductions are larger than the cumulative savings of the three VAREX packages (for the Barcelona block, 17.6%, 42.8% and 82.3%), so a step in the model may deliver more saving per euro than the physical package.

3.4 Renovation cost

The cost of each measure is the average cost per dwelling of the corresponding VAREX package [3], [28] (Table 2). It is the same in all zones, because the intervention is the same, while the savings differ by zone, mostly because of the weather. The costs are in constant euros, constant in time and without learning effects.

3.5 Renovation capacity: industry limits

The PNRE sets maximum annual renovation rates [2]: 680,000 dwellings a year from *Very Low to Low*, 185,201 from *Low to Medium* and 31,532 from *Medium to High* (3.40, 0.926 and 0.158 million dwellings per five-year period). The PNRE presents these rates as political goals. We use them as industry limits, that is, the maximum number of renovations that the construction sector can carry out in a year. With this reading the limits describe what is feasible, and the model shows how much of the feasible renovation is worth doing and when.

The limit of each measure is national: in each period, the dwellings that the measure moves, added over the six segments, cannot exceed it. The model chooses where to renovate (zone and building type), but not more than the national total. The limits are upper bounds, not targets. Together the three limits add up to 897,000 a year, about 5% above the upper end of the PNRE path (540,000 renovations a year in 2020–2023 to 850,000 in 2046–2050) [2].

3.6 Scenarios

We compare four scenarios, preceded by a test of the formulation and followed by an exploration of the renovation cost. All use the same costs and demand data. Split and Uncapped change only the limits.

- **Test with free renovation.** We set the renovation cost to zero. Renovation is then free, so the model should renovate the whole stock (as it did): all dwellings ended at the High level. This was done to verify the formulation; it is not a scenario.

- **Base.** All limits are set to zero, so renovation is switched off and no dwelling changes level. It is the reference comparison point.
- **Main.** All parameters are set: the costs of Section 3.4 and the national limits of Section 3.5. Each limit applies to the national total of its measure, so the model can concentrate renovation in the segments where it pays most. Most results come from this case.
- **Split.** The same limits are divided among the six segments (three climate zones, each with blocks and houses): each segment has its own limit, equal to the same share of its dwellings. Renovation cannot concentrate where it is most profitable, as in Main.
- **Uncapped.** We remove the limits, so the model can renovate the whole stock in one period if it pays.
- **Limit cost.** To find the cost at which the model stops renovating, we assign the same cost to each of the three measures, keep the main-scenario settings, and raise it progressively using an APPSI solver. The limit cost is therefore a value per measure, in G€ per million dwellings. We find it by bisection between 0.05 and 30 G€ per million dwellings, and a sweep from 0.05 to 35 in steps of 1 shows the behavior around it. The model stops renovating when the total is 0.05 million steps or less.

4. Data and model settings

4.1 Data sources and treatment

Table 3 lists the input data. The renovation parameters (levels, costs, limits) are in Section 3.

Input (model parameter)	Source	Treatment
Dwellings by zone and type, 2020 (*pMD*)	URBAN3R [1], SPAHOUSEC III [11]	18.54 million first homes in six segments
Dwellings 2021–2050 (*pMD*)	INE household projection [38]	20.61 million in 2030 and 24.75 million in 2050; linear growth of 0.21 million a year; segment shares constant
Distribution among levels (*pDC*)	URBAN3R [1]	Share of each level in each segment in 2020; new dwellings follow the same shares
Energy service per dwelling (*pAFOth*)	IDAE [29], adjusted to the URBAN3R distribution	Demand per dwelling by service, level and segment (Section 3.3)
Hourly demand profiles (*pESLoad*)	Calibration file of the model [13]	Profile of each service for seven representative days in each of four seasons
Installed supply technologies, 2020 (*pSTInsCap*)	Calibration file of the residential sector [13]	Capacity by technology and vintage (2005, 2010, 2015, 2020); retires with the lifetime of the technology

TABLE 3, INPUT DATA SUMMARY WITH SOURCES

The hourly profiles, the installed capacities of 2020 and the supply technology data are those of the original model [13].

