Adaptation and mitigation to climate change of envelope wall thermal insulation of residential buildings in a temperate oceanic climate

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Abstract

In the context of climate change, it is difficult to maintain the energy performance of houses, especially in countries with building codes that regulate the maximum allowed amount of energy that a building can consume. For this reason, there is a need for a review of building standards and adaptation to the context of energy performance in planning future projects. The objective of this research was to ascertain the thermal transmittance of external walls for single-family homes and to establish the energetically optimal thickness of thermal insulation by using an energy simulation to maintain heating energy consumption in conditions of climate change while following the state regulations in the Los Ríos region of Chile. It was demonstrated that for each time period and in each geographical location of the region the optimal U-value of the external walls is different. For a house to have a heating energy consumption corresponding to 90 kWh/m^2/year, it must have an optimal average U-value of the walls of 0.49±0.11 W/m^{2}K (year 2006 in the study region);

however, for the period 2035–2050, this value is expected to reach 0.78 ± 0.14 W/m^{2}K. In addition, it was shown that designing the house with an energy performance perspective of 15 years helps to reduce the carbon footprint of the use of thermal insulation in the walls by 20%. The results obtained demonstrate the importance of considering the effects of future climate change in the housing design process in terms of both energy and ecology.

Keywords: Climate change; Thermal insulation; Building envelope; LCA; Building.

Highlights

- Methodology for determining the energetically optimal walls U-value was presented.
- Importance of considering future energy consumption in design of buildings was shown.
- Future-oriented design demonstrated a reduction of the insulation carbon footprint.
- The importance of considering microclimatic features in the design of dwellings was shown.

1. Introduction

In order to minimise the energy consumption of buildings, multi-parametric building optimisation methodologies have been developed in recent decades [1–5]. Given the effect that this energy optimisation generates in other aspects, for example, economic efficiency [6,7], ecological impact [8–11], thermal comfort [12,13], visual comfort [14,15] and indoor air quality [16], these methodologies are also called multi-objective methodologies [17,18]. One or more of these objectives are priority [19,20], depending on the optimisation task as well as the type of building. For example, in school buildings, optimisation is carried out under the concept of a balance between energy efficiency, indoor thermal comfort and indoor air quality [21,22]. In the case of public buildings such as airports, the main objectives are related to economic and energy efficiency [23,24]. In the case of office and residential buildings, the objective of interior comfort has recently become a priority [25,26]. For this reason, it has been necessary to develop special tools for optimisation that facilitate the simplification and automation of the task depending on the type of building [27,28].

One of the important parameters to minimise the energy consumption of a building is the correct thermal insulation of the building envelope [29,30]. Various investigations have focused on the optimisation of the thermal insulation and the thermal transmittance of external walls [31,32], as is the case of the study of scientific groups in Turkey. Specifically, the research by Ozkahraman and Bolatturk presents a methodology to find the optimal thickness of the thermal insulation of external walls in a cold climatic zone, which includes an economic–energy balance approach that minimises costs of both heating and thermal insulation material [33]. This methodology has been further developed in subsequent works [34] that show that the optimum thickness of the insulation will depend on (i) degree-days of heating, (ii) the cost of the insulating material and (iii) the cost of the fuel that will be used to heat a house in a decade. Ucar and Balo added the search for optimal fuel for different climatic zones [35]. In another study, Ucar presented a methodology to determine the optimal thickness of the thermal insulation of the roof and also evaluated the effect on the environment—reduction of CO_2 and SO_2 emissions—of the optimum thickness of the thermal insulation of a house [36]. Ekici *et al.* expanded the number of materials analysed for thermal insulation and determined the optimal type of external walls for different climatic zones [37]. The research presented above is based on a methodology in which the optimal thickness and the amount of energy consumed are variable and depend on the geographical location of the dwelling. Using the assumption of a constant level of heating and cooling energy consumption of the house, this methodology has been widely applied and can be used in different regions of the world [38–40].

Recently, Resalati *et al.* published a methodology for estimating the optimal U-value and thickness of the thermal insulation of external walls based on the total energy consumption of the house as well as on the life cycle assessment (LCA) method of the insulation materials [41]. In this case, the optimal U-value and the optimal thickness of the thermal insulation are determined as a function of the minimum of the sum of the embodied carbon of the insulation materials and the building operation carbon.

In the context of global climate change, in recent decades, special attention has been paid to evaluating the effects of increased temperature in the world [42]. In the area of building construction, various scientific works have focused on the analysis of changes in cooling and heating energy consumption in different types of buildings. In general, it is observed that in the future cooling energy consumption will increase and heating energy consumption will decrease. In particular, in warmer climatic zones the total energy consumption for cooling/heating of houses will increase; this is due to the fact that the increase in cooling energy consumption will exceed the decrease in heating energy consumption in future periods [43–45]. In the case of countries with colder climates, it has been estimated that total energy consumption for cooling/heating will decrease, in this case because the rate of decrease in heating energy consumption will exceed the rate of increase in cooling energy consumption [46–48]. A similar trend is predicted in cold climatic zones of countries with a large territory [49,50]. For all the above, the optimal insulation currently found in dwellings cannot guarantee the stability of total energy consumption during its life cycle; this affects the energy ranking of the house because it may not meet the energy requirements of future building standards.

Walsh *et al.* pointed out that 36% of the countries analysed have building codes and that in all of them, for different climatic zones, a maximum permitted value of total energy consumption of the house is established [51]. For example, the *"Réglementation Thermique 2012"* in France seeks to limit the consumption of primary energy in new buildings to a maximum of an average of 50 kWh/m^2/year [52]. In Finland, the maximum allowed value of total energy consumption for a house depends on its total area; a house of 100 m^2 must have a total energy consumption that does not exceed 140 kWh/m^2/year [53]. In Chile, the main and mandatory document that governs energy issues in the construction of civil buildings is the Thermal Regulation (RT) of the General Urban Planning and Construction Ordinance (OGUC) of the Ministry of Housing and Urban Development of Chile (MINVU) [54,55]. In this document, for each of the seven building climatic zones into which the country is divided, the maximum permitted values of thermal transmittance are established for the construction elements of the building. This document has been criticised in several aspects [56–59], which is why in 2018 the MINVU published the Sustainable Construction Standards (ECS) for homes in Chile [60]. This informative document includes an update of the climatic zones and the values of thermal transmittance for constructive elements of buildings, in addition to the maximum permissible values of energy consumption in dwellings both for cooling and heating. These values are considered for the current period as well as for future periods.

The aim of this research is to determine the thermal transmittance and the energetically optimal thickness of the thermal insulation of external walls in single-family dwellings in a temperate oceanic climate through energy simulation to obtain energy stability under conditions of future climate change.

2. Material and methods

In the following sections, a description of the study region, the current building codes in the country, the type of studied dwelling, and the methodology used for this research will be presented. Fig. 1 summarises the methodology followed in this study.

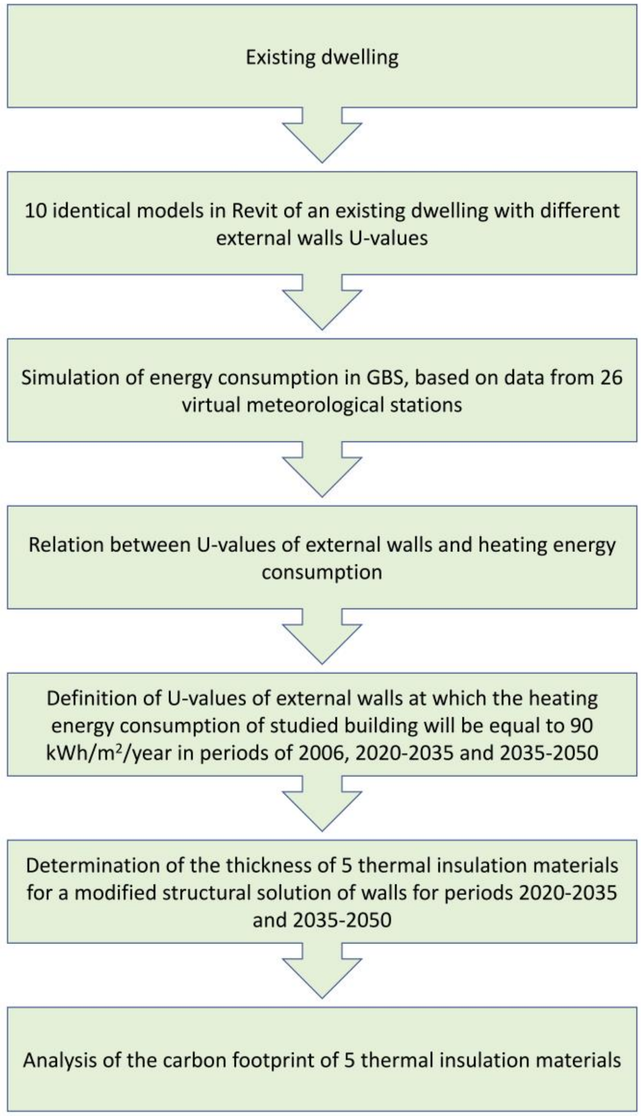

Fig. 1. Methodological structure of the research.

