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Affordable, Energy-Efficient Housing Design for Chile: Achieving Passivhaus Standard with the Chilean State Housing Subsidy

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Abstract: In Chile, it is estimated that the energy demand will continue to increase if substantial energy efficiency measures in housing are not taken. These measures are generally associated with technical and mainly economic difficulties. This paper aims to show the technical and economic feasibility of achieving Passivhaus standard house in Chile, considering the budget of the maximum state subsidy currently available (Chilean Unidad de Fomento (CLF) 2000 ≈ 81,000 USD). The design was simulated in the Passive House Planning Package software to determine if the house could be certified with the selected standard. At the same time, the value of all the items was quantified in order not to exceed the stipulated maximum budget for a house considered as affordable. It was shown that in terms of design it is possible to implement the Passivhaus standard given the current housing subsidy. The designed housing ensures a reduction of 85% in heating demand and a 60% reduction in CO_2 emissions during the operation, compared to an average typical Chilean house.

Keywords: energy consumption; building construction; Passivhaus; affordable housing

1. Introduction

The residential sector is responsible for 40% of global carbon dioxide, thus energy efficiency measures in this sector would help to support emission reduction targets for climate mitigation [1,2]. In Chile, the residential sector accounts for 30% of the primary energy consumption [3,4] with the majority of energy consumption used for space heating [5]. A study reviewing a representative sample of homes in Chile found that the majority are energy inefficient and do not offer adequate thermal comfort [6]. A total of 67% of the total housing stock in the last four decades was built with a housing subsidy or as part of the programs of Basic and Progressive Housing [7]. The housing subsidy is a state monetary contribution that allows families to purchase or construct a house, with the subsidy ranging between ≈35,000 and 81,000 USD, depending on the family's economic circumstances and the size of the house you want to build or buy.

Several authors have identified that the thermal insulation in the majority of homes built under the subsidy programme is insufficient or simply non-existent [6,8]. As such, significant focus is needed to improve the energy efficiency across the residential sector in Chile. Improved dwelling design has shown to reduce energy consumption as well as providing safer and more comfortable indoor environments. Current studies recommend a combination of bio-climatic design features, such as optimizing the orientation, size of glazing, effective ventilation, solar shading [9–11], combined with passive heating and cooling [12,13]. New architectural approaches [14] and supporting regulations are vital for an improved energy efficiency across the residential sector. In this regard, many high-income countries have established building regulations which have requirements for energy efficiency [15–17]. In 2000, Chile established thermal regulations that consider the energy performance of residential houses and stipulate minimum levels of the insulation [18]. However, these regulations are likely to fall short of achieving energy efficiency savings necessary to meet emission reduction targets.

There are several established standards and evaluation frameworks for supporting the design and assessment of energy-efficient housing. Conceived in Germany, the Passivhaus standard [19] was the first standard developed to achieve indoor thermal comfort with low energy demand, while reducing the CO_2 emissions throughout the useful lifecycle of the home; the Passivhaus standard has been commonly used for housing and is now established in many countries [20]. Other standards include the Minergie P standard [21] in Switzerland, the CasaClima standard in Italy, and the Association for Environment Conscious Building (AECB) standard in the UK.

The Passivhaus standard was originally designed for cold climates, and focused on Central and Northern Europe [20], but it has been proven that is possible to design Passivhaus buildings for different climate zones of the world [22]. A case study in a tropical climate (Malaysia) shows that a reduction of the solar radiation heat gain by wall and roof insulation, combined with shading measures, led to a significant reduction in cooling load in a Passivhaus [23]. A study in Australia demonstrated, through a year of monitoring, that a Passivhaus required 64% less energy than an average comparable house in the same city (Chifley) [24]. An evaluation of the building performance in several climates the Southern Hemisphere demonstrated that the requirements of the Passivhaus standard were fulfilled for all Southern Hemisphere cases [25]; the study was based on 38 different locations (including Santiago de Chile). A study realized in Russia considering seven different climates (Monsoon-influenced warm-summer humid continental Dwb, Subarctic climate Dfc, Warm-summer humid continental climate DfB, Tundra climate ET in the Köppen climate classification) show that all of the case studies complied with the Passivhaus standard with regards to the primary energy demand [26]. In general, different studies [22–30] have proven that the Passivhaus standard is suitable for different climates. Thus, Passivhaus could provide a useful guide to support the development of energy-efficient housing in Chile. However most of the studies are focused on the technical aspects, benefits of thermal comfort, and energy performance while approaches based on the costs associated with the construction of a Passivhaus are scarce [31,32]. Some authors have mentioned that economic aspects represent the greatest challenge for the application of the Passivhaus standard [33,34] and this challenge must be addressed individually in each country because the costs are not comparable between countries.

A previous study assessed the barriers and opportunities associated with the implementation of energy efficiency standards in Chilean social housing and determined that their implementation would not be economically feasible [4]; the study found that building in compliance with the Passivhaus standard has a higher cost per square meter [4] than a conventional house (ca. 30%). This has also been found in other countries with limited resources [34–36]. However, in the current market there is a wide variety of increasingly affordable insulation materials with low thermal conductivity.

This work aimed to evaluate the technical and economic feasibility of a Passivhaus dwelling in Chile, considering the current level of state subsidy for housing construction. We developed a design for a passive house in Chile and evaluated its affordability. In cases where construction costs are unaffordable to families, it is of vital importance to know what construction standards can be achieved. In this sense, this study aims to show the possibility of building an affordable dwelling with low energy demand.

2. Materials and Methods

2.1. Location

According to MINVU (Ministerio de Vivienda y Urbanismo, Ministry of Housing and Urbanism) statistics, more than 35% of the housing subsidies are used in Santiago [37]. Additionally, Santiago is located in the climate zone with average temperatures and has the largest number of dwellings in Chile. Furthermore, between 2011 and 2016 of the 36,000 housing subsidies delivered through the subsidy programme (see Section 2.2) around 13,500 (≈38%) were delivered in the Metropolitan Region of Santiago. Therefore, the case study Santiago was selected as it better represents the national residential housing stock and it is expected to have the greatest concentration of subsidized housing.

Santiago can be classified as a Mediterranean climate (Csb) in the international Köppen climate classification. According to the Chilean Meteorological Office [38], the average minimum temperature in Santiago in the last decade was 7.9 °C (normally in June) and the average maximum temperature was 21.8 °C (always in January). The average solar global radiation fluctuates between 68 and 252 KWh/m^2·month [39], the average relative humidity is 74%, and air velocity is 4 m/s [25].

The Passive House Planning Package (PHPP) provides climate data for Santiago. In Figure 1, it can be seen that the outdoor temperature reaches its highest level in the months 6 (December in this study) to 8 (February in this study); the lowest temperature occurs in months 12 (June in this study), 1 and 2 (July and August in this study). Correspondingly, the highest level of solar radiation occurs in the hottest months.