4.2 Time and system settings

The model runs from 2020 to 2050 in five-year periods (seven periods), with four seasons, seven representative days per season and 24 hours per day. Costs are in constant euros, discounted to 2020 at a real rate of 8%. The model is solved with Gurobi (barrier method without crossover). The model runs from 2020, but we report results from 2030. The installed equipment of 2020 (the brownfield) should be recalibrated. The results before 2030 mostly reflect this starting point. All runs share it, so the comparison between runs does not depend on it.

4.3 The base year

The stock is 18.54 million dwellings in 2020 and grows by 33% to 24.75 million in 2050. Interpolating gives 19.16 million in 2023, in line with the 19.17 million of the Ministry of Transport [35]. In 2020 the residential heating service demand is 60.8 TWh, the largest of all services (cooling 7.3, hot water 38.0, cooking 14.3, refrigeration 22.6 and other appliances 22.7 TWh). The Very Low level demands 60% of the heating, Low 33%, Medium 7% and High 0.2%, which shows the room for renovation.

5. Results

Four scenarios are compared (Section 3.6): Base, Main, Split and Uncapped. All runs share the same inputs. We report on the residential sector and the emissions of the whole system, and show results from 2030.

5.1 Renovation pace

In the Main scenario the model makes 16.6 million renovation steps by 2050: 11.2 million dwellings go from *Very Low* to *Low*, 4.4 million from *Low* to *Medium* and 0.95 million from *Medium* to *High* (a dwelling that goes through two steps counts twice). The first step stays at its national limit of 3.40 million dwellings in the periods ending 2025 and 2030, the Very Low stock is used up in 2035, and from 2040 the step continues only with the 45% of new dwellings that enter at *Very Low* (0.47 million per period). The second step is at its limit (0.93 million) in 2035, 2045 and 2050, and the third step (0.16 million) in every period (Figure 2). In the first three periods the model renovates 813,000 to 885,000 dwellings a year, close to the sum of the three limits (897,000) and above the 540,000 a year of the first years of the PNRE path, because it uses the limits while *Very Low* dwellings remain. From 2035 the rate falls to 150,000–310,000 a year.

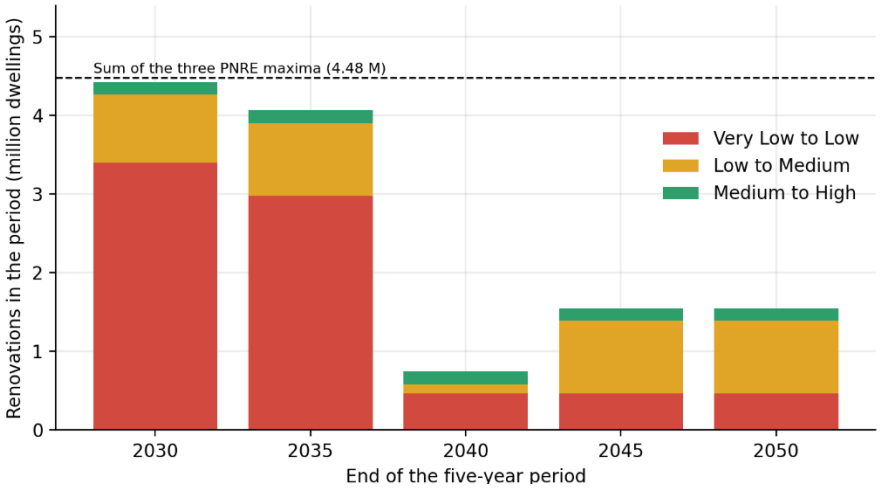


FIGURE 2, RENOVATIONS IN EACH FIVE-YEAR PERIOD BY MEASURE, MAIN SCENARIO, FROM THE PERIOD ENDING 2030, AGAINST THE SUM OF THE THREE LIMITS

The model starts with the houses, where the heating demand per dwelling is highest (Table 4). The Continental blocks follow, and the Mediterranean blocks, with the lowest demand per dwelling, come last. The second and third steps happen only in houses. *Medium* to *High* happens only in the Continental houses, where the saving per dwelling is largest (5,138 kWh a year, against 3,806 in the Atlantic and 2,395 in the Mediterranean houses).