2.1. Study area

The Los Ríos region is located in southern Chile, between 39°17′S and 40°41′S (Fig. 2a). The area of the region is 18,429.5 km² (slightly smaller than Slovenia) and it has a population of 384,837 people [61]. The geographic diversity of the region is represented by four types of natural landscapes, from west to east: (i) coastal mountain range, (ii) longitudinal valley,

(iii) foothills of the Andes and (iv) Los Andes (mountain range). Fig. 2b shows the profile of the relief at 40°S latitude.

The choice of this area for the study has been motivated by the fact that in this area the cooling/heating of buildings is represented only by heating [62], and this area is characterised by notable climate variability. In addition, this area has a cold climate where in the future there will be a decrease in energy consumption for cooling/heating generated by a decrease in heating energy consumption that will exceed the rate of increase in energy consumption for cooling.

The central part of the region and its capital, Valdivia, is characterised by the Marine climate of the west coast (hot and dry summers) under the influence of the ocean according to the Köppen climate classification. The lower ranges of the Andean mountains have a Mediterranean climate (with warm summers) and a Mediterranean climate influenced by mountains (with mild summers) [63]. The city of Valdivia is characterised by an average annual climatological temperature (1975–2004) of 11.1°C and precipitation of 1770 mm, with a monthly average temperature of 6.8°C for July and 15.9°C for January. In the study region, average annual temperatures and precipitation tend to decrease toward the Andes [64]. The research carried out in this study can be extrapolated to different areas of the world with similar types of climate.

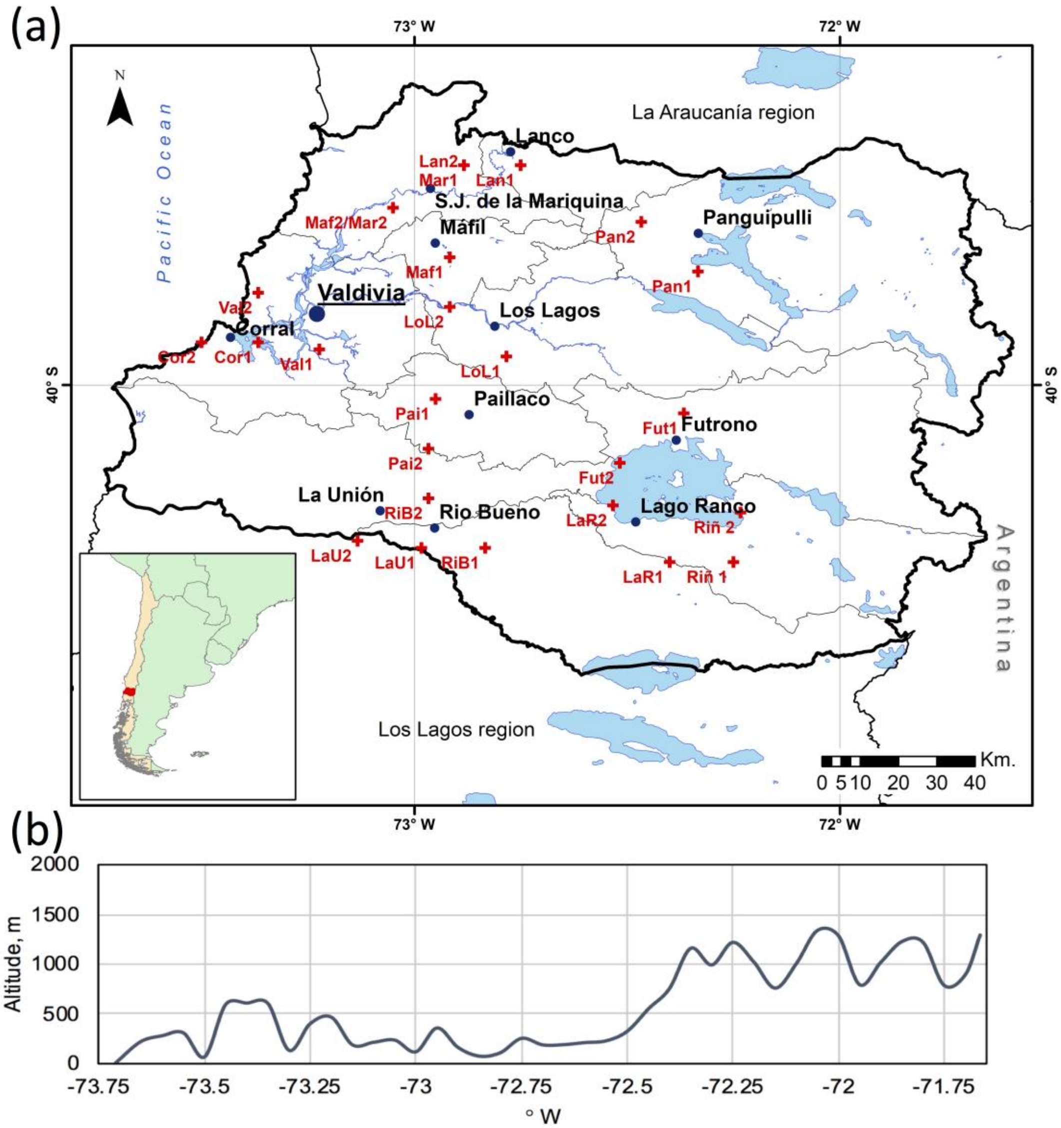

Fig. 2. Geographical location of the study area, main cities in the region and meteorological stations for energy simulation (a) and profile of the relief at 40°S latitude (b).

2.2. Building Codes of Chile in the study region

The analysis of the conformity of the dwelling in accordance with the building codes in Chile will be carried out on the basis of two normative documents related to energy efficiency in buildings: the RT OGUC [54,55] and the ECS Volume II “Energy” from MINVU [60]. According to these documents, the housing envelope must have a thermal transmittance (U-value) equal to or less than that indicated for the geographic area corresponding to the architecture project.

The MINVU in its official document RT OGUC defines seven climatic zones, based on the annual values of heating degree days with base temperature 15°C (HDD15), which it has called thermal zones; “thermal zone 1” is the warmest and “thermal zone 7” the coldest. On the other hand, Volume II – Energy of ECS [60] divides the country into zones from letter A to J (from warmer to colder zones). In the study area considered for this research, part of the coast of the Los Ríos region is located in thermal zone 5 with an annual HDD15 value of 1250–1500, while the area of the foothills of the region is located in thermal zone 6, with an annual HDD15 value of 1500–2000; in ECS terms, the Los Ríos region is located in two thermal zones: G and F (Fig. 3).

Table 1 summarises the maximum U-values required for RT OGUC and ECS in the indicated thermal zones depending on the reference document; differences between RT OGUC and ECS can be observed. For example, ventilated floors have the same value in thermal zone 6 of RT OGUC and in zone G of ECS; they also have the same value in thermal zone 5 of RT OGUC and zone F of ECS. For roofs, the ECS zones have a U-value equal to the coldest RT OGUC zone 6, but for external walls the ECS standard is more stringent than the RT OGUC. The RT OGUC makes it possible to use monolithic glass windows in the climatic conditions of the study region; furthermore, the total percentage of glazing is limited in such a way that it sets a maximum glazed area regarding the vertical faces of the thermal envelope, which depends on the type of window and its U-values. The ECS, however, establishes a maximum permitted percentage of glazing depending on the orientation of the house, and it incorporates thermal transmittance requirements for doors that do not exist in the RT OGUC. Finally, the RT OGUC standard does not set any restriction for the energy consumption of dwellings. However, the ECS standards require that the heating energy consumption of a house does not exceed a value of 100 kWh/m^2/year in thermal zone F and a value of 90 kWh/m^2/year in thermal zone G for the period after the year 2030.

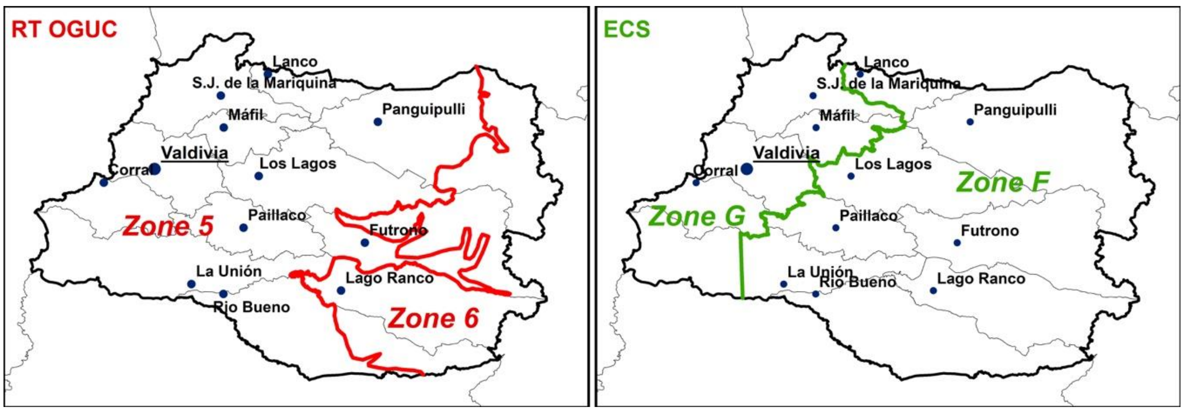

Fig. 3. Building thermal zones in the study area.