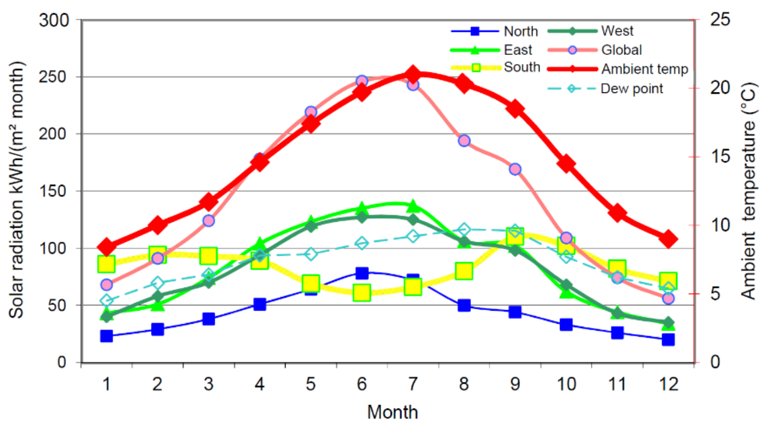

Figure 1. Solar radiation and outdoor temperature, monthly average. Climate Santiago, Chile. Note: For this study month 1 is July and month 7 is January. Data extracted from simulation in Passive House Planning Package (PHPP).

2.2. Affordability

In the last decade, the housing price index in Chile increased by 30% [40], while the median per capita income increased by 6% [41]. For this reason, the state subsidy in Chile is of great importance to support the purchase and construction of affordable housing. There are currently four subsidies for the purchase or construction of houses, which depend on the available budget and the degree of social vulnerability of the applicants. With subsidy DS 49 it is possible to buy or construct a house of up to 35,000 USD and with subsidy DS1 parts 1, 2, and 3 with which it is possible to buy or construct a house of up to 40,000 USD, 55,000 USD, and 81,000 USD respectively. Here it is important to note, that the construction of a traditional house in Chile costs on average 41,000 USD [42].

This paper presents the development of an affordable dwelling for a family in Chile, taking into consideration the highest subsidy (DS1) currently available for building a house. The subsidy DS1 offers a maximum budget of 2000 CLF/81,000 USD (CLF = Unidad de Fomento, CODE CLF according to ISO 4217 is a Unit of amount that is used in Chile adjusted with the inflation. A total of 2000 CLF is currently equal to approximately 81,000 USD). These resources were allocated towards a highly insulated thermal envelope and for the purchase of equipment required to meet the criteria of the Passivhaus Standard. This paper evaluates if the subsidy DS1 allows the construction of a Passivhaus dwelling with a floor area of 100 m^2.

2.3. Development of Design

The proposed dwelling was simulated with PHPP, the calculation tool used to evaluate the compliance of designs with the Passivhaus standard. At the same time, a financial plan for the construction of the house was calculated, considering all the costs associated with the construction in order not to exceed the maximum available budget determined by the subsidy. Within the design stage, the following aspects were considered:

(a) Architecture

For the architectural design of the dwelling (Figure 2), a compact, single-level house was considered. A certified Passivhaus professional using the principles of bioclimatic design developed the concept. The compact rectangular shape reduces the thermal energy losses by transmission because of the smaller number of surfaces exposed to the outdoor environment and by minimizing the number of thermal bridges. The majority of glazing is found on the north façade, as this will provide solar gains for heating that will be key for a low energy demand in winter. This is because Santiago is in the southern hemisphere and therefore the north façade provides most solar gains. The opposite case occurs in the Northern hemisphere where preferable planning window is in the south façade for solar gains.

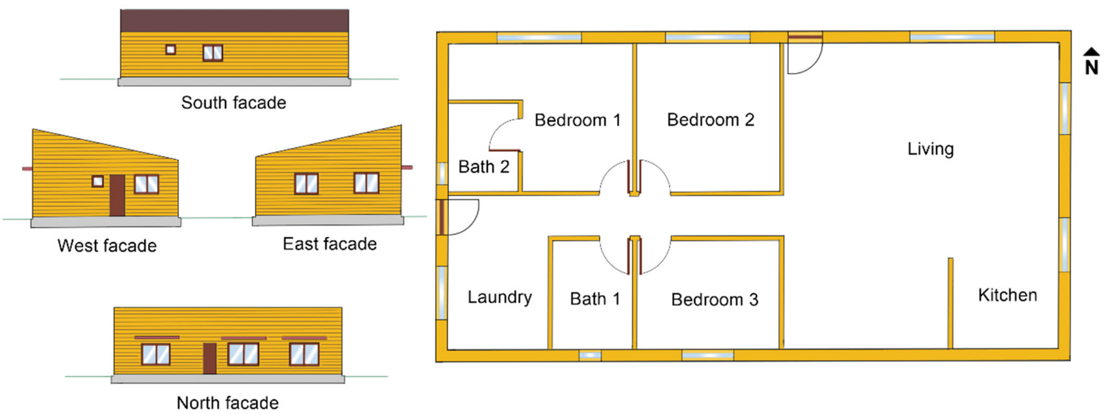

Figure 2. The architectural design of the house. Note: For data entry into PHPP, the cardinal direction "North" was changed by 180°. This is the recommended approach for buildings in the Southern hemisphere as per the PHPP User's Manual.

The designed dwelling consists of the same number of rooms as a conventional three-bedroom house, with two bathrooms, a kitchen, a living-dining room, and a space for laundry and a desk. Most living areas, such as the living room and bedrooms, were located on the north side to maximize the occupants' exposure to sunlight, leaving the services on the south side. Additionally, the number of internal divisions was minimized to reduce the junctions between internal partitions and perimeter walls and to avoid possible thermal bridges. The plot area is 112 m^2 while the useful floor area is 100 m^2, as the thickness of the perimeter walls covers about 12 m^2 of the plot area.

(b) Thermal envelope

For the thermal envelope, the design aimed to minimize the energy losses, with a particular focus on reducing thermal bridges. The external walls were composed of two elements separated with pieces of impregnated pressure-vacuum (IPV) timber; the design includes two 15 mm-thick Oriented Strand Boards, which support the load, hence avoiding the use of crosses and diagonals that would increase heat transmission (Figure 3). The system designed for the external walls allows having an envelope with continuous thermal insulation and with uniform thickness throughout its length, even in the corners of the wall, with the aim of minimizing the thermal bridges (seeing Appendix A). The insulating material corresponds to 120 mm-thick mineral wool, of density 40 kg/m^3 and a thermal conductivity of 0.042 W/(mK). Using the PHPP spreadsheets, it was determined that the thermal transmittance of the perimeter walls is 0.244 W/(m^{2}K). This represents a much lower value than what is required by the Chilean building regulations (Urban General Urban Planning and Construction Ordinance [18]), and even lower than that required in the areas where additional requirements related to thermal transmittance are applied due to the Atmospheric Decontamination Plan for particulate matter [43] (see the example for Temuco and Padre Las Casas in Table 1). It is noted as a disadvantage that the total thickness of the perimeter wall is 24.5 cm, so that multiplied by the perimeter of the house results in an area of approx. 12 m^2, which must be removed from the living area of the house. In Chile, a typical thickness of a wall is 14 cm [5].