Segment	VLE to LE	LE to ME	ME to HE
Atlantic, block	1.21	0.00	0.00
Atlantic, house	0.40	0.65	0.00
Continental, block	2.62	0.00	0.00
Continental, house	1.14	2.18	0.95
Mediterranean, block	3.98	0.00	0.00

Mediterranean, house	1.84	1.62	0.00
Total	11.19	4.45	0.95

TABLE 4, CUMULATIVE RENOVATIONS BY 2050, BY SEGMENT AND MEASURE, MAIN CASE (MILLION DWELLINGS)

Without renovation (Base case), the *Very Low* level is 45% of the stock in 2050 (11.2 million dwellings). In the Main scenario it disappears in 2035, and in 2050 the stock is 67% *Low* (16.7 million), 27% *Medium* (6.7 million) and 5.4% *High* (1.3 million) (Figure 3).

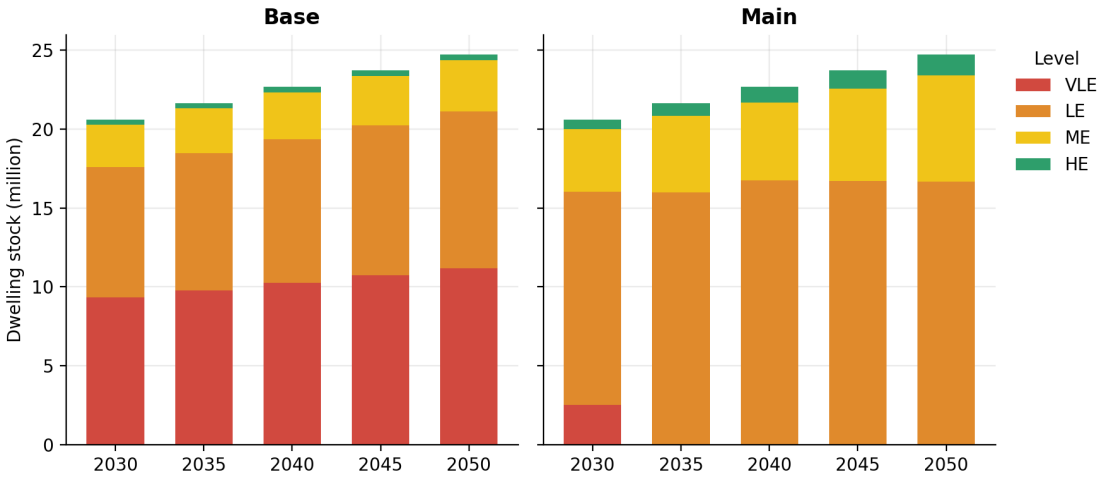


FIGURE 3, DWELLING STOCK BY EFFICIENCY LEVEL, BASE AND MAIN, 2030-2050 (MILLION DWELLINGS)

5.2 Energy service demand for heating

Without renovation, the heating service demand grows from 67.6 TWh in 2030 to 81.2 TWh in 2050, because the stock grows by 33% and the efficiency of the dwellings does not change. In the Main scenario it is 49.8 TWh in 2030 (26% below Base), 48.3 TWh in 2035 (32% below) and 51.8 TWh in 2050 (36% below). That is 15% less than in 2020, with 33% more dwellings. The demand is lowest in 2035, once the *Very Low* stock has been renovated, and then grows again with the stock.

Houses give 80% of the 29.4 TWh saved in 2050, and the Continental houses alone 14.1 TWh (48%). The demand of the Continental houses falls by 58% (from 24.2 to 10.1 TWh), that of the Atlantic houses by 47% and that of the Mediterranean houses by 35%. The blocks fall by 14% in the Continental zone and by 22–23% in the other two, because they only go through the first step (Figure 4). In absolute terms the Mediterranean zone demands more heat than the Atlantic zone (21.2 against 7.4 TWh in the Main scenario in 2050), although each of its dwellings needs less, because it holds 53% of the dwellings against 13%.

