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

Aner Martinez-Soto 1,*, Yarela Saldias-Lagos 1, Valentina Marincioni 2 and Emily Nix 2

1 Department of Civil Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Temuco 4780000, Chile; y.saldias01@ufromail.cl
2 UCL Institute for Environmental Design and Engineering, University College London, London WC1H 0NN, UK; v.marincioni@ucl.ac.uk (V.M.); emily.nix.12@ucl.ac.uk (E.N.)

* Correspondence: aner.martinez@ufrontera.cl; Tel.: +56-45-259-6816

Received: 12 July 2020; Accepted: 10 August 2020; Published: 22 October 2020

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 CO₂ 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 CO₂ 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 it 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/m²-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).](image-url)

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 DS49 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 (see Appendix A). The insulating material corresponds to 120 mm-thick mineral wool, of density 40 kg/m³ and a thermal conductivity of 0.042 W/(m·K). Using the PHPP spreadsheets, it was determined that the thermal transmittance of the perimeter walls is 0.244 W/(m²·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 m², 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.](image)

**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_TO | U   | R_TO | U   | R_TO |
| 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/m²·K and total thermal resistance values in m²·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/m²·K).
With this construction, a value of 0.307 W/m²K was obtained for the thermal transmittance of the floor. 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.

![Shading produced by eaves on the north façade of the building. Own elaboration.](image)

The windows considered in this work correspond to double glazing with timber frame with a U-value = 1.8 W/m²K 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/m²K) in current Chilean regulations [47].

(e) Ventilation with heat recovery

The value of the total volume enclosed in the house designed is 245 m³, 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 m³/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 m³/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/m².
(b) Annual total energy consumption for all systems (heating, cooling, hot water, electricity) not exceeding 120 kWh/m².
(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 \( \approx 81,000 \) 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).

| Parameter                  | Results       | Passivhaus Requirement | Standard Compliance Passivhaus |
|----------------------------|---------------|-------------------------|--------------------------------|
| Annual heating demand      | 10 kWh/(m²)  | \( \leq 15 \) kWh/(m²a) | Yes                            |
| Heating load               | 8 W/m²       | \( \leq 10 \) W/m²      | Yes                            |
| Thermal bridges \( \Delta U \) | 0.1 W/(m²K) | \( \leq 1 \) W/(m²K)   | -                              |
| Overheating frequency      | 7.8%         | \( \leq 10\% \)        | Yes                            |
| Annual total energy demand | 120 kWh/(m²) | \( \leq 120 \) kWh/(m²a)| Yes                            |

Implementing Passivhaus standard as affordable housing, specifically in Santiago, would result in a significant reduction in energy demand and CO₂ 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/m² for heating in the city of Santiago, whereas in Temuco it has a demand of 24 kWh/m². To comply with the annual heating energy demand limit (15 kWh/m²), the surface area of the windows in the north façade was increased by 7.8 m² 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 \( \approx 81,000 \) 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/m²K)                             |                    |
| 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/m²K) | 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/m²K.

** 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/m²). A conventional house can have a maximum of 140 m² with a total budget of CLF 2000 (≈81,000 USD). If the proposed house had a maximum area (140 m²) 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/m²a for heating energy consumption [6]. If we consider a 100 m² house located in Santiago with a referential annual energy demand of 86 kWh/m²a, 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 m²), for the Passivhaus a heating energy consumption of 10 kWh/m²a was considered (Table 2) and for a traditional house an average heating energy consumption of 120 kWh/m²a 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).](image)

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/m²K 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 m² 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/m²). 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.

Funding: This research received no external funding.

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

Appendix A
Table A1. Thermal Bridges.

| Identification of the Thermal Bridge | THERM of Simulation | Linear Thermal Transmittance (W/mK) |
|-------------------------------------|---------------------|-------------------------------------|
| 1. Corner of Wall                   |                     |                                     |
| ![Diagram](attachment:corner_of_wall.png) | ![Diagram](attachment:corner_of_wall_simulation.png) | $\Psi = -0.164$                     |
| 2. Wall and roof                    |                     |                                     |
| ![Diagram](attachment:wall_roof.png) | ![Diagram](attachment:wall_roof_simulation.png) | $\Psi = -0.093$                     |

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.