Table 1. Maximum U-values required of RT OGUC and ECS.

	RT OGUC		ECS	
	Zone 5	Zone 6	Zone F	Zone G
	U (W/m^{2}K)		U (W/m^{2}K)	
Roof	0.33	0.28	0.28	0.28
Walls	1.60	1.10	0.45	0.40
Ventilated floors	0.50	0.39	0.50	0.39
Doors	–	–	1.70	1.70
Glazed surface	*Alternative Method		**Alternative Method	

* RT OGUC Alternative method for glazed surfaces			
Type of glass	U-value	% Maximum glazed area relative to vertical faces of the envelope	
		Zone 5	Zone 6
Monolithic glass	–	18%	14%
Double hermetic glass	3.6 W/m^{2}K $\geq$ U > 2.4 W/m^{2}K	51%	37%
	U $\leq$ 2.4 W/m^{2}K	70%	55%

** ECS Alternative method for glazed surfaces	
Zone F	Zone G
No less then 3.0 W/m^{2}K	No less then 2.4 W/m^{2}K
% Maximum glazed area relative to vertical faces of the envelope and orientation	
50%(N); 35%(S); 25%(W or E)	40%(N); 30%(S); 15%(W or E)

2.3. Case study and existing house

In this study, a house already described in previous research has been used [65]. This building is a single-family house, totally isolated, with a constructed area of 76.20 m^2 and a useful area of 66.37 m^2 (Fig. 4), located in the city of Valdivia, in thermal zones 5 and G according to the RT OGUC and ECS, respectively. Table 2 shows a description of the component materials of the construction solution of the external walls. The structural system is made of timber, based on 41x90 mm uprights, with a distance between them of 40 cm, of lingue wood (*Persea lingue*), with fibre cement siding on the outer face and with an oriented strand board (OSB) and a plate of extra-resistant gypsum board on the inside. In the interior cavities and between uprights, a glass wool insulation is considered.

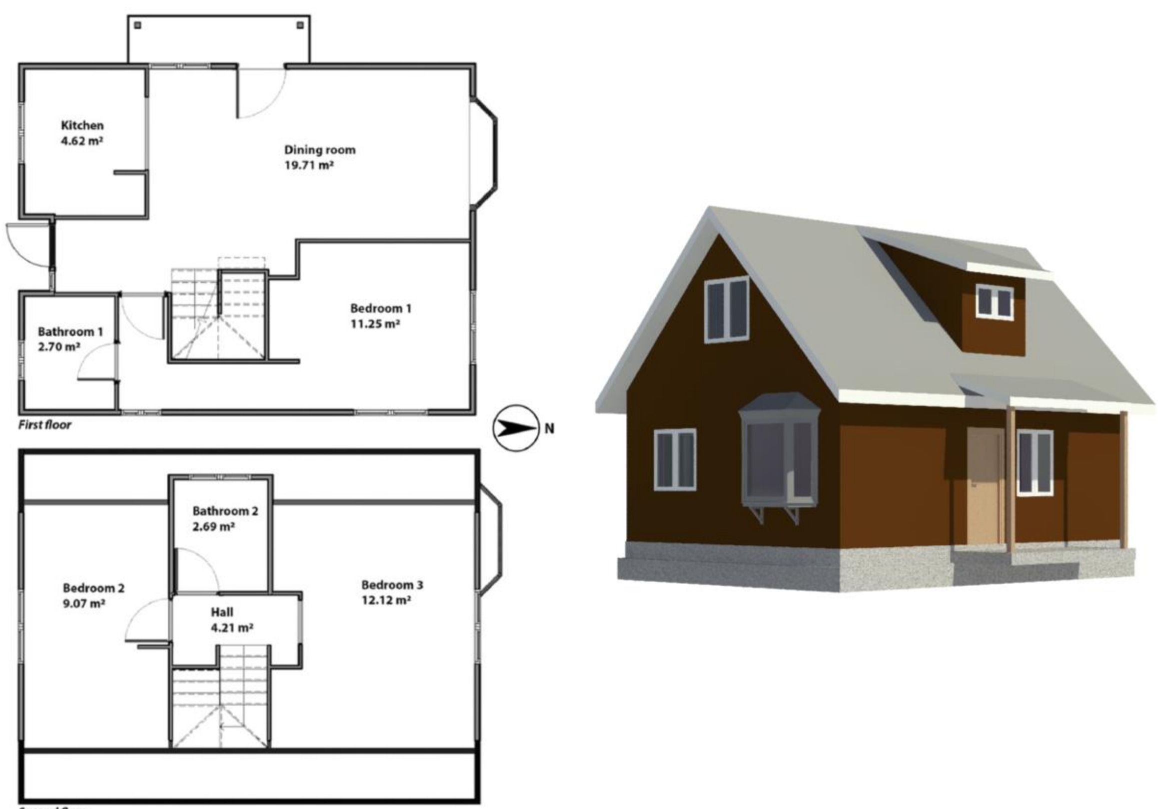

Fig. 4. Floor plan and 3D view of the house under study.

Table 2. Structural solution of the external walls of the existing house.

Insulation:				
	Thickness, [m]	λ [55,60], [W/mK]	R_t [55,60,66], [m²K/W]	U_{insul}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Glass wool 11kg/m³	0.0600	0.0424	1.4151	
Non-ventilated air chamber	0.0300		0.0165	
Gypsum board 650 kg/m³	0.0150	0.24	0.0625	
∑	0.1221		1.7624	0.567
Frame:				
	Thickness, [m]	λ [55,60], [W/mK]	R_t [55,60], [m²K/W]	U_{frame}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Lingue wood 640 kg/m³	0.0900	0.136	0.6618	
Gypsum board 650 kg/m³	0.0150	0.24	0.0625	
∑	0.1221		0.8441	1.185

$U_{tot}= U_{insul.}·0.9+U_{frame}·0.1=0.629$

Table 3 shows the thermal transmittance of the structural elements of the house used for 3D modelling and for energy simulation. The house under study fully complies with the construction requirements set in the RT OGUC for thermal zone 5, corresponding to the study zone; however, in the case of ECS, the house does not meet the recommendations for roof, external walls, and allowable thermal transmittance for windows.

Table3. Thermal transmittance of existing dwelling structural elements and compliance with standards for thermal zones of RT OGUC and ECS.

Structural elements	Modelling	Compliance to RT OGUC		Compliance to ECS	
		Zone 5	Zone 6	Zone F	Zone G
Roof – U [W/m²·K]	0.329	Yes	No	No	No
Walls – U [W/m²·K]	0.629	Yes	Yes	No	No
Floors – U [W/m²·K]	0.266	Yes	Yes	Yes	Yes
Doors – U [W/m²·K]	1.060	N/A	N/A	Yes	Yes
Hermetically double-glazed windows – U [W/m²·K]	3.160	Yes	Yes	No	No
Maximum glazed surface with respect to vertical thermal envelope [%]	16	Yes	Yes	Yes	Yes

2.4. Parameters for energy simulation

This study focuses on finding the optimal thickness of insulation for external walls, in terms of meeting the requirements for energy consumption of the ECS; therefore, the other elements of the building will not be subjected to changes (Table 3). To study the effect of the thermal transmittance of the external walls on the heating energy consumption, energy simulations of the same house were implemented with 10 different values of the thermal transmittance of the walls (0.5137 W/m^{2}K; 0.5023 W/m^{2}K; 0.4483 W/m^{2}K; 0.373 W/m^{2}K; 0.2915 W/m^{2}K; 0.2385 W/m^{2}K; 0.2018 W/m^{2}K; 0.1749 W/m^{2}K; 0.1544 W/m^{2}K; 0.1381 W/m^{2}K). In other words, there are 10 identical houses, but with different U-values in the walls.

The 3D modelling of these houses was carried out following the Building Information Modelling (BIM) methodology through Revit software [67]. Then, energy simulations were executed using Green Building Studio (GBS) [68]. Two GBS virtual weather stations were selected for being close to the main cities of the study region and with a minimum and maximum value of HDD18.3 (Table 4). The GBS meteorological data are from 2006 (last update) and have a spatial resolution of 12.7 km. A description of the GBS meteorological data and their comparison with real meteorological data for the study region is provided in the study carried out by Verichev, Zamorano and Carpio [65]. In the mountain range area, two additional stations were selected (Riñ1 and Riñ2). As can be seen in Table 4 and in Fig. 2a, the energy simulations were carried out 10 times in each of the 26 meteorological stations. The purpose of these simulations was to find a relationship between the U-value of the external walls and the amount of heating energy consumed by the house. This made it possible to determine the optimal U-value for external walls, in which at each geographical point there will be a certain equal value of heating energy consumption (90 kWh/m^2/year).

Table 4. GBS virtual weather stations where energy simulation was performed.