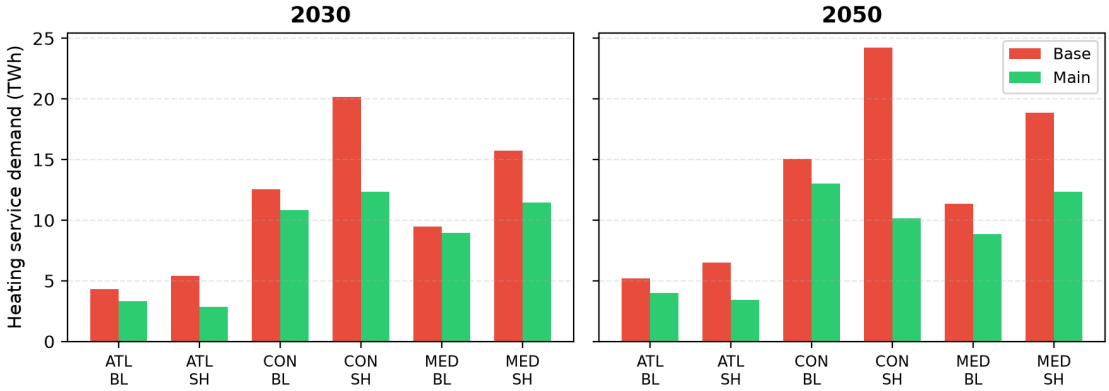


FIGURE 4, HEATING SERVICE DEMAND BY CLIMATE ZONE (*ATL, CON, MED*) AND BUILDING TYPE (*BL BLOCK, SH HOUSE*) IN 2030 AND 2050, BASE AND MAIN

5.3 Return on investment

The renovation investment in the Main case is 8.6 G€. All costs in this paper are totals over the whole modeling period (2020–2050), in constant euros discounted to 2020. The savings come from the energy system as a whole, because the model optimizes the whole system. Renovation avoids 36.9 G€ of costs: investment in supply technologies, operation, CO_2 costs and the cost of the system after 2050. After the renovation investment, the net saving is 28.3 G€. Each euro invested returns 4.3 € in avoided costs, or 3.0 € if we leave out the cost after 2050. That last cost matters because a smaller system in 2050 also lowers the cost after that year. We express the benefit as a return per euro and as a net saving, and not as the total cost of the system, because renovation also changes the supply of electricity and gas outside the homes.

5.4 Energy mix and emissions

Renovation lowers the final energy for heating and cooling by about a quarter in 2030 and by almost half from 2040 (Table 5).

Final energy for heating and cooling (TWh)	2030	2040	2050
Base	68.1	51.3	34.7
Main	50.3	26.5	18.3
Reduction, Main against Base	26%	48%	47%
Natural gas, Base	50.4	33.5	0.0
Natural gas, Main	33.4	9.0	0.0

TABLE 5, FINAL ENERGY FOR HEATING AND COOLING AND FOSSIL NATURAL GAS USE, BASE AND MAIN (TWH). BIOMETHANE IS NOT IN THE GAS ROWS: IN 2050 THE GAS BOILERS OF BASE BURN 9.9 TWH OF IT

Without renovation, condensing gas boilers supply 72% of the heat in 2030 (Figure 5), and the final energy stays at about 68 TWh until 2035. In 2050 neither run uses fossil natural gas, and heat pumps supply 89% of the heat in the Main scenario against 78% in Base. The gas boilers of Base still supply 9.9 TWh (12% of the heat) in 2050, but they burn biomethane, a renewable gas, so Figure 5 shows them and Table 5 shows no natural gas. Renovation also reduces the capacity to install: heat pumps in 2050 are 27% smaller (53.4 against 73.3 GW) and the peak of condensing gas boilers in 2030 is 34% lower (37.6 against 56.6 GW).