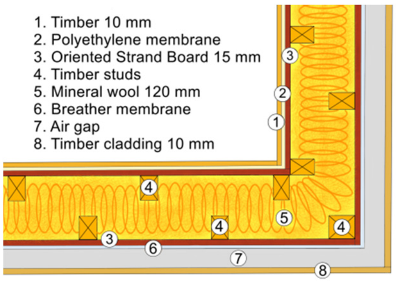

Figure 3. Detailed perimeter wall, plan view. Own elaboration.

Table 1. Requirements of transmittance and thermal resistance for elements of the envelope according to Article 4.1.10 General Urban Planning and Construction Ordinance and according to the Atmospheric Decontamination Plan for the communes of Temuco and Padre Las Casas in Chile.

Zone	Roofing		Walls		Floors	
	U	R_{TOT}	U	R_{TOT}	U	R_{TOT}
1	0.84	1.19	4.00	0.25	3.60	0.28
2	0.60	1.67	3.00	0.33	0.87	1.15
3	0.47	2.13	1.90	0.53	0.70	1.43
4	0.38	2.63	1.70	0.59	0.60	1.67
5	0.33	3.03	1.60	0.63	0.50	2.00
6	0.28	3.57	1.10	0.91	0.39	2.56
7	0.25	4.00	0.60	1.67	0.32	3.13
PDA Temuco, Padre las Casas	0.28	3.57	0.45	2.22	0.50	2.00

Thermal transmittance values U in W/m^{2}K and total thermal resistance values in m^{2}K/W. The proposed PassivHaus is located in zone 3.

The ceiling was considered timber-framed with 50 × 50 mm joists, 120 mm mineral wool thermal insulation, and Oriented Strand Board (OSB) on the inside. As in the walls, the thermal insulation layer is available in a continuous and uniform thickness (Figure 4). To calculate the thermal transmittance, only the ceiling structure and the insulating layer are considered, and the attic space and roof are not considered, due to their little influence on the calculations as recommended by the PHPP manual. The thermal transmittance obtained for the ceiling is 0.238 (W/m^{2}K).

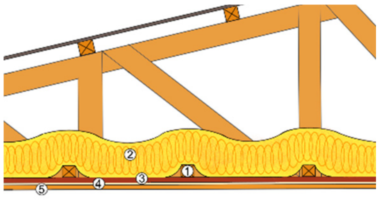

Figure 4. Ceiling cross-section, view in section. Own elaboration.

The construction for the floor (Figure 5) consists of expanded polystyrene of high density (20 kg/m^3) in a thickness of 100 mm on a screed of 300 mm and on it a solid floor layer of 100 mm of lightweight concrete with low thermal conductivity. To break the thermal bridge that occurs in the wall–floor junction, a layer of additional insulation (polyurethane in a thickness of 40 mm and height of 100 mm) is placed between the footplate and the wall. With this, it was determined that the linear thermal transmittance value at that point is negative (see Appendix A). The concrete of the foundation and sole plate are based on light aggregates of expanded clay, which has a thermal conductivity of 0.330 W/(mK). With this construction, a value of 0.307 W/m^{2}K was obtained for the thermal transmittance of the floor.

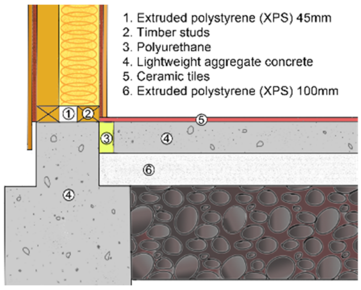

Figure 5. Details of the wall–floor junction, view in section. Own elaboration.

The climate classification used in Table 1, is according to the Chilean national Norm Ordenanza General de Urbanismo y Construcciones (General Urban Planning and Construction Ordinance), which establishes thermal zoning for new housing designs located in different regions of the country. According to the Instituto Nacional de Estadisticas of Chile [44], it is possible to link the national climate classification to the international Köppen climate classification. For example, the north (Zone 1) and south of Chile (Zone 7) can be classified as Arid desert climate (BWk) and Oceanic climate (Cfc), respectively. In this sense, the location considered in this work (Santiago, Zone 3) can be classified as a Mediterranean climate (Csb).

(c) Thermal bridges

The PHPP recommends the identification and classification of thermal bridges. In addition, to determine the energy demand, the linear transmittance with its respective length in meters must be determined. In this work the coefficients of linear transmittance were determined with the THERM software, in accordance with ISO 10211:2007. The results are presented in Appendix A. Here we sought to minimize all the geometric thermal bridges.

(d) Windows and shading

To optimize passive solar gains, it is essential to know the predominant elevation angle of the sun in winter and summer. Figure 6 shows the predominant elevation of the sun in the city of Santiago (33° in winter and 79° in summer). The design of the house considered an eave of 50 cm and an overhang on the north-facing window of 30 cm. In summer, these measures protect a large part of the north wall from direct solar radiation; in winter, all the north-facing windows receive direct solar radiation. It considered eaves only in the north façade, because the radiation does not arrive with such intensity in the east and west façades, as it is present only in the early hours of the morning and the late hours of the afternoon where the temperature is on average 13 °C [45]. The south façade is not exposed to direct radiation throughout the day; it only receives diffuse and reflected radiation, which has a lower influence on energy use. In the north-facing windows, solar gains were 972 kWh/yr, while transmission losses reached 698 kWh/yr.

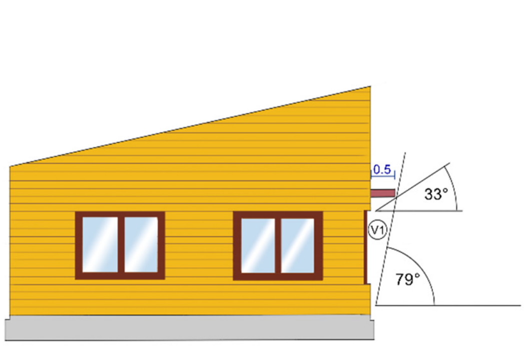

Figure 6. Shading produced by eaves on the north façade of the building. Own elaboration.

The windows considered in this work correspond to double glazing with timber frame with a U-value = 1.8 W/m^{2}K and g = 0.74 which is currently available in the Chilean market [46]. This type of windows has a transmittance that is 38% lower than that established as the limit for traditional windows (2.9 W/m^{2}K) in current Chilean regulations [47].

(e) Ventilation with heat recovery

The value of the total volume enclosed in the house designed is 245 m^3, so to ensure the air renewal required by the Passivhaus standard was considered an ECOWATT series fan, with heat recovery, high efficiency (between 86% and 92%), with a maximum air renewal flow rate of 325 m^3/h and consumption of less than 40 W. The building is heated with a Compact Heat Pump System (Aerex—PHK 180). For this heat pump, the effective heat recovery efficiency is 80% and useful air flow rates are 130–230 m^3/h with a COP_{heat} between 2.85 and 3.31.