ID	Alt. [m]	Lat.	Lon.	HDD18.3
Val1	180	-39.9167	-73.2233	2602
Val2	104	-39.7833	-73.3667	2449
Cor1	174	-39.9000	-73.3667	2556
Cor2	44	-39.7833	-73.5000	2355
Pal1	275	-40.0333	-72.9500	2829
Pal2	232	-40.1500	-72.9667	2790
LaU1	100	-40.3833	-72.9833	2727
LaU2	110	-40.3667	-73.1333	2684
LaR1	657	-40.4167	-72.4000	3552
LaR2	277	-40.2833	-72.5333	2963
Lan1	234	-39.4833	-72.7500	2718
Lan2	168	-39.4833	-72.8833	2586
LoL1	213	-39.9333	-72.7833	2819
LoL2	171	-39.8167	-72.9167	2674
Maf1	101	-39.7000	-72.9167	2586
Maf2	88	-39.5833	-73.0500	2486
Mar1	168	-39.4833	-72.8833	2586
Mar2	88	-39.5833	-73.0500	2486
Pan1	434	-39.7333	-72.3333	3202
Pan2	309	-39.6167	-72.4667	2975
RiB1	132	-40.3833	-72.8333	2857
RiB2	149	-40.2667	-72.9667	2727
Fut1	571	-40.0667	-72.3667	3338
Fut2	225	-40.1833	-72.5167	2854
Riñ1	803	-40.4167	-72.2500	3800
Riñ2	462	-40.3000	-72.2333	3246

The detailed methodology for the energy simulation, the technical characteristics of the Heating Ventilation Air Conditioning system (HVAC) and the house´s occupancy schedule is described in a previously published study [65]. Table 5 shows the main parameters for the energy simulation using an electric cooling/heating system in the dwelling and only the results of the energy simulation for heating because the energy consumption for cooling is almost zero in the study region [60,62].

Table 5. Parameters for energetic simulation of houses.

HVAC system	"Residential 14 SEER/8.3 HSPF Split/Packaged Heat Pump" with heating SCOP 2.43; SEER 4.10
Heating set-point temperature	20°C
Occupation	2 persons
Sensible heat gains per person	73.27 W
Latent heat gains per person	45.43 W
Outdoor airflow	Outdoor air per person – 2.36 L/s and per area – 0.30 L/sm^2

2.5. Energetically optimal thermal envelope of walls in the future

To carry out the estimation of the energetically optimal envelope of the house in the future, the following study stages have been followed: (i) determination of the optimal U-value of external walls for future periods, (ii) determination of the optimal thickness of 5 types of thermal insulators and (iii) evaluation of the carbon footprint of thermal insulators. The procedure used in each of the indicated phases is described below.

2.5.1. Determination of the optimal U-value of external walls for future periods

If national building regulations establish for the future the maximum limit allowed for the energy consumption of a house for heating, the effect of global climate change must be considered. Therefore, it was decided to use the results of the previous research [65], which determined the percentage value by which the heating energy consumption of the house under study will decrease under the conditions of climate change based on two scenarios (RCP2.6 and RCP8.5) for future periods. Table 6 shows average values (between scenarios RCP2.6 and RCP8.5) of the decrease in heating energy consumption of the house in the main cities of the study area. For the period 2020–2035 it was shown that the heating energy consumption will decrease between 9 and 10.5%, depending on the geographical location of the meteorological stations, compared to 2006. For the period 2035–50, the decrease will be between 13.5 and 16%.

According to the ECS it is necessary that houses in future periods have a heating energy consumption equal to or less than 90 kWh/m^2/year. For example, for Val1, if an optimal U-value for external walls, determined for 2006 and corresponding to a heating energy consumption of 90 kWh/m^2/year, is used, it would follow that, according to Table 6 , in the period 2035–2050, the heating energy consumption would be 76 kWh/m^2/year, corresponding to a reduction of 15.5% compared to 2006. For this reason, an optimal U-value of 106.5 kWh/m^2/year for the year 2006 should be used for a consumption reference point (Table 6), since in the period of interest (2035–2050) the energy consumption will decrease by 15.5%, reaching 90 kWh/m^2/year, the maximum permitted by the ECS. Thus, in the present investigation, the search for optimal U-values of external walls was implemented such that the house had a heating energy consumption of 90 kWh/m^2/year during two future periods of time in different areas of the Los Ríos region.

Table 6. Estimated percentage decrease in energy consumption (average between RCP2.6 and RCP8.5 projections) according to [65] *and reference values for heating energy consumption.*

ID	Decrease in energy consumption for heating compared to 2006, [%]		Reference value of heating energy consumption to define optimal U-value, [kWh/m^2/year]	
	2020-2035	2035-2050	2020-2035	2035-2050
Val1	10.5	15.5	100.6	106.5
Val2	10.5	15.5	100.6	106.5
Cor1	10.5	16.0	100.6	107.1
Cor2	10.5	16.0	100.6	107.1
Pal1	9.5	14.5	99.4	105.3
Pal2	9.5	14.5	99.4	105.3
LaU1	10.0	15.0	100.0	105.9
LaU2	10.0	15.0	100.0	105.9
LaR1	9.0	14.0	98.9	104.7
LaR2	9.0	14.0	98.9	104.7
Lan1	10.0	15.5	100.0	106.5
Lan2	10.0	15.5	100.0	106.5
LoL1	9.5	14.5	99.4	105.3
LoL2	9.5	14.5	99.4	105.3
Maf1	10.5	15.5	100.6	106.5
Maf2	10.5	15.5	100.6	106.5
Mar1	10.5	15.5	100.6	106.5
Mar2	10.5	15.5	100.6	106.5
Pan1	9.0	13.5	98.9	104.0
Pan2	9.0	13.5	98.9	104.0
RiB1	10.0	14.5	100.0	105.3
RiB2	10.0	14.5	100.0	105.3
Fut1	9.0	13.0	98.9	103.4
Fut2	9.0	13.0	98.9	103.4
Riñ1	9.0	14.8	98.9	105.6
Riñ2	9.0	14.8	98.9	105.6

2.5.2. Determination of the optimal insulation thickness for future periods

Once the optimal U-values for the future were determined, the optimal thicknesses of 5 different types of thermal insulation for external walls were explored. To carry out this phase of the research, two modifications were made to the construction solutions (Table 3) of the external walls of the existing house: (i) lingue wood was replaced by a more popular, accessible and economical type of timber, insigne pine (41x90mm) of λ = 0.104 W/mK and ρ = 410 kg/m^3 and (ii) gypsum board of ρ = 650 kg/m^3 was replaced by gypsum board of λ = 0.31 W/mK and ρ = 870 kg/m^3, while the total thickness of the external walls remained unchanged (Table 7 compared to Table 3). These modifications were made because the existing house was built with timber that is not usually used in construction practices in Chile. The insigne pine wood frame and the highest density gypsum board in the structure of the external wall correspond to a structural solution recommended by the *Corporación Chilena de la Madera* (CORMA) (Chilean Wood Corporation) [69].

Table 7. Structural solution for external walls for restoration of optimal insulation thickness.

Insulation:				
	Thickness, [m]	λ [55,60], [W/mK]	R_t [55,60,66], [m²K/W]	U_{insul}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Thermal insulator	x_1	x_2	x_3	
Not ventilated air chamber	y_1		y_2	
Gypsum board 870 kg/m³	0.0150	0.31	0.0484	
$\sum$	0.1221		–	–
Frame:				
	Thickness, [m]	λ [55,60], [W/mK]	R_t [55,60], [m²K/W]	U_{frame}, [W/m²K]
Fibre cement siding 920 kg/m³	0.0060	0.22	0.0273	
OSB 690 kg/m³	0.0111	0.12	0.0925	
Insigne pine wood 410 kg/m³	0.0900	0.104	0.8654	
Gypsum board 870 kg/m³	0.0150	0.31	0.0484	
$\sum$	0.1221		1.0336	0.965

$U_{opt} = U_{insul.} \cdot 0.9 + U_{frame} \cdot 0.1$

The thermal insulators that were analysed in this study are (i) glass wool (λ = 0.042 W/mK; ρ = 11 kg/m^3), which was used in the existing house and is inorganic and recyclable; (ii) expanded polyurethane (λ = 0.025 W/mK; ρ = 40 kg/m^3), a flammable material that, when in contact with fire, releases toxic fumes, making it dangerous in the event of a fire, in addition to releasing greenhouse gases and containing non-renewable fossil fuel derivatives [70]; (iii) cork (λ = 0.039 W/mK; ρ = 40 kg/m^3), an organic, biodegradable and waterproof material that does not produce toxic gases in the event of fire; (iv) rockwool (λ = 0.040 W/mK; ρ = 100 kg/m^3), an inorganic and recyclable material; and (v) sheep wool (λ = 0.040 W/mK; ρ = 25 kg/m^3), an organic material that is biodegradable, sustainable and permeable to water vapour and which does not emit any type of irritating or harmful particle during its handling and use.