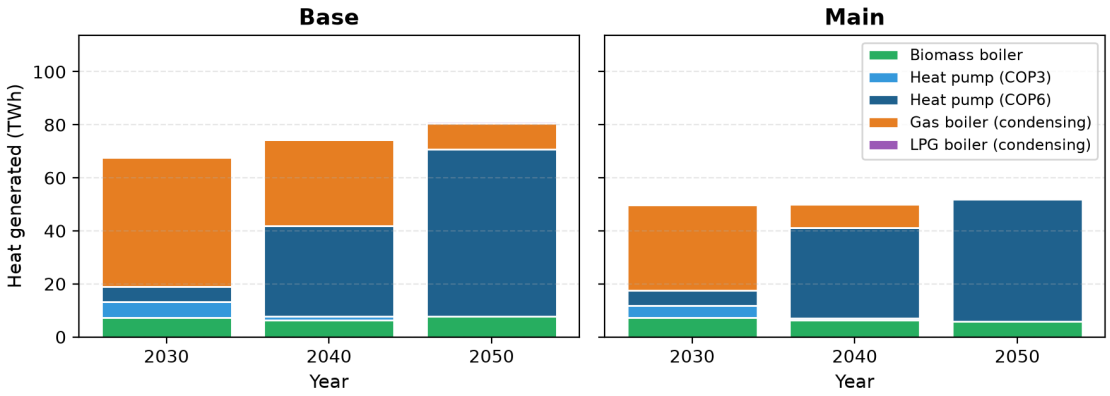


FIGURE 5, HEAT GENERATED BY TECHNOLOGY IN 2030, 2040 AND 2050, BASE AND MAIN (TWH). IN 2050 THE CONDENSING GAS BOILERS OF BASE BURN BIOMETHANE, NOT FOSSIL NATURAL GAS

Residential emissions in Base are 13.8 Mt of CO_2 in 2030 because of the gas boilers, and fall to 0.2 Mt in 2050. In the Main scenario they are 9.4 Mt in 2030 (32% lower), 7.6 Mt in 2035 (44% lower) and 2.4 Mt in 2040 (73% lower), and zero in 2050. Added over 2030–2050, residential emissions are 170 Mt in Base and 75 Mt in Main, 56% less.

Figure 6 places this result in the whole energy system. Emissions of the system fall from about 200 Mt in 2030 to 25–27 Mt in 2050 in all runs, as the model decarbonizes power, industry, transport and buildings together. Over 2030–2050 the system emits 1,818 Mt in Base and 1,684 Mt in the Main

scenario, so renovation saves 134 Mt (7.4%), 71% of it in the residential sector. The rest comes from the supply side of the system, which has to deliver less energy to homes.