2.4. Simulation Method

The designed house was simulated and evaluated with the calculation software PHPP (Passivhaus Planning Program) version 8.5, which is an extensively tested and validated simulation tool and is used to verify the fulfilment of the requirements for Passivhaus certification.

Although the Passivhaus standard establishes fixed energy demand limits for building design, this is rather a general concept aimed at achieving thermal comfort by heating or cooling an air volume with guaranteed quality [48]. In this sense, the design and execution of homes with Passivhaus standard have an unlimited number of constructive solutions; however, the following requirements must be met:

(a) Maximum annual energy demand for heating or cooling: 15 kWh/m^2.
(b) Annual total energy consumption for all systems (heating, cooling, hot water, electricity) not exceeding 120 kWh/m^2.
(c) Test of air tightness at n50 not higher than 0.6/h, value obtained by the “Blower Door” test.
(d) Interior surface temperatures of the thermal envelope during winter >17 °C and <25 °C during summer.

This study also considers the indoor set-point temperatures to be 20 and 25 °C in winter and summer, respectively.

The certification of a house with Passivhaus standard can be obtained through the PassivHaus Institut, attaching the PHPP spreadsheets, executive project documentation, technical information, air tightness test according to UNE EN 13829 standard, balance protocol ventilation system, inspection, and photographic documentation of the work. This paper considers the design stage, where PHPP is used to design a building that complies to points a, b, and d.

2.5. Costing of Design

The design of the house presented in this paper did not only consider meeting the criteria established for a Passivhaus but also a limited budget within what is regarded as affordable housing (construction budget not greater than CLF 2000 ≈ 81,000 USD). Here, CLF was used for two reasons: (a) the amount of the subsidy is delivered in that currency; (b) the value of CLF is adjusted monthly based on the Consumer Price Index (CPI), which is used to measures changes in the price level of the market of consumer goods and services purchased. The CLF is the principal measure to determine the real values of housing and any secured loan (monetary item), either private or of the Chilean government.

The calculation of the cost of the proposed house is carried out under a Unit Price Analysis based on the software ONDAC [49]. Here the price for workers, materials, transport, and tax is considered, these are based on the current market rates for construction in Chile.

The Unit price in ONDAC as well the real value of the subsidy are monthly actualized. This implies that, if the costs vary in the construction phase of housing in the future, the budget would be adjusted and covered by the amount delivered in the subsidy.

3. Results

Based on the PHPP tool under the climate conditions for the case study proposed here, energy is required only for heating. The summary of the results obtained from the PHPP (Appendix C) show that both the energy demand in heating, the heating load, and the percentage of overheating time are below the established requirements of the standard. (Table 2).

Table 2. Results and verification of compliance requirements Passivhaus (see Appendix C).

Parameter	Results	Passivhaus Requirement	Standard Compliance Passivhaus
Annual heating demand	10 kWh/(m^2)	≤15 kWh/(m^{2}a)	Yes
Heating load	8 W/m^2	≤10 W/m^2	Yes
Thermal bridges ΔU	0.1 W/(m^{2}K)	-	-
Overheating frequency	7.8%	≤10%	Yes
Annual total energy demand	120 KWh/(m^2)	≤120 kWh/(m^{2}a)	Yes

Implementing Passivhaus standard as affordable housing, specifically in Santiago, would result in a significant reduction in energy demand and CO_2 emissions. However, to demonstrate that the standard can be implemented in colder climates, a simulation of the same house was also carried out in the Temuco climate, where the ambient temperature is on average 3.3 °C lower. The results show that the same house that has an annual energy demand of 10 kWh/m^2 for heating in the city of Santiago, whereas in Temuco it has a demand of 24 kWh/m^2. To comply with the annual heating energy demand limit (15 kWh/m^2), the surface area of the windows in the north façade was increased by 7.8 m^2 and an additional 10 mm thickness was added to the outer wall covering of the perimeter wall. The cost of this change means an initial budget increase in CLF 75 to a total CLF 1848, which does not exceed the budget limit (CLF 2000 ≈ 81,000 USD).

In Table 3, it is observed that the thermal transmittance of the walls of the designed housing represents one-eighth of the thermal transmittance required by the norm, while for the roof this was reduced by half. It is further observed that the regulations establish a maximum value of glazed surface (60%) without breaking it down according to geographical orientation.

Table 3. Comparison between conventional housing characteristics and the designed Passivhaus.

	Conventional Housing Values Based on [18,48]	Passivhaus Housing
	Value U (W/m^2K)	
Walls	1.9	0.244
Roof	0.47	0.238
Solid floor	Does not apply *	0.307
	% Window surface	
Total (DGU 2.4 < U < 3.6 W/m^2K)	60% max	14%
North facade	Does not apply **	26%
Air changes/h	8/h	0.6/h

* The regulation does not consider values of thermal transmittance for floor in contact with the ground, only delivers values for ventilated floors, for thermal zone 3, for example, consider a thermal transmittance value of 0.7 W/m^2K. ** In the regulation surface of windows oriented towards the north is not considered, considers percentages in relation to the total surface of vertical walls.

For the complete execution of the house, a total budget of CLF 1773 (≈80,000 USD) was estimated (Appendix B). The per square-meter cost of the designed house is CLF 15.83 (approximately 640 USD/m^2). A conventional house can be a maximum of 140 m^2 with a total budget of CLF 2000 (≈81,000 USD). If the proposed house had a maximum area (140 m^2) the total cost would be CLF 2,216 (≈90,000 USD) and thus 10% higher than the maximum allowable subsidy. Therefore, achieving Passivhaus, while affordable given the current subsidy, may result in some restrictions to dwelling sizes particularly in the colder climate zones of Chile. Nevertheless, it is expected that the construction of affordable housing with the Passivhaus standard could represent a significant potential for energy savings in the residential sector.

4. Discussion

This study demonstrated the possibility of building a house considered as affordable in Chile with a budget less than CLF 2000 (≈81,000 USD) with the Passivhaus standard. It should be clarified that this study only considered costs relating to labor and material cost during the construction phase. The additional costs of managing, designing, or additional checks/testing were not considered due to the scarcity of data related to these aspects in the Chilean market. Consequently, it is necessary to focus efforts on gathering data to determine these additional potential costs related to the design and checks to achieve Passivhaus house. As awareness of Passivhaus increases within Chile and becomes more commonly practiced, it is likely that these costs will not significantly differ from current practices.

Another important aspect to discuss is the designed dwelling energy performance and its comparison with existing homes. Hatt et al. (2012) demonstrated that a standard house based on the Thermal Normative in Chile requires at least 86 kWh/m^2a for heating energy consumption [6]. If we consider a 100 m^2 house located in Santiago with a referential annual energy demand of 86 kWh/m^2a, the proposed Passivhaus represents just 11% of the standard house energy demand. The proposed design complies with the allowable Passivhaus energy consumption with thermal transmittance values (Table 3) that are likely too high for cold climates [22]. This has been similarly demonstrated by other authors that have shown that in warmer climates it is possible to reach the passive standard with higher values of thermal transmittance compared to cold climates [6,24].