Glass wool insulation fully corresponds to a solution recommended by CORMA [69] and complies with all Chilean building and fire safety standards [71]. In addition, the construction solutions of external walls contain a non-ventilated air chamber. According to the Chilean standard, NCh853 [66], the correspondence between the thickness of the air chamber with horizontal thermal flow (y_1 in Table 7) and the value of R_t (y_2 in Table 7) should be as follows: 5 mm – 0.105 m^{2}K/W; 10 mm – 0.140 m^{2}K/W; 15 mm – 0.155 m^{2}K/W; 20-100 mm – 0.165 m^{2}K/W. Taking this into account for each optimal U-value of the external walls, optimal thicknesses of thermal insulators were calculated (x_1 in Table 7).

2.5.3. Estimation of carbon footprint of the insulation materials

To demonstrate differences in the carbon footprint that will be produced by the use of different types of thermal insulation, carbon footprint values from other investigations were used [72,73]. In these works, the environmental impact of insulation materials was analysed with the “cradle to gate” variant, according to the common Life Cycle Assessment (LCA) with the methodology of ISO 14040:2006. Carbon footprints for insulation materials were also compared with other studies [74,75]. Table 8 shows carbon footprint values for each insulation material studied.

Table 8. Carbon footprints of thermal insulation materials.

	Carbon footprint per mass, [kg CO_2/kg]	Ref.
Glass wool	1.35	[72]
Expanded polyurethane	4.30	[73]
Cork	0.60	[73]
Rockwool	1.05	[72]
Sheep wool	2.13	[73]

Based on these data, an analysis of the environmental benefits of the possible replacement of one wall insulation with another for future periods is presented. The calculation of carbon footprints was carried out in meteorological stations where it is possible to apply the 5 insulators for the construction solution of external walls presented in Table 7. The total surface of insulating external walls in the house under study is 75.3 m^2.

3. Results and discussion

Considering the work methodology described, first, the results of determining the optimal U-value of external walls are presented and analysed for the periods of the energy simulations. Then, the results of determining the optimal thickness of the 5 types of thermal insulators are presented to finally analyse the results obtained for the evaluation of the carbon footprint of thermal insulators.

3.1. Energy simulation and optimal U-value definition

3.1.1. Period 2006

First, the simulation results of the heating energy consumption of the house under study will be analysed (Fig. 5). This figure shows the relationship between the heating energy consumption and the U-value of the external walls. A clear linear relationship is observed between the two parameters: The angles of inclination of the lines decreases from the oceanic coast toward the interior of the region due to the continental effect of the climate. Table 9 shows the results of the intercept and slope values of the lines that describe the relationship between the value of heating energy consumption and the U-value of the external walls of the house in all meteorological stations selected for this study.

Using the formulas obtained for each meteorological station, the optimal U-values of the external walls were calculated such that the simulated house has a heating energy consumption of 90 kWh/m^2/year, as shown in Table 9. It can be seen that in the stations where the formula was found for heating energy consumption values greater than 90 kWh/m^2/year, it is impossible to find an optimal U-value (stations with a value of HDD18.3>3300). This is because the relationship between the U-value and the energy for heating acquires a non-linear dependence. In these stations, the house would need a change in the construction solution for external walls as well as improvements in other construction elements or the installation of more efficient HVAC systems. For example, in the case of Riñ2 and other geographic points with excessive energy consumption, it is possible to improve the SCOP of the HVAC system to achieve the desired level of energy consumption of the house under study. In addition, consideration should be given to replacing the original HVAC system with one that is more efficient in terms of the technological progress expected in the future. But, in present research, this type of approach will not be considered because of the scope of the study. This improvement may be considered in future studies.

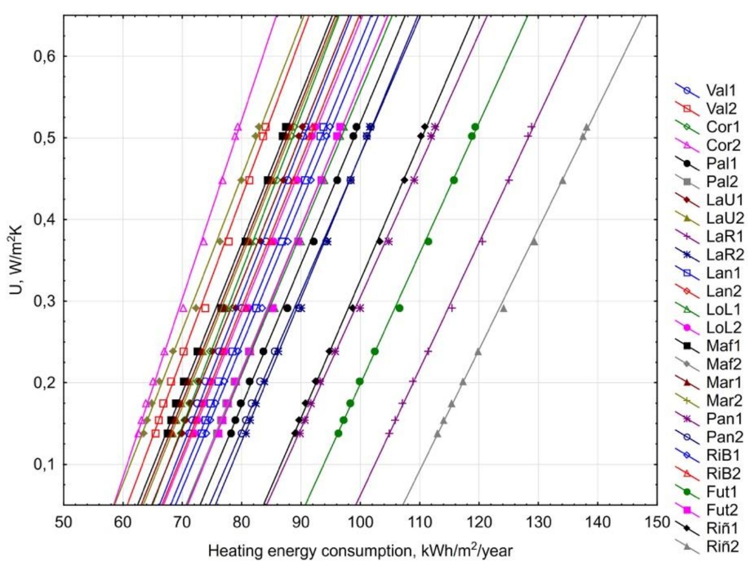

Fig. 5. Linear relationship between the U-value of external walls and the heating energy consumption of the studied house in different meteorological stations.

Table 9. Intercepts and slopes values for lineal relationships of Fig. 5.

	Intercept		Slope					
ID	Value	St. error	Value	St. error	R^2	HDD18.3	Energy consumption interval [kWh/m²/year]	Optimum U-value 2006, [W/m²K]
Val1	-1.17348	0.02822	0.01850	0.00035	0.99670	2602	71-91	0.492
Val2	-1.13632	0.02814	0.01954	0.00038	0.99660	2449	65-84	0.622
Cor1	-1.18471	0.02809	0.01902	0.00036	0.99683	2556	70-89	0.527
Cor2	-1.22447	0.02704	0.02182	0.00038	0.99751	2355	63-79	0.739
Pal1	-1.21293	0.02583	0.01731	0.00029	0.99742	2829	78-99	0.345
Pal2	-1.18904	0.02705	0.01756	0.00032	0.99738	2790	76-97	0.391
LaU1	-1.11602	0.02553	0.01799	0.00032	0.99712	2727	70-90	0.503
LaU2	-1.10940	0.02612	0.01828	0.00034	0.99696	2684	68-88	0.536
LaR1	-1.48548	0.02068	0.01548	0.00018	0.99881	3552	105-129	N/A
LaR2	-1.27305	0.02411	0.01752	0.00027	0.99792	2963	81-102	0.304
Lan1	-1.15458	0.02702	0.01771	0.00033	0.99695	2718	73-94	0.439
Lan2	-1.10122	0.02789	0.01827	0.00036	0.99650	2586	68-88	0.543
LoL1	-1.17528	0.02682	0.01731	0.00031	0.99707	2819	76-97	0.383
LoL2	-1.13972	0.02685	0.01782	0.00033	0.99692	2674	72-92	0.464
Maf1	-1.08682	0.02816	0.01822	0.00037	0.99636	2586	68-87	0.553
Maf2	-1.04525	0.02845	0.01871	0.00039	0.99605	2486	64-83	0.639
Mar1	-1.10122	0.02789	0.01827	0.00036	0.99650	2586	68-88	0.543
Mar2	-1.04525	0.02845	0.01871	0.00039	0.99605	2486	64-83	0.639
Pan1	-1.30618	0.02536	0.01611	0.00025	0.99779	3202	90-113	0.144
Pan2	-1.20451	0.02510	0.01683	0.00028	0.99753	2975	80-102	0.310
RiB1	-1.15542	0.02653	0.01752	0.00032	0.99706	2857	74-95	0.421
RiB2	-1.14688	0.02567	0.01799	0.00032	0.99721	2727	72-92	0.472
Fut1	-1.39861	0.02497	0.01597	0.00023	0.99808	3338	96-119	N/A
Fut2	-1.20909	0.02464	0.01776	0.00029	0.99764	2854	76-97	0.389
Riñ1	-1.35835	0.02397	0.01684	0.00024	0.99814	3246	89-111	0.157
Riñ2	-1.53583	0.02042	0.01480	0.00016	0.99890	3800	113-138	N/A

Next, the spatial distribution of the optimal U-value in the region for the study dwelling was considered. Fig. 6 shows the map of the distribution of this parameter. It is observed that when moving away from the ocean coast, the optimal U-value decreases, reaching its minimum in the mountain range. For example, the U-value should be equal to 0.65 W/m²K if the house is located in the city of Corral and approximately 0.40 W/m²K if the house is located in the city of Paillaco if the energy costs for heating are to reach 90 kWh/m²/year without any change to construction systems in the dwelling or HVAC systems. Such spatial distribution of the U-value for external walls is not in accordance with the recommendations proposed by the ECS. In this building standard, the most stringent construction recommendations for thermal transmittance are the characteristics of thermal zone G, located on the ocean coast. In other words, the ECS contains a climate logic mismatch in building zoning in the study region.