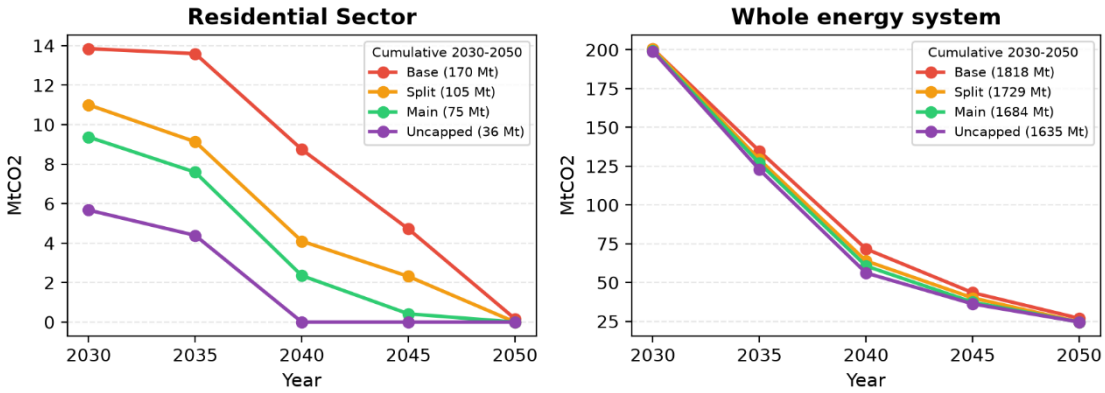


FIGURE 6, CO_2 EMISSIONS OF THE RESIDENTIAL SECTOR AND OF THE WHOLE ENERGY SYSTEM IN THE FOUR RUNS, 2030–2050 (MT). THE LEGENDS GIVE THE CUMULATIVE EMISSIONS OVER 2030–2050

5.5 Cap limits effect

The *Split* and *Uncapped* runs show how much the limits matter (Table 6). If we divide the national limits among the segments, the first step stays the same, but the second and third steps fall to 1.0 and 0.5 million, because the part of the limit given to the blocks is not used and the part given to the houses is too small. Without any limit, the model makes 6.2 and 6.9 million renovations in the second and third steps, the heating service demand in 2050 is 62% below Base, and the investment is 22.0 G€.

The net saving is 21.3 G€ in Split, 28.3 G€ in the Main case and 40.6 G€ without limits, so the limits cost the system up to 12 G€ of savings. The return per euro falls as more is renovated: 5.8 € in Split, 4.3 € in the Main case and 2.8 € without limits. Even so, the extra renovation of the Uncapped run, compared with the Main scenario, still returns 1.9 € per euro. Renovation generates net savings in all runs, and the national limits keep the model from some cost-effective steps.

Result	Base	Split	Main	Uncapped
VLE to LE by 2050 (million dwellings)	0.0	11.19	11.19	11.19
LE to ME by 2050 (million dwellings)	0.0	1.01	4.45	6.23
ME to HE by 2050 (million dwellings)	0.0	0.49	0.95	6.94
Heating service demand 2050 (TWh)	81.2	60.8	51.8	30.7
Final energy for heating and cooling 2050 (TWh)	34.7	21.6	18.3	6.1
Residential CO_2, 2030–2050 (Mt)	170	105	75	36
Renovation investment (G€)	0.0	4.4	8.6	22.0
Net saving in energy system costs (G€)	—	21.3	28.3	40.6
Return per euro invested (€)	—	5.8	4.3	2.8

TABLE 6, RESULTS OF BASE AND OF THE THREE RENOVATION RUNS. COSTS ARE TOTALS OVER 2020–2050, IN CONSTANT EUROS DISCOUNTED TO 2020 (NOT PER YEAR OR PER PERIOD). THE NET SAVING IS THE AVOIDED ENERGY SYSTEM COST MINUS THE RENOVATION INVESTMENT.

5.6 Limit cost of renovation

The limit cost is the cost above which the model stops renovating. We apply the same cost to each of the three measures. With the Main scenario settings, bisection gives 24.36 G€ per million dwellings (24,360 € per dwelling; all 102 solves are optimal). This is 39 times the cost of the first measure (0.62), 7.6 times that of the second (3.22) and 8.0 times that of the third (3.04). At the limit cost the model reproduces the *Base* scenario.

Renovation falls in steps as the cost rises (Figure 7). Up to 2 G€ per million dwellings the model makes 17.7 million steps; the total is 7.2 million at 5 G€ and 5.2 at 10 G€, 16 times the cost of the first measure. The three steps stop at different costs: *Low to Medium* at about 16 G€, *Very Low to Low* at 22.2 and *Medium to High* at the limit cost. The last renovation to disappear is 0.158 million dwellings of *Medium to High*, the national limit of a single period. The limit cost does not depend on the limits, because a cap on the quantity cannot change the cost at which the quantity becomes zero.