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.
### Table A1. Cont.

| Identification of the Thermal Bridge | THERM of Simulation | Linear Thermal Transmittance (W/mK) |
|-------------------------------------|---------------------|-------------------------------------|
| 3. Encounter Floor- Wall            |                     | $\Psi = -0.003$                     |
| 4. Window frame                     |                     | $\Psi = -0.85$                      |

**Horizontal and vertical**

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.

4. Result: considering the high thermal transmittance value of the double glaze (2.9 W/m²K), 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) |
|------------------------------------|---------------------|-------------------------------------|
| 5. Door Frame                      |                     |                                     |
| Superior Vertical and horizontal   | ![Diagram](image1)  | $\Psi = 0.109$                      |
| 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. |
| 6. Door – floor junction           | ![Diagram](image2)  | $\Psi = -0.159$                     |
| 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                    | m²     | 120      | $3041            | $364,889      |
| 1.2  | Excavations                                      | m³     | 15       | $8849            | $132,739      |
| 1.3  | Concrete                                         |        |          |                  |               |
| 1.3.1| Embedded H-5                                     | m³     | 2        | $50,751          | $101,501      |
| 1.3.2| Lightweight concrete foundation                   | m³     | 17       | $65,736          | $1,117,504    |
| 1.3.3| Radier lightweight concrete                      | m³     | 10       | $63,306          | $633,056      |
| 1.4  | Structure of walls                               |        |          |                  |               |
| 1.4.1| Perimeter walls                                  | m²     | 95       | $23,123          | $2,196,730    |
| 1.4.2| Internal partitions                              | m²     | 75       | $8,341           | $625,573      |
| 1.5  | Roof structure                                   |        |          |                  |               |
| 1.5.1| Trusses                                          | m²     | 116      | $9027            | $1,047,184    |
| 1.5.2| Wood structure                                   | m²     | 65       | $12,553          | $815,943      |
| 1.5.3| Ceiling curb                                     | m²     | 100      | $12,391          | $1,239,098    |
| 2    | Thermal insulation                               |        |          |                  |               |
| 2.1  | Mineral wool 120 mm walls                        | m²     | 95       | $13,049          | $1,239,665    |
| 2.2  | Mineral wool 120 mm ceiling                      | m²     | 100      | $12,239          | $1,223,910    |
| 2.3  | Polyurethane exp. 100 mm floor                   | m²     | 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                                  | m²     | 105      | $8000            | $840,039      |
| Item   | Description                     | Unit | Quantity | Unit Price (CLP) | Total (CLP) |
|--------|---------------------------------|------|----------|------------------|-------------|
| 3.1.2  | Dry zone partitions            | m²   | 110      | $8000            | $880,041    |
| 3.1.3  | Wet zone partitions            | m²   | 40       | $20,291          | $811,620    |
| 3.2    | Ceilings                       |      |          |                  |             |
| 3.2.1  | Dry zone                       | m²   | 84       | $8000            | $672,031    |
| 3.2.2  | Wet zone                       | m²   | 16       | $9782            | $156,518    |
| 3.3    | Exteriors                      |      |          |                  |             |
| 3.3.1  | Perimeter walls                | m²   | 120      | $8000            | $960,044    |
| 3.3.2  | Eaves                          | m²   | 5        | $14,953          | $74,763     |
| 3.3.4  | Corrugated zinc cover 0.35      | m²   | 110      | $7942            | $873,626    |
| 3.3.5  | Tinsmiths Gl                   | 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      | m²   | 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                   | m²   | 170      | $2552           | $433,755    |
| 4.6.2| Interior                   | m²   | 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 | m² | 120 | $878 | $105,365 |
| 1.2  | Excavations | m³ | 15 | $10,671 | $160,060 |
| 1.3  | Concrete   |      |          |                 |             |
| 1.3.1| Embedded H-5 | m³ | 2 | $52,406 | $104,812 |
| 1.3.2| Lightweight concrete foundation | m³ | 17 | $52,906 | $899,409 |
| 1.3.3| Radier lightweight concrete | m³ | 10 | $76,613 | $763,268 |
| 1.3.4| Reinforced concrete slab | m³ | 5 | $250,895 | $1,254,475 |
| 1.4  | Structure of walls | | | | |
| 1.4.1| Perimeter walls | m² | 95 | $16,844 | $1,600,255 |
| 1.4.2| Internal partitions | m² | 75 | $3785 | $283,883 |
| 1.5  | Roof structure | | | | |
| 1.5.1| Trusses/wood structure | m² | 116 | $10,488 | $1,216,604 |
| 1.5.2| Ceiling curb | m² | 100 | $2120 | $212,024 |
| 2    | Thermal insulation | | | | |
| 2.1  | Mineral wool 90 mm walls | m² | 95 | $3246 | $308,360 |
| 2.2  | Mineral wool 120 mm ceiling | m² | 100 | $2139 | $213,926 |
| 3    | Coatings | | | | |
| 3.1  | Interiors | | | | |
| 3.1.1| Perimeter walls | m² | 105 | $3907 | $410,208 |
| 3.1.2| Dry zone partitions | m² | 110 | $1681 | $184,930 |
| 3.1.3| Wet zone partitions | m² | 40 | $8197 | $327,873 |
| 3.2  | Ceilings | | | | |
Table A3. Cont.

