

1 **Decision-support method for profitable residential energy retrofitting based** 2 **on energy-related occupant behaviour.**

3

4 **Abstract**

5 Low-carbon energy retrofitting in buildings plays an important role because 75% of European
6 buildings are considered inefficient and more than 40% are currently over 50 years old. The
7 economic reinvestment of energy retrofit actions through reduced energy bills, as energy
8 directives promote, greatly depends upon the energy consumption patterns. In support of the
9 decision-making process towards a low-carbon energy transition in multi-family buildings, this
10 paper introduces a novel assessment method that evaluates the profitability of energy efficiency
11 measures, according to standard operating conditions derived from energy performance
12 certificate procedures and real occupant energy consumption scenarios, through a parametric
13 analysis. The aim is to assess the real energy and economic savings of retrofitting actions,
14 depending on different energy-related occupant scenarios, and to enable comparisons with other
15 buildings, providing a valuable model to identify the most feasible and low-carbon energy
16 strategies in residential energy retrofitting. A Spanish multi-family building from 1942 is taken
17 as the reference case study. The results show that energy savings for dwellings vary up to 80%,
18 and the net present value per dwelling differs by up to 20,000€ between different energy
19 consumption patterns. The most appropriate energy efficiency measures according to low,
20 medium or high consumption scenarios are highlighted.

21

22 **Keywords:** energy renovation; low-carbon energy; occupant behaviour; consumption
23 scenarios; decision-making; multi-family buildings.

24 NOMENCLATURE

<i>a</i>	operation year
C_f	annual cash flow
COP	coefficient of performance
DHW	domestic hot water
ED	energy demand (kWh/m ² a)
EEM	energy efficiency measure
EER	energy efficiency ratio
EIFS	exterior insulation and finishing system
EPBD	Energy Performance of Building Directive
EPC	Energy Performance Certificates
EPS	expanded polystyrene insulation
HP	heat pump
IC	investment cost (€)
NPV	net present value (€)
OECD	Organisation for Economic Co-operation and Development
PBP	payback period
PEC	primary energy consumption
SHGC	seasonal heat gain coefficient of shading devices
<i>r</i>	discount rate
TB	thermal-break
U	thermal transmittance (W/m ² K)
XPS	extruded polystyrene

25

26 1. INTRODUCTION

27 The building sector is responsible for 36% of global final energy consumption and more than
28 55% of the electricity demand (International Energy Agency, 2017, 2013a). In the European
29 Union, this sector is responsible for approximately 40% of energy consumption and 36% of
30 CO₂ emissions (European Commission, 2018, 2014), of which 70% corresponds to heating,
31 cooling and domestic hot water (International Energy Agency, 2017, 2013a), being mostly
32 fossil fuels based (European Commission, 2016).

33
34 European statements consider that almost 75% of building stock is energy inefficient (European
35 Commission, 2015a). Regarding building aging, more than 40% of current housing stock are
36 over 50 years old (Aksoezen et al., 2015; International Energy Agency, 2017) and 75% of
37 buildings anticipated for 2050 are already built, in the case of the European Union and OECD
38 member countries (Cuchí and Sweatman, 2013; International Energy Agency, 2013b).
39 Therefore, the energy renovation of existing buildings has a huge potential to lead to significant
40 energy savings (Arumägi et al., 2017).

41
42 Following these guidelines, European policies aim to support low-carbon energy transition
43 through sustainable renovation strategies. The European Energy Performance of Buildings
44 Directive (EPBD) (European Commission, 2018) underlines the need to implement new
45 methods and protocols for energy retrofitting processes in the building stock, ensuring viable
46 and efficient operations to achieve environmental targets, as well as to improve the quality of
47 life of citizens (Thuvander et al., 2012). Moreover, EPBD considers that financing through
48 energy bill savings is the main option to finance the energy retrofitting process (European
49 Commission, 2018). However, it is also essential to consider the users' energy consumption
50 attitude, and each socioeconomic context, to achieve sustainable and efficient interventions
51 (Heiskanen et al., 2013). Lizana et al. (2016) stated that economic savings, related to energy
52 bills, might not be enough for end-users to support energy retrofitting at current energy prices.
53 In addition, as pointed by Vilches et al. (2017), families with low income levels represent an
54 important barrier for carrying out retrofitting actions.

55
56 European standards and regulations are developing energy performance calculation methods to
57 support the EPBD, focused on enabling comparisons with other buildings and evaluating real
58 energy and economic savings in building retrofitting processes. The most common are the
59 energy assessment methods, in the form of Energy Performance Certificates (EPC) (AENOR,
60 2012; European Commission, 2010), which are aimed at showing the energy performance of
61 buildings and informing end-users of potential energy savings (European Commission, 2015a).
62 However, most EPC procedures are based on standard operating conditions, occupancy
63 profiles, and other default values that generate discrepancies between energy simulation and
64 real energy use (Lizana et al., 2017). The results of these standard procedures distort the EPC
65 purpose of informing about the real energy saving potential (European Commission, 2015a), so
66 one of the main challenges in energy renovation is how to obtain realistic energy saving values
67 according to real energy consumption patterns.

68
69 Different studies have identified and discussed the high impact of energy-related occupant
70 behaviour on the economic and energy performance of low-carbon retrofitting actions. Wallis
71 et al. (2016) suggested that the use of energy behavioural attitudes provides more detailed
72 information about the electricity consumption and thus allows choosing a more appropriate
73 policy planning. According to Hong et al. (2016), occupant behaviour greatly influences the
74 real consumption by using the thermostat settings, opening or closing windows, use of air
75 conditioning systems, lights and stand-by of appliances, among others. Stieß and Dunkelberg

76 (2013) developed an empirical study of 1000 homeowners in Germany which considers the
77 importance of users' knowledge about energy consumption related to the decision-making
78 process in standard refurbishment measures. Bedir and Kara (2017) studied the influence of
79 consumption patterns on different profiles of electricity consumption in Dutch housing stock.
80 Liang et al. (2016) proposed the need to design a decision-making system that considers the
81 influence of the occupation model and the occupant behaviour to achieve a green retrofit. Li et
82 al. (2018) identified the influence of different types of end-users in the final success of
83 interventions, suggesting participatory decision/evaluation procedures that involve them in
84 sustainable projects. Perera et al. (2018) stated that, including a socioeconomic evaluation is
85 crucial, to identify the most desirable interventions in building renovation for different profiles,
86 through a multi criteria decision-making approach. Serrano-Jiménez et al. (2017) introduced a
87 new energy renovation strategy which proposed different levels of intervention (mild, moderate
88 and intense), based on the socioeconomic context of each region, going against the European
89 concept of deep renovation adopted by the Global Building Performance Network (GBPN,
90 2013), and evaluating interventions adapted to each requirement (Femenías et al., 2018).