Although it was possible to demonstrate the construction of Passivhaus within the current state subsidy, we found that there is likely to be a restriction in dwelling size. This restriction is likely to be more pronounced in cold climate regions of Chile, where average temperatures are much lower and may lead to issues of overcrowding if subsidy costs cannot be increased for these regions. For the construction of a traditional house compared one that complies with Passivhaus standard, a substantial difference in construction costs are noted (Appendix B). The initial cost of the Passivhaus is more than 40% higher than that of traditional Chilean housing in the construction phase. This is in line with similar work who found that achieving compliance with Passivhaus standard has around 30% higher cost per square meter [4]. In this study, the city of Santiago with a Mediterranean climate (Csb) was considered. It is expected that in the south of Chile, which experiences colder climates, greater investment will be needed to reach Passivhaus standard. Further work is needed to assess the viability of achieving energy efficiency housing given the available subsidy across all climate zones in Chile.

The annual energy cost of Passivhaus housing is cheaper compared to that of traditional housing, which leads to a lower accumulated cost of the Passivhaus over the years. Figure 7 shows the comparison of the accumulated cost (initial + operational) over 30 years for a Passivhaus and a traditional housing for the Chilean case (Appendix B). Both houses have the same floor area (100 m^2), for the Passivhaus a heating energy consumption of 10 kWh/m^{2}a was considered (Table 2) and for a traditional house an average heating energy consumption of 120 kWh/m^{2}a based on CDT, 2010 [5]. For both cases, electricity was considered as an energy source with a price of 0.18 USD/kWh. Approximately, in year 17 the accumulated costs are equivalent. After this period, the Passivhaus is economically more profitable, having 20% less of the accumulated cost for the year 30.

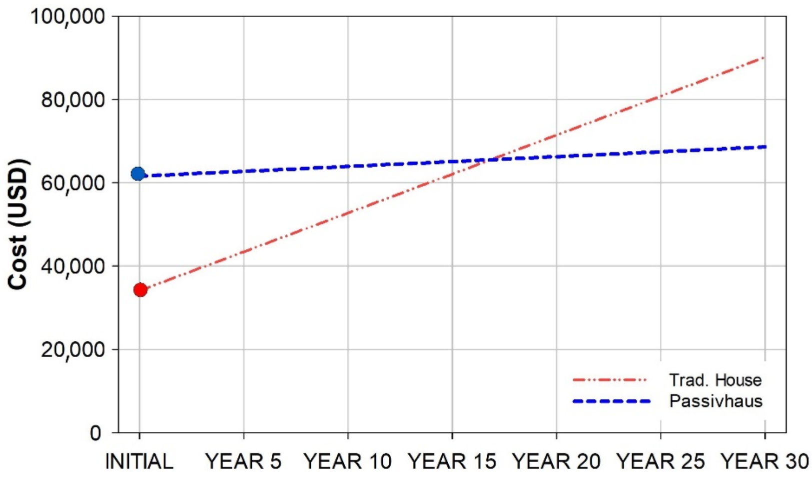

Figure 7. Accumulated annual energy cost of traditional house and Passivhaus. For the initial time, only the construction costs are considered (Appendix B).

5. Conclusions

In this paper, a house with the Passivhaus standard was designed with a budget of less than CLF 2000 (≈81,000 USD) in order to frame it within the subsidy program for affordable housing in Chile. The simulation of the housing design was made with the PHPP calculation software, which contains the requirements of the applied standard and finally defines if the house could be certified.

The construction materials proposed have a low thermal transmittance of the elements of the envelope. For example, in perimeter walls, a value of 0.244 W/m^{2}K was obtained, which represents a transmittance eight times less than what is required by regulation in the climate zone where the house was designed (Santiago). In addition, construction solutions were developed aimed at avoiding geometric thermal bridges and optimizing solar gains utilizing the appropriate percentage of the surface area of facing north windows.

It was demonstrated that in terms of design and construction costs, it is possible to develop an achieve Passivhaus standard of 112 m^2 within the Chilean state Subsidy of CLF 1773 (≈80,000 USD) to build a house. It was determined that the value of building with this standard reaches 640 USD per square meter. Although it was possible to achieve Passivhaus standard, it is likely to lead to a restriction in the floor area of a dwelling particularly in colder climate zones of Chile. Nevertheless, implementing Passivhaus standard would likely achieve a reduction in energy demand of 85% compared to a typical house in Chile (≈120 KWh/m^2). This is not only important for the economy of the individual families from weaker socio-economic groups but also it would help to significantly reduce energy consumption in Chile's residential sector.

Author Contributions: Conceptualization, A.M.-S.; Methodology, A.M.-S. and E.N.; Research, A.M.-S. and Y.S.-L.; Writing Y.S.-L. and V.M.; Review and Editing, V.M. and E.N. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Thermal Bridges.

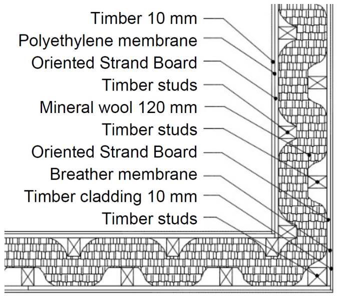
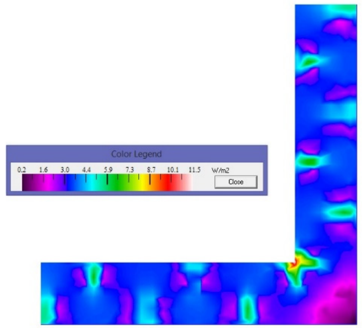
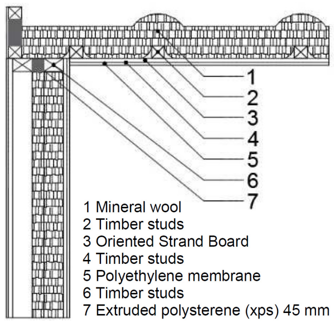
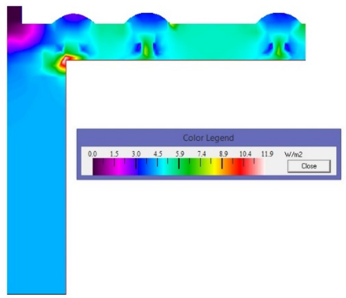
<table>
<tr><th></th><th>Identification of the Thermal Bridge</th><th>THERM of Simulation</th><th>Linear Thermal Transmittance (W/mK)</th></tr>
<tr><td rowspan="3">Vertical</td><td colspan="3">1. Corner of Wall</td></tr>
<tr><td>
</td><td></td><td>Ψ = −0.164</td></tr>
<tr><td colspan="3">1. Result: when simulating the thermal bridge with the THERM software and calculating the linear thermal transmittance, a negative value is obtained, therefore, it can be verified that the thermal bridge was broken and there was even a point improvement in the thermal envelope, allowing to have less energy flow at that point.</td></tr>
<tr><td rowspan="3">Horizontal</td><td colspan="3">2. Wall and roof</td></tr>
<tr><td>
</td><td></td><td>Ψ= −0.093</td></tr>
<tr><td colspan="3">2. Result: the simulation of the thermal bridge in the wall–sky encounter gives a negative linear thermal transmittance value, it can be said then that the thermal bridge was broken and there was a small point improvement in the thermal envelope.</td></tr>
</table>

