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Energy, emissions and economic impact of the new nZEB regulatory framework on residential buildings renovation: Case study in southern Spain

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ABSTRACT

Spanish residential buildings built in the decade of the housing bubble (2000–2009) had to comply with the Basic Buildings Standard on thermal conditions in buildings. At the end of this period, the Basic Energy Savings Document of the Technical Building Code published in the Royal Decree 314/2006, transposing European Directive 2002/91/EC, entered into force. Recently, this regulatory framework has been updated by the Royal Decree 732/2019, which transposes European Directives 2010/31/EU, 2012/27/EU and 2018/844/EU. A case study is used to analyse the energy, emissions and economic impact of these regulatory changes on an attached house located in all municipalities of Andalusia (South of Spain). The thermal behaviour of this house is compared with the one adapted to the new regulations. The TRNSYS transient system simulation tool is used for the energy study. The house adaptation is carried out by partially modifying the envelope, including a solar-thermal contribution to domestic hot water supply, and photovoltaic energy production to reduce electricity consumption. The results showed that the European objectives are greatly exceeded. Energy savings range from 69% to 127%, carbon dioxide emissions decrease by 65%–118%, and energy bills are reduced from 71% to 125%.

1. Introduction

Over the past two decades, the European Environment Agency (EEA) has documented a considerable increase in the size of urban areas [25]. Despite the wide variety of regional features and the dynamic structure of the European landscape [92], urban growth and population distribution across the European Union (EU) is generally tending to dispersion [85]. Although a scattered model is considered less sustainable than a compact model [11], discrepancies keep appearing [72]. In Spain, housing density has fallen below thirty-five dwellings per hectare [80], especially during the central years of the housing bubble 1998–2007 [12]. Moreover, this urban expansion is not being restricted by the current legislation but promoted by the deregulation of non-urbanized land use [56]. In short, the decrease in urban density, the loss of non-urban land, the depopulation of inland urban centres and the expansion of transport infrastructures confirm a scattered urban model, in which the presence of single-family homes stands out [13], the majority being attached houses [37].

In the 2000–2009 decade, just over 4.5 million new homes were built in Spain. Of these, almost a million can be found in Andalusia, with more than 200,000 single-family homes, either attached (51%), semi-detached (6%) or detached (43%). However, in the last decade (2010–2019) only 600,000 new homes have been built in Spain, of which only 50,000 were single-family homes in Andalusia (61% attached). Table 1 shows the evolution of the type of houses built in Andalusia, Spain and the EU over the past two decades. It compares the number of single-family homes (attached, detached and semi-detached) with the total number of homes (both single-family and multi-family), according to data from the Spanish National Statistical Institute (INE) [46] and the EU Statistical Office (Eurostat) [29]. Although the number of single-family homes has increased in Spain over 10% (12% in Andalusia), this category still represents 32% (38% in Andalusia), well below the EU average (which is around 60%). In addition, the number of

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Nomenclatures

A	Area (solar collector)
B	Bathroom
BS	Base Scenario (house with thermal envelope complying with NBE CT-79)
Bsh	Hot semi-arid climate (Köppen-Geiger climate classification)
Bsk	Cold semi-arid climate (Köppen-Geiger climate classification)
Bwh	Hot desert climate (Köppen-Geiger climate classification)
Bwk	Cold desert climate (Köppen-Geiger climate classification)
C	Backyard
C1	Case 1:BS (Base Scenario)
C2	Case 2: BS + ST (Base Scenario with a Solar Thermal system)
C3	Case 3: BS + PV (Base Scenario with a Photovoltaic system)
C4	Case 4: BS + ST + PV (Base Scenario with Solar Thermal and Photovoltaic systems)
C5	Case 5: RS + ST (Renovated Scenario with a Solar Thermal system)
C6	Case 6: RS + ST + PV (Renovated Scenario with Solar Thermal and Photovoltaic systems)
C7	Case 7: NS + ST (New Scenario with a Solar Thermal system)
C8	Case8: NS + ST + PV (New Scenario with Solar Thermal and Photovoltaic systems)
CO_2eq	Carbon Dioxide Equivalent
COOL	Cooling
Csa	Hot dry-summer (Mediterranean) climate (Köppen-Geiger climate classification)
Csb	Cool dry-summer (Mediterranean) climate (Köppen-Geiger climate classification)
CTE	(Spanish) Technical Building Code (Royal Decree 384/2006)
CTE HE-19	(Spanish) Technical Building Code (Royal Decree 732/2019)
CZ	Climate Zone
D	Bedroom
DHW	Domestic Hot Water
E_F	Thickness of Thermal Insulation of the Floor in contact with the Outside
E_G	Thickness of Thermal Insulation of the Floor in contact with the Ground
E_R	Thickness of Thermal Insulation of the Roof in contact with the Outside
E_W	Thickness of Thermal Insulation of the Wall in contact with the Outside
EC JRC	European Commission Joint Research Centre
EEA	European Environment Agency
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EU	European Union
Eurostat	Statistical Office of the European Union
F	Floor (in contact with the Outside)
G	Floor (in contact with the Ground)
GHG	Greenhouse Gas
GIS	Geographic Information System
GWP	Global Warming Potential
HEAT	Heating
IDW	Inverse Distance Weighted
INE	(Spanish) National Statistics Institute
IRR	Internal Rate of Return
K	Kitchen
K_G	Global Heat Transfer Coefficient (for the NBE CT-79)
K_L	Limit Heat Transfer Coefficient (for the CTE HE-19)
L	Living-dining room
λ_{Fi}	Thermal Conductivity of the Floor ith Layer Material in contact with the Outside
λ_{Gi}	Thermal Conductivity of the Floor ith Layer Material in contact with the Ground
λ_{Ri}	Thermal Conductivity of the Roof ith Layer Material in contact with the Outside
λ_{Wi}	Thermal Conductivity of the Wall ith Layer Material in contact with the Outside
LOE	(Spanish) Building Act (Law 38/1999)
MITECO	(Spanish) Ministry for Ecological Transition and Demographic Challenge
NBE CT-79	(Spanish) Basic Building Standard on Thermal Conditions in buildings
NRPE	Non-Renewable Primary Energy
NS	New Scenario (house with thermal envelope complying with CTE HE-2019)
nZEB	nearly Zero-Energy Building
O	Openings (Doors and Windows)
PV	Photovoltaic system
PVGIS	European Photovoltaic Geographical Information System
R	Transitable Roof (in contact with the Outside)
R_{Fi}	Thermal Resistance of the Floor ith Layer Material in contact with the Outside
R_{Gi}	Thermal Resistance of the Floor ith Layer Material in contact with the Ground
R_{Ri}	Thermal Resistance of the Roof ith Layer Material in contact with the Outside
R_{Wi}	Thermal Resistance of the Wall ith Layer Material in contact with the Outside
RD	(Spanish) Royal Decree
REE	Spanish Electricity Network
RES	Renewable Energy Sources
RS	Renovated Scenario (house with thermal envelope renovated to meet the CTE HE-2019)
S	Storeroom
S_F	Area of the Floor in contact with the Outside
S_G	Area of the Floor in contact with the Ground
S_R	Area of the Roof in contact with the Outside
S_W	Area of the Wall in contact with the Outside
ST	Solar-Thermal system
SiAR	(Spanish) Agroclimatic Information System for Irrigation
T	Terrace
TMY	Typical Meteorological Year
TPE	Total Primary Energy
U_F	Thermal Transmittance of the Floor in contact with the Outside
U_G	Thermal Transmittance of the Floor in contact with the Ground
U_O	Thermal Transmittance of Openings
U_R	Thermal Transmittance of the Roof in contact with the Outside
U_W	Thermal Transmittance of the Wall in contact with the Outside
V	Volume (storage tank)
W	Wall (in contact with the Outside)
Y	Front Yard

homes built in Andalusia and Spain fell by 86% as a result of the crisis after the economic bubble [69]. This decline was similar to the one suffered in the rest of southern Europe in countries such as Greece (85%) and Portugal (81%). But it remained above the average decline in the EU (54%), where there was neither so much expansion during the bubble nor so much contraction during the subsequent crisis.

Regardless of the type of housing, 70% of the European population currently live in urban areas, with this figure expected to reach 84% by 2050 [57]. In Europe, this urban development has led to a paradigm shift in the 21st century [19], with clean energy sources gaining importance, and consumer participation becoming increasingly active. Nevertheless, this has not resulted in a reduction of the price of the energy, which has increased in parallel with urban development [30] and amplified the energy poverty of European [90] and Spanish [5] households.

Houses are indeed are major consumers of energy and materials, as well as major producers of environmental waste and emissions [63]. They consume approximately 40% of the energy generated in the EU, and produce 36% of the greenhouse gas (GHG) emissions. This means they are the single largest energy consumers in Europe [23]. As a result, the EU residential building stock offers high potential for energy efficiency and GHG emissions reduction [91]. However, in this endeavor they also face the challenge of contributing to economic growth, social well-being, sustainability of non-renewable resources and preservation of the natural environment [18]. Hence, besides intervening high energy prices and low wages (beyond the scope of this research), the construction quality of existing buildings with high energy consumption must be improved.

The Energy Performance of Buildings Directives (EPBDs) are aimed at ensuring compliance with the objectives of the EU regarding GHG emissions, energy consumption, energy efficiency and energy generation from renewable sources in buildings. EPBD 2002/91/EC [24] establishes energy use requirements in new buildings and those existing buildings undergoing renovation works. With this end, the EPBD introduces the buildings energy performance certificate (EPC). EPBD 2010/31/EU [26] specifies that by the end of 2020, all new buildings should be nearly zero-energy buildings (nZEB). EPBD 2012/27EU [27] establishes a specific obligation for Member States to develop national plans to increase the number of nZEBs. These plans should include a detailed definition of the concept of nZEB so as to reflect their national, regional or local conditions, including a numerical indicator of their primary energy use. EPBD 2018/844/EU [28] modifies the two prior directives, underlining the EU's commitment to fighting climate change and energy poverty. To do this, the EU sets these objectives: decarbonisation of the housing stock (from an energy point of view); ensuring equal access to building renovation funding, rewarding energy efficiency; and guaranteeing building quality by adopting sustainable solutions, high-efficiency alternative systems and promoting research of new solutions. For instance, Member States must promote the EU buildings energy performance improvement in order to reduce GHG emissions in the Union by 80–95% compared to 1990. This entails taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness [28]. Overall, this will ensure a highly energy efficient and decarbonized European building stock, which will hopefully facilitate a cost-effective transformation of existing buildings into nZEBs.

In Spain, many regulations have been approved seeking superior buildings energy performance and sustainability [6]. The Spanish Building Act (LOE) 38/1999 [39] required the adoption of a Technical Building Code (CTE), which was published in the Royal Decree 384/2006 [40] and came into force in 2008. The LOE finally transposed the European Directive EPBD 2002/91/EC, which implied the definitive repeal of the Basic Building Standard on Thermal Conditions in buildings (NBE CT-79) [38]. This NBE CT-79 was just limited to controlling energy demand by establishing a maximum limit on the global heat transfer coefficient (K_G) of the building.

Then, a number of Royal Decrees (RD 1371/2007, RD 238/2013) and Ministerial Orders (VIV/984/2009, FOM/1635/2013, FOM/588/2017) were passed, transposing EPBDs 2010/31/EU and 2012/27EU. Their aim mostly encompassed issuing energy certifications, regulating thermal systems, updating energy demands and limiting energy consumption. Not much later, Royal Decree 244/2019 [43] regulated the conditions of electricity for self-consumption, eliminating the so-called "sun tax" and allowing the sale of energy surplus from small-scale producers to electricity generation plants below 100 kWp. Finally, the Royal Decree 732/2019 [44] modified the Technical Building Code (CTE HE-19). The CTE HE-19 established a maximum consumption limit of the non-renewable primary energy (NRPE) and total primary energy (TPE) consumed by the building. It also focused on limiting the energy demand by limiting the buildings heat transfer coefficient (K_L). Therefore, this latest version incorporated the considerations of the EPBD 2018/844/EU directive, including the definition of nZEBs for Spain.