| Item          | Description                  | Unit | Quantity | Unit Price (CLP) | Total (CLP)  |
|---------------|------------------------------|------|----------|-----------------|--------------|
| 3.2.1         | Dry zone                     | m²   | 84       | $2390           | $200,782     |
| 3.2.2         | Wet zone                     | m²   | 16       | $3308           | $52,921      |
| 3.3           | Exteriors                    |      |          |                 |              |
| 3.3.1         | Perimeter walls              | m²   | 120      | $8867           | $1,064,028   |
| 3.3.2         | Eaves                        | m²   | 5        | $19,358         | $96,788      |
| 3.3.3         | Corrugated zinc cover 0.35   | m²   | 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    | m²   | 100      | $13,027         | $1,302,676   |
| 4.6           | Paint                        |      |          |                 |              |
| 4.6.1         | Exterior                     | m²   | 170      | $4105           | $697,777     |
| 4.6.2         | Interior                     | m²   | 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.

| Space heating | Heating demand | 10 kWh/(m²a) | 15 kWh/(m²a) | yes |
| Space cooling | Overall specific space cooling demand | kWh/(m²a) | - | - |
| Cooling load | | W/m² | - | - |
| Frequency of overheating (> 25 °C) | 7.8 % | | - | - |
| Primary energy | Heating, cooling, dehumidification, DHW, auxiliary electricity, lighting, electrical appliances | 119 kWh/(m²a) | 120 kWh/(m²a) | yes |
| Specific primary energy reduction through solar energy | 49 kWh/(m²a) | | - | - |
| Airtightness | Pressurization test result \( \Delta P \) | 0.6 1/h | 0.6 1/h | yes |

**Figure A1. Verification.**

**Figure A2. Climate.**

**Figure A3. Cont.**
### Figure A3. U Values.

| Thermal bridge inputs | Group | Assigned to group | Description | Area (m²) | Length (m) | Heat loss coefficient (W/m²K) | Input of thermal bridge heat loss coefficient (W/m²K) |
|-----------------------|-------|-------------------|-------------|-----------|------------|-------------------------------|-------------------------------------------------|
| 1                     |       |                   | Corner of Wall 15 | 9.70      | 0.00       | 0.164                         | 0.164                                           |
| 2                     |       |                   | Wall and roof 15 | 43.00     | 0.00       | 0.093                         | 0.093                                           |
| 3                     |       |                   | Encounter Floor- Wall 15 | 43.00 | 0.00 | 0.003                         | 0.003                                           |
| 4                     |       |                   | Window frame 15 | 33.80     | 0.00       | 0.850                         | 0.850                                           |
| 5                     |       |                   | Door Frame 15 | 9.60      | 0.00       | 0.109                         | 0.109                                           |
| 6                     |       |                   | Door – floor junction 15 | 1.60 | 0.00 | 0.159                         | 0.159                                           |

**Total** = 0.07 W/m²K

### Figure A4. Thermal Bridges.

### Figure A5. Windows.
| Orientation | Glazing area (m²) | Reduction factor winter ($r_w$) | Reduction factor summer ($r_s$) |
|-------------|-------------------|-------------------------------|-------------------------------|
| North       | 0.71              | 62%                           | 62%                           |
| East        | 1.22              | 66%                           | 72%                           |
| South       | 6.30              | 77%                           | 60%                           |
| West        | 0.71              | 68%                           | 72%                           |
| Horizontal  | 0.00              | 100%                          | 100%                          |

Figure A6. Shading.

| Total PE Value | Total emissions CO₂ equivalent | Primary Energy Requirement |
|----------------|-------------------------------|-----------------------------|
| 118.6 kWh/m² yr | 29.7 kg CO₂/m² yr             | 120 kWh/m² yr, yes          |

Figure A7. Primary Energy.