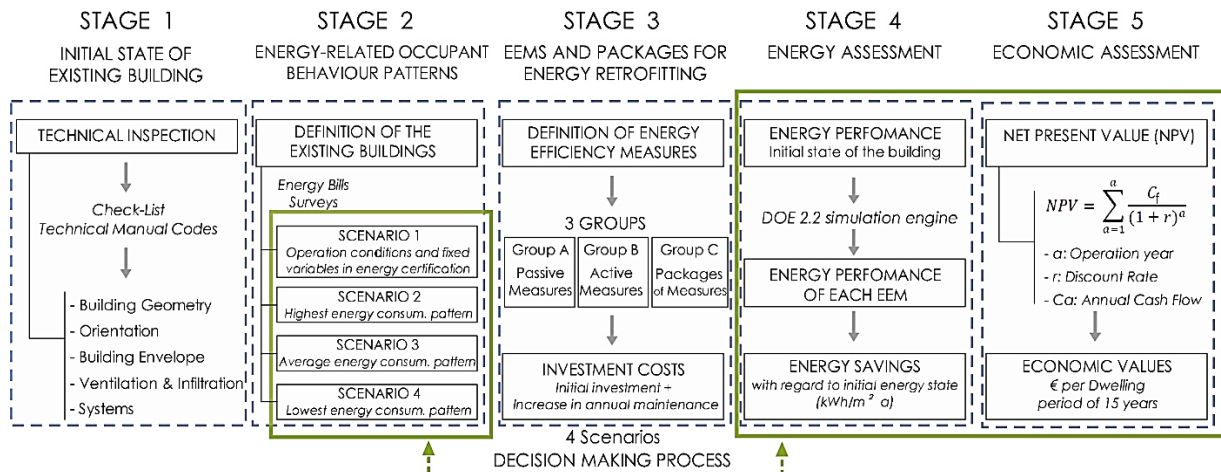
91
92 As a step forward, this research defines a new economic and energy assessment method of
93 energy efficiency measures to support decision-making in energy retrofitting of multi-family
94 buildings. It involves a parametric analysis between different energy retrofit alternatives and
95 energy consumption scenarios of dwellings (standard and real energy consumption profiles:
96 high, medium and low), overcoming the problem that emerges when different users or
97 stakeholders do not follow the consumption standards of EPC procedures. The method allows
98 identifying best available solutions for all dwelling scenarios, guaranteeing the global
99 profitability of actions, according to every energy-related occupant behaviour.

100
101 The novelty of this method is based on the integration of real scenarios based on energy-related
102 occupant behaviour in energy simulations together with those operating parameters established
103 by the EPC standards, to evaluate both the energy and economic savings of energy efficiency
104 measures, through a sensitivity analysis. This procedure fulfils two main purposes of the EPBD
105 and EPC [24]: showing the energy performance of the building to enable comparisons with
106 other buildings; and, informing end-users of potential energy savings, in order to motivate them
107 to invest in improving the energy efficiency of the building. It uses a model's iterative
108 calibration procedure, based on real building performance, which allows a high final accuracy
109 to be achieved. This method enables a new procedure that allows homeowners, landlords or
110 investors to identify the most appropriate energy retrofitting actions in each scenario, as
111 suggested by Bolis et al. (2017) or Pombo et al. (2016), showing real economic feasibility. In
112 addition, the graphic output of the results allows sustainable strategies to be designed, according
113 to the effectiveness and feasibility of solutions, for all energy-related behaviour contexts.

114
115 The paper is structured as follows. Firstly, the method is defined in a general scheme, where
116 the main contributions are highlighted, and the five stages into which it is divided are defined.
117 Secondly, the method is applied in a residential neighbourhood in Southern Europe, considered
118 as a reference multi-family building typology, due to its construction period, constructive
119 composition and low-medium income population. Thirdly, energy efficiency measures (EEMs)
120 and packages are evaluated in different energy consumption scenarios, where the total
121 investment cost (IC), the annual thermal energy demand (ED), the primary energy consumption
122 (PEC), and the Net Present Value (NPV), are calculated and compared. Finally, the results are
123 discussed, and the most appropriate measures or packages are identified, according to each
124 scenario, as well as reporting strategies and guidelines to support the decision-making process
125 for a sustainable low-carbon energy retrofitting.

126 **2. MATERIALS AND METHOD**

127 Figure 1 defines the assessment method to evaluate the energy savings and economic
 128 reinvestments of energy retrofit projects in residential buildings. The method is designed to be
 129 applied and adapted to any residential neighbourhood by previously requiring real energy data,
 130 per dwelling, to identify the different energy consumption patterns of their occupants.
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132
 133 Figure 1. Five-stage operation of the decision-support assessment method.
 134

135 As a step beyond the previous studies reported in the introduction, this research involves extra
 136 variables by carrying out a parametric analysis with four consumption scenarios, three of them
 137 according to real data from the occupants, and one of them, following the standard parameters
 138 of EPC procedures. This research extends the results obtained in previous studies where the
 139 return on investment, in different cost-optimal measures, are compared with one energy
 140 consumption pattern, such as in Tadeu et al. (2016), Lizana et al. (2016), or Serrano-Jiménez
 141 et al. (2017). This concept promotes decision-making in energy retrofitting through a joint
 142 assessment of different energy consumption patterns. Stages 4 and 5 are in continuous relation
 143 with Stage 2, which generates a more complete sensitivity analysis and helps the investor to
 144 identify which proposals would be the most appropriate for each case study. In addition, the
 145 inclusion of Stage 3, which is organised into three groups of passive, active and packages of
 146 actions, allows useful results to be obtained for the small investor on the performance of
 147 individual actions, and offers an overall analysis of the wide range of possibilities that induces
 148 energy retrofitting in different proposals or packages (Ascione et al., 2015). The five stages,
 149 into which this method is structured, are defined in detail below.
 150

- 151 • **Stage 1. Initial state of the existing building.** The diagnosis of the initial state of the building
 152 is obtained through technical inspections and energy audits following different normalised
 153 procedures (AENOR, 2015; Gobierno de España, 2013a, 2013b) and specific technical manuals
 154 and codes (Ministerio de Fomento, 2013; Ministerio de Vivienda, 2006). Building geometry,
 155 location, orientation, constructive composition of the building envelope (façades, roofs, floors
 156 and windows), ventilation and infiltration rates, as well as heating, cooling and hot water
 157 systems, are characterised.
 158
- 159 • **Stage 2. Energy-related occupant behaviour patterns.** The operating conditions and energy
 160 consumption patterns in each dwelling are evaluated for the energy simulation, through
 161 occupant surveys and energy bill assessments. Hourly operating schedules of occupation
 162 (weekday and weekend), operating profiles of systems, lighting for internal gains, and set-point
 163 temperatures, are specifically defined for each energy-related scenario. Four scenarios are

164 considered for the sensitivity analysis. Scenario 1 is characterised by the operating conditions
165 and default values of local EPC procedures. Scenarios 2, 3 and 4 represent the low, medium
166 and high consumption profiles for the case study, which are calibrated according to real energy
167 consumption data (energy bills), through an iterative calibration process. Further details of the
168 scenarios are described below:

- 169 – **Scenario 1** is defined by the operating conditions and fixed parameters used for the EPC
170 in the region (European Commission, 2010; Gobierno de España, 2013b; Ministerio de
171 Vivienda, 2009). Set-point temperatures for on-peak and off-peak occupancy periods are
172 fixed at 25°C and 27°C for cooling, respectively, and 20°C and 17°C for heating. The
173 internal gains generated by occupants, lighting and appliances are considered according
174 to specific schedules.
- 175 – **Scenario 2** considers the highest energy consumption pattern among all dwellings,
176 according to the results obtained in surveys and energy bills. Operating conditions are
177 based on survey results and calibrated according to energy bill data.
- 178 – **Scenario 3** is characterised by the medium energy consumption pattern of all dwellings
179 according to the results obtained in surveys and energy bills. Operating conditions are
180 based on surveys and calibrated according to the performance, which is determined
181 through the average of the energy bill data.
- 182 – **Scenario 4** considers the lowest energy consumption pattern among all dwellings
183 according to the results obtained in surveys and energy bills. Operating conditions are
184 based on surveys and calibrated according to energy bill data.