In short, EPBDs set sustainable EU building targets to mitigate climate change, reduce greenhouse gas (GHG) emissions, energy consumption and capitalise on the contribution of renewable energy. Particularly, by 2020, the EPBDs set these targets: 20% reduction in GHG emissions and energy consumption, and minimum contribution of 20% from renewable energy (all compared to 1990). By 2030, it establishes a 40% reduction in GHG emissions, 32.5% in energy consumption and a 32% contribution from renewable energy.

In this context, the objective of this study is to gauge the potential impact of energy (consumption), economy (savings) and environment (emissions) of recent changes in the Spanish regulatory framework. This on homes built over the last 20 years, but that are being renovated because of the transposition of energy efficiency regulations to the EPBDs. For the sake of representativity, we will analyse how these energy, economic and environmental impacts are distributed over an entire territory in the most common type of single-family house (attached houses). Namely, the energy behaviour of single-family homes built up to the standards before and after the transposition of Spanish building regulations will be compared. The analysis will be carried out with an energy simulation tool in the 785 municipalities of the Autonomous Community of Andalusia. This region is located in the south of Spain and is one of the most populated and extensive regions in the EU.

Namely, Andalusia is characterized by a mild climate in winter and dry in summer. However, this climate also experiences significant variations throughout the year. Andalusia encompasses the border between the Atlantic Ocean and the Mediterranean Sea as well as the separation between Africa and Europe. In accordance with the Köppen-Geiger climate classification [9], Andalusia has a mostly Mediterranean climate (Csa, Csb), with some minority enclaves (approximately 15%) of warm semi-arid (BSh), cold semi-arid or steppe (BSk), warm arid (BWh) and cold (BWk) climate. In addition, Andalusia has a very complex orography with an average altitude of nearly 600 m above sea level, but also

Table 1
Newly built homes inAndalusia, Spain and the EU in 2000–2019.

Decade	Andalusia			Spain			EU
	Single-Family	Total	%	Single-Family	Total	%	%
2000–2009	225,578	850,301	26.53%	1,123,224	4,604,857	24.39%	63.58%
2010–2019	44,518	117,272	37.96%	200,776	622,635	32.25%	57.63%

%: Percentage of single-family homes over total number of homes.

with an abundance of flat areas in coastal locations and the great Guadalquivir Valley. Andalusia also has high altitudes in the Baetic Mountains and Sierra Morena where conventional meteorological observation networks struggle to capture such diversity [62]. All this makes of Andalusia a very good candidate for a GIS-based analysis, as the effects of taking measurements in such a diverse range of climates enables highly representative results.

On the other hand, energy consumption in buildings is gaining interest due to its direct relationship with the energy economy and sustainable development. Space cost and optimization require a reduction in the use of materials too. However, this reduction significantly affects the building's envelope thermal inertia and may make it insufficient to effectively absorb the fluctuations of the outside temperature [60]. In Spain, one of the common features of the two regulatory frameworks (NBE CT-79 first, and CTE HE-19 later) is that they require building envelopes to be designed for limiting their heat transfer coefficient. Hence, optimizing the insulation thickness (by maximizing its contribution to the K_G or the K_L) plays an important role in reaching a compromised agreement between thermal comfort, construction cost and energy consumption. However, in locations where temperatures can be high in the Summer (such as Andalusia), energy efficiency may also be achieved by taking the surrounding environment and climate conditions into account, as well as with an intelligent use of the building's thermal inertia [49].

The use of renewable energies is also enabling the EU Member States to achieve their GHG emission reduction goals (besides reducing other environmental impacts [75]). The share of Renewable Energy Sources (RES) has risen from 11% in 2005 to 19.5% in 2017 [66]. The case of Spain stands out, though, as the share of electricity production from renewable sources reached 43.66% in 2020 [82], whereas carbon dioxide equivalent emission-free production accounted for 66.9% of the total produced. This represented the cleanest year registered. Additionally, in mainland Spain and Continental Europe, Andalusia is the region with the highest number of sunshine hours per year. This also makes of the region under study a good candidate to analyse the incorporation of renewable energies in a household. In fact, as the potential of different renewable energy sources in buildings is a hot area of research from different points of view (efficiency [34], sustainability [59], markets [10], employment [51], etc.), researchers are now paying increasing attention to the evaluation of different renewable energy sources such as hydrogen, Photovoltaic (PV), Solar Thermal (ST), wind, etc., but with a life cycle approach [48,52,61,68,70,75]. Most of these pieces of research include an economic and/or environmental analyses to determine the return of the investment [15,71]. Some research covers the performance evaluation of different renewable energy technologies [65,76]. Others focus on the energy assessment on the overall use of renewable energy sources at a wider level [33,66]. However, very few include the triple energy, environmental and economic assessment on both the incorporation of renewable energy sources and building renovation. None of them covers a wide territory with varied climate conditions either.

The energy performance of households has been analysed in most Southern European countries, such as Greece [31], Italy [83], Portugal [67], Turkey [58] and Spain. These analyses have also encompassed cold climates [64] as well as warm and mild climates [65]. These studies have frequently resorted to multifamily or single-family homes as a unit of analysis, but always for a single geographic area or climate zone (CZ). Additionally, these studies have been traditionally focused on comparing the primary energy consumption before and after transposition of the EPBD, for which they usually calculate the heating, cooling and domestic hot water (DHW) demands. These studies have also avoided a relatively thorough analysis of economic or environmental issues, as well as the use of renewable energies as alternative methods for energy generation. Most studies have also been focused on new buildings, rather than in renovation (which undoubtedly accounts for most buildings nowadays).

Yet, there are options in the renovation of existing buildings that can lead to significant energy efficiency improvements by, for example, optimizing their envelope and/or installing renewable energy systems. That is why this study will take all these aspects into account while considering a complete region characterized by mild winters and extreme summers. Eventually, this will allow us to gain a deeper understanding of the implications introduced by the new regulatory framework, as well as its implications in terms of energy, emissions and economic savings for a large number of homes with a long shelf life ahead.

To sum up, there are few new buildings under construction in Spain. However, the number of buildings between 10 and 20 years old constitutes a much larger set. These buildings still have a long remaining shelf life (at least 30 years more [14]) and most of these buildings are residential homes. This makes worth researching the renovation of existing buildings, rather than just improving the construction equipment of new ones [73,79,88,94]. Similarly, most previous studies have been aimed at either solving a case study with a relatively narrow representativity (single location [81,93], single typology [16,77], single technology [35,36], etc.) or at analysing future technological developments that are not yet available on the market [2,50].

Hence, moving forward, our analysis will be carried out with three different sources of climate data to ensure representativeness of our spatial and time results: (a) official climate data from the corresponding climate zones and/or provinces provided by the Ministry for Ecological Transition and Demographic Challenge (Environment Ministry) (MITECO) [45]; (b) with the actual data for the period 2010–2019 extracted from the weather stations closest to each locality of the Agroclimatic Information System for Irrigation (SiAR) [41]; and (c) with satellite data from the European Photovoltaic Geographical Information System (PVGIS) [53] from the latest typical meteorological year (TMY) available (calculated from the 2007–2016 period). This triple process will also be performed to assess the degree of simplification that MITECO assumes when studying the climate of different Spanish locations depending on the province and/or climate zone in which they are located. Namely, we will observe how results may greatly differ according to different climate sources, which may cause a number of errors in the construction solutions adopted (alternatives that are actually not suitable for some places because of a climate zone misspecification [84]). That is why this research will compare the results obtained with MITECO climate data with those provided from SiAR stations and PVGIS. Hence, this study will prove useful to construction professionals (architects, engineers, builders, developers and legislators) to quantify the real impact of building renovation works performed after the Spanish regulatory changes on energy, economic and emissions savings, taking into account the entire life cycle of the residential building.

2. Material and methods

To quantify the impact of regulatory changes in Andalusia to align with nZEB EPBDs, the energy behaviour and emissions of houses built before the CTE regulation have been compared with the behaviour and emissions of a house built after the current regulatory framework, i.e. after the EPBDs were transposed. This comparison has been made considering three scenarios: house built in 2000–2009 under the pre-CTE regulatory framework (base scenario: BS); house built in 2000–2009 but renovated in 2020 under the current regulatory framework (renovated scenario: RS); and house built in 2000–2009 under the current regulatory framework conditions (new scenario: NS). Additionally, two renewable energy sources (Solar Thermal ST, and Photovoltaic PV) are considered in some cases. It is noted that the final configuration adopted for RS and NS is the same. Hence, from an energy point of view there are no differences between these two scenarios. However, both the economic investment and the emissions are not the same, given the greater effort used in transforming the BS into RS (instead of departing directly from the NS). These variable combinations result in the following eight case studies:

C1 House built in 2000–2009 with thermal envelope complying the K_G from NBE CT-79 (BS).
C2 House built in 2000–2009 with thermal envelope complying with the K_G from NBE CT-79 to which a solar-thermal system has been incorporated (BS + ST) in 2020.
C3 House built in 2000–2009 with thermal envelope complying with the K_G from NBE CT-79 to which a photovoltaic system has been incorporated (BS + PV) in 2020.
C4 House built in 2000–2009 with thermal envelope complying with the K_G from NBE CT-79 to which solar-thermal and photovoltaic systems have been incorporated (BS + ST + PV) in 2020.
C5 House built in 2000–2009 with thermal envelope complying with the K_G from NBE CT-79, renovated in 2020 to meet the K_L from CTE HE-2019, to which a solar-thermal system has been incorporated (RS + ST).
C6 House built in 2000–2009 with thermal envelope complying with the K_G from NBE CT-79, renovated in 2020 to meet the K_L from CTE HE-2019, to which solar-thermal and photovoltaic systems have been incorporated (RS + ST + PV) in 2020.
C7 House built in 2000–2009 with thermal envelope complying with the K_L from CTE HE-2019 to which a solar-thermal system has been incorporated (NS + ST) in 2020.
C8 House built in 2000–2009 with thermal envelope complying with the K_L from CTE HE-2019 to which solar-thermal and photovoltaic systems have been incorporated (NS + ST + PV) in 2020.

Once the case studies are defined, it is necessary to assume some simplification steps so that the total number of analysed scenarios in different locations does not skyrocket. This process consists of the following steps (to be further developed in the following subsections):

1. Description of the house. A medium-sized single-family attached house is chosen for the study. This type of house is chosen for its average compactness [1] and for being an emerging type in Andalusia [78] (already a majority in the rest of the EU), as justified earlier in Table 1.
2. Definition of the thermal envelope characteristics. For the sake of clarity, the construction details of this house are quite conventional and frequently found in Andalusia over the last 20 years. Therefore, the same house characteristics are adopted for the 3 scenarios (BS, RS and NS). The main variables to be considered in the building envelope are the thermal transmittances of the building elements. If the construction configuration is the same, the thickness of the thermal insulation and the configuration of doors and windows (frames and glazing) become the variables. This allows to the definition of the minimum thickness of the thermal insulation layer(s) of the envelope, and the choice of appropriate glazing, depending on the climatic zones (established by the NBE-CT-79 or the CTE-DB-HE-19).
3. Characterization and sizing of renewable energy systems (ST and/or PV) if included. This configuration remains the same for all locations analysed and all climate data.
4. Construction, economic and environmental study of the thermal envelope complying with the NBE CT-79, and the thermal envelope complying with the CTE HE-19. It also encompasses the operations required for the former envelope to be transformed into the latter, as well as those of the renewable energy systems included (ST, PV).
5. Generation of climate data for each location: from the information provided by MITECO (provincial data with height difference correction for each town); extracted from the SiAR stations (taken from the weather station closest to each town); or from data supplied by PVGIS (for each town, depending on its latitude and longitude).
6. Energy simulation of all possible combinations (2 definitions of the thermal envelope (1 for BS, 1 for RS/NS), 2 orientations (north for heating demands (HEAT), and west for cooling (COOL) [7]), 2 renewable energy systems (ST, PV), 785 locations, and 3 climate databases.
7. Energy, emissions and economic assessment of the 6280 case studies (8 scenarios in 785 locations with 3 climate datasets). This evaluation will allow checking which of the 2 requirements of the new regulatory framework is more restrictive for building renovation (limitation of the primary energy or the K_L).
8. Representation of the evaluated data by means of a geographic information system (GIS). These will show the average energy consumption, carbon dioxide emissions and energy costs over the remaining 30 years of shelf life of most houses under study (also considering the initial emissions and investments and the corresponding performance losses of each case study).