Table A1. *Cont.*

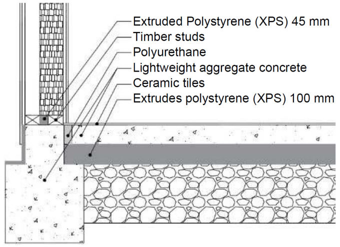
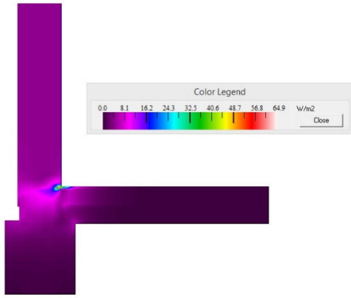
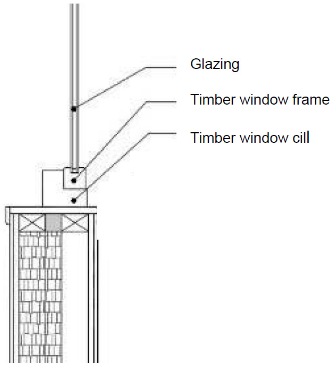
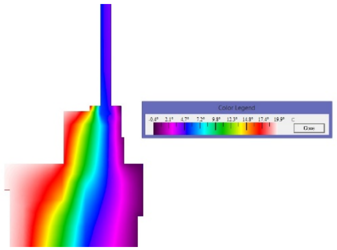
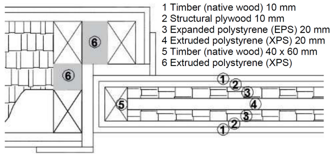
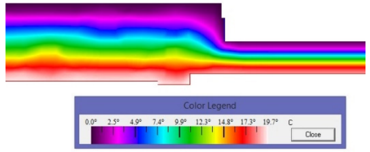
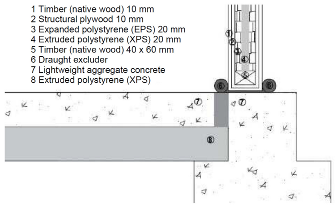
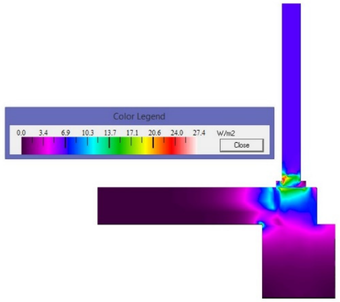
	Identification of the Thermal Bridge	THERM of Simulation	Linear Thermal Transmittance (W/mK)
Horizontal	**3. Encounter Floor- Wall** 		Ψ= −0.003
	3. Result: the constructive solution that was given to the wall–floor encounter allows having a linear thermal transmittance with a very small value and with a negative sign, therefore it can be said that the thermal bridge was eliminated.		
Horizontal and vertical	**4. Window frame** 		Ψ = −0.85
	4. Result: considering the high thermal transmittance value of the double glaze (2.9 W/m^{2}K), the linear thermal transmittance value in the frame is favorable, that is, the heat transfer with respect to the glazed area does not increase.		

Table A1. *Cont.*

	Identification of the Thermal Bridge	THERM of Simulation	Linear Thermal Transmittance (W/mK)
Superior Vertical and horizontal	**5. Door Frame** 		Ψ= 0.109
	5. Result: the constructive solution that was used in the doorway allows to have a decrease in heat transfer, with respect to the area of the door in contact with the exterior.		
Horizontal	**6. Door – floor junction** 		Ψ= −0.159
	6. Result: the result of negative linear thermal transmittance in the lower part of the door indicates that there is no thermal bridge, on the contrary, there is less heat flow through this point.		

Appendix B

Table A2. Detailed Budget. Passivhaus.

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
1	Heavy work				
1.1	Scarp, levelling, and tracing	m^2	120	$3041	$364,889
1.2	Excavations	m^3	15	$8849	$132,739
1.3	Concrete				
1.3.1	Embedded H-5	m^3	2	$50,751	$101,501
1.3.2	Lightweight concrete foundation	m^3	17	$65,736	$1,117,504
1.3.3	Radier lightweight concrete	m^3	10	$63,306	$633,056
1.4	Structure of walls				
1.4.1	Perimeter walls	m^2	95	$23,123	$2,196,730
1.4.2	Internal partitions	m^2	75	$8.341	$625,573
1.5	Roof structure				
1.5.1	Trusses	m^2	116	$9027	$1,047,184
1.5.2	Wood structure	m^2	65	$12,553	$815,943
1.5.3	Ceiling curb	m^2	100	$12,391	$1,239,098
2	Thermal insulation				
2.1	Mineral wool 120 mm walls	m^2	95	$13,049	$1,239,665
2.2	Mineral wool 120 mm ceiling	m^2	100	$12,239	$1,223,910
2.3	Polyurethane exp. 100 mm floor	m^2	100	$8007	$800,685
2.4	Polyurethane 40 mm floor	Gl	1	$43,619	$43,619
3	Coatings				
3.1	Interiors				
3.1.1	Perimeter walls	m^2	105	$8000	$840,039

Table A2. *Cont.*

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
3.1.2	Dry zone partitions	m^2	110	$8000	$880,041
3.1.3	Wet zone partitions	m^2	40	$20,291	$811,620
3.2	Ceilings				
3.2.1	Dry zone	m^2	84	$8000	$672,031
3.2.2	Wet zone	m^2	16	$9782	$156,518
3.3	Exteriors				
3.3.1	Perimeter walls	m^2	120	$8000	$960,044
3.3.2	Eaves	m^2	5	$14,953	$74,763
3.3.4	Corrugated zinc cover 0.35	m^2	110	$7942	$873,626
3.3.5	Tinsmiths	Gl	1	$76,262	$76,262
4	Terminations				
4.1	Doors				
4.1.1	Interior	Un	5	$24,972	$124,862
4.1.2	Exterior	Un	2	$71,952	$143,905
4.2	Window DGU				
4.2.1	Window type 1 (2.0 × 1.5 m)	Un	3	$613,454	$1,840,361
4.2.2	Window type 2 (1.2 × 1.0 m)	Un	2	$306.285	$612,571
4.2.3	Window type 3 (0.5 × 0.5 m)	Un	2	$126,465	$252,931
4.3	Smock	Ml	105	$2641	$277,348
4.4	Cornices	Ml	105	$2479	$260,338
4.5	Interior ceramic pavement	m^2	100	$12,304	$1,230,390