185
186 • **Stage 3. EEMs and packages for energy retrofitting.** A portfolio of individual technical
187 EEMs and packages to reduce thermal energy demand and consumption are defined and
188 characterised. Aiming to facilitate the comparison between the results, solutions are organised
189 into three groups: individual passive measures (group A); individual active measures (group
190 B); and, packages of measures (group C). The investment cost (IC) and the increased
191 maintenance costs are defined for each EEM. Data are obtained from local databases and
192 manufacturers' reports.

193
194 • **Stage 4. Energy assessment.** The current energy performance of the building is evaluated by
195 the DOE 2.2 simulation engine. Then, the implementation of the proposed EEMs and packages
196 are simulated in each energy consumption scenario. The initial energy models for each scenario
197 are calibrated considering the different energy consumption profiles, which were characterised
198 in Stage 2.

199
200 • **Stage 5. Economic assessment.** The economic reinvestment of EEMs for each energy
201 consumption scenario is calculated through the Net Present Value (NPV). The NPV is a useful
202 economic concept for analysing the profitability of a planned investment or project. This term
203 is calculated within this research for each energy efficiency measure or package, and offers the
204 difference between the present value of cash inflows, and the present value of cash outflows
205 over a period of time. NPV is evaluated according to Eq. 1, where a is the operation year, r the
206 discount rate, and C_f the annual cash flow.

207

$$NPV = \sum_{a=1}^a \frac{C_f}{(1+r)^a} \quad (1)$$

208

209 The operation year (a) to calculate the NPV can vary between 15 and 30 years, according to
210 each socioeconomic context of application (Short et al., 2005). For the selected case study, the

211 operation year is set at 15 years, due to the high percentage of aging population and the socio-
 212 economic level being low-medium, which demands a short-term amortization period (Kovacic
 213 et al., 2015). After 15 years, most of the elderly will be over 80 years old, which is nearly the
 214 average national life expectancy (Instituto Nacional de Estadística, 2013; Serrano-Jiménez et
 215 al., 2018).

216
 217 The discount rate (r) is the rate of return used in a discounted cash flow analysis to determine
 218 the present value of future cash flows. This is an important value that should be decided for
 219 each context, according to the economic situation. Figure 2 shows the discount rate values of
 220 low-risk banking products from the National Bank of Spain (Banco de España, 2017), during
 221 recent years. Although there has been a significant drop in the trend, due to the financial crisis,
 222 the end of the quantitative easing has meant that new economic expectations for the European
 223 context estimate an increase of these rates, in a range of between 3 and 6%, for the coming
 224 years (Hermelink et al., 2016; Mata et al., 2015). Therefore, 4.5% has been fixed as a discount
 225 rate that is adapted to these new expectations, in addition to taking into account this application
 226 context with reduced investments, and a moderate investor profile.

227



228
 229 Figure 2. Evolution of the discount ratio values during the last years.
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231 Lastly, C_f is calculated as a function of the initial IC (€) and the annual economic savings per
 232 dwelling (€), which is based on annual operating costs and the increase in annual maintenance
 233 costs. In fact, annual operating costs (€) include an annual energy price increase of 4.5%,
 234 according to its evolution over recent years (IDAE, 2015a, 2015b), and the different expected
 235 scenarios for each energy source (IDAE, 2011; Prasanna et al., 2018). These values also need
 236 to be adapted to each region and socioeconomic context.

237 3. REFERENCE CASE STUDY

238 A residential set of multi-family buildings known as "Remedios Viejo", and located in Seville
 239 (Spain), was selected as the case study (Figure 3). It was built in 1942 and represents a reference
 240 building sample of the mid-twentieth century in Mediterranean cities that currently has several
 241 energy renovation needs (Barrios-Padura et al., 2015; Gamarra et al., 2018). This case study
 242 pertains to the large housing stock of European cities, with more than a third of multi-family
 243 buildings, prior to 1970 (European Commission, 2015b). Moreover, it presents an aging
 244 population with 32% of its inhabitants over 65 years of age, representative of the world
 245 population aging trend.

246
 247 The neighbourhood has 324 dwellings that are divided into nine closed blocks. Each block
 248 consists of four multi-family residential buildings of three storeys in height, enclosing a private

249 inner courtyard. All the dwellings have the same size, and occupancy ranges between one and
 250 four residents per dwelling, with an average occupation value of 2.61 (IECA, 2012).

251
 252 The residents of these buildings participated in this research, by responding to a brief survey
 253 about the operating conditions and occupation periods in their dwellings, as well as to questions
 254 related to behavioural patterns in energy consumption. The occupants also provided energy bills
 255 with real energy consumption values from recent months. The participation sample was
 256 collected from 176 dwellings, which represents 54% of the apartments in the neighbourhood.
 257



Figure 3. Aerial location of the case study.

258
 259 The case study was also characterised through technical inspections and audits. Main
 260 characterisation parameters for the energy simulation are summarised in Table 1. Data are
 261 divided into two groups: building envelopes and systems.
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 264
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Table 1. Building characterisation for the energy assessment. Main parameters.