2.1. House description

An attached house with a net floor area of 120 m^2 (gross floor area of 150 m^2) is chosen for the study. It consists of 2 floors and another floor with access to a terrace (T). The house also has a front yard (Y) and a backyard (C). As shown in Fig. 1, there are 4 bedrooms (D), 3 bathrooms (B), a living-dining room (L), a kitchen (K) with storeroom (S), and a roof (T) on which the renewable energy systems (ST and/or PV) can be located. The house has a volume of 300 m^3 enclosed by an envelope of 215 m^2, the breakdown of which can be seen in Table 2. The house has a form factor (envelope/volume) of 0.7 and a compactness (volume/envelope) of 1.4. For single-family homes, average compactness values range from 0.8 to 2.2 [21]. Hence, this house can be considered an average compact case [1].

2.2. Definition of the thermal envelope

Before continuing, it is necessary to highlight two particular facts that occurred in Spain since the LOE legislation came into force. First, residential projects have to be signed by architects and approved by the Professional Association of Architects. This as a prerequisite for applying for municipal building construction permit applications. Second, it is mandatory to complete a survey on the typology, layout, areas and construction qualities of the building before construction. This information is sent by these Professional associations to the corresponding Ministry. Therefore, a statistical database to verify the most commonly used building typologies and constructive solutions is available [42]. These sources have provided information for several European research projects, such as EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimization of Refurbishment Processes in European Housing Stocks), which can be visited in https://episcope.eu/, and OERCO2 (Online Educational Resource for Innovative Study of Construction Materials Life Cycle), which can be visited in https://oerco2.eu/, among others.

Housing envelopes under the NBE CT-79 or CTE HE-19 regulatory frameworks are thermally designed so that their global heat transfer coefficient (K_G for the NBE CT-79) or limit coefficient (K_L for the CTE HE-19) are not higher than those indicated by these regulations (considering their corresponding climate zones (CZ) classified in five zones by both regulations: A, B, C, D, E). The global or limit heat transfer coefficients of a building are weighted averages (by surface areas) of the transmittances of the elements that make up its envelope. Nevertheless, it should be noted that the CZ vary for the same location from one regulation to another, with fifteen possible combinations occurring in Andalusia (first letter from the NBE CT-79 and the second letter from the CTE HE-19 classification): A-A, A-B and A-C, B-A, B–B and B–C, C-A, C–B, C–C and C-D, D-C, D-D and D-E, E-D and E-E. As the house under study is designed so that the same construction solutions are used, the only elements that change from one regulation to another (BS for NBE CT-79 or RS/NS for CTE HE-19) are the type of glazing and the thickness of the thermal insulation.

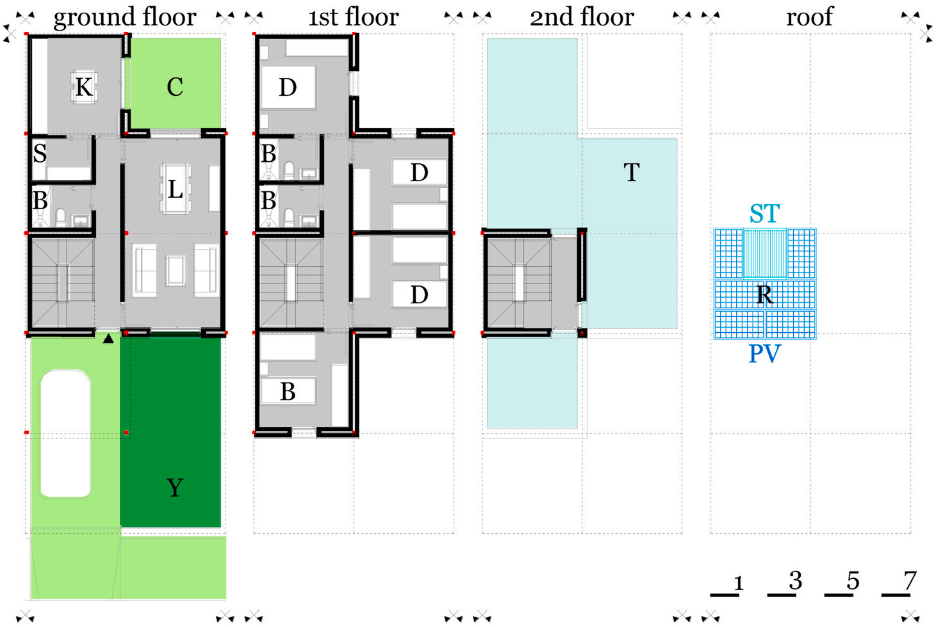

Fig. 1. Description of the house.

Table 2
Areas of the thermal envelope.

Code	Thermal envelope	Exchange Area
S_W	W: Wall in contact with the Outside	70
S_F	F: Floor in contact with the Outside	10
S_R	R: Roof in contact with the Outside	60
S_G	G: Floor in contact with the Ground	50
S_O	O: Openings (Doors and Windows)	25

Areas in m^2.

Regarding the openings in the envelope (doors and windows), the maximum transfer allowed by the CTE HE-19 (U_O) is taken for both envelope definitions. This because there is no limitation in the NBE CT-79 regulation. However, it is also necessary to check whether the openings are significant in single-family residential buildings built over the last twenty years in Spain. This because the aim of this study is to work with representative information of the Andalusian housing stock. With this intention, the characteristics of the envelope openings is presented in Table 3. If the Spanish Building Construction Statistics [42] are examined, the use of PVC frames as opposed to aluminium (with thermal break) or wood frames was intensified, especially in these building typologies. On the other hand, the use of glazing with air chambers was quite common (all this is discussed in more detail in Ref. [32], a piece of research within the European project EPISCOPE. Namely, 1980–2006 single-family homes and 2006-Present homes can be checked). With this information, it is possible to focus on the opaque elements exclusively.

Table 3
Thermal characterization of openings (O: Windows and Doors).

CZ CTE HE-19	Glass-Air Chamber-Glass (Thickness)	Frame	Solar Control	U_O
A	4-6-4	3-Chamber PVC	–	2.7
B	4-12-4	3-Chamber PVC	–	2.3
C	4-6-4	3-Chamber PVC	Low Emissive ($\varepsilon \leq 0,03$)	2.1
D, E	4-12-4	3-Chamber PVC	Low Emissive ($\varepsilon \leq 0,03$)	1.8

Thickness of Glazing in mm, Transmittance (U_O) in $W/m^2{\cdot}K$.

Hence, as the constructive configurations are the same, we will exclusively concentrate our analyses on the building's thermal insulation.

The opaque elements that make up this thermal envelope: walls in contact with the outside, floors in contact with the outside, roofs in contact with the outside and floors in contact with the ground (W, F, R, G) are characterized by their thermal transmittances (U_W, U_F, U_R, U_G), which are calculated according to the guidelines provided by the NBE CT-79 and the CTE HE-19. Moreover, in the case of houses under the CTE HE-19 regulation, it is necessary to consider thermal bridges, which are calculated based on the equivalent linear thermal conductivity [55]. Tables A1–A4 included in the Appendix summarize the characteristics of the envelope's opaque components for both housing configurations (BS, RS/NS). For the construction definition of these elements, the price and environmental impact generator from the CYPE Engineers' Archimedes budget project management program, version 2021.d [17] was used. This facilitated the construction elements traceability (alphanumeric codes used by this piece of software for all elements are kept).

Tables 4 and 5 show, for each climate zone CZ, the configuration of the envelope in the base scenario (BS) complying with the requirements of NBE CT-79, and the renovation and new construction scenarios (RS, NS) complying with CTE HE-19. The thermal transmittances of the envelope's opaque elements (U_W, U_F, U_R, U_G) are calculated as the inverse of their thermal resistances ($U = 1/R$). These resistances are calculated as the sum of the resistances of all its layers (i). The resistance of the ith layer is the product of the layer thickness (E_i) and the thermal conductivity of the layer material (λ_i). As the constructive solutions are the same, the thickness of the thermal insulation layer is a variable. The insulation thickness is worked out for each type of envelope so that (meeting the maximum limits of U_W, U_F, U_R, K_G for NBE CT-79 or of U_W, U_F, U_G, U_O, K_L for CTE HE-19) it minimizes the volume of insulation material. By doing so, compliance with all design parameters is ensured, minimizing costs and emissions by minimizing the amount of insulation used. To this end nominal thickness increments of 5-mm is used in the calculations.

Fig. 2 shows the minimum weighted average thickness (by surface area of the elements of the envelope: W, F, R, G) required by each regulatory framework. This legislative adaptation produces a significant increase in the insulation thickness of the different opaque elements of the envelope. Namely, the envelope insulation increases from an average of 12 mm (between 1 and 29) to 35 mm (between 38 and 91). It

Table 4
Configuration of the envelope by climate zone in accordance with NBE CT-79.

CZ	Regulatory Compliance (NBE CT-79)						Envelope Configuration (BS)					
	K_G max	U_W max	U_F max	U_R max	U_G max	U_O max	K_G	E_W1	E_F1	E_R1	E_G1	U_O
A_W[a]	1.518	1.8	1.0	1.4	–	–	1.279	0	15	0	0	2.7
A_W-A_X[b]	1.518	1.8–1.6	1.0–0.9	1.4–1.2	–	–	1.232	0	15	0	0	2.3
A_W-A_X-A_Y[c]	1.518	1.8-1.6-1.4	1.0-0.9-0.8	1.41.2-0.9	–	–	1.209	0	15	0	0	2.1
B_W[a]	0.998	1.8	1.0	1.4	–	–	0.986	5	30	5	5	2.7
B_W-B_X[b]	0.998	1.8–1.6	1.0–0.9	1.4–1.2	–	–	0.981	5	20	5	0	2.3
B_W-B_X-B_Y[c]	0.998	1.8-1.6-1.4	1.0-0.9-0.8	1.4-1.2-0.9	–	–	0.951	5	20	0	5	2.1
C_W[a]	0.737	1.8	1.0	1.4	–	–	0.732	20	40	20	10	2.7
C_W-C_X[b]	0.737	1.8–1.6	1.0–0.9	1.4–1.2	–	–	0.699	15	40	20	15	2.3
C_W-C_X-C_Y[c]	0.737	1.8-1.6-1.4	1.0-0.9-0.8	1.4-1.2-0.9	–	–	0.692	15	40	15	15	2.1
C_W-C_X-C_Y[d]	0.737	1.8-1.6-1.4	1.0-0.9-0.8	1.4-1.2-0.9	–	–	0.686	15	25	15	10	1.8
D_W[c]	0.651	1.8	1.0	1.4	–	–	0.647	20	45	25	10	2.1
D_X[d]	0.651	1.4	0.8	0.9	–	–	0.592	20	45	25	15	1.8
E_X-E_Y[d]	0.564	1.8-1.6-1.4	1.0-0.9-0.8	1.4-1.2-0.9	–	–	0.563	30	50	35	15	1.8

Thickness of Insulation (E) in mm, Transmittance (U) in W/m^2·K.

[a] Municipalities in CZ A (CTE HE-19).

[b] Municipalities in CZ B (CTE HE-19).

[c] Municipalities in CZ C (CTE HE-19).

[d] Municipalities in CZ D or E (CTE HE-19).

Table 5
Configuration of the envelope by climate zone in accordance with CTE HE-19.

CZ	Regulatory Compliance (CTE HE-19)						Envelope Configuration (RS, NS)					
	K_L max	U_W max	U_F max	U_R max	U_G max	U_O max	K_L	E_W2	E_F2	E_R2	E_G2	U_O
A_3-A_4	0.623	0.70	0.50	0.70	0.80	2.7	0.622	65	55	70	25	2.7
B_3–B_4	0.602	0.56	0.44	0.56	0.75	2.3	0.601	60	55	65	25	2.3
C_2–C_3–C_4	0.552	0.49	0.40	0.49	0.70	2.1	0.551	70	65	75	30	2.1
D_2-D_3	0.502	0.41	0.35	0.41	0.65	1.8	0.501	80	70	85	40	1.8
E_1	0.452	0.37	0.33	0.37	0.59	1.8	0.451	100	100	100	65	1.8

Thickness of Insulation (E) in mm, Transmittance (U) in W/m2·K.