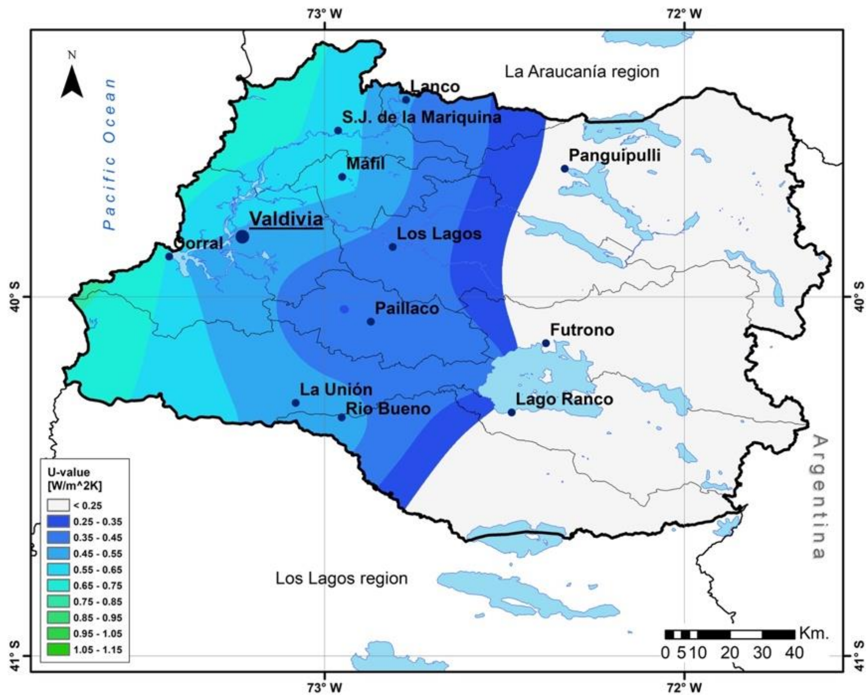

Fig. 6. Optimal U-value of external walls of the house under study with a heating energy consumption of 90 kWh/m^2/year in 2006.

3.1.2. Future periods

The results for the optimal U-value shown in the previous section are based on a simulation of energy consumption obtained based on GBS meteorological data for the year 2006. Next, the effect that climate change will have on them will be analysed.

Table 10 shows the optimal U-values for the external walls of the dwelling under study for different geographical points of the analysed region. In Fig. 7 the optimal U-value maps are presented, in which the dwelling under study will have a heating energy consumption equal to 90 kWh/m^2/year in the two future periods.

Table 10. Optimal U-value of external walls of the house under study for future periods in the different meteorological stations.

ID	Optimum U-value, [W/m²K] 2020-2035	2035-2050
Val1	0.687	0.797
Val2	0.829	0.945
Cor1	0.728	0.853
Cor2	0.970	1.113
Pal1	0.509	0.609
Pal2	0.557	0.659
LaU1	0.683	0.789
LaU2	0.719	0.826
LaR1	N/A	N/A
LaR2	0.460	0.560
Lan1	0.616	0.732
Lan2	0.726	0.845
LoL1	0.546	0.647
LoL2	0.632	0.736
Maf1	0.745	0.854
Maf2	0.836	0.948
Mar1	0.736	0.845
Mar2	0.836	0.948
Pan1	0.287	0.370
Pan2	0.460	0.547
RiB1	0.597	0.689
RiB2	0.652	0.747
Fut1	N/A	N/A
Fut2	0.547	0.628
Riñ1	0.307	0.419
Riñ2	N/A	N/A

For example, for the city of Lago Ranco, in the period 2020–2035, the optimal U-value of the external walls is equal to 0.30 W/m^{2}K (Fig. 7a), and for the period 2035–2050 (Fig. 7b) this value is 0.39 W/m^{2}K. The consideration of one of these values when implementing a project will help to maintain the average level of heating energy consumption in the house in accordance with the building codes recommendations for future periods. If the optimal U-value of the current period is used (Table 9), it can cause an excessive use of thermal insulating materials in the project realisation stage. This means that each year in the future, there will be a decrease in the value of heating energy consumption, which can change the energy rating of the house.

In any case, whether it is a positive or negative change in the energy rating of a building, the problem of considering changes in energy consumption for heating and cooling under future climate conditions arises. Therefore, this problem needs a more detailed study applied in different parts of the world [76].

Additionally, it can be noted that the methodology presented can have a practical application for clients, construction companies, public administrations, users, and so forth. Having only one housing model and only needing to transform the construction solutions of the external walls can make it energy efficient, in terms of national building recommendations, in the context of climate change and for a wide geographic area. This is a good example of the possibility of optimising the production, prefabrication and implementation of construction projects. Next, it will be shown how to get from an optimal U-value to the optimal thickness of the thermal insulation of a specific construction solution for external walls of houses.

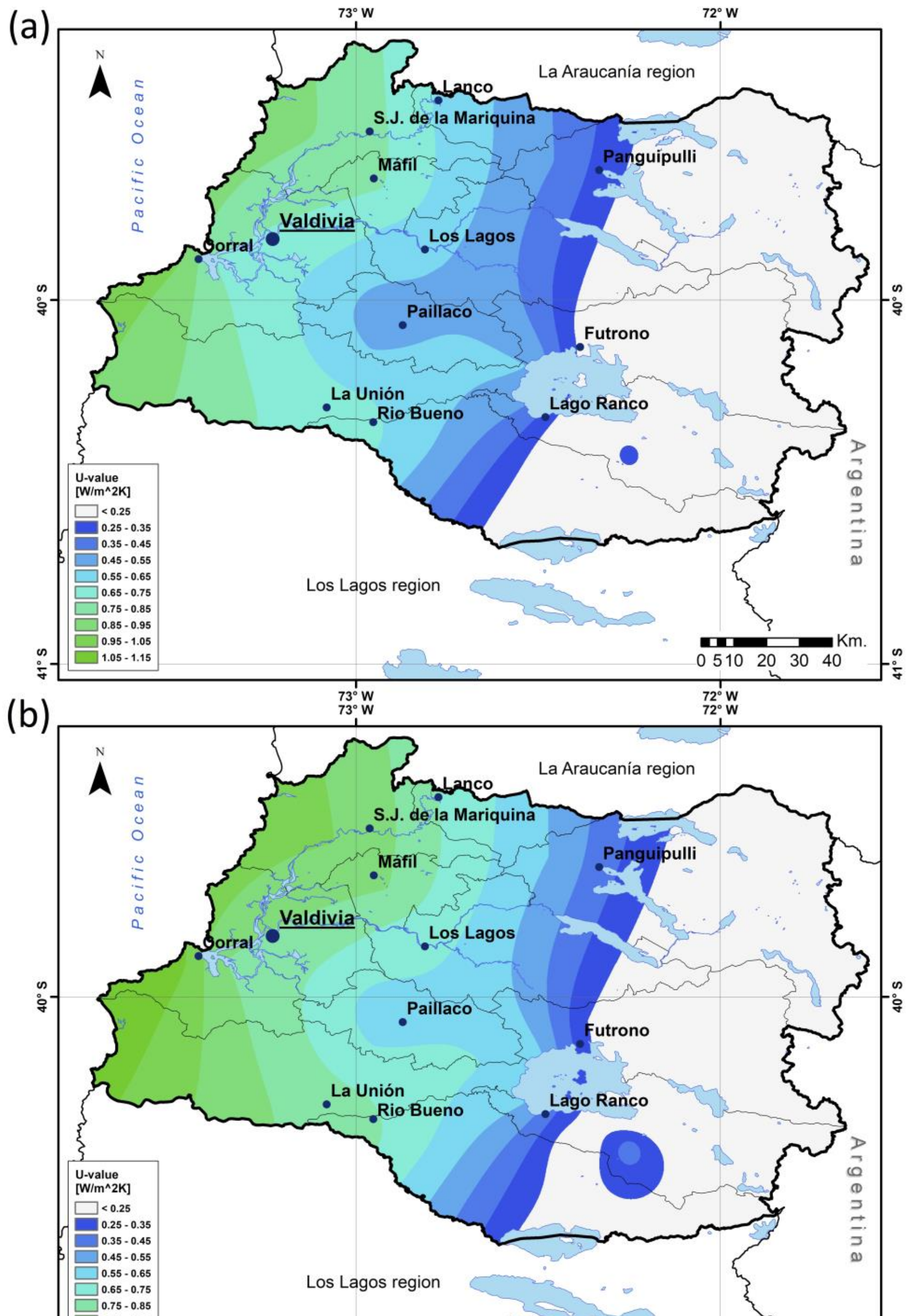

Fig. 7. Optimal U-value of external walls of studied house with a heating energy consumption of 90 kWh/m^2/year in the future periods of 2020–2035 (a) and 2035–2050 (b).

3.2. Optimal insulation thickness in future periods

Table 7 shows the results obtained in the calculation of the optimal thickness for the 5 thermal insulators in the construction solution, and Table 11 provides the optimal thicknesses for the 5 thermal insulation materials in the weather stations and for the two future periods for the construction solution with 41x90mm insigne pine wood frame.

Table 11. Insulation thickness (x_1) for the construction solution of external walls with timber frame 41x90mm (Table 7).