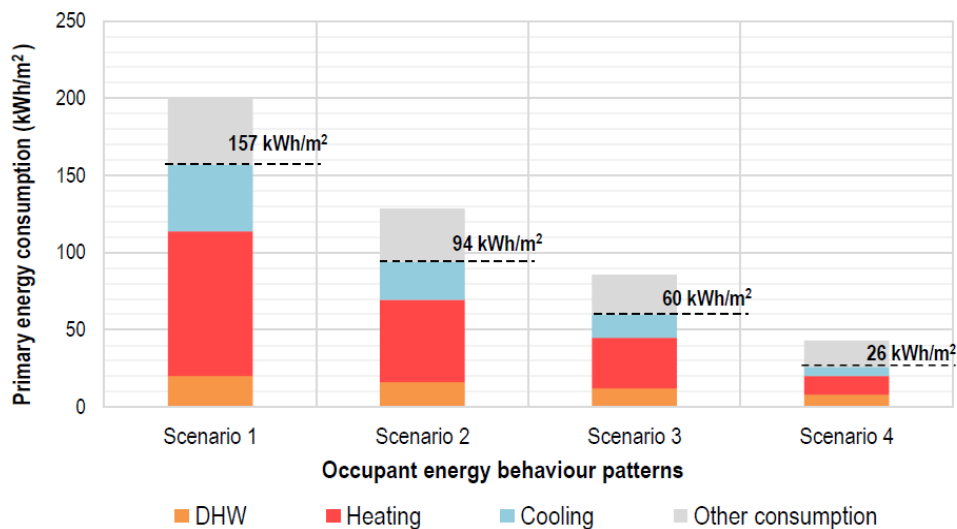
Element	Characterisation		Values	
Envelope	Ventilation and infiltration ¹	Permeability of windows (P_{window})	80 ($m^3/h \cdot m^2$ at 100 Pa of pressure)	
		Permeability of walls (P_{wall})	$2.7 \cdot Volume$ (m^3/h)	
	Windows	Thermal Transmittance (U)	Frame (20%) 5.7 $W/m^2 \cdot K$ Glass (80%) 5.7 $W/m^2 \cdot K$	5.7 $W/m^2 \cdot K$
		Solar Factor (SF) (0-1 value)		0.75
		Absorptivity of frame (α)		0.70
		Permeability of windows		$\geq 80 m^3/h \cdot m^2$
		Seasonal solar heat gain coefficient of Window assembly (SHGC)	30% of external solar protection for winter and summer	0.7
	Façade			2.68 $W/m^2 \cdot K$
	Roof	Thermal transmittance (U)		1.49 $W/m^2 \cdot K$
	Floor			3.58 $W/m^2 \cdot K$
Systems	DHW	Type: LPG Boiler	Nominal yield (%)	0.85
		Percentage of use: 100%	Nominal power (kW)	24 kW
			Minimum solar contribution (%)	0 %
	Cooling	Type: Air-air direct expansion, HP-E (Split) Percentage of use: 100%	EER	2.5
			Capacity	4.2 kW
			Consumption	1.68 kW
			COP	2.7
	Heating	Type: Air-air direct expansion, HP-E (Split) Percentage of use: 60%	Capacity (kW)	4.5 kW
			Consumption	1.66 kW
			Type: Electrical heating (Joule Effect)	Nominal yield (%)
	Percentage of use: 40%	Capacity (kW)	2 kW	

266

267 The building typology has a poor energy performance, with no insulation and low-quality
 268 materials. The façades present a deteriorated conservation status. Windows are characterised
 269 by a simple glazing and high infiltrations. Most of the heating and cooling conditioning
 270 systems are newly incorporated with mono-split, and/or, electric heating (electric radiators).
 271 Domestic hot water is usually obtained through a gas boiler or electric water heater.

272 3.1. Economic and energy consumption patterns

273 The economic and energy consumption scenarios considered for sensitivity are defined in
 274 Figure 4 and Table 2. Figure 4 illustrates the primary energy consumption (PEC) values
 275 (kWh/m² a), relative to DHW, heating and cooling and other consumption sectors, in each
 276 scenario. These PEC values were obtained as a function of final energy consumption results
 277 taken from energy audits, and PEC conversion factors of used energy sources, for the specific
 278 region under assessment. Associated annual energy bills, per scenario, are shown in Table 2.
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Figure 4. Occupant energy behaviour patterns evaluated in the case study.

Table 2. Annual energy bill per dwelling with occupant behaviour patterns.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual PEC (kWh/m ²) ^a	199.91	128.47	85.75	43.04
Annual energy bill (€) ^b	2,445.86	1,651.94	1,182.72	713.50

a. Including energy consumption of DHW, Heating, Cooling and other consumption sectors.
 b. Not including national taxes.

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- **Scenario 1** corresponds to the energy consumption pattern according to fixed values considered for national EPC procedures, representing an annual energy cost of 2,445.86€ per dwelling, which is not adjusted to reality. This is due to the fact that default values for energy simulation engines generate discrepancies with regard to real energy use, resulting in seemingly distorted consumption.
- **Scenario 2**, which represents the highest value from the energy bills in all the dwellings, is characterised by 1,651.94€ per year per dwelling.
- **Scenario 3**, which identifies the average value of the energy consumption in all dwellings, consists of an annual energy bill of 1,182.72€ per dwelling.
- **Scenario 4**, which represents the lowest value from the energy bills in all dwellings, is characterised by 713.50€ per year per dwelling.

296 It is essential to highlight that the medium scenario (Scenario 3) supposes 42-48% of the
 297 economic and energy results, for the prefixed standard profile for EPC procedures (Scenario 1).
 298 Thus, although the official certification allows evaluation and comparison of energy
 299 performance in different existing buildings, it is shown that it uses excessive consumption
 300 profiles, with respect to the real values evidenced in energy bills.

301
 302 Considering these scenarios, four energy simulation models, one per scenario, were carried out
 303 through the DOE 2.2 simulation engine, by means of an iterative calibration procedure. Once
 304 each building model was characterised, those uncertain operating conditions were adjusted to
 305 calibrate the energy model, according to real energy bill values reported in each scenario.

306 3.2. Energy efficiency measures. Criteria and proposals

307 Table 3 shows the set of individual measures and packages of energy efficiency interventions
 308 selected for improving the energy performance of the residential building. For each group,
 309 initial investment cost, increase in annual maintenance cost, and main characterisation
 310 parameters, are defined. Three groups of EEMs are presented: group A consists of passive
 311 measures; group B consists of active measures to upgrade heating, cooling and hot water
 312 systems; and, group C consists of packages of measures combining specific solutions of group
 313 A and B. The defined measures cover a wide variety of possibilities in energy renovation in
 314 residential buildings, with actions that involve modifying the building envelope (a1-a3),
 315 improving thermal performance in windows (a4-a5), adding insulation (a6-a8), or improving
 316 the system performance, with different energy sources and operating conditions. The
 317 organisation of these three groups allows easy comparison of the performance of passive, active
 318 and packages of measures in the four consumption scenarios.

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Table 3. Definition and economic characterisation of proposed EEMs.