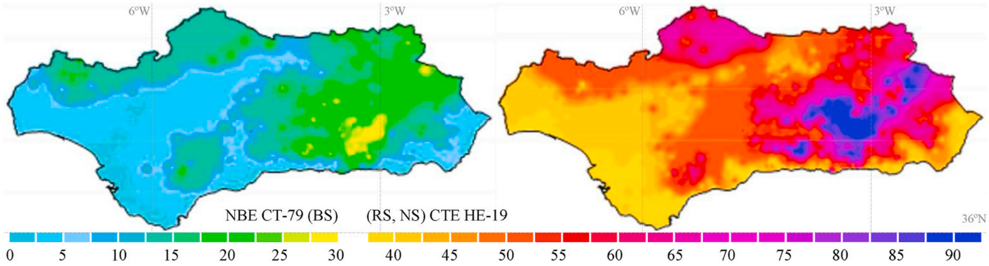

Fig. 2. Average thicknesses of insulation for each envelope configuration (BS, RS, NS) in mm.

must be highlighted, though, that these thicknesses do not depend on the climate database used, but on the CZ allocated to each town by the corresponding standard.

2.3. Characteristics of renewable energy systems

Two renewable energy sources have been selected for the study. On the one hand, a solar thermal (ST) system is fitted so that approximately 75% of the demand for DHW can be covered. This system uses a 10-pipe evacuated tube collector, with an area of 2 m^2, an optical efficiency of 93% and an overall loss coefficient of 1.06 W/m^2/K. This type of renewable energy partially covers the demand of DHW (at least 60%) and is mandatory under the regulatory framework of the first CTE for all new buildings or renovations of existing buildings. A DHW flow rate of 140 l/d (5 occupants at a rate of 28 l/d per person) is considered, so an accumulation volume of 150 l can be used. Spanish CTE establishes limits for the ratio of the accumulation volume divided by the solar collector area (V/A). According to this, this parameter for DHW must be located between 50 and 180 L per square meter. In this study, this ratio is 75 l/m^2 (150/2).

On the other hand, a PV system of 2.4 kWp is installed so that nearly 100% of the domestic electricity demand can be covered. This system boasts 6 monocrystalline cell modules with an area of 2 m^2, a nominal power of 400 W, a nominal operating cell temperature (NOCT) of 47 °C, and a temperature degradation coefficient of 0.36%/°C. This type of renewable energy is not mandatory for residential buildings even in the latest version of the CTE. Additionally, prior to the RD 244/2019, the surpluses produced by domestic facilities could not be fed into the national electric grid. This made the optimal size of a Spanish domestic PV installation to be lower than other countries such as France, despite its higher generation potential [4]. However, the RD 244/2019 already allows surpluses to be sold, making the entire production available for use.

As the bigger latitude difference between the southernmost and northernmost locations of Andalusia is only 2.5°, it was decided to set a single installation angle for the ST collector and PV panels in all study locations. The chosen tilt angle was 37.25°.

2.4. Economic and environmental study of the thermal envelope and renewable energy systems

Both the improvement of the envelope and the incorporation of the renewable energy systems (ST mandatory for both renovation and new construction buildings, and PV which is optional for residential buildings) generate an economic and environmental impact. In accordance with regulations used prior to the CTE coming into force (such as Eurocode ENV 1991-1, NBE EA-95 and NBE EHE-98) applicable to homes built in the years 2000–2009, a residential building must have a minimum lifespan of fifty years. This means that the lifespan of houses built in years 2000–2009 should last until year 2050, at the very least. However, the lifespan (shelf life) value established by these standards depends on a number of variables, such as type of environmental exposure, type of cement or steel, characteristic strength, envelope's layer/s thickness, paint condition, etc. Therefore, assuming the building is used and maintained correctly (as envisaged by international standard ISO 15686-2012), these houses' lifespan could last even up to 75 or 100 years [54].

In terms of environmental impact, a life cycle analysis is carried out on the construction work items needed to transform the BS configuration into the RS or NS configurations (incorporating the ST and PV systems depending on each case). This is done by calculating the global warming potential (GWP) and measuring carbon dioxide emissions from these interventions, as summarized in Table 6 (emissions in kg CO_2eq/m^2 are referring to the CYPE Arquimedes 2021.d. LCA database. The first term of each definition corresponds to the CZ in accordance with NTE CT-79 and the second to the CZ in accordance with CTE DB-HE-2019). In economic terms, construction unit prices include the following indirect costs: waste management (WM), health and safety (HS), overheads (OH), industrial profits (IP), technical fees (TF), municipal licenses (construction tax and urban taxes: CT + UT) and indirect taxes (VAT). These costs are also summarized in Table 6 for each case study (prices in €/m^2 are referring to the CYPE Arquimedes 2021.d. LCA database. The first term of each definition corresponds to the CZ in accordance with NTE CT-79 and the second to the CZ in accordance with CTE DB-HE-2019). All emissions and upfront costs must be offset by a decrease in energy consumption for the rest of the building's lifespan. This leads to lower greenhouse gas emissions, as well as reducing energy bills (electricity and natural gas), even offsetting the electricity surplus, in accordance with the RD 244/2019.

2.5. Climate data

The MITECO provides data on the reference climates of all existing climate zones in Spain depending on winter or summer weather severity (α_1, α_2, α_3 and α_4 for the Canary Islands; and A_1, A_2, A_3, A_4, B_1, B_2, B_3, B_4, C_1, C_2, C_3, C_4, D_1, D_2, D_3 and E_1 for the whole country). These reference climates defined in the CTE allow for the standardization of external applications that require climate information to define a series of climate parameters that are representative of a specific zone in Spain. In this case, it will help us to calculate the energy consumption limits and conditions for the control of energy demand. Where a location is not exactly one of the 52 reference locations (50 province capitals, of which 8 are from Andalusia, and 2 autonomous cities), the CTE proposes a simplified method for calculating the CZ for each location by interpolation. This interpolation uses the distance from the closest province capital to which that place belongs. This distance is corrected due to the North-South difference (latitude), the difference in altitude, and proximity to the sea.

During the years 1998–2001, under the INTERREG II-C Community Initiative, the Ministry of Agriculture, Fisheries and Food ran a project in Spain (except in the communities of Asturias, Cantabria, Catalonia, La Rioja and the Basque Country), consisting of the installation of an Agroclimatic Irrigation Information System (SiAR). SiAR was aimed at providing basic climate information to calculate irrigation needs and improve water efficiency use. It still is an infrastructure that captures, records and transmits data necessary for the calculation of water demand: air temperature and humidity, wind speed and direction, solar radiation and precipitation. Currently, there are 101 active stations in Andalusia. We chose the closest weather station to each town for our analyses. As a result, 93 different stations were selected in the end at an average distance of 15 km (between 1 and 54 km). Once selected, the typical meteorological year (TMY) was calculated for each station using data from 2010 to 2019. With the seasonal data, the temperature was corrected according to the difference in altitude between the station and the town, in a similar way to the MITECO approach.

The PVGIS database comes from a project developed in 2001 by the publicly accessible European Commission Joint Research Centre (EC JRC). PVGIS was designed to allow the user to calculate photovoltaic electricity production anywhere in Europe, among other ends. From the PVGIS tool, monthly, daily or hourly weather data can be extracted from a set of coordinates (longitude and latitude), as well as a TMY. PVGIS obtains this data by interpolation [74], based on solar radiation data obtained by satellite, solar irradiation measured in Europe's network of weather stations, turbidity and digital elevation. This eventually provides all climate values which are necessary for the generation of a TMY [47]. This study used 785 TMYs for the period 2007–2016 (the most recent available data) corresponding to the geographical location of each town in Andalusia.

2.6. Energy simulation

The simulations carried out for the energy assessment of the house were carried out using the TRNSYS tool 17 [86]. This tool allows the simulation of dynamic thermal systems (Types) and can be used to assess the thermal behaviour of buildings and their associated systems [8]. To perform these simulations, the weather data from each town was used (extracted from the databases described earlier: MITECO, SiAR and PVGIS). The simulation time was of one year at hourly intervals. Simulations require the geometric, construction and operational definition of the building, as well as the systems involved. The TRNSYS model is explained along with the Types of components used for each model element, including the building. A basic scheme of the developed

Table 6

Initial interventions in the case-study house according to CZ (BS to RS, BS to NS, ST, PV).

Emissions	**A-A**	**A-B**	**A-C**	**B-A**	**B–B**	**B–C**	**C-A**	**C–B**	**C–C**	**C-D**	**D-C**	**D-D**	**D-E**	**E-D**	**E-E**
BS to RS	19.11	18.45	19.78	18.45	17.78	19.11	16.44	16.44	17.78	19.11	17.11	18.45	21.12	17.11	19.78
BS to NS	8.68	8.02	9.35	8.02	7.35	8.68	6.01	6.01	7.35	8.68	6.68	8.02	10.69	6.68	9.35
ST	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
PV	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67	22.67
Investments	**A-A**	**A-B**	**A-C**	**B-A**	**B–B**	**B–C**	**C-A**	**C–B**	**C–C**	**C-D**	**D-C**	**D-D**	**D-E**	**E-D**	**E-E**
BS to RS	51.45	51.95	52.54	52.76	49.99	51.83	47.90	47.31	49.34	51.78	48.61	50.26	54.44	48.88	52.97
BS to NS	19.68	20.18	20.76	20.98	18.21	20.06	16.13	15.53	17.56	20.00	16.83	18.49	22.66	17.10	21.20
ST	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90	26.90
PV	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08	23.08

TRNSYS model is described in Fig. 3.

2.6.1. Solar thermal system

The ST system is responsible for satisfying the DHW needs, which were calculated according to the Annex F of the CTE HE-19. A linear loss of performance of this system over the years was also considered in accordance with the data fact sheets of the equipment described earlier. The ST system consists of the following elements:

- Solar thermal collector. Type 71 was used for simulating the 10-pipe evacuated tube collector, which is connected to the data reader Type 9 containing the meteorological data and Type 16 providing the total solar radiation on the collector from total horizontal and horizontal diffuse radiation. Total horizontal and horizontal diffuse radiation are included in Type 9c along with the other meteorological data.
- DHW tank. Type 4 was used, with six levels of stratification and without auxiliary heating elements.
- Controller and pump. Type 2 was used for controlling the pump activation (Type 3). Pump is turned on/off by a control signal depending on the solar collectors output temperature and those from the tank.
- DHW auxiliary boiler. Calculator was used for modelling a natural gas boiler of unlimited capacity which can raise the user-supplied water temperature to a set-point value of 60 °C, assuming an efficiency of 92%.
- Other elements. Type 9 was also used to supply the network water temperature and the profile of DHW consumption. Data about network water temperature are available in the Annex G of the CTE HE-19. Daily DHW consumption profile was generated according to the Annex D of the CTE HE-19, which is summarized in Table A5 and included in the Appendix. One tempering valve or diverter, and one tee piece (Type 11) were also used to complete the system.

2.6.2. Photovoltaic system

The PV system provides electricity to the building cooling unit. If electricity from PV system exceeds the electric consumption of the cooling unit, this surplus can be used for other appliance or be sold. Monocrystalline cell modules were modelled by using Type 94, which were connected to Type 9 and 16 containing the required meteorological data. Type 175 was used for the inverter. PV installation was connected to the building cooling unit. A calculator was used for obtaining the balance between the electricity required for the cooling unit and that produced by the PV installation, so the available electricity surplus could be calculated. A linear loss of performance of this system over the years was also taken into account. Again, this performance loss was estimated in accordance with the data sheets of the equipment used and by means of another calculator.

2.6.3. Heating and cooling systems

Heating and cooling systems are responsible for satisfying the building temperature conditioning:

- Heating boiler: As for the DHW, a calculator was used for modelling a natural gas boiler of unlimited capacity with an efficiency of 92% for heating demand.
- Cooling unit: A calculator was used for modelling an air-conditioning system of unlimited capacity and a performance of 2.6 for cooling demand.