References

1. Williams, J.; Mitchell, R.; Raicic, V.; Vellei, M.; Mustard, G.; Wismayer, A.; Yin, X.; Davey, S.; Shakil, M.; Yang, Y.; et al. Less is more: A review of low energy standards and the urgent need for an international universal zero energy standard. J. Build. Eng. 2016, 6, 65–74. [CrossRef]
2. Martinez-Soto, A.; Jentsch, M.F. Comparison of prediction models for determining energy demand in the residential sector of a country. Energy Build. 2016, 128, 38–55. [CrossRef]
3. División de Prospectiva y Política Energética del Ministerio de Energía (DPPE), Balance Nacional de Energía (1990–2013). Santiago, Chile. 2015. Available online: http://www.minenergia.cl/archivos_bajar/LIBRO-ENERGIA-2050-WEB.pdf (accessed on 25 July 2019).
4. Wegerteseder, P.; Schmidt, D.; Hatt, T.; Saelzer, G.; Hempel, R. Barreras y oportunidades observadas en la incorporación de estándares de alta eficiencia energética en la vivienda. Arquit. Urban. 2014, 15, 37–49.
5. Corporación de Desarrollo Tecnológico (CDT). Estudio de Usos Finales y Curva de Oferta de la Conservación de la Energía en el Sector Residencial. Santiago, Chile. 2010. Available online: http://dataset.cne.cl/Energia_Abierta/Estudios/Miner%20Usos%20finales.pdf (accessed on 25 July 2019).
6. Hatt, T.; Saelzer, G.; Hempel, R.; Gerber, A. Alto confort interior con mínimo consumo energético a partir de la implementación del estándar Passivhaus en Chile. Rev. Constr. 2012, 11, 123–134. [CrossRef]
7. Simian, J.M. Logros y Desafíos de La Política Habitacional en Chile. Estudios Públicos 2010, 1, 117. Available online: https://www.cerpchile.cl/cep/site/article/20160304/asocfile/20160304095214/rev117_simian.pdf (accessed on 25 July 2019).
8. Martinez, P.; Sarmiento, P.; Urquieta, W. Evaluación de la humedad por condensación dentro de viviendas sociales. Revista INVÍ 2009, 20, 154–165. Available online: http://revistainvi.uchile.cl/index.php/INVVI/article/view/323/887 (accessed on 25 July 2019).
9. Subhashini, S.; Thirumaran, K. A passive design solution to enhance thermal comfort in an educational building in the warm humid climatic zone of Madurai. J. Build. Eng. 2018, 18, 395–407. [CrossRef]
10. Golshan, M.; Thoen, H.; Zeiler, W. Dutch sustainable schools towards energy positive. J. Build. Eng. 2018, 19, 161–171. [CrossRef]
11. Košir, M.; Gostiša, T.; Kristl, Ž. Influence of architectural building envelope characteristics on energy performance in Central European climatic conditions. J. Build. Eng. 2017, 15, 278–288. [CrossRef]
12. Scoccia, R.; Toppi, T.; Aprile, M.; Motta, M. Absorption and compression heat pump systems for space heating and DHW in European buildings: Energy, environmental and economic analysis. J. Build. Eng. 2018, 16, 94–105. [CrossRef]
13. Venkatesan, K.; Ramachandraiah, U. Climate responsive cooling control using artificial neural networks. *J. Build. Eng.* 2018, 19, 191–204. [CrossRef]

14. Short, C.A. The recovery of natural environments in architecture: Delivering the recovery. *J. Build. Eng.* 2018, 15, 328–333. [CrossRef]

15. Eyre, N.; Baruah, P. Uncertainties in future energy demand in UK residential heating. *Energy Policy* 2015, 87, 641–653. [CrossRef]