Definition of measures and packages	Investment cost per building ^a (€)	Investment cost per dwelling ^a (€)
Group A. Passive measures		
a1. Sealing of frames in windows (<i>Improvement of airtightness</i>). (1.17 ach/h)	1,725.92	143.83
a2. Rollable awnings in the façade (<i>Rigid slats</i>). (SHGC: Summer=0.2; Winter=0.7)	16,424.30	1,368.69
a3. Hanging awnings in the façade (<i>Textile</i>). (SHGC: Summer=0.4; Winter=0.7)	18,566.60	1,547.22
a4. Double windows (<i>adding a new window with double glazing to the previous one</i>). (0.97 ach/h, $\leq 27 \text{ m}^3/\text{h m}^2$; Uwindow correct factor=0.37)	33,235.40	2,769.62
a5. New windows (<i>aluminium frames thermal break TB and double glazing</i>). (0.90 ach/h, $\leq 9 \text{ m}^3/\text{h m}^2$; Uwindow=2.3W/m ² ·K; $\alpha=0.30$)	42,299.60	3,524.97
a6. Exterior insulation in the façade EIFS (<i>Expanded polystyrene – EPS</i>). (0.90 ach/h ; Ufaçade=0.57W/m ² ·K)	37,415.00	3,117.92
a7. Exterior insulation in the façade EIFS (<i>Cork</i>). (0.90 ach/h ; Ufaçade=0.61W/m ² ·K)	41,904.80	3,492.07
a8. Interior insulation in the roof by interior cladding (<i>Extruded Polystyrene - XPS</i>). (1.15 ach/h; Uroof=0.37W/m ² ·K)	12,334.80	1,027.90
Group B. Active measures		
b1. Reversible heat pump (<i>Heating and cooling</i>). (EER=4.2; Cap: 4.2kW; Cons:1.00kW- COP: 4.6; Cap:4.5kW; Cons: 4.5kW)	20,400.00	1,700.00
b2. Aerothermal heat pump (<i>Heating, cooling and DHW</i>). (EER=3.8; Cap: 7.1kW; Cons:1.9kW - COP: 3.6; Cap:8 kW; Cons: 2.3kW)	81,600.00	6,800.00
b3. Solar thermal energy (<i>DHW</i>). (Minimum Solar Contribution: 70%)	17,304.00	1,442.00
b4. Photovoltaic energy support system (<i>Heating, cooling and DHW</i>). (Contribution: 2,050kWh; 14m ² panels; Forecast gen. 2.78 kWh/year)	12,320.00	1,026.67
b5. Centralised biomass boiler (<i>Heating and DHW</i>). (Nom. Yield: 78%; Nom. Power: 130kW - Num. radiator: 4; Power:1.6kW)	35,000.00	2,916.67
b6. Individual biomass boiler (<i>Heating</i>). (Nom. Yield: 91%; Nom. Power: 5kW)	19,320.00	1,610.00

b7. Centralised condensing boiler (<i>Heating and DHW</i>). (Nom. Yield: 93%; Nom. Power: 170kW - Num. radiator: 4; Power:1.6kW)	16,420.00	1,368.33
b8. Micro-cogeneration (<i>Heating and DHW</i>). (Nom. Yield: 81%; Nom. Power: 30.5kW - Num. radiator: 4; Power:1.6kW)	55,420.00	4,618.33

Group C. Packages of measures

c1. Rollable awnings + New windows. (a2 + a5)	58,723.90	4,893.66
c2. Rollable awnings + New windows + Façade insulation. (a2 + a5 + a6)	96,138.90	8,011.58
c3. New windows + Façade and roof insulation. (a5 + a6 + a8)	93,023.20	7,751.93
c4. Rollable awnings + New windows + Façade and roof insulation. (a2 + a5 + a6 + a8)	109,447.50	9,120.63
c5. Rollable awnings + New windows + Solar thermal energy. (a2 + a5 + b3)	76,027.90	6,335.66
c6. New windows + Reversible heat pump. (a5 + b1)	62,699.60	5,224.97
c7. New windows + Reversible heat pump + Solar thermal energy. (a5 + b1 + b3)	80,003.60	6,666.97
c8. New windows + Aerothermal heat pump. (a5 + b2)	123,899.60	10,324.97
c9. Rollable awnings + New windows + Façade and roof insulation + Solar thermal energy. (a2 + a5 + a6 + a8 + b3)	126,751.50	10,562.63

^a All costs incurred up to the point when the building or the dwelling element is delivered to the customer, ready to use. These costs include design, purchase of building elements, connection to suppliers and installation, and commissioning processes, not including national taxes.

321
322 This method necessarily involves evaluating the energy and economic performance of packages
323 of measures, since it is very common to combine them in building renovation proposals. The
324 criteria for grouping the packages have mainly considered technical, constructive and economic
325 factors that promote a significant reduction of the energy use. The packages are formed by
326 passive measures with a high potential to reduce energy demand (c1-c4), as well as including
327 those active measures with better energy performance (c5-c9).

328 4. RESULTS AND DISCUSSION

329 The results of this decision-support method are presented for each group of measures in two
330 different sections. First, the results relate the investment cost and the reduction of thermal
331 energy demand of each measure or package, and second, the sensitivity analysis relates the
332 energy savings and the NPV values, according to the four defined consumption scenarios.

333 4.1. Analysis between investment cost and annual energy demand of EEMs

334 Figures 5 and 6 illustrate the relationship between investment costs and the annual thermal
335 energy demand, per dwelling (kWh/m² a), of the building in its initial situation and in scenarios
336 considering the implementation of selected energy efficiency measures. Illustrated annual
337 thermal energy demand is associated with heating, cooling and DHW, according to the
338 occupancy and operating conditions defined for Scenario 1, which represents the standard
339 operating conditions corresponding to the Spanish EPC procedure. This figure allows the
340 measures with the highest potential to improve indoor thermal comfort, with respect to the
341 investment costs, to be identified. The aim of this analysis is to highlight EEMs with the lowest
342 investment cost per dwelling (IC, €), and lowest annual energy demand (ED, kWh/m² a), with
343 respect to the initial state.
344

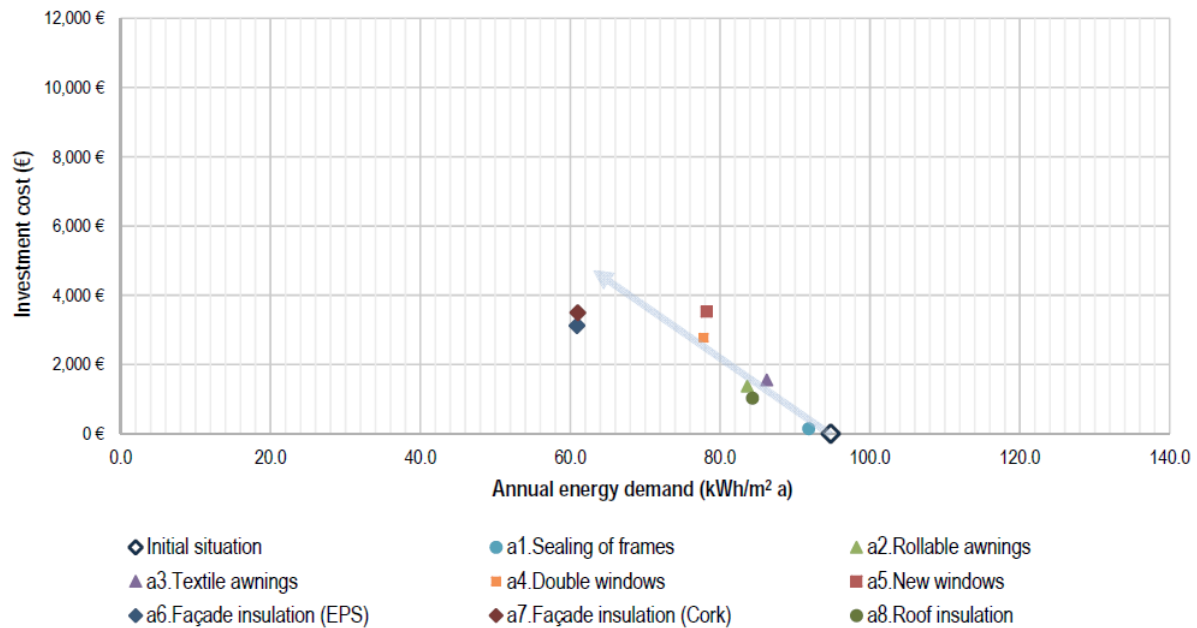


Figure 5. Analysis of IC and ED of individual passive measures.