2.6.4. Building

Type 56 was used for modelling the energy performance of the building. This type is available in the TRNSYS standard library and is used by most researchers in multi-zone building simulations [3]. A detailed description of the model can be found at [87]. Further to the Annex D of the CTE HE-19, the set-point temperature was assumed to be 20 °C during the day from 08:00 to 23:00 and declining at night to 17 °C in winter time (from January to May and from October to December). In summer time (from June to September), the set-point temperature was assumed to be 25 °C during the day and 27 °C at night. Concerning internal gains (occupancy, lighting and appliances), the hourly profiles summarized in Table A6 (included in the Appendix) were assumed, according to Annex D of the CTE HE-19 in all simulated cases. These profiles are the same used for issuing the buildings energy performance certificate (EPC) in Spain.

On the other hand, according to Annex C of the CTE HE-19, ventilation air flow rate was assumed as 33 l/s or 0.4 ACH, except in summer time from 1:00 to 8:00 where ventilation was set to 4 ACH. Ventilation was assumed the same for all simulations as well.

In addition, because the ST collectors and PV modules shaded the building roof, the total incident radiation on the roof top surface and the heat gains through the roof, were both reduced. Similarly, the fraction of sky seen by the roof top was also reduced, with the concomitant

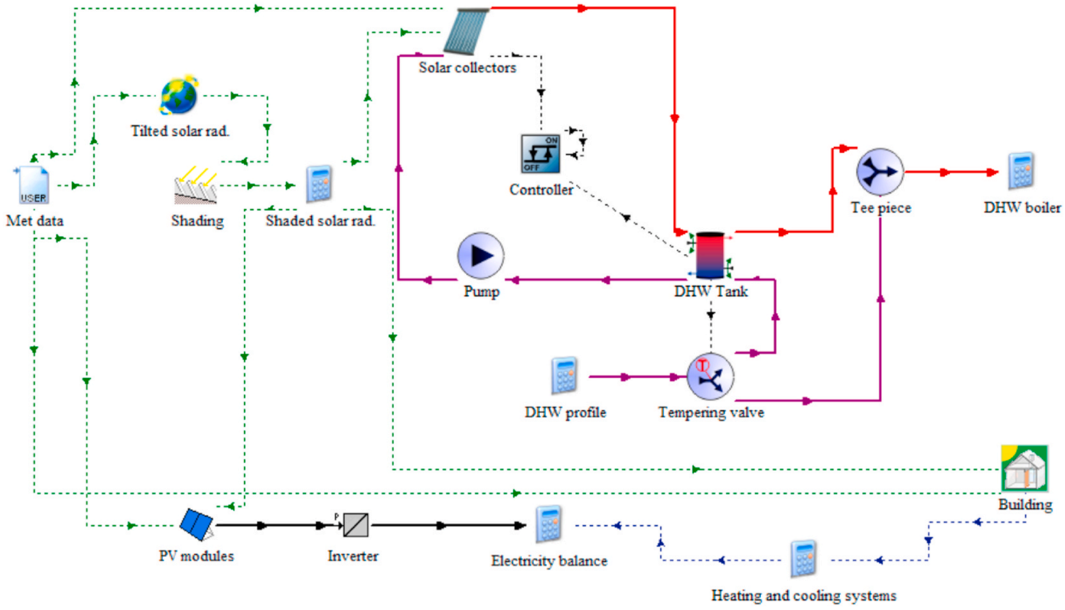

Fig. 3. TRNSYS model.

reduction of the longwave radiation heat transfer between that surface and the sky. Type 30 was used to calculate the total incident radiation upon the array of collectors and modules shading each other. However, the source code was modified in this research to include as output the fraction of the roof area between the rows of panels that were shaded from beam radiation. It also included the output of the overall view factor from the roof surface between the rows of panels to the sky, which were calculated internally by this type. They were then used in the TRNSYS model to determine the actual incident beam radiation and diffuse radiation onto the roof surface from the unshaded incident beam radiation and horizontal diffuse radiation, respectively. The sky view factor value of Type 30 was introduced roof in the "FSKY" keyword of the roof in Type 56 also, which used it as a weighting factor between the sky temperature and the back surface of the panels (assumed to be at ambient temperature) to derive the sky-roof heat transfer rate.

2.7. Energy, emissions and economic assessment

This evaluation will be shown in the following section. The results will include, among others, the energy saved thanks to the improved envelope, the energy produced by the renewable energy systems analysed, the economic savings generated by these systems over their life cycle, and the emissions avoided during their operation.

2.8. GIS representation

The results spatial representations have been obtained using the inverse distance weighted (IDW) technique of ESRI's ARCGIS version 10.6.1 [20] from the Andalusia's 785 towns. For each type of evaluation, a series of maps were elaborated considering the 8 case studies (C1: BS, C2: BS + ST, C3: BS + PV, C4: BS + ST + PV, C5: RS + ST, C6: RS + ST + PV, C7: NS + ST, C8: NS + ST + PV) and the 3 climate databases.

3. Results and discussion

Results on energy consumption, carbon dioxide equivalent (CO_2eq) emissions and economic cost for each of the case studies and climate databases are presented below. To facilitate the replicability and comparison, the majority of the data, analyses and results have all been included as Supplemental Online Material.

3.1. Impact on energy consumption

Table 7 summarizes the annual consumption of the 8 case studies and Fig. 4 includes their geographical distribution throughout Andalusia. Results show the total energy consumption over the next 30 years of building shelf life (2021–2050) divided by these 30 years in order to obtain a yearly data. The BS has an average energy consumption of between 69 and 82 kWh/m^2/year, depending on the climate database (62–77 kWh/m^2/year in natural gas and 5–8 kWh/m^2/year in electricity). If the previously defined ST system is included in the BS (C2), consumption is reduced by 20%–22% on average, to 54–66 kWh/m^2/year (47–50 kWh/m^2/year in natural gas and 5–8 kWh/m^2/year in electricity). If the defined PV system is included in the BS (C3), consumption is reduced by 31%–39% on average, to 42–57 kWh/m^2/year (consumption of 62–77 in natural gas and electricity surplus between 19 and 20). Furthermore, if both ST and PV systems are included in the BS (C4), consumption is reduced by 51%–62% on average (consumption of 47–50 in natural gas and electricity surplus between 19 and 20). Case studies (C5, C7) with the modified envelope, either rehabilitated or new building (RS, NS), include the de facto ST system, and reduce consumption compared to the BS by 51%–54% on average, to 33–38 kWh/m^2/year (23–30 in natural gas and 5–8 in electricity). If, in addition, the PV system is added to these scenarios (C6, C8), the reduction reaches between 82% and 92% on average, down to 5–13 kWh/m^2/year (consumption of 23–30 in natural gas and electricity surplus between 19 and 20).

Regarding to the heating energy demands (HEAT), north-facing

Table 7
Anual energy consumption.

MITECO	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	43.79	26.84	16.10	17.16	23.61	0.21	40.36	18.47	25.11	−8.15	51.74	18.47	25.11	−8.15	51.74
Mean	82.24	65.56	16.68	56.93	25.31	40.25	41.99	38.00	44.24	12.69	69.55	38.00	44.24	12.69	69.55
Maximum	114.14	97.36	17.35	90.53	26.63	73.75	43.59	54.75	67.84	31.14	93.97	54.75	67.84	31.14	93.97
SiAR	**C1**	**C2**	**Savings (2-1)**	C3	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	45.59	29.30	13.96	17.44	20.18	1.00	35.63	18.48	24.49	−9.63	51.22	18.48	24.49	−9.63	51.22
Mean	69.30	53.85	15.45	41.97	27.33	26.52	42.78	32.80	36.50	5.47	63.83	32.80	36.50	5.47	63.83
Maximum	104.59	89.04	16.55	77.26	30.06	61.70	45.48	49.48	61.06	23.30	88.39	49.48	61.06	23.30	88.39
PVGIS	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	42.73	26.66	12.62	14.78	22.18	−0.32	34.67	16.01	26.40	−11.62	53.37	16.01	26.40	−11.62	53.37
Mean	74.53	58.78	15.75	47.50	27.03	31.97	42.56	36.21	38.33	9.18	65.36	36.21	38.33	9.18	65.36
Maximum	127.75	111.75	16.92	100.27	28.65	84.29	45.64	67.49	61.15	40.01	87.73	67.49	61.15	40.01	87.73

Consumption in kWh/m^2/year. Life cycle from 2001 to 2050. Period included: 2021–2050.
Performance electricity systems (as energy vectors): 2.6 (for COOL). Performance natural gas systems (as energy vectors): 0.92 (for HEAT and DHW).
Performance PV: A linear decrease from 0.97 in 2021 to 0.80 in 2045 (25 years guaranteed) and 0.765 in 2050. Performance ST: 0.95 from 2021 to 2040 (20 years guaranteed) with a linear decrease to 0.50 in 2050 (assuming that after 30 years half of the vacuum tubes will fail).

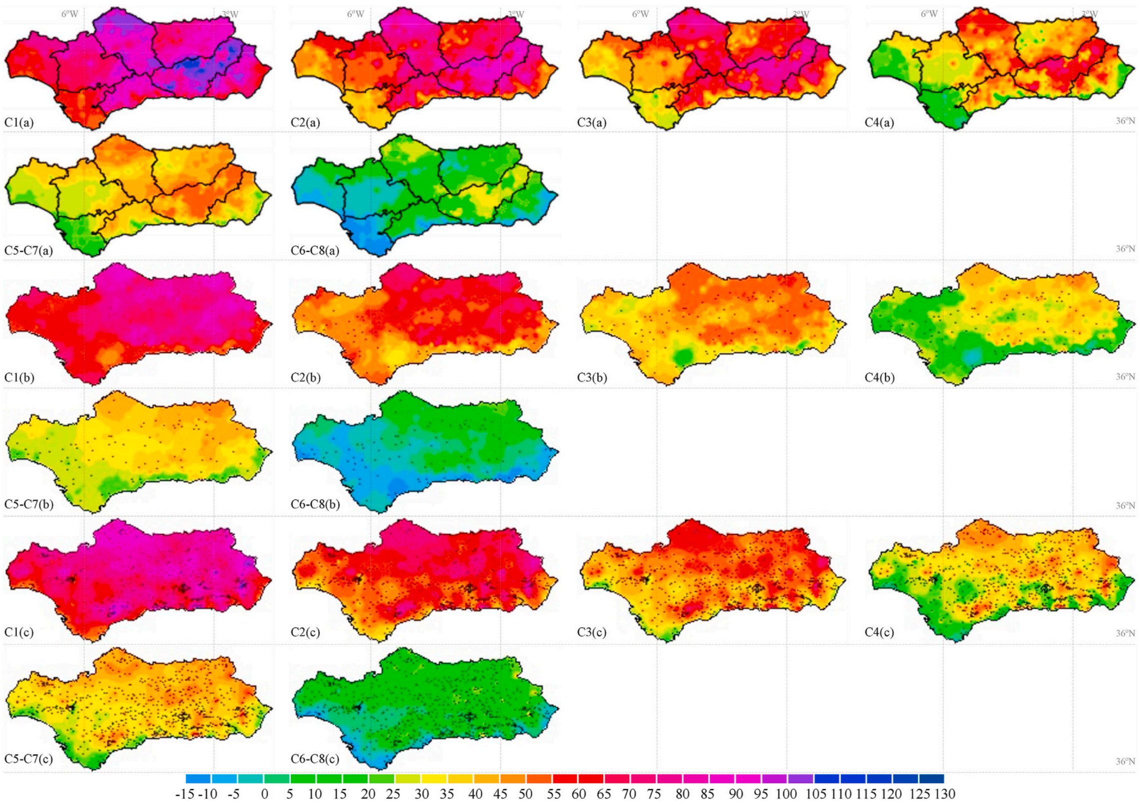

Fig. 4. Annual energy consumption by case study (Climate database: MITECO (a), SiAR (b), PVGIS (c)) in kWh/m^2/year.

houses were studied, with the configurations of the two regulatory frameworks (NBE CT-79, CTE HE-19) and the three climate databases (MITECO, SiAR, PVGIS). For the sake of clarity, Fig. 5 shows these demands by CZ, with the towns sorted by increasing altitude. In the original configuration, with the MITECO data just one location does not exceed the annual demand of 15 kWh/m^2/year. With SiAR stations, this number rises to 31 locations. With the point-to-point data from PVGIS, it rises to 9 points. However, with the configuration adapted to the current regulations, the number of locations below 15 kWh/m^2/year grows to 245 with MITECO data, to 407 with SiAR data, and to 309 with PVGIS data. In fact, average demand decreases in all towns, by 53%, 57% or 54% depending on the database, respectively. Furthermore, while the results obtained with SiAR and PVGIS differ by only 12%–16% on average, the difference between these and the results obtained with MITECO varies significantly. Namely, MITECO-derived results overestimate the other databases' results by 19–28% for original configurations and 21–34% for updated configurations. These differences increase with the winter climate (underestimating by 14% in CZ A, matching in CZ B and overestimating by 33%, 65% and 111% in CZ C, D and E, respectively).