Table A2. *Cont.*

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
4.6	Paint				
4.6.1	Exterior	m^2	170	$2552	$433,755
4.6.2	Interior	m^2	95	$2552	$242,393
5	Artefacts				
5.1	W.C.	Un	2	$70,571	$141,143
5.2	Sink with pedestal	Un	2	$58,421	$116,843
5.3	Bathtub	Un	2	$97,099	$194,198
5.4	Dishwasher with furniture	Un	1	$117,551	$117,551
5.5	Heater	Un	1	$149,951	$149,951
6	Equipment				
6.1	Fan with rec. of heat	un	1	$4,050,000	$4,050,000
7	Services and infrastructure				
7.1	Drinking water and sewage	Gl	1	$1,620,000	$1,620,000
7.2	Electricity	Gl	1	$1,000,000	$1,000,000
7.3	Gas	Gl	1	$810,000	$810,000
			Direct cost		$30,545,574
			Genera expenses 10%		$3,054,557
			Utility 20%		$6,109,115
			Total net		$39,709,246
			IVA 19%		$7,544,757
			Total cost		$47,254,003
			Total cost * CLF		1773

* Value of CLF July 2019.

Table A3. Detailed Budget. Traditional house.

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
1	Heavy work	——			
1.1	Scarp, levelling, and tracing	m^2	120	$878	$105,365
1.2	Excavations	m^3	15	$10,671	$160,060
1.3	Concrete				
1.3.1	Embedded H-5	m^3	2	$52,406	$104,812
1.3.2	Lightweight concrete foundation	m^3	17	$52,906	$899,409
1.3.3	Radier lightweight concrete	m^3	10	$76,613	$763,268
1.3.4	Reinforced concrete slab	m^3	5	$250,895	$1,254,475
1.4	Structure of walls				
1.4.1	Perimeter walls	m^2	95	$16,844	$1,600,255
1.4.2	Internal partitions	m^2	75	$3785	$283,883
1.5	Roof structure				
1.5.1	Trusses/wood structure	m^2	116	$10,488	$1,216,604
1.5.2	Ceiling curb	m^2	100	$2120	$212,024
2	Thermal insulation				
2.1	Mineral wool 90 mm walls	m^2	95	$3246	$308,360
2.2	Mineral wool 120 mm ceiling	m^2	100	$2139	$213,926
3	Coatings				
3.1	Interiors				
3.1.1	Perimeter walls	m^2	105	$3907	$410,208
3.1.2	Dry zone partitions	m^2	110	$1681	$184,930
3.1.3	Wet zone partitions	m^2	40	$8197	$327,873
3.2	Ceilings				

Table A3. *Cont.*

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
3.2.1	Dry zone	m^2	84	$2390	$200,782
3.2.2	Wet zone	m^2	16	$3308	$52,921
3.3	Exteriors				
3.3.1	Perimeter walls	m^2	120	$8867	$1,064,028
3.3.2	Eaves	m^2	5	$19,358	$96,788
3.3.3	Corrugated zinc cover 0.35	m^2	110	$7348	$808,246
3.3.4	Tinsmiths	Gl	1	$149,499	$149,499
4	Terminations				
4.1	Doors				
4.1.1	Interior	Un	5	$48,878	$244,389
4.1.2	Exterior	Un	2	$90,098	$180,195
4.2	Window DGU				
4.2.1	Window type 1 (2.0 × 1.5m)	Un	3	$145,309	$435,928
4.2.2	Window type 2 (1.2 × 1.0m)	Un	2	$137,058	$274,116
4.2.3	Window type 3 (0.5 × 0.5m)	Un	2	$59,858	$119,716
4.3	Smock	Ml	105	$2207	$231,770
4.4	Interior ceramic pavement	m^2	100	$13,027	$1,302,676
4.6	Paint				
4.6.1	Exterior	m^2	170	$4105	$697,777
4.6.2	Interior	m^2	95	$2903	$275,737
5	Artefacts				
5.1	W.C.	Un	2	$54,925	$109,850
5.2	Sink with pedestal	Un	2	$95,345	$190,690

Table A3. *Cont.*

Item	Description	Unit	Quantity	Unit Price (CLP)	Total (CLP)
5.3	Bathtub	Un	2	$65,605	$131,210
5.4	Dishwasher with furniture	Un	1	$62,180	$62,180
5.5	Heater	Un	1	$107,625	$107,625
6	Equipment				
6.1	Stove	Un	1	$360,783	$360,783
7	Services and infrastructure				
7.1	Drinking water and sewage	Gl	1	$253,281	$253,281
7.2	Electricity	Gl	1	$624,366	$624,366
7.3	Gas	Gl	1	$268,393	$268,393
			Direct cost		$16,020,018
			Genera expenses 10%		$1,602,002
			Utility 20%		$3,204,004
			Total net		$20,826,023
			IVA 19%		$3,956,944
			Total cost		$24,782,967
			Total cost * CLF		867

* Value of CLF July 2019.

Appendix C

Most important calculation sheets from PHPP.

				Requirements	Fulfilled?*
	Treated floor area	112,0	m²		
Space heating	Heating demand	**10**	**kWh/(m²a)**	15 kWh/(m²a)	**yes**
	Heating load	**8**	**W/m²**	10 W/m²	**yes**
Space cooling	Overall specif. space cooling demand		**kWh/(m²a)**	-	**-**
	Cooling load		**W/m²**	-	**-**
	Frequency of overheating (> 25 °C)	7,8	%	-	**-**
Primary energy	Heating, cooling, auxiliary electricity, dehumidification, DHW, lighting, electrical appliances	**119**	**kWh/(m²a)**	120 kWh/(m²a)	**yes**
	DHW, space heating and auxiliary electricity	49	kWh/(m²a)	-	-
	Specific primary energy reduction through solar electricity		kWh/(m²a)	-	-
Airtightness	Pressurization test result n_{50}	**0,6**	**1/h**	0,6 1/h	**yes**

Figure A1. Verification.