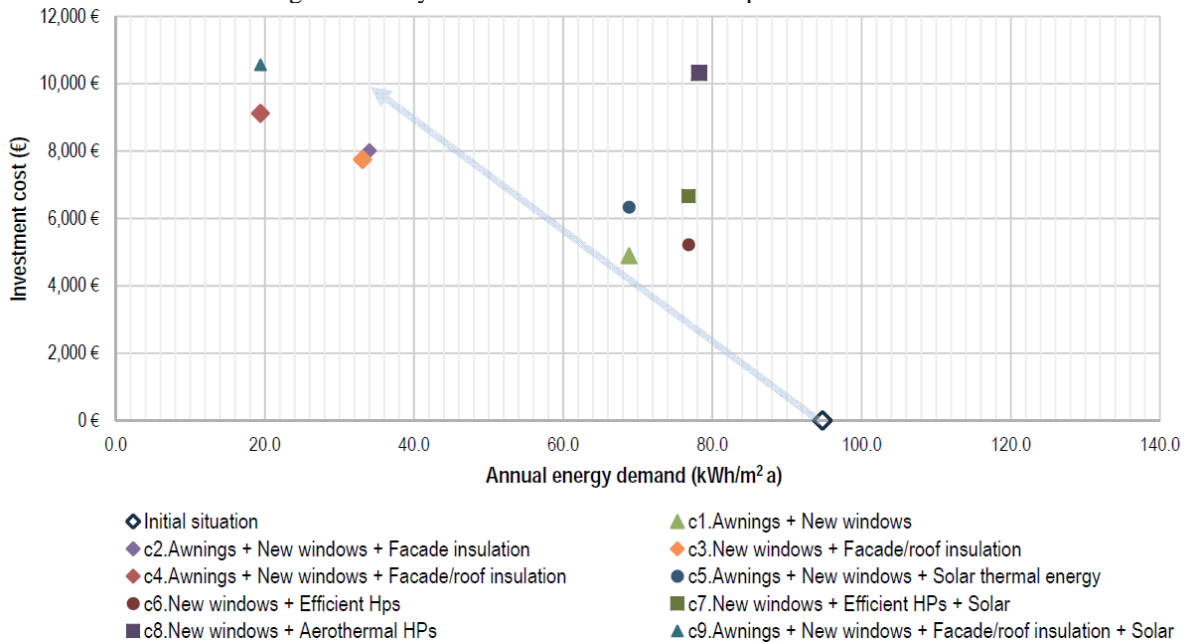


Figure 6. Analysis of IC and ED of packages of measures.

Following Figure 5, the most favourable passive measures are a6 and a7, both related to the incorporation of insulation in the façade of the building. These measures lead to a reduction of the annual energy demand of 35%, with an investment cost lower than 4,000€ per dwelling. The group B of active measures was not illustrated as they do not show reduction in energy demand. Finally, according to Figure 6, the most favourable package is c4, which includes only passive measures: awnings + new windows + façade/roof insulation. This package introduces a very significant reduction in energy demand, of almost 80%, with respect to its initial state, and an investment cost of less than 10,000€ per dwelling.

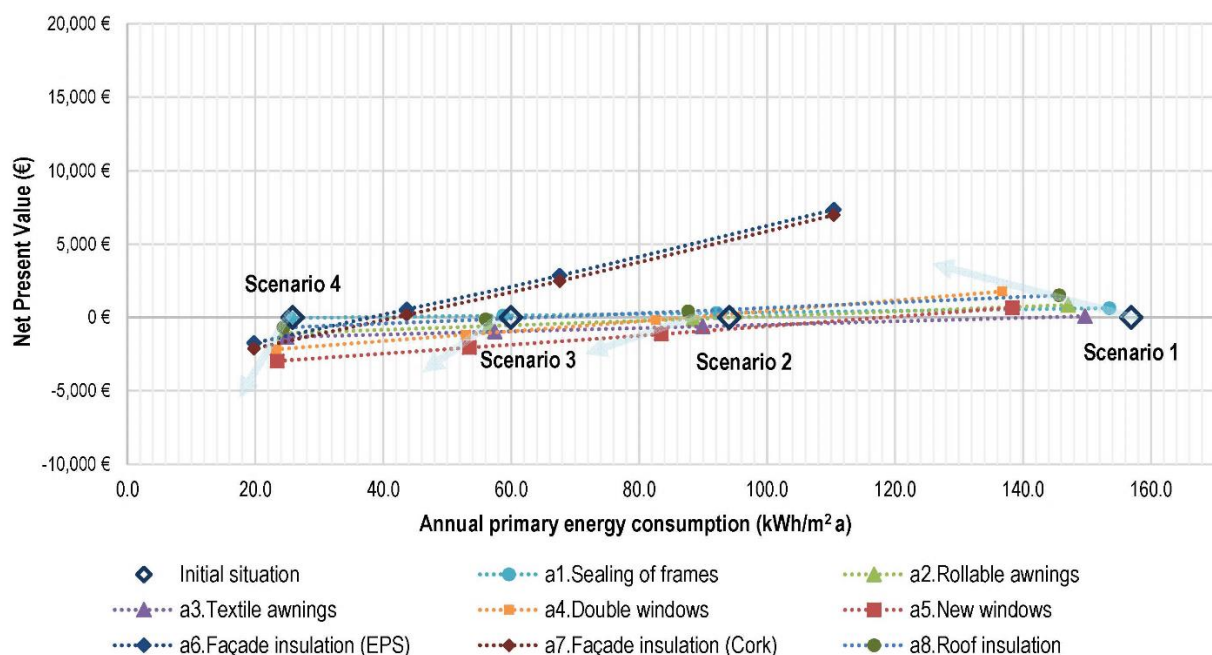
361 This preliminary analysis of the results under Scenario 1 allows a comparison of the
 362 performance of these measures with other scenarios in the following section, under a sensitivity
 363 analysis, considering users' consumption scenarios.

364 4.2. Sensitivity analysis between NPV and annual PEC

365 Figures 7, 8 and 9 show the NPV and annual PEC (considering heating, cooling and DHW)
 366 performance of each EEM, through a sensitivity analysis for different energy-related occupant
 367 behaviour scenarios. The aim is to highlight the EEMs with the highest NPV, per dwelling (€),
 368 and the lowest annual PEC (kWh/m² a). These figures allow the identification of the measures
 369 with the best potential to reduce energy consumption, with highest economic reinvestment, and
 370 lowest investment risk.