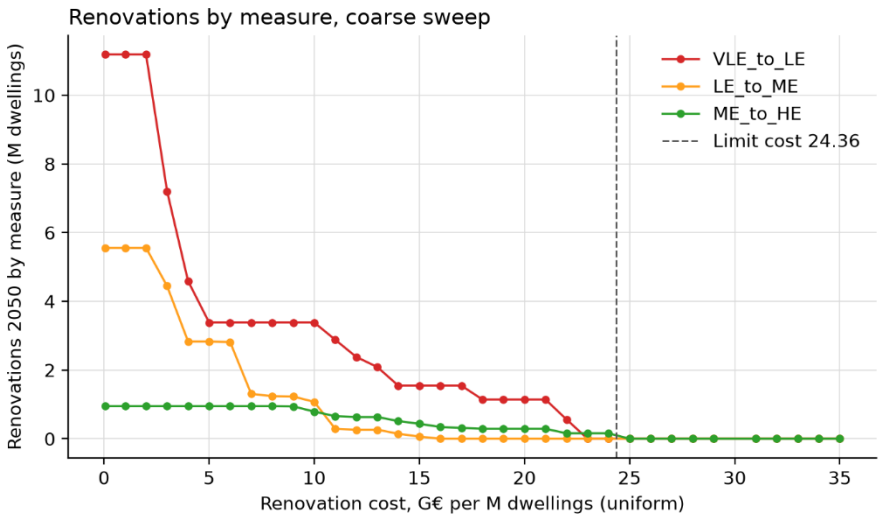


FIGURE 7, RENOVATIONS IN 2050 BY MEASURE AGAINST THE UNIFORM COST PER MEASURE (G€ PER MILLION DWELLINGS), COARSE SWEEP

6. Discussion and limitations

6.1 Interpretation of the results

The pace limits renovation, not its cost. With the costs of the Naturgy Foundation and VAREX [3], [28] and the PNRE rates read as industry limits [2], each euro invested returns 4.3 € in the Main scenario. Without limits the return falls, but the extra renovation still returns 1.9 € per euro, so the Main case does not use all the cost-effective renovation. The limit cost (24.4 G€ per million dwellings, 8 to 39 times the package costs) points the same way: moderate errors in the costs do not change the result. A measure that lowers the package cost matters less than a measure that lets the sector renovate faster, such as financing, capacity of the construction sector and decisions in blocks.

Renovation follows the saving per dwelling. Houses go first, because they need more heat than blocks, and the Continental houses above all: they give 48% of the 29.4 TWh saved in 2050. The blocks only go through the first step. This combines costs that do not depend on the zone with savings that do, and it would change if a block cost differently from a house (shared walls, communal works).

The effect is larger in the energy system than in the home. Renovation lowers the final energy for heating and cooling by 47% in 2050, speeds up the exit from gas and reduces the capacity of heat pumps and boilers to install. In the whole system it saves 134 Mt of CO_2 in 2030–2050, of which 95 Mt are residential. This is one of the advantages of using a general energy model such as openMASTER: we can see the interaction between sectors and its effects.

Comparison with the PNRE. The PNRE has 17.8 million renovations in 2020–2050, 81% of them light [2], and the Main case 16.6 million steps. The amounts are of the same order, although the model counts a step each time a dwelling moves up one level. The timing differs: the model renovates 813,000–885,000 dwellings a year in the first three periods, against 540,000 a year in the first years of the PNRE, because it renovates the *Very Low* stock as soon as the limits allow. Since the current pace lags behind the plan [2], the plan could start faster. ModESTo and openMASTER complement each other: a building model can define the packages and the savings of each building prototype,

and a system model can tell which of them to carry out first, at what cost and with what effect on the rest of the system.

The results take the point of view of the energy system. The model does not include who pays, subsidies or the financing of households, so it does not say how much public support a household needs.

6.2 Limitations

Savings and costs. The reductions of demand come from IDAE [29] and the costs from the VAREX packages [3], [28], so they do not come from the same intervention, and the reductions are larger than the cumulative savings of the packages (Section 3.3). A step in the model can deliver more saving per euro than the physical package. Costs are the same in all zones, constant in time and without learning. The model assumes that a renovation delivers the full reduction in energy service demand. Households that under-consume energy (hidden energy poverty) may heat more after a renovation to reach a decent comfort level, so part of the saving becomes comfort. In the VAREX cases consumption rose in some households [6]. This rebound effect reduces the real energy savings, and the model does not value the comfort gain.