16. McKenna, R.; Merkel, E.; Fehrenbach, D.; Mehne, S.; Fichtner, W. Energy efficiency in the German residential sector: A bottom-up building-stock-model-based analysis in the context of energy-political targets. *Build. Environ.* 2013, 62, 77–88. [CrossRef]

17. Nik, V.M.; Mata, E.; Kalagasidis, A. A statistical method for assessing retrofitting measures of buildings and ranking their robustness against climate change. *Energy Build.* 2015, 88, 262–275. [CrossRef]

18. Ministerio de Vivienda y Urbanismo (MINVU). Ordenanza General de Urbanismo y Construcciones, Santiago, Chile. 2018. Available online: [https://www.minvu.cl/elementos-tecnicos/normativa-de-urbanismo-y-construcciones/d-s-n47-de-1992-ordenanza-general-de-urbanismo-y-construcciones/](https://www.minvu.cl/elementos-tecnicos/normativa-de-urbanismo-y-construcciones/d-s-n47-de-1992-ordenanza-general-de-urbanismo-y-construcciones/) (accessed on 25 July 2019).

19. Passivhaus Institut (PHI). About Passive House—What Is a Passive House? Darmstadt, Germany. 2018. Available online: [https://passipedia.org/basics/what_is_a_passive_house](https://passipedia.org/basics/what_is_a_passive_house) (accessed on 25 July 2019).

20. Pitts, A. Passive house and low energy buildings: Barriers and opportunities for future development within UK practice. *Sustainability* 2017, 9, 272. [CrossRef]

21. Minergie. Baustandard Minergie-P. 2018. Available online: [https://www.minergie.ch/de/verstehen/baustandards/](https://www.minergie.ch/de/verstehen/baustandards/) (accessed on 25 July 2019).

22. Schnieders, J.; Feist, W.; Rongen, L. Passive Houses for different climate zones. *Energy Build.* 2015, 105, 71–87. [CrossRef]

23. Tatarestaghi, F.; Ismail, M.A.; Ishak, N.H. A comparative study of passive design features/elements in Malaysia and passive house criteria in the tropics. *J. Des. Built Environ.* 2018, 18, 15–25. Available online: [https://ejournal.um.edu.my/index.php/jdbe/article/view/15577](https://ejournal.um.edu.my/index.php/jdbe/article/view/15577) (accessed on 14 July 2019).

24. Truong, H.; Garvie, A.M. Chifley Passive House: A Case Study in Energy Efficiency and Comfort. *Energy Procedia* 2017, 121, 214–221. [CrossRef]

25. Badescu, V.; Rotar, N.; Udrea, I. Considerations concerning the feasibility of the German Passivhaus concept in Southern Hemisphere. *Energy Effic.* 2015, 8, 919. [CrossRef]

26. Tataru, A. Possibility to Implement the Concept of Passivhaus in Russia. In Proceedings of the 18th International Multidisciplinary Science GeoConference: Ecology, Economics, Education and Legislation (SGEM 2018), Sofia, Bulgaria, 30 June–9 July 2018; pp. 723–731.

27. Liang, X.; Wang, Y.; Royapoor, M.; Wu, Q.; Roskilly, T. Comparison of building performance between Conventional House and Passive House in the UK. *Energy Procedia* 2017, 142, 1823–1828. [CrossRef]

28. Elsarrag, E.; Alhorr, Y. Modelling the thermal energy demand of a Passive-House in the Gulf Region: The impact of thermal insulation. *Int. J. Sustain. Built Environ.* 2012, 1, 1–15. [CrossRef]

29. Mihai, M.; Tanasiev, V.; Dinca, C.; Badea, A.; Vidu, R. Passive house analysis in terms of energy performance. *Energy Build.* 2017, 144, 74–86. [CrossRef]

30. Udrea, I.; Croitoru, C.; Nastase, I.; Crutescu, R.; Badescu, V. Thermal Comfort in a Romanian Passive House: Preliminary Results. *Energy Procedia* 2016, 85, 575–583. [CrossRef]

31. Galvin, R. Are passive houses economically viable? A reality-based, subjectivist approach to cost-benefit analyses. *Energy Build.* 2014, 80, 149–157. [CrossRef]

32. Dalbem, R.; Cunha, E.G.; Vicente, R.; Figueiredo, A.; Oliveira, R.; Da Silva, A.C.S.B. Optimisation of a social housing for south of Brazil: From basic performance standard to passive house concept. *Energy* 2019, 167, 1278–1296. [CrossRef]

33. Chovancová, J.; Kocourková, G.; Kozumplíková, L. Assessment of operating cash flow of the investment in a construction of passive houses. *Tehnički Glasnik* 2014, 8, 339–346.