371 Each EEM is represented by a symbol and located, according to its NPV value and its PEC
 372 value, in the four defined scenarios. Each dotted line links the performance of the same measure
 373 in Scenarios 1-4. In addition, a semi-transparent trend line with arrow appears for highlighting
 374 the trend line of the group of measures in each scenario. The initial energy state of the building
 375 in each scenario is represented with an open diamond, so the energy savings would be evaluated
 376 with respect to the starting point of each scenario. Finally, those values of NPV that exceed 0€,
 377 in the NPV axis, indicate a trend to a positive reinvestment of the global cost over the period of
 378 15 years.

380
 381 Figure 7 summarises the energy and economic performance of passive measures (group A) for
 382 all energy consumption scenarios.
 383



384
 385 Figure 7. Sensitivity analysis between NPV and PEC of passive measures.
 386

387 The trend line of passive measures varies according to each scenario. It is observed that the
 388 percentage reduction of energy consumption, with respect to the initial state, is almost constant
 389 in the four scenarios, being situated between 2% and 20% from the initial state. The
 390 performance of the measures a6 and a7 particularly shows a great reduction of energy
 391 consumption in all scenarios. However, NPV values are variable according to each scenario.
 392 The impact of the consumption patterns on the PEC-NPV relationship, in passive measures,

393 reaches variations of up to 10,000€ and 90kWh/m²a between different scenarios. Scenario 3
 394 shows reduced NPV economic reinvestment values, and in Scenario 4 most of them are
 395 unfavourable, having negative NPV values. In addition, the dotted lines that link the
 396 performance of some measurements are practically horizontal, which indicates that the NPV
 397 value has low economic risk of implementation.

399 Figure 8 shows the energy and economic performance of active measures to upgrade heating,
 400 cooling and hot water systems (group B) for all energy consumption scenarios.
 401

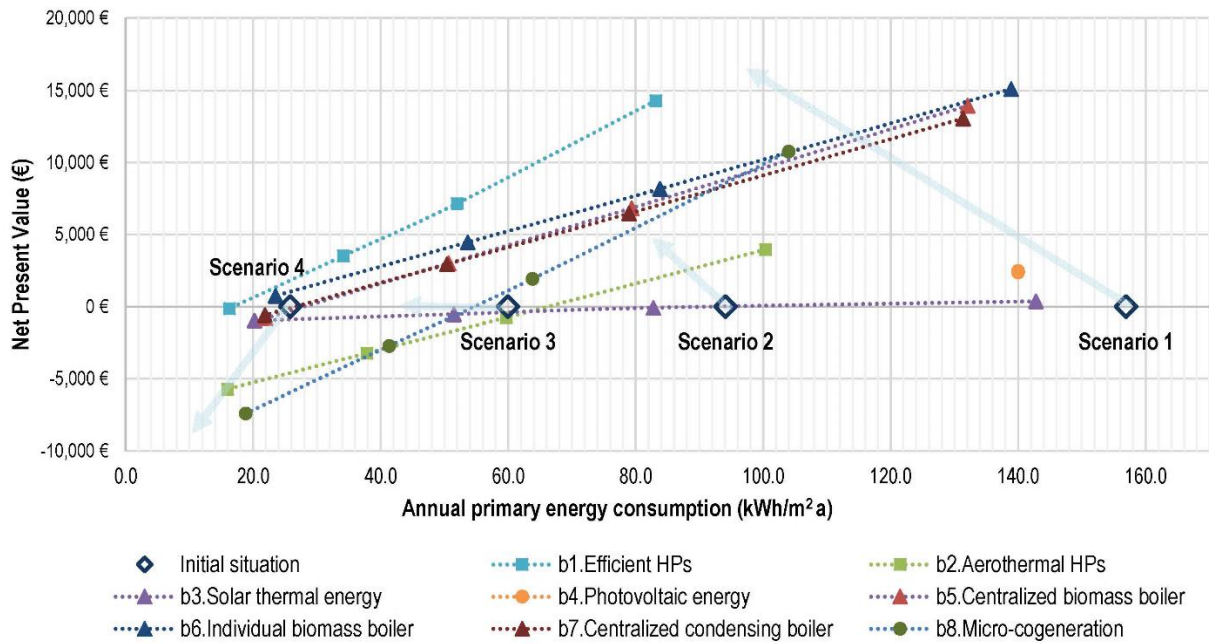


Figure 8. Sensitivity analysis between the NPV and PEC of active measures.

402 The energy and economic performance is much more variable than in the passive solutions.
 403 Moreover, regarding PEC values, unlike passive measures, the percentage of energy
 404 consumption reduction varies, according to each scenario. In addition, the impact of users'
 405 consumption scenarios on active measures offers highly different values to those previously
 406 analysed, reaching NPV variation values for the same energy efficiency measure of up to
 407 17,000€, and an energy reduction of 140kWh/m²a, between Scenario 1 and 4.
 408

411 Active measures introduce consumption reduction values up to 45%, highlighting measure b1.
 412 Regarding NPV values, most measures have a positive economic reinvestment, in many cases
 413 surpassing a 5,000€ benefit. In addition, the dotted lines that join measures are much steeper,
 414 which indicate significant changes in NPV values, according to the considered scenario. In
 415 analysing each measure, measures b1 and b2 introduce percentages of energy reduction of more
 416 than 30% in all scenarios, although the percentage may be variable, according to the
 417 consumption pattern. Exceptionally, measures b1 and b6 have positive NPV values in all
 418 scenarios.
 419

421 Figure 9 illustrates the energy and economic performance of packages of measures combining
 422 specific solutions regarding groups A and B (group C) for all the energy consumption scenarios.