Stock. New dwellings enter with the same shares by level as the 2020 stock (45% *Very Low*), with no demolition or replacement. This is a temporary assumption: new dwellings would in reality follow the current regulation. It overstates the *Very Low* stock after 2020 (about 2.8 million dwellings by 2050, a quarter of the first renovation step) and it is the only source of first-step renovation after 2035. We model only first homes and do not disaggregate households by income.

Limits and economic parameters. The limits are exogenous maxima taken from the PNRE. They are an assumption about the capacity of the sector, not a measurement, and their sum is 5% above the upper end of the PNRE path (Section 3.5). The discount rate (8%, real) is high for a planner and penalizes renovation, which has an upfront cost and later savings, so the results are probably conservative. The terminal cost is 14.5% of the total cost and 10.9 of the 36.9 G€ of gross avoided costs, so the return depends on it (3.0 € per euro without it).

Model structure. The model is deterministic, with perfect foresight, and decides by system cost. It does not represent the household decision (barriers, access to credit, split incentives between owner and tenant). It does not include the emissions of construction and of renovation materials.

6.3 Future work

We plan six extensions: (1) include income in the vulnerability levels of households, so that vulnerable households and energy poverty indicators are explicit; (2) represent financing and subsidies, to estimate the support that households need to carry out the renovation the model recommends; (3) represent the rebound effect, with a heating service demand that rises after renovation in households that under-consume; (4) refine the renovation limits with data on the capacity of the construction sector; (5) model new buildings, demolition and learning in the costs; and (6) recalibrate the model with updated data.

7. Conclusions

A national renovation plan needs two answers: what a renovation does to a building, and what it does to the energy system and when it is worth doing. Building models such as ModESTo answer the first. This paper shows that a system model such as openMASTER can answer the second, once renovation is a decision of the model and not an input.

The answer has a practical consequence. Because renovation generates savings at the cost of shallow packages and still does so at several times those costs, the energy system gains from renovating the oldest homes as fast as the construction sector allows. The policy question therefore moves from "how cheap can a renovation be" to "what lets the sector renovate more homes each year": financing, workers and decisions in multi-dwelling blocks. The houses of the Continental zone are the first place to apply it, because each dwelling saves the most there.

Two features of the approach make this result useful beyond Spain. The model works with energy service demand, so it compares insulation, heat pumps and other options for delivering the same comfort. And it covers the whole energy system, so the effects of renovation on supply and on the

other sectors appear in the same result. Reading the PNRE rates as industry limits, and not as goals, also turns a plan into a test of what the sector must deliver.

The results do not say who pays or how much support a household needs. The next version will add household vulnerability, with budget restrictions included in the vulnerability levels, and will represent financing and subsidies. With them, the model can estimate the public support that turns a profitable renovation for the energy system into one that vulnerable households can afford.

Annex A

Heating service demand per dwelling at each efficiency level.

Segment	VLE	LE	ME	HE	Reduction LE / ME / HE vs VLE
Atlantic, block	2,682	1,698	994	226	37% / 63% / 92%
Atlantic, house	10,807	7,154	4,659	853	34% / 57% / 92%
Continental, block	3,178	2,402	1,707	390	24% / 46% / 88%
Continental, house	12,486	7,846	6,053	915	37% / 52% / 93%
Mediterranean, block	1,631	998	681	116	39% / 58% / 93%
Mediterranean, house	6,543	3,751	2,883	488	43% / 56% / 93%

TABLE A1, HEATING SERVICE DEMAND PER DWELLING AND YEAR AT EACH EFFICIENCY LEVEL (KWH PER DWELLING AND YEAR) AND REDUCTION AGAINST VERY LOW, BY CLIMATE ZONE AND BUILDING TYPE. SOURCE: PAFOTH OF THE MODEL INPUT, BASED ON IDAE [29].

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