34. Zhang, X.; Platten, A.; Shen, L. Green property development practice in China: Costs and barriers. *Build. Environ.* 2011, 46, 2153–2160. [CrossRef]

35. Coyle, D. An investigation into the cost optimality of the Passive House retrofit standard for Irish dwellings using Life Cycle Cost Analysis. *J. Sustain. Des. Appl. Res.* 2016, 4, 4–14. [CrossRef]

36. Shim, J.; Song, D.; Kim, J. The economic feasibility of passive houses in Korea. *Sustainability* 2018, 10, 3558. [CrossRef]
37. MINVU. Estadísticas de Subsidios Otorgados Programa Regular y Reconstrucción, Equipo de estadísticas- Comisión de Estudios Habitacionales y Urbanos: Periodo 1990–Septiembre 2017; Ministerio de Vivienda y Urbanismo: Santiago, Chile, 2017. Available online: https://www.minvu.cl/elementos-tecnicos/estadisticas/viviendas-contratadas-y-subsidios-otorgados/ (accessed on 25 July 2019).

38. DGA. Anuario Climatológico; Dirección General Aeronáutica: Santiago, Chile, 2010. Available online: https://climatologia.meteochile.gob.cl (accessed on 25 July 2019).

39. Ministerio de Energía (MINE), Explorar Recurso Solar y Datos Meteorológicos. Santiago, Chile, 2019. Available online: http://www.minenergia.cl/exploradorsolar/ (accessed on 7 July 2019).

40. Banco Central de Chile. Índice de Precios de Vivienda en Chile: Metodología y Resultados. Estudios Económicos Estadísticos 2014, 107, 1. Available online: https://www.bcentral.cl/web/guest/-/indice-de-precios-de-vivienda-en-chile-metodologia-y-resultad-1 (accessed on 25 July 2019).

41. Instituto Nacional Estadísticas (INE). Síntesis de Resultados ESI, Encuesta Suplementaria de Ingresos 2017. Santiago, Chile. 2018. Available online: https://www.ine.cl/docs/default-source/ingresos-y-gastos/esi/ingreso-de-hogares-y-personas/resultados/2017/sintesis_esi_2017_nacional.pdf (accessed on 25 July 2019).

42. Construcción Chile. Precios de Construcción de Casas y Galpones. Santiago, Chile. 2019. Available online: https://www.construccionchile.cl/contacto (accessed on 5 August 2020).

43. Ministerio del Medio Ambiente, MMA. Plan de Descontaminación Atmosférica MP 2,5. Decreto Supremo número 8. Santiago, Chile. 2015. Available online: https://www.bcn.cl/leychile/navegar?idNorma=1084085 (accessed on 5 August 2020).

44. Instituto Nacional de Estadísticas, INE. Medio Ambiente Informe Anual 2014. Santiago, Chile. 2015. Available online: https://www.ine.cl/estadisticas/economia/energia-y-medioambiente/variables-basicas-ambientales (accessed on 5 August 2020).

45. Servicios Climáticos. Dirección meteorológica de Chile. Santiago, Chile. 2018. Available online: https://climatologia.meteochile.gob.cl/application/index/anuarios (accessed on 5 August 2020).

46. Hatt, T. El estándar ‘passivhaus’ en el centro-sur de chile un estudio paramétrico multifactorial. Ph.D. Thesis, University of Bio-Bio, Concepción, Chile, 2012.

47. Avendaño-Vera, C.; Martinez-Soto, A.; Marincioni, V. Determination of optimal thermal inertia of building materials for housing in different Chilean climate zones. Renew. Sustain. Energy Rev. 2020, 131. [CrossRef]

48. Feist, W. Passivhaus Definition; Passive House Institute: Darmstadt, Germany, 2005. Available online: https://passiv.de/former_conferences/neunte/Passivhaus_DEFINITION.html (accessed on 25 July 2019).

49. ONDAC. Manual de Precios de la Construcción. Santiago, Chile. 2019. Available online: www.ondac.com (accessed on 25 July 2019).

Publisher’s Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).