Building:	Vivienda DS01 con estandar PASSIVHAUS				
		Transfer to annual method (Annual Heating)			
Climate building	[CL] - Santiago de Chile	H_T	128	d/a	
		G_t	35	kKh/a	
Monthly data:	[CL] - Santiago de Chile	North	101	kWh/(m²a)	
Annual data:		East	184	kWh/(m²a)	
Use annual climate data set	no	South	322	kWh/(m²a)	
Results:		West	184	kWh/(m²a)	
Annual heating demand	10,3 kWh/(m²a)	Horizontal	308	kWh/(m²a)	
Heating load	8,5 W/m²				
Primary energy	118,6 kWh/(m²a)				

Region:	Latin-America	
Climate data set:	[CL] - Santiago de Chile	
Weather station (altitude):	474,0	m
Building location (altitude):		m

Month	1	2	3	4	5	6	7	8	9	10	11	12	Heating load		Cooling load	
Days	31	28	31	30	31	30	31	31	30	31	30	31	Weather 1	Weather 2	Weather 1	Weather 2
[CL] - Santiago de Chile	Latitude:	33,4	Longitude °	-70,8	Altitude m	474	Daily temperature swing Summer (K)			15,7	Radiation data:	kWh/(m²month)	Radiation: W/m²		Radiation: W/m²	
Ambient temp	8,4	10,0	11,7	14,6	17,4	19,7	21,0	20,3	18,5	14,5	10,9	9,0	4,7	10,4	30,0	30,0
North	23	29	38	51	64	78	72	50	44	33	26	20	32	15	93	93
East	43	51	74	104	123	135	137	106	102	62	44	34	63	14	195	195
South	86	94	93	89	69	61	66	80	110	102	82	71	117	13	96	96
West	40	58	70	94	119	127	125	106	98	68	43	35	54	14	181	181
Global	68	91	124	178	219	246	243	194	169	109	74	56	92	27	349	349
Dew point	4,5	5,8	6,4	7,8	7,9	8,7	9,2	9,7	9,6	7,7	6,2	5,4			12,7	12,7
Sky temp	-2,3	-0,9	0,1	1,9	1,4	3,5	4,1	5,2	3,6	2,1	0,6	-0,8			8,8	12,7
Ground temp	16,0	15,7	15,8	16,3	17,1	20,0	20,7	21,0	20,9	18,4	17,6	16,7	15,7	15,7	21,0	21,0
Comment:		Location in the south hemisphere. Data set adaptad for use in PHPP (see PHPP user's manual)!														

Figure A2. Climate.

1	Muros Perimetrales						
	Heat transfer resistance [m²K/W]	interior R_{si}: 0,13					
		exterior R_{se}: 0,04					
	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Madera pino insigne	0,104					10
2.	Terciado estructural	0,094					15
3.	Madera IPV	0,104					75
4.	Lana Mineral	0,042	Poliestireno exp.	0,036			45
5.	Lana Mineral	0,042	Madera IPV	0,104			75
6.	Terciado estructural	0,094					15
7.	Madera IPV	0,104					10
8.							
	Percentage of sec. 1		Percentage of sec. 2		Percentage of sec. 3		Total
	90%			10,0%			24,5 cm
	U-value supplement		W/(m²K)	U-Value:	0,244	W/(m²K)	

Figure A3. *Cont.*

Assembly no. Building assembly description: 2 Piso radier — Interior insulation?

Heat transfer resistance [m²K/W] interior R_{si}: 0,17; exterior R_{se}: 0,00

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Ceramica	1,750					5
2.	Adhesivo	1,000					5
3.	Hormigon	0,330					100
4.	Poliestireno exp. H/D	0,036					100
5.							
6.							
7.							
8.							

Percentage of sec. 1: 100% Percentage of sec. 2: Percentage of sec. 3: Total: 21,0 cm

U-value supplement: W/(m²K) **U-Value: 0,307** W/(m²K)

Assembly no. Building assembly description: 3 Cielo — Interior insulation?

Heat transfer resistance [m²K/W] interior R_{si}: 0,10; exterior R_{se}: 0,04

	Area section 1	λ [W/(mK)]	Area section 2 (optional)	λ [W/(mK)]	Area section 3 (optional)	λ [W/(mK)]	Thickness [mm]
1.	Madera pino insigne	0,104					10
2.	Terciado estructural	0,094					15
3.	Madera IPV	0,104					50
4.	Lana Mineral	0,037					120
5.			Lana Mineral	0,042			120
6.							
7.							
8.							

Percentage of sec. 1: 90% Percentage of sec. 2: 10,0% Percentage of sec. 3: Total: 31,5 cm

U-value supplement: W/(m²K) **U-Value: 0,238** W/(m²K)

Figure A3. U Values.

Thermal bridge inputs

Nr.	Thermal bridge description	Group Nr.	Assigned to group	Quantity	x (	User determined length [m]	-	Subtraction user-determined length [m]	)=	Length l [m]	Input of thermal bridge heat loss coefficient W/(mK)	Ψ W/(mK)
1	Corner of Wall	15	Thermal bridges Ambient	1	x (	9,70	-		) =	9,70	Corner of Wall	-0,164
2	Wall and roof	15	Thermal bridges Ambient	1	x (	43,00	-		) =	43,00	Wall and roof	-0,093
3	Encounter Floor- Wall	15	Thermal bridges Ambient	1	x (	43,00	-		) =	43,00	Encounter Floor- Wall	-0,003
4	Window frame	15	Thermal bridges Ambient	1	x (	33,80	-		) =	33,80	Window frame	-0,850
5	Door Frame	15	Thermal bridges Ambient	1	x (	9,60	-		) =	9,60	Door Frame	0,109
6	Door – floor junction	15	Thermal bridges Ambient	1	x (	1,60	-		) =	1,60	Door – floor junction	-0,159

Figure A4. Thermal Bridges.

Climate: [CL] - Santiago de Chile

Window area orientation	Global radiation (cardinal points)	Shading	Dirt	Non-perpendicular incident radiation	Glazing fraction	g-Value	Solar irradiation reduction factor	Window area	Window U-Value	Glazing area	Average global radiation
maximum:	kWh/(m²a)	0,75	0,95	0,85				m²	W/(m²K)	m²	kWh/(m²a)
North	101	0,52	0,95	0,85	0,490	0,77	0,21	1,45	2,03	0,71	101
East	184	0,66	0,95	0,85	0,552	0,77	0,29	2,40	2,14	1,32	184
South	322	0,77	0,95	0,85	0,699	0,77	0,44	9,00	2,25	6,30	322
West	184	0,66	0,95	0,85	0,490	0,77	0,26	1,45	2,03	0,71	184
Horizontal	308	1,00	0,95	0,85	0,000	0,00	0,00	0,00	0,00	0,00	308
		Total or average value for all windows.				0,77	0,37	14,30	2,18	9,04	

Figure A5. Windows.

Orientation	Glazing area m²	Reduction factor winter r_{Sw}	Reduction factor summer r_{Ss}
North	0,71	52%	62%
East	1,32	66%	72%
South	6,30	77%	60%
West	0,71	66%	72%
Horizontal	0,00	100%	100%

Figure A6. Shading.

Heating, cooling, DHW, auxiliary electricity, lighting, electrical appliances			65,6	118,6	29,7
Total PE Value	118,6	kWh/(m²a)			
Total emissions CO_2 Equivalent	29,7	kg/(m²a)			(Yes/No)
Primary Energy Requirement			120	kWh/(m²a)	yes

Heating, DHW, auxiliary electricity (no lighting and electrical appliances)			38,9	49,4	11,6
Specific PE demand - Mechanical system	49,4	kWh/(m²a)			
Total emissions CO_2-equivalent	11,6	kg/(m²a)			

Figure A7. Primary Energy.

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