	2020-2035				2035-2050			
ID	Glass wool (λ=0.0424 W/mK; ρ=11kg/m³), e [m]	Expanded Polyurethane (λ=0.025 W/mK; ρ=40kg/m³), e [m]	Cork (λ=0.039 W/mK; ρ=40kg/m³), e [m]	Rock/sheep wool (λ=0.040 W/mK; ρ=100/25 kg/m³), e [m]	Glass wool (λ=0.0424 W/mK; ρ=11kg/m³), e [m]	Expanded Polyurethane (λ=0.025 W/mK; ρ=40kg/m³), e [m]	Cork (λ=0.039 W/mK; ρ=40kg/m³), e [m]	Rock/sheep wool (λ=0.040 W/mK; ρ=100/25 kg/m³), e [m]
Val1	0.051	0.030	0.046	0.048	0.040	0.024	0.037	0.038
Val2	0.038	0.022	0.035	0.036	0.031	0.018	0.028	0.029
Cor1	0.046	0.027	0.043	0.044	0.036	0.021	0.033	0.034
Cor2	0.030	0.017	0.027	0.028	0.023	0.014	0.022	0.022
Pai1	0.080	0.046	0.072	0.074	0.060	0.036	0.056	0.057
Pai2	0.069	0.041	0.063	0.065	0.054	0.032	0.049	0.051
LaU1	0.051	0.030	0.047	0.048	0.041	0.024	0.038	0.039
LaU2	0.047	0.028	0.043	0.045	0.038	0.023	0.035	0.036
LaR1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
LaR2	mod[1]	0.054	0.086	0.086	0.068	0.040	0.063	0.064
Lan1	0.059	0.035	0.055	0.056	0.046	0.027	0.042	0.043
Lan2	0.047	0.027	0.043	0.044	0.037	0.022	0.034	0.035
LoL1	0.071	0.042	0.065	0.067	0.055	0.033	0.051	0.052
LoL2	0.057	0.034	0.053	0.054	0.046	0.027	0.042	0.043
Maf1	0.045	0.026	0.041	0.042	0.036	0.021	0.033	0.034
Maf2	0.037	0.022	0.034	0.035	0.031	0.018	0.028	0.029
Mar1	0.046	0.027	0.042	0.043	0.037	0.022	0.034	0.035
Mar2	0.037	0.022	0.034	0.035	0.031	0.018	0.028	0.029
Pan1	N/A	mod.[3]	N/A	N/A	mod.[5]	0.074	mod.[8]	mod.[10]
Pan2	mod[2]	0.054	0.086	0.088	0.071	0.042	0.065	0.067
RiB1	0.062	0.037	0.057	0.059	0.050	0.030	0.046	0.047
RiB2	0.055	0.032	0.050	0.051	0.045	0.026	0.041	0.042
Fut1	N/A	N/A	N/A	N/A	N/A	mod.[7]	N/A	N/A
Fut2	0.071	0.042	0.065	0.067	0.058	0.034	0.053	0.055
Riñ1	N/A	mod.[4]	N/A	N/A	mod.[6]	0.061	mod.[9]	mod.[11]
Riñ2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

2020-2035: [1] LaR2 – 41x114mm timber frame with e=0.086 m of glass wool. [2] Pan2 – 41x114mm timber frame with e=0.086 m of glass wool. [3] Pan1 – 41x114mm timber frame with e=0.100 m of expanded polyurethane. [4] Riñ1 – 41x114mm timber frame with e=0.090 m of expanded polyurethane.

2035-2050: [5] Pan1– 35x124mm timber frame with e=0.115 m f glass wool. [6] Riñ1 – 41x114mm timber frame with e=0.098 m de of glass wool. [7] Fut1 – 35x124mm timber frame with e=0.118 m of expanded polyurethane. [8] Pan1 – 41x114mm timber frame with e=0.108 m of cork. [9] Riñ1– 41x114mm timber frame with e=0.090 m of cork.[10] Pan1– 35x124mm timber frame with e=0.108 m of rock/sheep wool. [11] Riñ1– 41x114mm timber frame with e=0.092 m of rock/sheep wool.

In the case of the use of glass wool, the minimum U-value of walls should be 0.492 W/m^{2}K (Table 7) when it is possible to use it as an insulator (8.5 cm thick) and maintain the energy performance of the dwelling. For this reason, in the period of 2006, the use of glass wool was possible only in 11 of the 26 geographical locations (Table 9); however, as can be seen in Table 11, for the two future periods 2020–2035 and 2035–2050 it will already be possible to use glass wool in 19 and 22 geographical locations, respectively (without changing the timber frame). In addition, for the LaR2 and Pan2 stations in the 2020–2035 period, there is the possibility of using glass wool if the 41x90mm insigne pine frame is replaced by a 41x114mm frame (use recommended by CORMA). Also, for the period 2035–2050, there is the possibility of using this type of insulation in the Riñ1 station with the same replacement of the timber frame. It was decided to show, using a cartographic method, the spatial distribution of the recommended optimal glass wool thickness values for the construction solution for external walls (Table 11). Fig. 8 presents the maps with the glass wool thickness that will guarantee a heating energy consumption of the house studied of 90 kWh/m^2/year for the two future periods. A clear increase in the thickness of the thermal insulation can be observed by moving from the ocean coast to the interior of the region and to the mountain range. In addition, the geographical area of the possible application of the proposed construction solution (Table 7) of using glass wool as an insulator will increase in the period 2035–2050 (Fig. 8b) compared to the period 2020–2035 (Fig. 8a).

Due to its low value of thermal conductivity (0.025 W/mK) compared to glass wool, the use of expanded polyurethane as a thermal insulator for external walls (Table 11) will allow the application of the proposed construction solution for external walls with a 41x90mm timber frame in the LaR2 and Pan2 stations in the 2020–2035 period and at Pan1 and Riñ1 stations in the 2035–2050 period. In this way, the replacement of insulation material will help to increase the geographical area of application of the construction solution for the external walls (Table 7). In addition, the geographical area could be further increased by replacing the timber frame with frames with larger dimensions, such as 41x114 mm or 41x124 mm. Finally, cork, rockwool, and sheep wool have thermal conductivities similar to glass wool. For this reason, there is not a great difference in the thickness values of these materials (Table 11), although there is in their environmental impact due to their diverse nature, so they will be analysed in the next section.

Also, based on the results and conclusions of this section, it should be noted that in the case of methodologies in which the insulation of the building envelope is improved and the HVAC system is replaced by a more efficient one in climates where heating prevails [77], the expected climate changes should be considered.

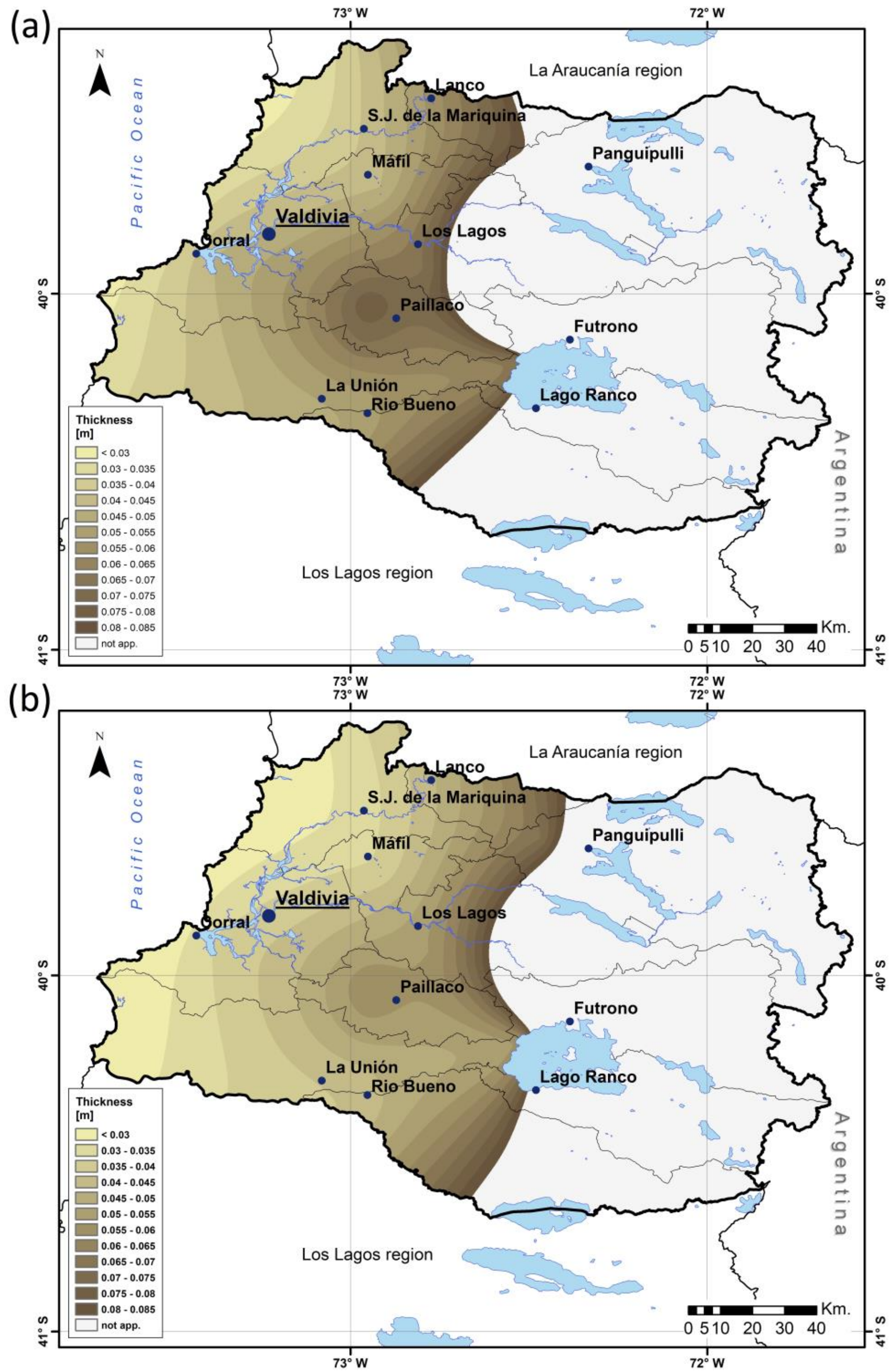

Fig. 8. Optimum thickness of glass wool insulation for the periods 2020–2035 (a) and 2035–2050 (b).