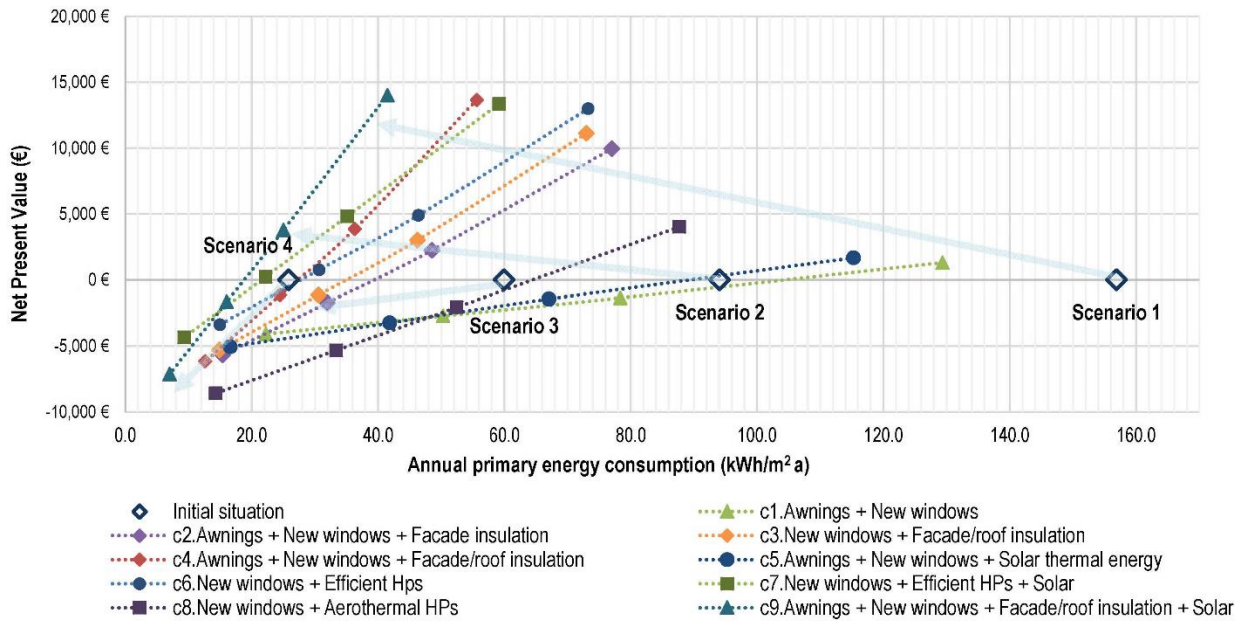


Figure 9. Sensitivity analysis between NPV and PEC of packages.

423
 424
 425
 426
 427 The impact of energy consumption patterns on PEC and NPV is highly significant. There are
 428 some packages that reach an 80% energy saving. Regarding the NPV values, there are very
 429 high variations between one scenario and another. The same package can have enormous gains
 430 for one scenario, or huge losses for another, with variations of up to 20,000€.

431
 432 For Scenario 1 and 2, the profitability of solutions is mostly positive, however for Scenarios 3
 433 and 4, most of the values are negative. In addition, the dotted lines that join each package are
 434 very steep, which supposes a great variation between one consumption pattern and another.
 435 Comparing every package, although c9 has the best energy performance, the NPV reinvestment
 436 values can be favourable or unfavourable, according to each scenario. In fact, no package of
 437 measures has favourable NPV values in Scenario 4, so the economic effectiveness of these
 438 actions is only obtained with medium or high consumption patterns.

439
 440 Comparing the reported results, a high variation in economic and energy performance of energy
 441 retrofitting measures is found per energy consumption scenario. These new findings highlight
 442 the importance of adjusting decision-making models in energy retrofitting to real energy
 443 consumption patterns, and not only taking into account standard operating conditions, to fulfil
 444 two main purposes of the EPBD and EPC procedures: enabling comparisons with other
 445 buildings, and informing end-users of potential energy savings. All these advances justify the
 446 significance of this study, promoting profitable and efficient energy renovation proposals
 447 adjusted to the socioeconomic context of each neighbourhood.

448
 449 Lastly, other particular contribution of this method is the graphic output of the obtained results,
 450 which summaries the sensitivity analysis of solutions, comparing energy performance and the
 451 economic return on investment per scenario. It allows technicians, property owners, end-users
 452 and other stakeholders an easy check of different measures through an understandable graph,
 453 in which horizontal and vertical slopes highlight the economic affordability of solutions. It also

454 facilities the decision-making in an early design stage of energy retrofitting interventions, and
455 promotes a responsible and optimized building renovation.

456 **5. CONCLUSIONS**

457 This research develops a new procedure to support the decision-making process towards a
458 sustainable energy retrofitting in the multi-family building stock. Different energy efficiency
459 measures and packages are evaluated, through a parametric analysis in a reference multi-family
460 building in Spain. The novelty of this method is based on the combination of energy and economic
461 assessment of solutions in four different energy consumption scenarios, one from standard
462 operating conditions from the national Energy Performance Certificate (EPC) procedure, and
463 the others, from real energy consumption patterns (high, medium and low). This procedure
464 fulfils two main purposes of the EPBD and EPC procedures, showing the energy performance
465 of the building to enable comparisons with other buildings and informing end-users of potential
466 energy savings, in order to motivate them to invest in improving the energy efficiency of the
467 building. This method addresses new strategies for policy making processes by promoting
468 energy renovation strategies through a profitability analysis based on real energy consumption
469 data, and highlighting most appropriate energy efficiency measures according to real needs,
470 leading to sustainable and profitable energy retrofitting actions.

471
472 The results obtained show that significant variations can be achieved between the different
473 scenarios per dwelling, reaching, for the same energy efficiency measure, from 20 to 80% energy
474 savings, and up to 20,000€ of variation in NPV values, according to the occupant behaviour
475 scenario. Thus, to reach a high level of cost effectiveness, each intervention must be fully analysed
476 according to each energy consumption pattern.

477
478 Considering NPV values, there are actions that have a positive or negative economic performance,
479 according to the scenario in which they are analysed. It is also important to stress the importance
480 of previously establishing the discount rate, as it is a highly influential factor in the economic
481 context in which the study is located. The lines linking the economic performance of each measure,
482 in different scenarios, vary considerably depending on whether they are active, passive or packages
483 of measures. Horizontal slopes in graphics ensure a major investment security for the users,
484 whereas higher slopes lead to large profits or losses, in the long-term, according to the consumption
485 patterns.

486
487 Regarding the performance of energy efficiency measures, passive measures are the best energy
488 efficiency actions for low-energy consumption patterns. Some active measures might be included
489 in medium-energy consumption levels, while in high-energy consumption levels, it would be
490 highly beneficial to include active energy efficiency measures, or packages, as they are likely to
491 produce high reduction in energy consumption and very high economic reinvestment, according
492 to the NPV results. There are active measures, such as b1 (efficient heat pump), and b6 (individual
493 biomass boiler), that have a beneficial NPV assessment in the four scenarios, so their
494 implementation would be economically viable in all the consumption patterns of this case study.
495 Otherwise, passive measures, beyond regulating interior thermal comfort, introduce substantial
496 reduction of the percentages of energy consumption with low investment risk, according to the
497 most unfavourable scenario.

498
499 Finally, it is highlighted that fixed operating conditions in EPC procedures are excessive when
500 compared with real consumption data, which implies imbalances in the results offered by official
501 procedures for retrofitting criteria. This important finding represents a political challenge to

502 overcome by official procedures, being a possible starting point for future research, towards more
503 realistic procedures of energy and economic assessment for energy retrofitting solutions.

504 **ACKNOWLEDGEMENTS**

505 This work was supported as part of the European Regional Development Fund (ERDF) of the
506 European Union for financial support through the project “(Re)habitation + (Re)generation +
507 (Re)programming. The recycling and sustainable management of Andalusian building stock.
508 Management of habitable surroundings from criteria of active aging, gender and urban
509 habitability”, and also as part of the ClimACT Project (SOE1/P3/P0429EU), within the Interreg
510 Sudoe Programme. The authors gratefully acknowledge the financial support of the Spanish
511 Ministry of Education and Research through two, pre-doctoral contracts, granted to Francisco
512 Jesús Lizana Moral (FPU14/06583) and Antonio José Serrano Jimenez (FPU15/00070). This
513 research was also made possible due to the support of the “Institute of Architecture and Building
514 Science” IUACC from the University of Seville (V-IUACC grants, mode B, 2018).

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