Regarding the cooling energy demands (COOL), a similar method was followed, but with a west-facing house orientation. With the original configuration, while with the MITECO data only 293 locations exceeded the annual demand of 15 kWh/m^2/year, with SiAR stations this number rose to 519, and to 566 with PVGIS data. However, with the configuration adapted to comply with the current regulations, the number of locations below 15 kWh/m^2/year with MITECO data was maintained at 294, but grew to 554 with SiAR data, and 613 with PVGIS data. In fact, the demand increased by 368, 384 and 580 towns, respectively. On average, the situation improved by 2% and 1% with MITECO and SiAR data, respectively, but worsened by 3% with PVGIS data. Moreover, while the results obtained with SiAR and PVGIS data differed by only 5%–8% on average, the difference between these and the results from MITECO, differed significantly. Namely, the latter

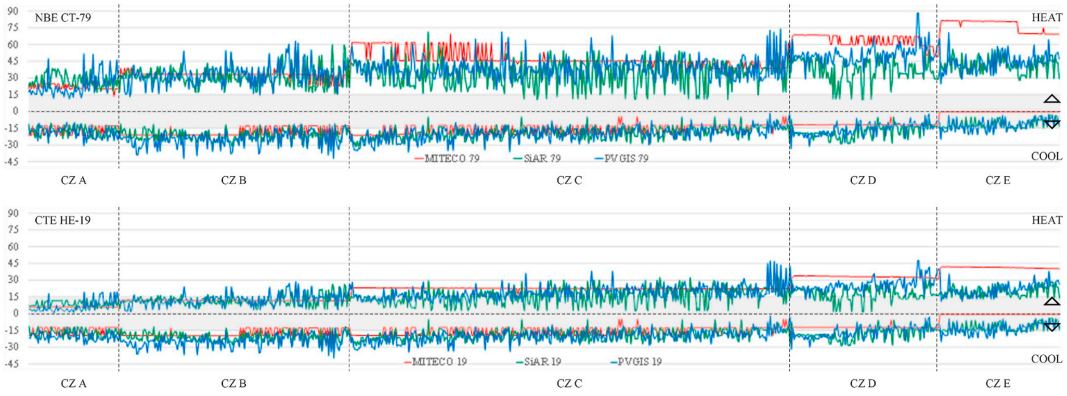

Fig. 5. Anual heating and cooling demand in kWh/m^2/year.

underestimated the official data by 23–27% for the original configurations and 24–31% for updated configurations. These differences also increased as winter climate severity increased (from 17% for CZ A to 343% for CZ E).

In relation to DHW demands, the ST system causes demand to be reduced by 78% according to MITECO data, and is down to 72% or 74% with SiAR or PVGIS data respectively. Therefore, the demand for natural gas to meet HEAT and DHW needs is reduced from the BS scenario (C1, C3) to the RS and NS scenarios (C2, C4, C5, C6, C7, C8) with ST contribution by between 61% and 63%.

In relation to PV production, the PV system cancelled out the electricity demand to meet HEAT needs. It also generated a surplus of 24–26 kWh/m^2/year according to the data of MITECO, SiAR and PVGIS. These electricity surpluses can be used to remove the remainder of the energy costs from the electricity bill (electrical appliances and lighting) or be sold to a third party. According to the data provided by the Spanish Electricity Network (REE) [89], this remainder accounts for approximately 83% of the bill (27% for small appliances, 16% for lighting, 14% for the fridge, 10% for television, 7% for hob and oven, 3% for the dishwasher, 3% for the washing machine, 2% for appliances on stand-by, and 1% for the tumble dryer), approximately 22.81 kWh/m^2/year (as the REE suggests).

With regard to the results obtained from climate data from the SiAR weather stations and the European PVGIS satellite system, the official climate database showed some differences that must be highlighted. For HEAT demand, SiAR stations only estimated 72% of the demands obtained with official data for the configuration of NBE CT-79 regulations and 66% for CTE HE-19 regulations. Likewise, the PVGIS system only estimated 81% for NBE CT-79 and 79% for CTE HE-19. Therefore, official data overestimated the HEAT demand between 145% and 125% depending on the alternative chosen. This means that only 219 or 249 locations for the NBE CT-79 envelope configuration and 185 for the CTE HE-19 regulation envelope configuration (out of the total 785 locations), suffered from an overestimation or underestimation below 15% (that is the maximum allowable deviation for the accuracy of the results performed by the approved software for EPCs in the EU).

For COOL demand, SiAR stations estimated 131% of the demand obtained with official data for the NBE CT-79 regulation configuration and 132% for CTE HE-19 regulations. Likewise, the PVGIS system estimated 137% for NBE CT-79 and 144% for CTE HE-19. Therefore, official data underestimated the COOL demand by 24% or 29% depending on alternative chosen. This means that only 213 or 188 locations for the NBE CT-79 envelope configuration, and 217 or 161 for the CTE HE-19 envelope configuration, out of the total 785 locations, experienced an overestimation or underestimation below 15%. For ST, SiAR stations estimated 93% of the demand obtained with official data and the PVGIS system estimated 94%. This means that, according to SiAR data, overestimation or underestimation is less than 15% in all locations and, according to PVGIS data, only 2 locations differed by more than 15%. For PV, SiAR stations estimated 108% of the demand obtained with official data and the PVGIS system estimated 107%. This means that, according to SiAR data, overestimation or underestimation is above 15% in 128 locations and, according to PVGIS data, only in 21 locations.

In summary, on an energy level, standardised system performances for cold, heat and DHW production, and a standard insulation material, as well as commercial solutions for ST and PV systems, have been considered. With these restrictions, the energy savings achieved greatly exceeded the guidelines of directives EPBD-2002/91/EC (20% by 2020) and EPBD-2010/31/EU (27% by 2030). The annual savings achieved by cases C6–C8 with respect to baseline case C1 ranged from 70% to 115% with MITECO data, between 73% and 132% with SiAR data, and between 65% and 129% with PVGIS data. Saving exceeding 100% happened in 124, 227 and 136 of the 785 Andalusian towns depending on the same climate datasets, respectively.

Nevertheless, these improvements obtain these results due to the lower HEAT demand (caused by the modification of the envelope) and DHW (stemming from the ST system), as well as from the generation of electricity through the PV system. While the envelope managed to mitigate 55% of the HEAT demand, the COOL demand did not suffer from any variation on average. This confirms that the strategy proposed by both regulatory frameworks to define the envelope using a heat transmission coefficient and varying the thickness of the insulation is optimized for winter but has little impact in summer. On the other hand, the ST contribution reaches 75% of the DHW demand and, since the electricity surplus can be used to meet 100% of the demand for electrical appliances and lighting (or be sold), all renewable energy production can be considered as useable energy. Therefore, it is necessary for the regulations to include proposals aimed at alleviating the consequences of climate in locations with an important summer climate severity. This without neglecting the technologies and strategies associated with the summer regime, as verified by the results obtained from the HEAT and COOL demands.

To conclude this energy assessment, the degree of compliance of primary energy consumption in the different scenarios was checked. This because these had been sized according to demand compliance using K_G or K_L heat transfer coefficients. Table 8 shows the number of locations per scenario that did not exceed the non renewable primary energy (NRPE) and the total primary energy (TPE) limits for renovated buildings. All the cases in which the envelope had been designed or renovated to comply the K_L of the CTE HE-19 (C5, C6, C7 and C8) did not surpass the maximum allowable values of NRPE and TPE either. However, if SiAR or PVGIS climate data are used, a few towns did exceed these limit values.

3.2. *Impact on CO_2eq emissions*

Table 9 summarizes the annual emissions for the 8 different scenarios. Fig. 6 includes their distribution in Andalusia. Results show the total GHG emissions over the next 30 years of building shelf life (2021–2050) including the initial emissions from the interventions divided by these 30 years in order to obtain a yearly data. The BS (C1) generated average carbon dioxide equivalent emissions from 17 to 21 kg CO_2eq/m^2/year, depending on the climate database used. If an ST system is added to the BS (C2), emissions were reduced by 20%–22% on average, to 14–17 kg CO_2eq/m^2/year. If a PV system is added to the BS (C3), emissions are reduced by 28%–37% on average, down to 11–15 kg CO_2eq/m^2/year. If both systems (ST + PV) were to be included in the BS (C4), the reduction would reach between 47% and 57% on average, down to 7–11 kg CO_2eq/m^2/year. Furthermore, the RS with ST system (C5) managed to reduce these emissions by 48% and 51% on average, down to 9–10 kg CO_2eq/m^2/year. If the PV system is added to this intervention (C6), the emission savings are between 78% and 84% on average, down to 3–5 kg CO_2eq/m^2/year. Finally, the NS with ST system (C7) manages to reduce these emissions by 50%–52% on average, to 9–10 kg CO_2eq/m^2/year. If the PV system is added to this intervention (C8), the emission savings are between 80% and 86% on average, falling to 2–4 kg CO_2eq/m^2/year, contributing to an amelioration of global warming.

Regarding emissions, the CO2eq emissions transfer factors approved

Table 8
Locations complying the primary energy requirements by case study and climate database.

NREP	**C1**	**C2**	**C3**	**C4**	**C5–C7**	**C6–C8**
MITECO	0/785	79/785	1/785	368/785	785/785	785/785
SiAR	37/785	313/785	170/785	632/785	774/785	785/785
PVGIS	1/785	250/785	78/785	540/785	753/785	779/785

TEP	**C1–C2–C3–C4**	**C5–C6–C7–C8**
MITECO	79/785	785/785
SiAR	368/785	777/785
PVGIS	283/785	752/785

Table 9
Anual CO_{2eq} emissions.

MITECO	C1	C2	Savings (2-1)	C3	Savings (3-1)	C4	Savings (4-1)	C5	Savings (5-1)	C6	Savings (6-1)	C7	Savings (7-1)	C8	Savings (8-1)
Minimum	10.99	6.80	3.97	4.85	5.24	0.80	9.37	5.29	5.70	−0.71	11.69	4.94	6.04	−1.05	12.04
Mean	20.67	16.55	4.12	14.85	5.82	10.89	9.78	10.22	10.45	4.56	16.12	9.87	10.80	4.21	16.46
Maximum	28.76	24.62	4.29	23.53	6.14	19.38	10.19	14.58	16.35	9.35	22.22	14.23	16.70	9.00	22.57
SiAR	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	11.40	7.39	3.44	4.78	4.49	0.96	8.17	5.33	5.50	−1.04	11.51	4.99	5.84	−1.39	11.86
Mean	17.40	13.59	3.81	11.02	6.38	7.41	9.99	8.89	8.50	2.72	14.68	8.55	8.85	2.37	15.03
Maximum	26.34	22.50	4.09	20.11	7.17	16.33	10.67	13.10	14.67	7.20	20.85	12.75	15.02	6.86	21.19
PVGIS	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	10.71	6.75	3.10	4.22	5.02	0.65	7.94	4.66	5.96	−1.58	12.07	4.32	6.31	−1.93	12.42
Mean	18.71	14.83	3.88	12.40	6.32	8.78	9.93	9.75	8.96	3.65	15.07	9.40	9.31	3.30	15.41
Maximum	32.14	28.20	4.18	25.78	6.89	21.98	10.69	17.68	14.68	11.47	20.68	17.33	15.03	11.12	21.03

Emissions in kg CO_2eq/m^2/year. Life cycle from 2001 to 2050. Period included: 2021–2050.
Factor of 0.331 kg $C0_2$/kWh for electricity. Factor of 0.252 kg $C0_2eq$/kWh for natural gas. Electricity mix: Renewables +2.2% by year from 2021 to 2030 and + 1.90% by year from 2031 to 2050.

by the Permanent Commission for Energy Certification have been considered, both for electricity and natural gas. Additionally, initial emissions as a result of an envelope modification and/or including an ST system and/or a PV system have also been tested. Analysing the annual emissions balance, the guidelines laid out in directives EPBD-2002/91/CE (20% for 2020) and EPBD-2010/31/UE (40% for 2030) are far exceeded again, with annual savings between 69% and 110%, 74% and 110% or 65% and 118%, depending on the climate database. In this sense, the locations where a balance of over 100% is obtained (69, 78 or 66 towns out of 785), while generating HEAT and DHW emissions, no longer emitted a significant amount from electricity consumption to meet the COOL demands, appliances and/or lighting.

3.3. *Economic impact*

Table 10 summarizes the annual cost of the energy consumed from the 8 scenarios. Fig. 7 includes their distribution in Andalusia, which affects the initial investment for the different combinations. Results show the total energy costs over the next 30 years of building shelf life (2021–2050) including the initial costs from the interventions divided by these 30 years in order to obtain a yearly data. In the BS (C1), between 8 and 9 €/m^2/year is allocated to pay the energy bills. If the BS has an ST system (C2), the cost of the bills is reduced by 9% on average, to 7–8 €/m^2/year. If the BS has a PV system (C3), the cost is reduced by 51%–64% on average, to 3–4 €/m^2/year. If both the ST and PV systems are included (C4), the reduction varies between 60% and 73% on average, dropping to 2–3 €/m^2per year. Furthermore, the RS with an ST system (C5) manages to reduce the bill by 15%–79% on average, to 7 €/m^2/year. If a PV system is considered (C6), the economic savings are between 73% and 79% on average, to 2 €/m^2/year. Finally, the NS with an ST system (C7) manages to reduce the bill between 28% and 34% on average, to 5–6 €/m^2/year. If a PV system is added to this intervention (C8), the economic savings range between 85% and 93% on average, falling to 1–2 €/m^2/year.

On an economic level, all scenarios recover the investment in less than 30 years, with savings between 70% and 115%, 70% and 143% or 63% and 133%, respectively, for each climate dataset. The internal rate of return (IRR) obtained varies between 3% and 29% (5% for C2, 26–29% for C3, 15–16% for C4, 3–4% for C5, 9–10% for C6, 7–9% for C7 and 15% for C8). All of them are higher than the opportunity costs of 30-year government-backed bonds [22] (usually with a <1% discount rate over the last 9 auctions).

4. Conclusions

This work has analysed the energy, environmental and economic impacts of the Spanish building regulatation changes while transposing the European Directives to meet the nZEBs requirements. To this end, an attached house located in every municipality of Andalusia has been simulated. The thermal behaviour of the original house was compared with that obtained after being adapted to the new regulations. A ST system contributing to partially supply the DHW demand, and a PV system producing electricity to cover self-consumption were also considered. Different climate databases were also analysed. Results showed that the European objectives were greatly exceeded under the most recent legislation requirements.

On an energy level, standardised performances for the production of COLD, HEAT and DHW, traditional construction systems and commercial solutions for ST and PV systems were considered. With these restrictions, the energy savings exceeded by far the targets set by the EPBDs (20% in 2020 and 27% in 2030), ranging from 69% to 127% (exceeding 100% in one fifth of the territory of Andalusia). However, first, regulatory changes have significantly reduced HEAT demands (about a 55%) but have not been very effective in mitigating COOL demands. Second, DHW demands are drastically reduced thanks to the ST system (about a 75%). It can be noted that a ST system of higher

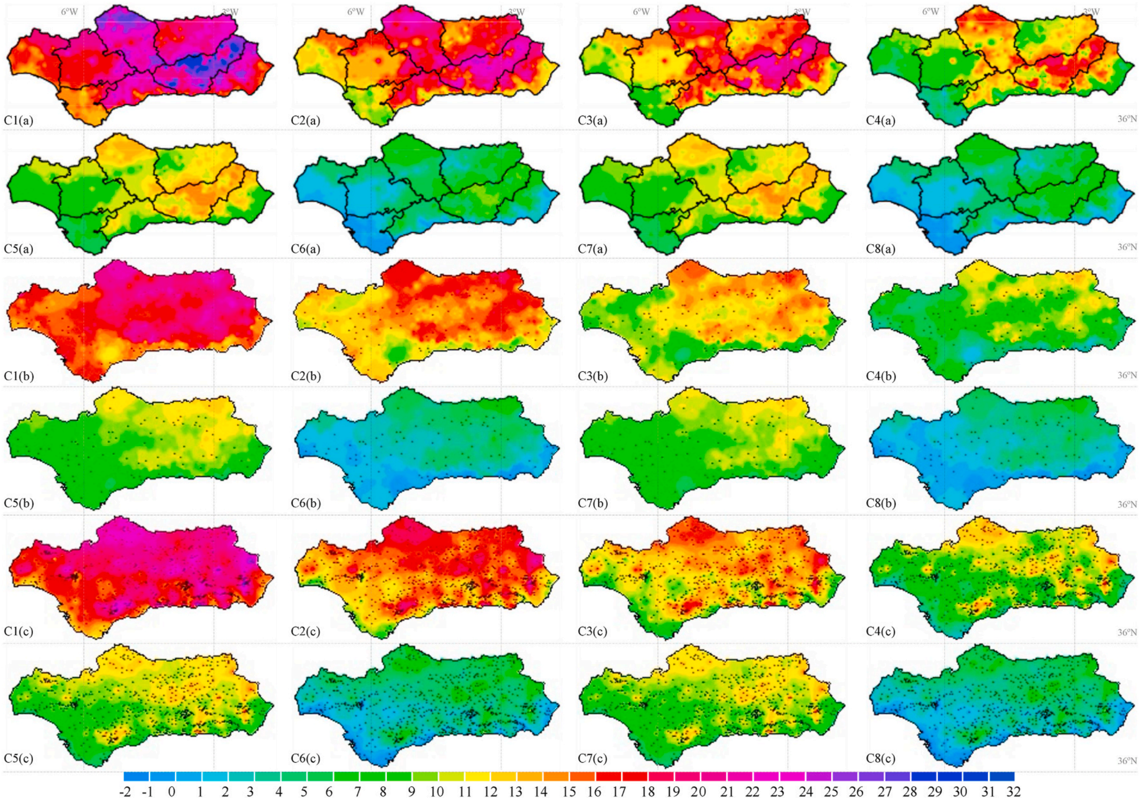

Fig. 6. Annual carbon dioxide emissions by case study (Climate database: MITECO (a), SiAR (b), PVGIS (c)) in kg CO_2eq/m^2/year.

Table 10
Anual economy cost.

MITECO	C1	C2	Savings (2-1)	C3	Savings (3-1)	C4	Savings (4-1)	C5	Savings (5-1)	C6	Savings (6-1)	C7	Savings (7-1)	C8	Savings (8-1)
Minimum	4.89	4.05	0.76	0.11	4.15	−0.73	4.98	4.82	0.08	0.03	4.77	3.76	1.13	−1.03	5.83
Mean	8.81	8.00	0.81	4.31	4.51	3.49	5.32	6.91	1.91	2.40	6.42	5.85	2.97	1.34	7.48
Maximum	11.49	10.66	0.88	7.33	4.78	6.51	5.63	8.21	4.20	4.05	8.88	7.15	5.26	2.99	9.94
SiAR	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	5.11	4.43	0.54	0.18	3.44	−0.50	4.13	4.98	−0.05	0.05	3.99	3.92	1.01	−1.01	5.05
Mean	7.68	6.99	0.69	2.75	4.93	2.06	5.62	6.56	1.12	1.63	6.05	5.50	2.18	0.57	7.11
Maximum	10.69	9.99	0.80	5.76	5.50	5.06	6.18	8.13	3.53	3.50	8.46	7.07	4.59	2.44	9.52
PVGIS	**C1**	**C2**	**Savings (2-1)**	**C3**	**Savings (3-1)**	**C4**	**Savings (4-1)**	**C5**	**Savings (5-1)**	**C6**	**Savings (6-1)**	**C7**	**Savings (7-1)**	**C8**	**Savings (8-1)**
Minimum	4.86	4.11	0.40	−0.20	3.86	−0.95	4.25	4.81	−0.07	−0.13	4.79	3.75	0.99	−1.19	5.85
Mean	8.24	7.52	0.72	3.38	4.87	2.66	5.59	6.96	1.28	2.10	6.15	5.90	2.34	1.04	7.20
Maximum	13.35	12.61	0.84	8.39	5.20	7.65	5.97	9.89	3.60	4.93	8.43	8.83	4.66	3.87	9.49

Energy costs in €/m^2/year. Life cycle from 2001 to 2050. Period included: 2021–2050.

Electricity price: Linear decrease from 0.223 €/kWh/year in 2020 to 0.201 in 2030 to 0.197 in 2050. Natural gas price: Linear decrease from 0.102 €/kWh/year in 2020 to 0.101 in 2030 to 0.099 in 2050.

capacity would produce overheating in Summer, which is not allowed by the Spanish regulatory framework. Third, the generation of electricity thanks to the photovoltaic system can be used to meet 100% of the demand for household appliances and lighting, either directly, or by offsetting the bill through the sale of surpluses, as allowed by RD 244/2019 for facilities below 100 kWp. It can be noted that a PV system with higher capacity would become viable should energy surpluses can be sold once self-consumption is satisfied. However, this scenario would depend on external factors such as taxes or future market conditions.

Regarding GHG emissions, the CO2eq emission transfer factors have been considered, both for electricity and natural gas. In addition, initial emissions as a result of modifying the envelope and/or including an ST and/or a PV system have also been tested. Analysing the annual emissions balance, the guidelines laid out in EPBDs (20% in 2020 and 40% in 2030) are also far exceeded, with annual savings between 65% and 118% (exceeding 100% in one tenth of the territory). On an economic level, all scenarios recover the investment in less than 30 years, with savings between 71% and 125%. This is confirmed by the internal rate of return obtained, which is higher than the usual opportunity costs in all the case studies analysed.

Hence, all combinations of actions studied in all towns of Andalusia are able to return the investments derived from their implementation, while significantly improving their energy, environmental (emissions) and economical (energy costs) performance. Consequently, it is highly

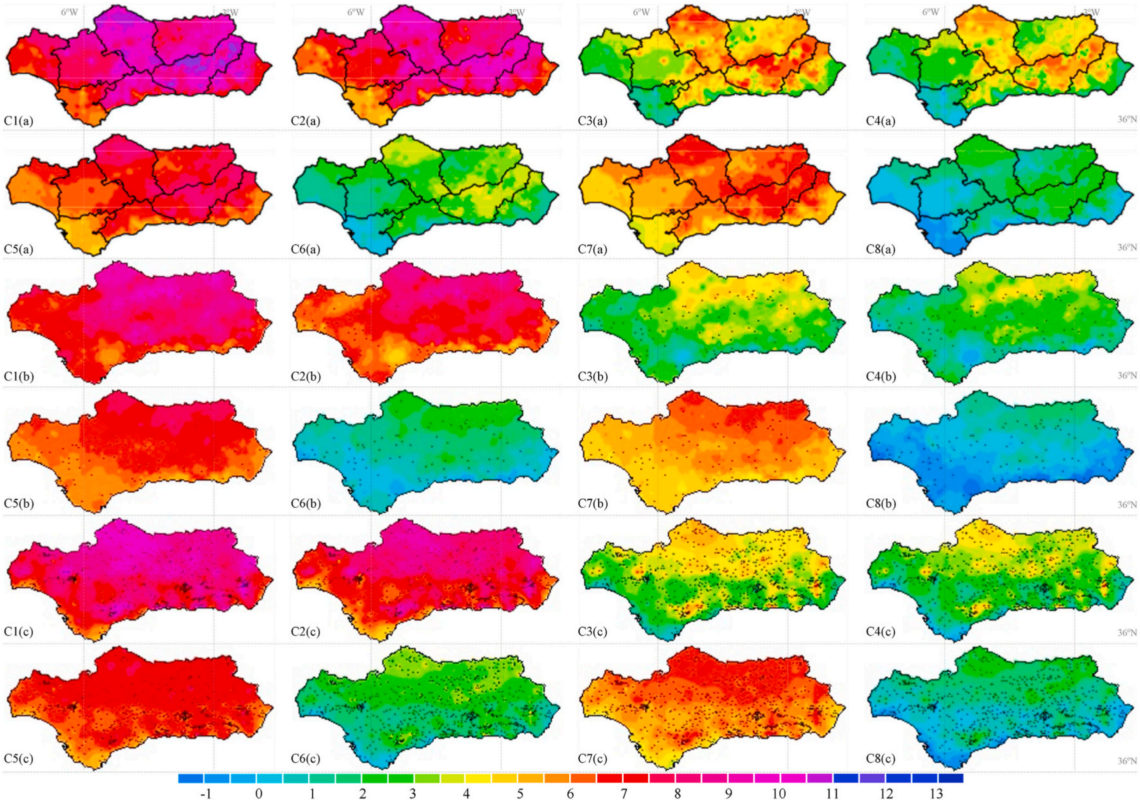

Fig. 7. Annual energy costs by case study (Climate database: MITECO (a), SiAR (b), PVGIS (c)) in €/m^2/year.

recommended that the large stock of single-family homes built in Andalusia during the decade 2000–2009 is modified to meet the new energy efficiency regulations. This modification would involve renovating their envelopes, incorporating a ST system for reducing the DHW demands and including a PV system for self-consumption with surpluses. These actions would transform these buildings, into nZEBs.

Yet, the strategy proposed by both regulatory frameworks is optimized for winter and is of little interest in summer. It is necessary for the current regulations to include proposals aimed at alleviating the consequences of climate in locations with an important summer climate severity. This may involve, perhaps, neglecting some technologies and strategies associated with the summer regime (percentage of openings, orientation and solar control, cross and night-time ventilation, compactness, use of vegetation and water sheets, etc.), as verified by the results obtained from the HEAT and COOL demands. This latter approach, however, needs further research.

The use of climate data derived from weather observations (SiAR stations or satellite data from PVGIS) allows detecting important discrepencies in the results obtained with those obtained by the official MITECO climate database. This confirms that the latter is too simplistic, at least for Andalusia. Additionally, the GIS-based approach allows contrasting strengths and weaknesses of building envelope configurations, renewable energy systems and climate databases from different points of view. GIS maps, for example, can provide more accurate information to improve the design, construction and policy making regarding whether or not to undertake certain building renovations. This with the eventual aim of ensuring a minimum energy efficiency and emissions improvement of any building in any location.

Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

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

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Appendix

Table A1
Construction characteristics of the thermal envelope. W: Wall in contact with the Outside

BS: Baseline Scenario				RS: Rehabilitated Scenario				NS: New Scenario			
Code	Component	Thickness	λ_{Wi}	Code	Component	Thickness	λ_{Wi}	Code	Component	Thickness	λ_{Wi}
RFP010	Exterior Paint			RFP010	Exterior Paint			RFP010	Exterior Paint		
RPE010	Cement Plastering	15	1.30	RPE010	Cement Plastering	15	1.30	RPE010	Cement Plastering	15	1.30
FFZ015	½ Foot Perforated Brick	125	0.51	FFZ015	½ Foot Perforated Brick	125	0.51	FFZ015	½ Foot Perforated Brick	125	0.51
RPE011	Cement Grouting	10	1.30	RPE011	Cement Grouting	10	1.30	RPE011	Cement Grouting	10	1.30
NAF010	*PUR foam spray*	$E_{W}1$	*0.03*	*NAF010*	*PUR foam spray*	$E_{W}1$	*0.03*	*NAF010*	*PUR foam spray*	$E_{W}2$	*0.03*
				NAE010	*Blown-in PUR Insulation*	$E_{W}2$- $E_{W}1$	*0.03*				
	Air Cavity	125- $E_{W}1$	*0–0.09*		*Air Cavity*	125-$E_{W}2$	*0–0.09*		*Air Cavity*	125-$E_{W}2$	*0–0.09*
FFR010	Double Hollow Brick	60	0.45	FFR010	Double Hollow Brick	60	0.45	FFR010	Double Hollow Brick	60	0.45
RPG010	Plaster Trim	15	0.57	RPG010	Plaster Trim	15	0.57	RPG010	Plaster Trim	15	0.57
RIP030	Interior Paint			RIP030	Interior Paint			RIP030	Interior Paint		
				RPY011	*Cladding Repair*						
				RIP030	*Interior Paint*						
Sum		350		Sum		350		Sum		350	

Thickness (E_W: E_W1 in NBE CT-79, E_W2 in CTE HE-19) in mm, Transmittance (U_W) in W/m^2·K, which varies from 0.20 (if $E_W = 125$) to 1.48 (if $E_W = 0$).

Table A2
Construction characteristics of the thermal envelope. F: Floor in contact with the Outside

BS: Baseline Scenario				RS: Rehabilitated Scenario				NS: New Scenario			
Code	Component	Thickness	λ_{Fi}	Code	Component	Thickness	λ_{Fi}	Code	Component	Thickness	λ_{Fi}
RSC010	Terrazzo Tiling	40	3.50	RSC010	Terrazzo Tiling	40	3.50	RSC010	Terrazzo Tiling	40	3.50
RSB005	Sand Bed	30	1.30	RSB005	Sand Bed	30	1.30	RSB005	Sand Bed	30	1.30
RSB012	Self-levelling Mortar	40	2.00	RSB012	Self-levelling Mortar	40	2.00	RSB012	Self-levelling Mortar	40	2.00
EHU015	Reinforced Concrete Slab	300	1.23	EHU015	Reinforced Concrete Slab	300	1.23	EHU015	Reinforced Concrete Slab	300	1.23
NAF010	*PUR foam spray*	E_F1	*0.03*	*NAF010*	*PUR foam spray*	E_F1	*0.03*	*NAF010*	*PUR foam spray*	E_F2	*0.03*
				NAF010	*PUR foam spray*	E_F2-E_F1	*0.03*				
	Air Cavity	220-E_F1	*0.18*		*Air Cavity*	*220-F2*	*0.18*		*Air Cavity*	220-E_F2	*0.18*
RTA010	False Plaster Ceiling	20	0.25	RTA010	False Plaster Ceiling	20	0.25	RTA010	False Plaster Ceiling	20	0.25
RFP030	Exterior Paint			RFP030	Exterior Paint			RFP030	Exterior Paint		
				DRT010	*Demolition False Ceiling*	*−20*					
				RTA010	*False Plaster Ceiling*	*20*					
				RFP030	*Exterior Paint*						
Sum		650		Sum		650		Sum		650	

Thickness (E_F: E_F1 in NBE CT-79, E_F2 in CTE HE-19) in mm, Transmittance (U_F) in W/m^2·K, which varies from 0.21 (if $E_F = 125$) to 1.63 (if $E_F = 0$).

Table A3
Construction characteristics of the thermal envelope. R: Roof in contact with the Outside

BS: Baseline Scenario				RS: Rehabilitated Scenario				NS: New Scenario			
Code	Component	Thickness	λ_{Ri}	Code	Component	Thickness	λ_{Ri}	Code	Component	Thickness	λ_{Ri}
QAB010	Walkable Flat Roof	180	0.74	QAB010	Walkable Flat Roof	180	0.74	QAB010	Walkable Flat Roof	180	0.74
NAF010	*PUR foam spray*	E_R1	*0.03*	*NAF010*	*PUR foam spray*	E_R1	*0.03*	*NAF010*	*PUR foam spray*	E_R2	*0.03*
EHU015	Reinforced Concrete Slab	300	1.23	EHU015	Reinforced Concrete Slab	300	1.23	EHU015	Reinforced Concrete Slab	300	1.23
				NAF010	*PUR foam spray*	E_R2-E_R1	*0.03*				
	Air Cavity	150-E_R1	*0.18*		*Air Cavity*	150-E_R2	*0.18*		*Air Cavity*	150-E_R2	*0.18*
RTA010	False Plaster Ceiling	20	0.25	RTA010	False Plaster Ceiling	20	0.25	RTA010	False Plaster Ceiling	20	0.25
RIP030	Interior Paint			RIP030	Interior Paint			RIP030	Interior Paint		
				DRT010	*Demolition False Ceiling*	*−20*					
				RTA010	*False Plaster Ceiling*	*20*					
				RFP030	*Interior Paint*						
Sum		650		Sum		650		Sum		650	

Thickness (E_R: E_R1 in NBE CT-79, E_R2 in CTE HE-19) in mm, Transmittance (U_R) in W/m^2·K, which varies from 0.18 (if $E_R = 125$) to 1.05 (if $E_R = 0$).

Table A4
Construction characteristics of the thermal envelope. G: Floor in contact with the Ground

BS: Baseline Scenario				RS: Rehabilitated Scenario				NS: New Scenario			
Code	Component	Thickness	λ_{Gi}	Code	Component	Thickness	λ_{Gi}	Code	Component	Thickness	λ_{Ei}
				RSG010	*Porcelain Stoneware Tiles*	*15*	*3.50*				
				RSB011	*Mortar Screed*	$55-E_G2+E_G1$	*2.00*				
				NAF010	*PUR foam spray*	E_G2-E_G1	*0.03*				
				DRS010	*Removal Terrazzo Paving*	*−70*					
RSC010	Terrazzo Tiling	40	3.50	RSC010	Terrazzo Tiling	40	3.50	RSC010	Terrazzo Tiling	40	3.50
RSB005	Sand Bed	30	1.30	RSB005	Sand Bed	30	1.30	RSB005	Sand Bed	30	1.30
RSB012	Self-levelling Mortar	40	2.00	RSB012	Self-levelling Mortar	40	2.00	RSB012	Self-levelling Mortar	40	2.00
ANS010	Reinforced Concrete Floor	200	1.65	ANS010	Reinforced Concrete Floor	200	1.65	ANS010	Reinforced Concrete Floor	200	1.65
NIS011	Waterproofing	10	0.23	NIS011	Waterproofing	10	0.23	NIS011	Waterproofing	10	0.23
NAF010	*PUR foam spray*	E_G1	*0.03*	*NAF010*	*PUR foam spray*	E_E1	*0.03*	*NAF010*	*PUR foam spray*	E_G2	*0.03*
ANE010	*Gravel fill*	$330-E_G1$	*2.00*	*ANE010*	*Gravel fill*	$330- E_G1$	*2.00*	*ANE010*	*Gravel fill*	$330- E_G2$	*2.00*
Sum		650		Sum		650		Sum		650	

Thickness (E_G: E_G1 in NBE CT-79, E_G2 in CTE HE-19) in mm, Transmittance (U_G) in $W/m^2 \cdot K$, which varies from 0.19 (if $E_G = 125$) to 1.79 (if $E_G = 0$).

Table A5
Daily profile of DHW (% with respect to the maximum water flow rate of 150 l/d)

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
%	0	0	0	0	1	3	10	7	7	6	6	5	5	4	3	4	4	5	7	6	6	5	5	1

Table A6
Indoor internal gains (in W/m2)

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy	2.15	2.15	2.15	2.15	2.15	2.15	2.15	0.54	0.54	054	0.54	0.54	0.54	0.54	0.54	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	2.15
Lighting	0.44	0.44	0.44	0.44	0.44	0.44	0.44	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	2.20	4.40	4.40	4.40	4.40	2.20
Appliances	0.44	0.44	0.44	0.44	0.44	0.44	0.44	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32	2.20	4.40	4.40	4.40	4.40	2.20

Appendix B. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jobe.2021.103054.

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