3.3. Carbon footprint of the insulation materials

The materials studied as insulation can be classified into three groups: (i) those of an organic nature, such as cork and sheep wool, characterised by being biodegradable, sustainable and not emitting any type of irritating or harmful particle during handling, use or in case fire; (ii) those of an inorganic nature, recyclable and non-flammable, which include fiberglass and rockwool; and (iii) expanded polyurethane, of inorganic and flammable nature, with toxic emissions in case of fire and release of greenhouse gases since it is manufactured with fossil fuels.

The use of each material will depend on the environmental responsibility of both the client and the construction company or construction agent that carries out the building [70]. The carbon footprint of each material will be analysed below (until the end of the production stage) according to the LCA and assuming that the house in the study is built in different geographical locations in the region. For this, the values of the estimates of the carbon footprint of insulating materials from current investigations, such as those of Soler *et al.* [73], are used. In the research of Resalati *et al.* the results of the evaluation of embodied carbon footprints in houses are shown but have great uncertainty [41]. These uncertainties depend on many factors and difficulties in carbon footprint estimation methodologies. Among these factors, there is one to determine in which life cycle stage the carbon footprint was evaluated – “cradle to gate,” “cradle to gate with options” or “cradle to grave.” Consequently, quantitative estimates of the carbon footprint are debatable results; however, percentage changes between time periods in the future can be considered sufficiently reliable results.

Table 12 shows the results of the calculation of the carbon footprint of the use of each material as thermal insulation for the proposed construction solution for external walls with a 41x90 mm timber frame. For the period 2020–2035, the average carbon footprint of glass wool insulation is 59 kg CO_2, the lowest carbon footprint of the materials studied. Replacing this material with rockwool would increase the average carbon footprint 6.7 times, while if materials of an organic nature are used this increase is 1.5 and 3.4 times for cork and sheep wool, respectively. In the case where the design of the house is made with a projection to the period 2035–2050, it is possible to minimise the carbon footprint of the materials used as thermal insulation by an average of 20% compared to the period 2020–2035. It was also noted that in order to expand the geographical area of application of external walls with a wooden frame of 41x90 mm, it is possible to replace glass wool with expanded polyurethane. Table 12 shows that the carbon footprint of expanded polyurethane is, on average, 6.8 times greater than the carbon footprint of glass wool. For this reason, it is advisable to apply the change of wooden frame as in the LaR2 and Pan2 stations for the period 2020–2035 (Table 11).

It should also be noted that due to the microclimatic diversity of the study area, it is important for each geographical point to find the optimum thickness of the thermal insulation, because the carbon footprint of the thermal insulation of the walls can be 2.54-2.71 times smaller at the warmest point in the study region (Cor2), compared to the coldest point (Pai1) (Table 12). This will help to implement of climate-responsible construction projects.

Of course, the contribution of thermal insulation to the total life cycle carbon footprint of existing homes in temperate climates is not as significant as, for example, operational energy use. But, in any case, the carbon footprint of all stages of the life cycle of residential houses is 5 times higher than acceptable values (not significant for the climate system). Therefore, any methodology to reduce the carbon footprint is useful for the product, maintenance and replacement stage, which represent up to 25% of the total life cycle carbon footprint of the housing [78].

Table 12. Carbon footprints [kg CO_2] of thermal insulation materials applied for housing in study and constructive solution of exterior walls (Table 7).

	2020-2035					2035-2050				
ID	Glass wool	Expanded Polyurethane	Cork	Rock wool	Sheep wool	Glass wool	Expanded Polyurethane	Cork	Rock wool	Sheep wool
Val1	57.0	388.5	83.1	379.5	192.5	44.7	310.8	66.9	300.4	152.4
Val2	42.5	284.9	63.3	284.6	144.4	34.7	233.1	50.6	229.3	116.3
Cor1	51.4	349.7	77.7	347.9	176.4	40.3	272.0	59.6	268.8	136.3
Cor2	33.5	220.2	48.8	221.4	112.3	25.7	181.3	39.8	173.9	88.2
Pai1	89.5	595.8	130.1	585.1	296.7	67.1	466.3	101.2	450.7	228.6
Pai2	77.2	531.0	113.9	513.9	260.6	60.4	414.5	88.6	403.2	204.5
LaU1	57.0	388.5	84.9	379.5	192.5	45.8	310.8	68.7	308.4	156.4
LaU2	52.6	362.6	77.7	355.8	180.4	42.5	297.9	63.3	284.6	144.4
Lan1	66.0	453.3	99.4	442.8	224.5	51.4	349.7	75.9	340.0	172.4
Lan2	52.6	349.7	77.7	347.9	176.4	41.4	284.9	61.4	276.7	140.3
LoL1	79.4	544.0	117.5	529.7	268.7	61.5	427.4	92.2	411.1	208.5
LoL2	63.7	440.4	95.8	427.0	216.5	51.4	349.7	75.9	340.0	172.4
Maf1	50.3	336.7	74.1	332.1	168.4	40.3	272.0	59.6	268.8	136.3
Maf2	41.4	284.9	61.4	276.7	140.3	34.7	233.1	50.6	229.3	116.3
Mar1	51.4	349.7	75.9	340.0	172.4	41.4	284.9	61.4	276.7	140.3
Mar2	41.4	284.9	61.4	276.7	140.3	34.7	233.1	50.6	229.3	116.3
RiB1	69.3	479.2	103.0	466.5	236.6	55.9	388.5	83.1	371.6	188.5
RiB2	61.5	414.5	90.4	403.2	204.5	50.3	336.7	74.1	332.1	168.4
Fut2	79.4	544.0	117.5	529.7	268.7	64.9	440.4	95.8	434.9	220.5

4. Conclusions

In the present research, a methodology was presented and implemented to determine the optimal U-value for external walls as well as the thickness of the insulating material through energy simulation in the context of maintaining the energy performance of the house under conditions of climate change. The implementation of this methodology was motivated by the fact that there was no evidence of studies in the scientific literature analysed that address the same set of problems. In the present study, the problem of accounting for information on the expected change in a dwelling's energy consumption in the future in the context of climate change was considered in the process of designing a dwelling. In addition, the need for a locally oriented approach was identified in the search for energetically optimum insulation to optimize the carbon footprint of this material in different geographical locations and under conditions of climate change. The main conclusions reached are summarised below:

- The optimal U-values were determined for the external walls such that the house under study will have a heating energy consumption equal to 90 kWh/m^2/year. The average value for the study region was 0.49$\pm$0.11 W/m^{2}K for 2006; 0.67$\pm$0.13 W/m^{2}K for the period 2020–2035; and 0.78$\pm$0.14 W/m^{2}K for the period 2035–2050.
- It was shown that, considering climatic changes, the geographical area of possible application of glass wool as an insulating material for the studied external wall construction solution is almost doubled for the period 2035–2050 compared to 2006.
- It was demonstrated that with just the replacement of the insulation material, it is possible to increase the geographical area of construction of the studied house model without changes in energy performance.
- In addition, a carbon footprint assessment was carried out on 5 external wall insulation materials, revealing that glass wool has the lowest carbon footprint of all the materials studied. By designing housing from an energy performance perspective with targets for 2035–2050, the carbon footprint can be reduced by 20% compared to 2020–2035.

- The results and methodology of this work demonstrate that the effects of climate change must be taken into consideration for methodologies where the search of the optimal thickness of the thermal insulation depends on the total carbon emissions, on the building operational carbon emissions or on the energy consumption of the house in the future.
- Finally, it should be noted that this research has a methodological orientation that can be developed to expand on the ideas that were used in this work. For example, it would be interesting to analyse the variations that occur in thermal comfort due to the choice of an exterior wall construction solution in future periods. Furthermore, the methodology presented has potential for application to different geographical areas of the world with different climatic conditions.

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CRediT authorship contribution statement

Konstantin Verichev: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Montserrat Zamorano:** Formal analysis, Investigation, Writing - review & editing, Supervision. **Armin Fuentes Sepúlveda:** Methodology, Software, Validation, Investigation, Data curation. **Nadia Cárdenas Mayorga:** Methodology, Writing - original draft, Investigation. **Manuel Carpio:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition.