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# Towards low-carbon housing in Chile: Optimisation and life cycle analysis of energy-efficient solutions

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ABSTRACT

Significant action is needed across the Chilean housing sector to reduce energy consumption and meet climate change mitigation goals. In this study, the performance of a typical house, an optimised house and a Passivhaus in various climates is evaluated and compared, considering eight distinct climatic zones of Chile. For the thermal optimisation of the house, an OpenBIM workflow between REVIT-CYPETHERM and EnergyPlus with JEPlus were interfaced to analyse over a thousand possible combinations of energy optimisation measures for each climate zone. Additionally, a Life Cycle Assessment is used to compare the cases studied. The results show that in the manufacturing stage, building a Passivhaus would have greater environmental impacts than a traditional house. Additionally, it is shown that in warm climatic zones, a thermally optimised house can have an energy performance equivalent to housing constructed to Passivhaus standards but with less environmental impacts in all its phases of the life cycle.

## 1. Introduction

Buildings and construction together account for 36% of global energy use and 39% of energy-related $CO_2$ emissions [1]. Reducing environmental impacts associated with construction processes and ensuring efficiency of buildings to reduce energy use is crucial to meet global climate agreements [2]. In Chile, energy demand in buildings are responsible for one-quarter of all greenhouse gas (GHG) emissions [3], with the highest emissions due to gas and biomass consumption for heating. High energy consumption for heating is attributable to the cold climatic conditions in some climate zone and the poor efficiency of housing that does not offer appropriate thermal comfort [4]. It has been recognised that insulation in existing houses is insufficient or, and in the majority of cases, non-existent [4,5]. Improving the thermal performance of houses could help substantially to improve the thermal comfort, health and well-being and reduce energy consumption and associated greenhouse gas (GHG) emissions in the housing sector in Chile. As in other countries, the great challenge in reducing energy demand in Chile's housing sector is rooted in the thermal retrofitting of existing housing [6–8]. The majority of existing houses were constructed before the development and introduction of thermal regulations; thus these houses represent the majority of total energy consumption across the residential sector [9]. Research evaluating the performance of energy-efficient housing is vital to support to progress towards a low-carbon housing sector in Chile.

To date, there has been limited research evaluating energy-efficient housing solutions for the context of Chile. Previous studies have

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**Nomenclature**

| | |
|---|---|
| λ | Thermal conductivity W/(m·K) |
| ρ | Density kg/m$^3$ |
| $C_p$ | Specific heat capacity J/(kg·K) |
| $U_w$ | Window thermal transmittance W/(m$^2$·K) |
| $g_{gl,n}$ | Solar factor |

considered individual energy performance of case study housing in single climatic locations [10–13], or considered energy efficiency measures for a typical housing across various climate zones in Chile, but these studies only considered operational energy use and not the total life cycle energy. One study [14] considering life cycle energy of housing in Chile, analyses a typical reference house, house built to thermal regulations and an improved house across four climate regions, finding that improved performance in cold climate regions and up to 50% reduction in $CO_2$ emissions. Further research is needed to understand the potential of energy-efficient housing solutions to reduce energy consumption, whilst maintaining thermal comfortable standards to guide pathways to a low-carbon residential sector.

Currently, the thermal regulations for housing in Chile are insufficient and unlikely to be able to reach the energy reductions needed to meet climate targets, thus alternative approaches are required [4]. Passivhaus has been widely promoted as an approach for low-energy housing, although originally developed in Europe the approach is suitable in different climates [15–18], suggesting that it could be applied in Chile. Studies employing Passivhaus have reviewed the benefits to thermal comfort and reductions in operational energy consumption [19–21], but there is little work quantifying the environmental impacts of each phase of the life cycle (manufacture of materials, construction, use) of Passivhaus [22]. Furthermore, there is little evidence on the effectiveness of energy-efficient retrofits in housing compared to housing constructed to the Passivhaus standard.

In this context, this work aims to compare the performance of different energy-efficient housing solutions for the context of Chile, considering both life cycle energy use. The work interfaces a range of building simulation tools to find the optimal housing for each climate zone in Chile from over a thousand possible combinations of energy efficiency measures. A Life Cycle Assessment (LCA) of the optimised house is compared to a house constructed to Passivhaus standards. The eight different climate zones are used to understand variation in performance across Chile.

## 2. Materials and methods

### 2.1. Case study dwellings

The case-study buildings selected represent a transition from a typical house, an upgraded energy-efficient typical house optimised for each climate zone and a Passivhaus dwelling. The case study housing are as follows:

#### 2.1.1. Typical house

The typical house was based on Type 1 dwelling of the 'Study of Final Uses and the Energy Conservation Supply Curve in the Housing Sector in Chile, this typology represents the majority of the Chilean building stock [8]. This is a detached house on a single floor, with a useable floor area of 58.21 m$^2$ and ceiling height of 2.40 m. The surface area of the outside walls is 78.35 m$^2$ and the roof is 62.94 m$^2$. The house is shown in Fig. 1.

The traditional house is constructed with a reinforced concrete floor, with walls constructed from brick and the roof out of corrugated galvanised steel sheet and pine wood. Table 1 details the construction used for the floor, walls, and roof of the typical house

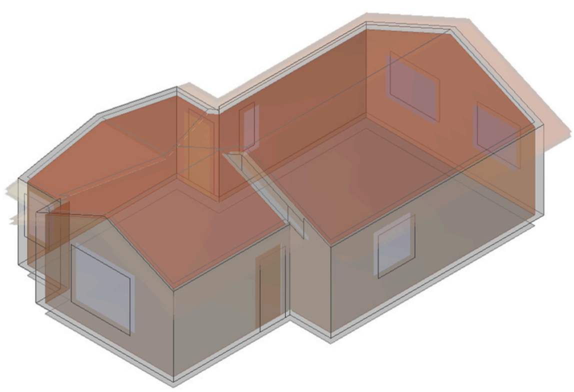

**Fig. 1.** Model of a typical house for energy optimisation.

along with its thicknesses, while thermal density, thermal conductivity and specific heat capacity are taken from the Chilean Standard NCh 853–2007, that is dedicated to "Thermal conditioning - Thermal envelope of buildings - Calculation of thermal resistances and transmittances".

### 2.1.2. Optimised house

The typical house was optimised for each climate zone in Chile. The wall and roof materials were optimised, and windows replaced to find the best performing solution to reduce energy consumption. The reconditioned outside wall consisted of a *principal material* with variable thermal characteristics with an exterior thermal insulation system based on E.I·F·S (Exterior Insulation and Finish System). This thermal insulation system consists of a lining incorporating a layer of insulating material of variable thickness and variable thermal characteristics, attached to the existing wall by an adhesive paste reinforced with a fibreglass mesh embedded in a thin layer of elastomeric mortar. The system is designed to be covered with an external coat of either smooth or textured wash. The thermal solution for the roof consists of the incorporation of thermal insulation. This thermal insulation is installed on the inside surface of the roof by attaching insulating material of variable thickness between the exposed support beams, plus a damp-proof membrane. Details of the optimisation methodology are given in section 2.3.

### 2.1.3. Passivhaus

The reference for the Passivhaus house was taken from the study carried out by Universidad del Bío-Bío [20], which details the technical characteristics of a standard Passivhaus house for the climate zone F in Chile. It is a two-floor house with a useable area of 115.21 $m^2$ and a ceiling height of 2.40 m. The outside wall of the house consists of cement-fibre external lining, ventilation space, damp-proof membrane, two layers of glass wool insulation and plasterboard internal lining. The geometry of the Passivhaus house is shown in Fig. 2.

The house was designed to Ref. [20]:

- Guarantee thermal comfort in winter and summer, while limiting energy demand.
- Limit the minimum temperature of the internal surface of the outside walls to avoid the risk of condensation and the propagation of mould.
- Limit the minimum temperature of the internal surface of the outside walls to guarantee high thermal comfort inside the house.
- Limit the air velocity to avoid the negative effect of draughts.
- Limit air infiltration by highly hermetic walls, windows, and doors, as well as sealing the openings through which the utilities pass.
- Limit the primary energy consumption: maximum demand for heating 15 kWh/($m^2$·y) and maximum demand for cooling 15 kWh/($m^2$·y).
- Primary energy consumption for all systems (heating, cooling, ACS, electricity, auxiliary, etc.) no greater than 120 kWh/($m^2$·y).
- Internal surface temperatures of the outside walls during winter >17 °C.

## 2.2. Determination of climatic zones

Chile lies between a longitude of 17°S and ~56°S. The country is 4329 km long and covers a total area of 756,253 $km^2$, divided into 15 administrative regions [23]. It is the longest country in the world from north to south and includes many different climate zones (from tropical in the north to polar in the south) [24]. For this study, 14 cities were selected to cover the diversity of the eight different

**Table 1**
*Thermal properties of materials and construction elements of the typical house.*

| Layers | e<br>cm |
|---|---|
| **Floor (total area 58.21 $m^2$)** | |
| Pebbles | 10.00 |
| Damp-proof membrane | – |
| Reinforced concrete | 8.00 |
| **Outside wall (total area 78.35 $m^2$)** | |
| Plaster wash (exterior) | 0.04 |
| External plasterboard | 0.30 |
| EIFS Adhesive | 0.50 |
| Brick wall | 14.00 |
| Plaster termination (interior) | 0.20 |
| **Roof (total area 62.94 $m^2$)** | |
| Corrugated galvanised steel sheet | 0.04 |
| Pine-boards | 1.40 |
| Air chamber | 5.00 |
| Pine-boards | 1.00 |
| Damp-proof membrane | – |
| Plasterboard | 1.00 |

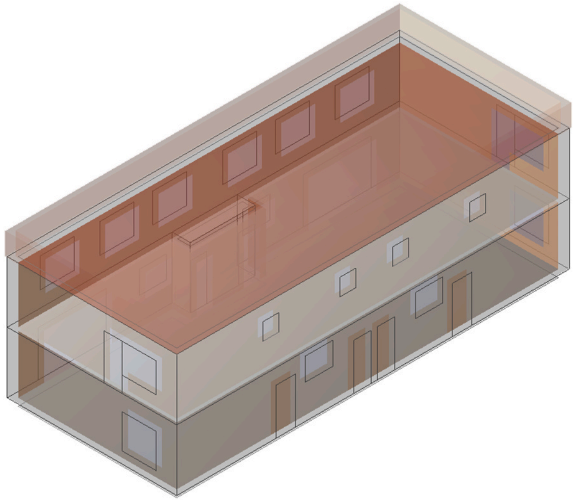

**Fig. 2.** *Model of Passivhaus based on* [20].

climate zones considered, following the classification defined under the Chilean regulation (NCh 1079) which considers temperature as the principal characteristic in defining the climate zones. However, this classification does not consider other characteristics, such as: humidity levels, pressure and wind speed or direction. Additional cities were therefore included to consider further variation in climate within different climate zones. Cities were only included where there was sufficient meteorological data for use with the building energy simulation software, EnergyPlus. No climatic data were found for cities located in climatic zone E, so that zone will not be addressed in this study. For the climate zones, Table 2 lists (in order from north to south) the cities which were considered on the basis of their geographical location [25], climate zone under the current regulation and its main characteristics [26,27].

**Table 2**
*Cities selected for the study, with climate zone under the current regulation.*

| CITY | Geographical location [25] | Climate zone based on NCh 1079 [26] | Characteristics of the climate based on [26,27] |
|---|---|---|---|
| Iquique | Lat.: 20.21; Long.: 70.15 | Zone A | Desert zone with dominant maritime climate. Mean temperatures oscillate between 18 and 21 °C. Cloud cover and humidity which dissipate at midday, mean monthly relative humidity 67%. |
| Calama | Lat.: 22.46; Long.: 68.92 | Zone H | Semi-desert zone. Long, hot summers. Microclimates in the valleys. Low annual precipitation, max. 3.0 mm. Strong solar radiation and temperatures ranging between 2 and 23 °C. |
| Antofagasta | Lat.: 23.65; Long.: 70.39 | Zone A | Desert zone with dominant maritime climate. Mean temperatures oscillate between 16 and 19 °C. Mean monthly relative humidity 71%. |
| Copiapó | Lat.: 27.37; Long.: 70.33 | Zone B | Semi-desert zone. Long, hot summers. Microclimates in the valleys. Temperatures range between 13 and 23 °C. |
| La Serena | Lat.: 29.90; Long.: 71.25 | Zone C | Zone with maritime climate. Short winters of four to six months. Moderate temperature, ranging between 13 and 18 °C. Cloud cover in summer dissipates at midday. |
| Valparaiso | Lat.: 33.04; Long.: 71.63 | Zone C | |
| Santiago | Lat.: 33.46; Long.: 70.65 | Zone D | Zone with Mediterranean climate. Moderate temperatures ranging between 15 and 24 °C. Winters of four to five months. Vegetation normal. |
| Chillán | Lat.: 36.61; Long.: 72.10 | Zone F | Cold, rainy zone with frequent frosts. Mean temperatures ranging between 10 and 17 °C. Short summers of four to five months with moderate sunshine. |
| Temuco | Lat.: 38.74; Long.: 72.60 | Zone F | |
| Valdivia | Lat.: 20.21; Long.: 70.15 | Zone G | Zone with maritime climate, rainy with annual precipitations around 1400 mm. Moderate to cold temperatures, ranging between 10 and 15 °C. |
| Osorno | Lat.: 22.46; Long.: 68.92 | Zone G | |
| Puerto Montt | Lat.: 23.65; Long.: 70.39 | Zone G | |
| Coyhaique | Lat.: 27.37; Long.: 70.33 | Zone I | Cold, very rainy zone, with precipitations all year round. Almost permanent cloud cover, short summers. Frost and snow at higher altitudes and towards the south of the zone, where high winds are also experienced. Moderate solar radiation in summer |
| Punta Arenas | Lat.: 29.90; Long.: 71.25 | Zone I | |

### *2.3. Methodology for energy optimisation of the typical house*

The optimisation method used in this study is based on recent publications in which optimisation algorithms are linked with dynamic building simulation [21,28,29]. The work followed the OpenBIM methodology [30] which allows simulations to move freely between the different software. The main feature of the OpenBIM technology, and in some senses its main advantage, is that it is based on free, public IFC exchange formats, so that the content of the BIM project is not linked to any specific application or programme and is decodable in time. Fig. 3 shows the workflow, starting with a version 4 IFC file exported by Autodesk Revit 2018, the main BIM modelling software used. Then Cype's IFC Builder software (2018.m) was used to revise and modify the IFC model for compatibility with the CYPETHERM EPlus software. This tool was used for the dynamic energy modelling and simulation of the case studies by EnergyPlus™. After the simulations for the case study, the EnergyPlus (E+) calculation file was exported from CYPETHERM EPlus in. idf format and saved in EP-Launch, an optional component of E+ for Windows which allows entry and exit files to be opened and modified by a text editor. Finally, the resulting.idf file was used in JEPlus; this is an open-source tool developed originally to manage

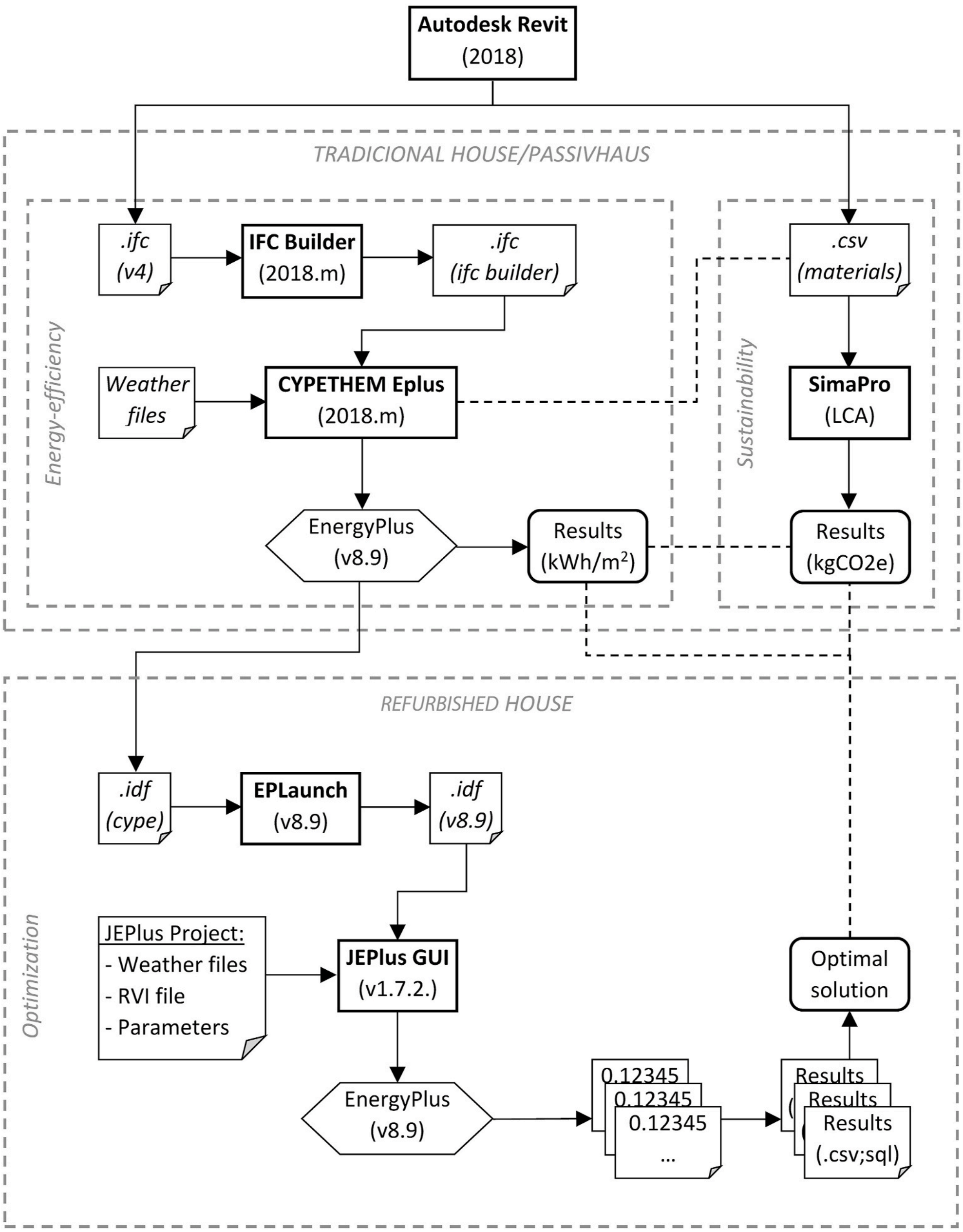


**Fig. 3.** Work-flow diagram for energy modelling and optimisation of the typical house (© 2020, M. Iannantuono).

complex E+ parametric simulations in combination with optimisation algorithms. This offers a convenient and highly efficient way of optimising building design and operation [31].

The same workflow for energy modelling (Fig. 3) was used for optimising the measures for the reconditioning of a typical house in Chile. Over one thousand design options were simulated from a combination of the variation of six parameters, as indicated in Table 3. The first parameter (*Parameter 0*) was the location which corresponded to the different climatic conditions as detailed in [25–27]; the next four parameters refer to the variants for the walls and roofs. For *Parameter 1*, five main types of outside wall material were considered (brick, wood, concrete, lightweight concrete, and adobe). The insulating material (*Parameter 3*) used in the outside wall and roof was either expanded polystyrene or glass wool, indicating the appropriate thickness for the walls (*Parameter 2*) and roof (*Parameter 4*). Finally, the last variable parameter (*Parameter 5*) refers to replacing the windows (different types of windows) and included four possible options (aluminium with single or double-glazing, PVC with double-glazing or low emissivity double-glazing). Here it was defined that each combination of possible solutions (Table 3) represents a design option. Table 3 shows the parameters and the ranges used in JEPlus for the optimisation of the case study.

Parameters which did not depend on the construction characteristics of each house: undisturbed temperature of the soil, orientation, occupation and radiant fraction, operational conditions (heating and cooling temperatures) were kept constant across all simulations to ensure comparable results. Table 4 shows the limit conditions and the inputs used for the dynamic energy simulations in EnergyPlus. Table 4 also shows that the values of the parameters that depend on characteristic construction elements of each house: ventilation and heat recovery (non-existent in the hypothetical typical and optimised houses), thermal transmittance of the doors, transmission coefficient and solar factor of the windows, permeability to air of doors and windows, infiltration (calculated as a function of the values of each case according to the Enhanced Model of the ASHRAE) if they vary and are considered to be parameters to be used in energy optimisation modelling.

### 2.4. Life Cycle Assessment

Life Cycle Assessment (LCA) is an important tool for the prevention of environmental pollution and prior evaluation of process sustainability [32]. Various models of LCA exist [33], however they are all covered by the methodology proposed in ISO 14.040, which establishes four main phases as described below:

- Phase 1: Define the objective and scope of the study: in this phase, the study product (e.g., a dwelling) is described and the functional unit to be used in the assessment is defined, together with the system limits.
- Phase 2: Model the life cycle of the product with all the environmental inputs and extractions. This data-collection work is generally known as the Life Cycle Inventory (LCI).
- Phase 3: Understand the environmental importance of all the inputs and extractions. This is known as the Life Cycle Impact Assessment (LCIA)
- Phase 4: Interpretation of the study.

**Table 3**
Definition of the parameters and ranges used in JEPlus.

| Parameter | Description | Range | | | |
|---|---|---|---|---|---|
| *Parameter 0* | Location[a] | Iquique, Calama, Antofagasta, Copiapó, La Serena, Valparaíso, Santiago, Chillán, Temuco, Valdivia, Osorno, Puerto Montt, Coyhaique, Punta Arenas | | | |
| *Parameter 1* | Outside wall material[b] | | λ | ρ | $C_p$ |
| | | Brick | 0.460 | 1000 | 750 |
| | | Wood | 0.104 | 410 | 2805 |
| | | Concrete | 1.630 | 2400 | 920 |
| | | Lightweight concrete | 0.269 | 840 | 1094 |
| | | Adobe | 0.900 | 1450 | 1100 |
| *Parameter 2* | Wall insulation thickness, m | 0.02, 0.04, 0.06, 0.08, 0.10, 0.12 | | | |
| *Parameter 3* | Insulation material[b] | | λ | ρ | $C_p$ |
| | | Expanded polystyrene | 0.0410 | 15.0 | 1200 |
| | | Glass wool | 0.0406 | 12.5 | 840 |
| *Parameter 4* | Roof insulation thickness, m | 0.04, 0.06, 0.08, 0.10, 0.12, 0.14, 0.16 | | | |
| *Parameter 5* | Type of window[c] | | | $U_w$ | $g_{gl,n}$ |
| | | Aluminium, single-glazed | | 5.7 | 0.85 |
| | | Aluminium, double-glazed | | 3.0 | 0.75 |
| | | PVC, improved double-glazed | | 2.0 | 0.65 |
| | | PVC, low emissivity double-glazed | | 1.6 | 0.70 |

[a] City with higher density per climate zone.
[b] Values based on the List of Materials published by MINVU – NCh853.
[c] Values based on UNI EN 13363–1.

**Table 4**
Definition of limit conditions and inputs.

| General parameters | Case Study | | Passivhaus |
|---|---|---|---|
| | Typical | Optimised | |
| Location data | | | |
| Orientation | 0.00 | 0.00 | 0.00 |
| Undisturbed temperature of the soil (average annual temperature) °C | 18.00 | 18.00 | 18.00 |
| Climate data file | *Parameter 0* | *Parameter 0* | *Parameter 0* |
| Ventilation | | | |
| Ventilation, ACH | 1.00[b] | 1.00[b] | 0.60[b] |
| Heat recovery, % | 0.00 | 0.00 | 80.00 |
| People | | | |
| People, $m^2$/person | 20.00[b] | 20.00[b] | 20.00[b] |
| Activity level, W/person | 115.00 | 115.00 | 115.00 |
| Radiant fraction | 0.60 | 0.60 | 0.60 |
| Internal equipment | | | |
| Design power, W/$m^2$ | 5.00[b] | 5.00[b] | 2.90[b] |
| Operational conditions | | | |
| Heating (24h), °C | 20.00[b] | 20.00[b] | 20.00[b] |
| Cooling (24h), °C | 26.00[b] | 26.00[b] | 26.00[b] |
| Doors | | | |
| Heat transfer coefficient, W/($m^2$·K) | 4.00 | 1.70 | 1.50 |
| Windows | | | |
| Heat transfer coefficient, W/($m^2$·K) | 5.70 | *Parameter 5* | 1.60 |
| Solar heat gain coefficient | 0.85 | *Parameter 5* | 0.70 |
| Air permeability of the building envelope (Reference pressure 100 Pa), $m^3$/(h·$m^2$) | | | |
| Doors | 50 (class 1) | 9[a] (class 3) | 3 (class 4) |
| Windows | 50 (class 1) | 9[a] (class 3) | 3 (class 4) |
| Infiltration | | | |
| Analysis method | Enhanced Model (ASHRAE) | | |

[a] Minimum value based on NCh 3297.
[b] Values based on [20].

### 2.4.1. Phase 1. definition of study objective and scope

The objective of the assessment for the cases studied is to assess the impacts and compare the real benefits of the thermal reconditioning of existing houses with the benefits of a Passivhaus in Chile.

The useful life chosen for the study was based on the values indicated in the "Table of the useful life of immovable physical assets" of the Chilean Internal Revenue Service (SII) [34]: 1) Buildings, houses and other constructions, with walls of brick or concrete, with ties, pillars and beams of reinforced concrete, with or without concrete floors, 50 years; 2) Constructions of adobe or wood in general, 30 years.

The functional unit of analysis chosen, for residential buildings, is the square metre of useable area for an annual period of a year

**Table 5**
Definition of processes and materials of the reconditioned typical house in SimaPro.

| Materials/assemblies | Sector | Amount | Unit |
|---|---|---|---|
| Concrete, sole plates and foundation {RoW} | Construction/Concrete | 5.43 | $m^3$ |
| Gravel, crushed {RoW} | Minerals | 11,543 | kg |
| Gypsum plasterboard {GLO} | Construction/Coverings | 2858 | kg |
| Base plaster {GLO} | Construction/Coverings | 366 | kg |
| Light clay brick {GLO}[a] | Construction/Bricks | 11,390 | kg |
| Concrete block {GLO}[b] | Construction/Concrete | 27,336 | kg |
| Sawnwood, hardwood, raw {GLO}[c] | Wood/Products | 11.39 | $m^3$ |
| Lightweight concrete block, polystyrene {RoW}[d] | Construction/Concrete | 9568 | kg |
| Zinc {GLO} | Metals/No iron | 2567 | kg |
| Particle board, for outdoor use {GLO} | Wood/Products | 2.13 | $m^3$ |
| Sawnwood, hardwood, raw {GLO} | Wood/Products | 0.63 | $m^3$ |
| Door, inner, wood {GLO} | Construction/Doors | 19.31 | $m^2$ |
| Window frame, aluminium, U = 1.6 W/$m^2$K {GLO} | Construction/Windows | 13.24 | $m^2$ |
| [e]Window frame, poly vinyl chloride, U = 1.6 W/$m^2$K {GLO} | Construction/Windows | 13.24 | $m^2$ |
| Glazing, double, U < 1.1 W/$m^2$K {GLO}[e] | Glass/Construction | 13.24 | $m^2$ |
| Glass wool mat {GLO}[e] | Construction/Insulation | 52.25–245.5 | kg |

[a] Outside wall materials. Only one type used for each calculation.
[b] Outside wall materials. Only one type used for each calculation.
[c] Outside wall materials. Only one type used for each calculation.
[d] Outside wall materials. Only one type used for each calculation.
[e] Materials used in reconditioning.

($m^2$/year); this choice allows comparison between the cases studied, and with other studies [22,35,36]. The energy consumption and the climate change indicator (carbon dioxide equivalent) were used to compare environmental impacts in this study.

The limits of the system are the set of materials formed by the construction elements of the typical house (floors, outside walls, partitions walls, roofs, windows) plus the materials used for reconditioning, as well as the whole set of materials used in the Passivhaus. The phases considered in the timescale were extraction, production, and transport of the materials; construction; and use to the end of the useful life of the house.

#### 2.4.2. Phase 2. Life Cycle Inventory (LCI)

The inventory activities fell into three phases:

1. Pre-construction: from the extraction, production, and transport of all the materials.
2. Construction of the house.
3. Use: the occupation of the house (during its useful life) with electricity consumption (heating and cooling, ventilation, lighting, use of white goods, other electricity consumption).

For the pre-construction phase, the precise quantities of materials were calculated for the Revit models, following the workflow (Fig. 1), using the SimaPro software and the ecoinvent v3 database (Tables 5 and 6).

This study used the ecoinvent v3 database in SimaPro, which contains LCI data from various sectors, such as energy production, transport, construction materials, metal production, etc. The complete database consists of more than 10,000 interconnected datasets, each of which describes a Life Cycle Inventory for a process. SimaPro provides different libraries which contain all the processes found in the ecoinvent database, but they use different system models and contain both unit and system processes. Tables 5 and 6 summarise the quantity of materials used for each construction lot involved.

#### 2.4.3. Phases 3 and 4. construction and use

In the construction phase energy is used both in the domestic transport of materials for construction works and, in the processes, associated with the installation of those materials in the construction of the house. The amount of energy used depends on the complexity of the work and the quantity of materials. In this work different energy consumption values were used for the construction of the typical house (9.80 kWh/$m^2$), the optimised house (12.70 kWh/$m^2$) and the Passivhaus (25.40 kWh/$m^2$). This is based on a study carried out by Cárdenas et al. (2015) which refers to the quantification of energy consumption in the construction phase of different house types in Chile [12].

For the house operational phase, the final energy demand for HVAC was modelled for the three types (typical, optimised and Passivhaus) in each city included in this study. In the case of the Passivhaus the conditioners of energy demand established in section 2.1 were included and electricity was the only energy source. In the case of the typical house, the energy use distributed among the different energy sources for each city studied was considered to obtain a case study more representative of reality (Table 7). Table 7 also shows the results of the final energy demand of the typical house. In the case of the optimised house, the results are shown in the following section (3.1), where the optimisation measures are also discussed.

From Table 7 it may be deduced that independent of the energy consumption, the energy source used is also important, especially if comparisons are made using the climate change indicator which includes carbon dioxide equivalent emissions as the main unit. The following data were used in the present study to transform the energy demand into carbon dioxide equivalent emissions depending on the type of source (Table 8).

## 3. Results and discussion

### 3.1. Energy optimisation

Fig. 4 shows the results of the energy demand for heating and cooling based on the 23,520 energy simulations carried out for the fourteen cities included in this study. The results show that the heating consumption in the cities located in northern Chile (Iquique, Antofagasta) is lower than 13.00 kWh/$m^2$·y, but the mean cooling consumption is 33.50 kWh/$m^2$·y; in southern Chile, on the other

**Table 6**
Definition of processes and materials of the Passivhaus in SimaPro.

| Materials/assemblies | Sector | Amount | Unit |
|---|---|---|---|
| Glass wool mat {GLO} | Construction/Insulation | 582 | kg |
| Three-layered laminated board {GLO} | Wood/Products | 75.88 | $m^3$ |
| Concrete, sole plates and foundation {RoW} | Construction/Concrete | 22.67 | $m^3$ |
| Concrete roof tile {GLO} | Construction/Concrete | 14,297 | kg |
| Gypsum plasterboard {GLO} | Construction/Coverings | 10,728 | kg |
| Fibre cement facing tile {GLO} | Construction/Coverings | 3634 | kg |
| Door, inner, wood {GLO} | Construction/Doors | 112.43 | $m^2$ |
| Window frame, poly vinyl chloride, U = 1.6 W/$m^2$K {GLO} | Construction/Windows | 76.02 | $m^2$ |
| Glazing, double, U < 1.1 W/$m^2$K {GLO}\| market for \| Alloc Def, S | Glass/Construction | 76.02 | $m^2$ |

**Table 7**
Final energy demand in the typical house in HVAC and distribution by different energy sources.

| City | Energy consumption ($KWh/m^2 \cdot y$) | Distribution of energy sources (%), *based on* [37]. | | | |
|---|---|---|---|---|---|
| | | Biomass | Electricity | Liquefied gas | Paraffin |
| Iquique[a] | 56 | 3.60 | 51.10 | 44.00 | 1.20 |
| Calama | 210 | 16.30 | 30.40 | 52.00 | 1.30 |
| Antofagasta[a] | 74 | 16.30 | 30.40 | 52.00 | 1.30 |
| Copiapó | 45 | 14.80 | 34.00 | 46.10 | 5.00 |
| La Serena[b] | 48 | 14.80 | 34.00 | 46.10 | 5.00 |
| Valparaíso[b] | 64 | 64.90 | 16.20 | 16.70 | 2.20 |
| Santiago | 151 | 64.90 | 16.20 | 16.70 | 2.20 |
| Chillán[c] | 131 | 64.90 | 16.20 | 16.70 | 2.20 |
| Temuco[c] | 100 | 88.10 | 4.40 | 6.80 | 0.80 |
| Valdivia[d] | 137 | 88.10 | 4.40 | 6.80 | 0.80 |
| Osorno[d] | 138 | 92.40 | 2.50 | 4.60 | 0.50 |
| Pto. Montt[d] | 145 | 92.40 | 2.50 | 4.60 | 0.50 |
| Coyhaique[e] | 177 | 31.50 | 1.20 | 67.10 | 0.20 |
| Pta. Arenas[e] | 206 | 31.50 | 1.20 | 67.10 | 0.20 |

[a] These cities belong to the same climatic zone (Zone A).
[b] These cities belong to the same climatic zone (Zone C).
[c] These cities belong to the same climatic zone (Zone F).
[d] These cities belong to the same climatic zone (Zone G).
[e] These cities belong to the same climatic zone (Zone I).

**Table 8**
*Emission factors by energy source* [37].

| Energy Source | Emission factor ($KgCO_2/kWh$) |
|---|---|
| Biomass | 0.390 |
| Electricity[a] | 0.199 |
| Liquefied gas | 0.252 |
| Paraffin | 0.260 |

[a] The emission factor for electricity in Chile was calculated based on the use of hydroelectric (43%), oil (18%), coal (27%), gas (9%) and other (3%).

hand (Coyhaique and Punta Arenas) the minimum energy consumption for heating is 92.70 $kWh/m^2 \cdot y$, while the cooling consumption is below 2.20 $kWh/m^2 \cdot y$. These figures show an asymmetry in energy consumption depending on the climate zone studied: in the extreme north of the country more energy is consumed in air cooling than in heating, while the reverse is the case in the south.

Fig. 4 also shows that 13% of the combinations considered in the energy optimisation measures help to meet the energy consumption standard of a Passivhaus (15.00 $kWh/m^2 \cdot y$) and that this result can be achieved in the cities of Iquique, Antofagasta, La Serena and Copiapó without a mechanical air conditioning system. In all the other cases, the energy demand calculated is higher than the maximum energy consumption established by the standard. It should be noted here that the standard can be met using mechanical ventilation systems with heat recovery. However, this measure was not considered as it would imply a replica of a Passivhaus, and it would not be possible to compare houses with different approaches to energy optimisation.

Table 9 shows the energy efficiency measures associated with the house whose energy consumption is closest to that established in the Passivhaus standard (15.00 $kWh/m^2 \cdot y$), for both cooling and heating. In the north of the country, where high temperatures predominate, the use of materials with high thermal inertia is recommended, like concrete or lightweight concrete. In the south on the other hand, where low temperatures predominate, the use of wood is recommended as its lower thermal conductivity reduces transmission losses. From Table 9 it may also be inferred that in the northern cities (Iquique, Calama, La Serena) the recommended thickness of insulation (<8 cm) is half of that recommended in the south (<16 cm). The use of mineral wool is recommended in all cases, as its thermal conductivity is lower than that of expanded polystyrene and its production produces lower $CO_2$-eq. emissions. Finally, it may be deduced that in most cases the use of hermetic double-glazed windows with low conductivity frames is recommended to reduce total heat transmission (Ug). This measure can be omitted in Antofagasta and Copiapó where it is estimated that the energy demand for heating is low (<14.9 $kWh/m^2 \cdot y$).

### 3.2. LCA comparison

First, we present a comparison of the absolute energy consumption of the three types of houses (typical, optimised and Passivhaus) considering three phases of their life cycle (manufacture of materials, construction, and use) and the different sizes considered for the typical house (52 $m^2$) and Passivhaus (115 $m^2$). The results of the comparison show that the absolute energy consumption of the Passivhaus is on average 3.1 times higher than that of the typical house and 5.6 times higher than in the optimised house. The

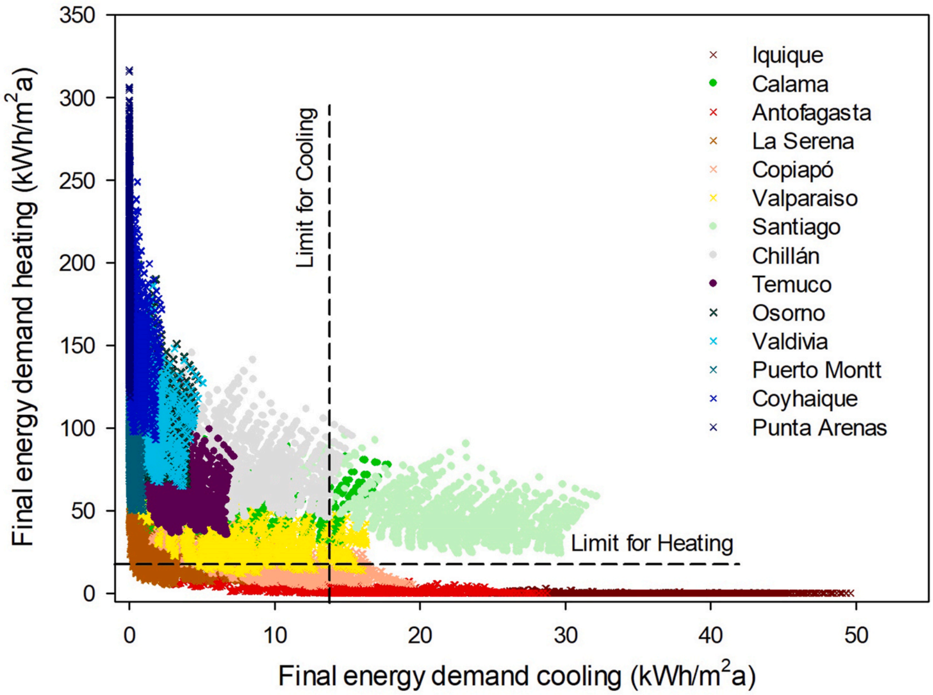


**Fig. 4.** *Results of energy simulations to determine the energy demand for air heating and cooling, carried out in fourteen Chilean cities with different climate conditions. Limits for cooling and heating energy demand* = 15 KWh/$m^2a$.

**Table 9**
*Efficiency measures and minimum energy consumption in* kWh/m$^2$·y, *broken down for the cities selected in the study.*

| City | Energy efficiency measures | | | | Energy consumption kWh/m$^2$·y | |
|---|---|---|---|---|---|---|
| | **Principal material** | **Insulation specification Walls/Roof (cm)** | **Type of insulation** | **Ug-Value Windows** | **Heating** | **Cooling** |
| Iquique | Concrete | 2/4 | Mineral wool | 1.60 | 0.00 | 14.70 |
| Calama | Lightweight Concrete | 12/16 | Mineral wool | 1.60 | 28.30 | 8.90 |
| Antofagasta | Brick | 6/16 | Mineral wool[a] | 5.70 | 14.90 | 2.20 |
| Copiapó | Wood | 6/8 | Mineral wool | 3.00 | 14.90 | 14.90 |
| La Serena | Wood | 8/6 | Mineral wool[a] | 1.60 | 14.80 | 6.10 |
| Valparaíso | Lightweight concrete | 12/14 | Mineral wool | 1.60 | 14.60 | 12.70 |
| Santiago | Concrete | 12/16 | Mineral wool | 1.60 | 23.90 | 22.70 |
| Chillán | Concrete | 12/14 | Mineral wool | 1.60 | 45.50 | 7.10 |
| Temuco | Wood | 12/16 | Mineral wool | 1.60 | 35.50 | 6.70 |
| Valdivia | Wood | 12/16 | Mineral wool | 1.60 | 64.80 | 3.70 |
| Osorno | Wood | 12/16 | Mineral wool | 1.60 | 65.90 | 3.90 |
| Pto. Montt | Wood | 10/16 | Mineral wool | 1.60 | 49.60 | 1.00 |
| Coyhaique | Wood | 12/16 | Mineral wool | 1.60 | 92.70 | 1.90 |
| Pta. Arenas | Wood | 12/16 | Mineral wool | 1.60 | 118.03 | 0.10 |

[a] This solution can be replaced by expanded polystyrene, but the $CO_2$-eq. emissions are higher than for mineral wool.

difference is due principally to the amount of energy contained in the materials used for the construction of a Passivhaus, which is up to 10 times more than that required by the materials used in a typical house.

Another important feature shown in Fig. 5 is the low consumption in the operational phase in colder climates (Pto. Montt, Coyhaique and Pta. Arenas) compared with the warmer climates (Iquique, Antofagasta, Copiapó). These results can be largely explained because the Passivhaus design used in this study was oriented towards cold climates and was therefore not suited to the zones with warmer climates. In the latter, the energy consumption for cooling is observed to increase substantially to counteract overheating in the house. Here it is recommended to reduce solar gains with shading measures and reduction of thermal insulation for houses located in warm cities as Iquique, Calama, Antofagasta or Copiapó (climatic zones A, B and C) and increasing thermal insulation for colder cities as Coyhaique and Punta Arenas (climatic zones H and I).

To achieve a fairer picture, a new comparison was made using the equivalent unit of area per year (1 m$^2$/y). The energy consumptions shown in Fig. 5 were divided by the years of useful life and the useable area. The results are shown in Fig. 6.

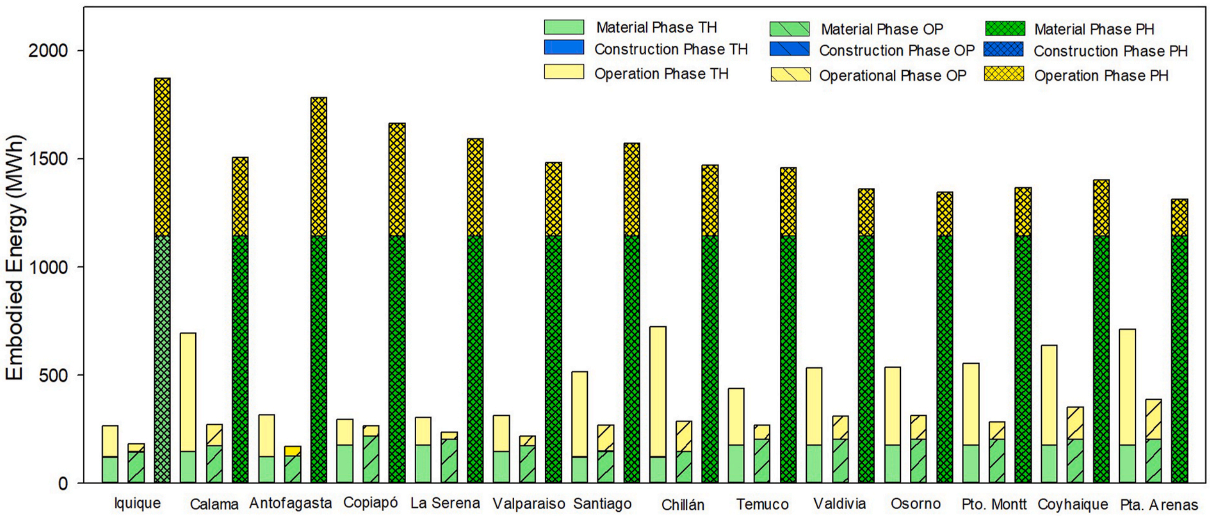


**Fig. 5.** Comparison of energy consumption in the three types of houses in the different cities of Chile.TH = typical house, OP = optimised house, PH= Passivhaus.

Fig. 6 shows that in the four most northerly cities (Iquique, Calama, Antofagasta, Copiapó) the typical and optimised houses have a lower energy consumption than the Passivhaus. In the cities from La Serena to Santiago, only the optimised house consumes less energy per equivalent unit than the Passivhaus. From Chillán southwards, the Passivhaus is found to have a lower consumption per equivalent unit than the other houses. This difference becomes very substantial in the southernmost city in the country (Pta. Arenas), where the energy consumption of the Passivhaus is one-quarter of that of the typical house and half that of the optimised house. The same results are observed if the climate change indicator is considered. These results suggest that to reduce carbon dioxide emissions in all the northern cities of Chillán it is better to use thermal insulation measures than build the Passivhaus considered in this work (Fig. 7). Only in Chillán and in the further southern area the volume of emissions is lower for the Passivhaus than for other houses.

In the typical Chilean house, it is possible to apply additional measures to improve the environmental performance through technological solutions for the hot water supply, either with a heat pump, geothermal energy, or a solar collection system, since geothermal energy and solar radiation have promising potential in Chile. Reductions can also be achieved in environmental impact by using insulation materials of natural origin, an industry that is starting to take off in Chile, so further studies are needed.

### *3.3. Limitations and further work*

The Passivhaus standard is not achieved by thermal insulation measures alone but also requires a mechanical ventilation system. In this study, the environmental impacts associated with the air exchange system were not quantified to allow comparison with typical

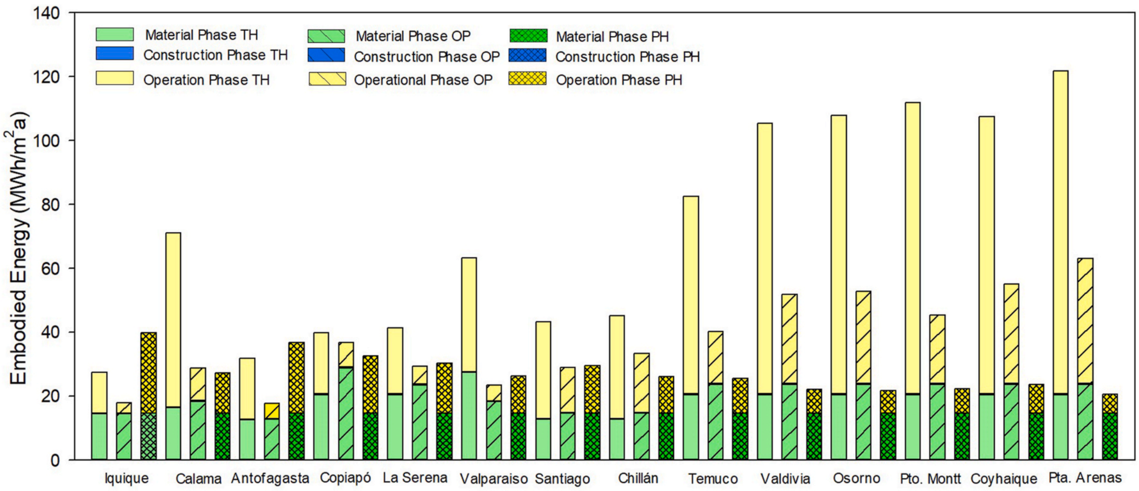


**Fig. 6.** Comparison of energy consumption in the three phases of the life cycle using a functional unit. TH = typical house, OP = optimised house, PH= Passivhaus.

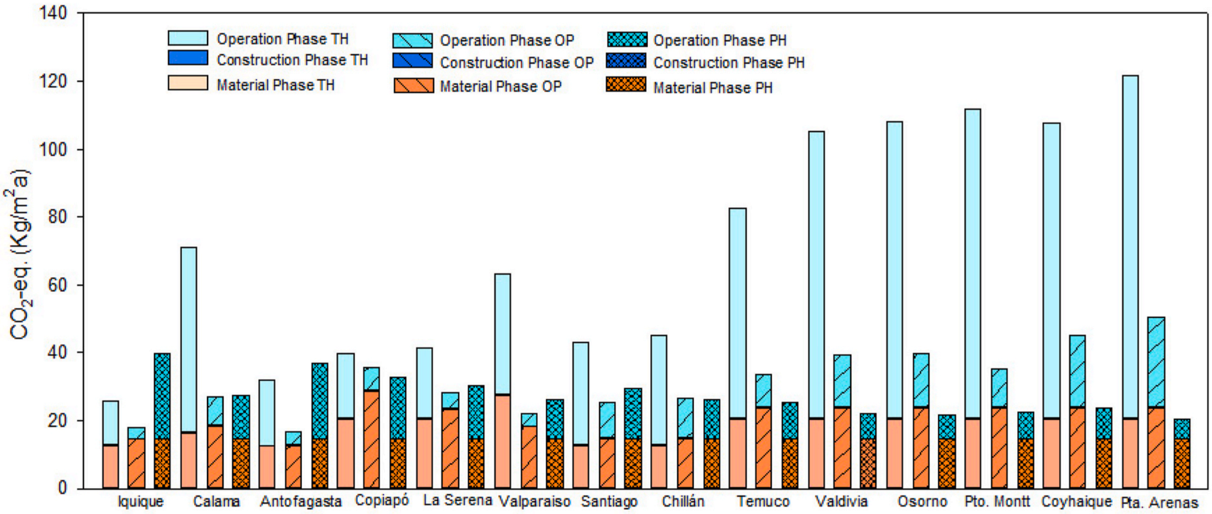


**Fig. 7.** Comparison of carbon dioxide equivalent in the three phases of the life cycle using a functional unit. TH = typical house, OP = optimised house, PH= Passivhaus.

houses in Chile which do not have this type of system. However, this aspect needs to be clarified for compete quantification of the environmental impacts associated with building a house to the Passivhaus standard. Preparing an inventory and an environmental impact declaration for this type of system needs to be addressed in future work.

Generally, studies have used city level temperature when considering climate zones, due to the available climate databases associated with building energy simulation software, whereby studies select and analyse performance of representative climate data from cities [38–42]. In these studies, it has been shown that there may be differences in the existing micro-climates [42]. In this study we used the climatic data from the software EnergyPlus, and selected cities located in the representative climatic zones established in the Chilean climatic regulations (NCh 1079) in order to determine possible variations in the energy performance of building in different cities but with same climate zone. The results show that for the typical house the percentage differences in energy demand fluctuate between 31% (Zone C and Zone F) and 6% (Zone G), reaching an absolute maximum of 31 KWh/m$^2$a (Table 7). The maximum absolute differences in energy demand decreases to 26 KWh/m$^2$a in the optimised home for the house in the climate zone I (Table 9). This on the one hand shows that as the thermal insulation measures in buildings are increased, the energy demand in them becomes less sensitive to outside temperatures. On the other hand, it shows that the same building (with the same construction systems and orientation) located within the same climatic classification based on NCh 1079 could have different energy performances. These differences may be due to the small difference in external temperatures that exist between the different cities grouped in the same climatic zones. Different authors have shown through sensitivity analysis that energy demand is highly sensitive to variations in outside temperature [43–45]. Empirical verifications of these effects in cases such as the Chilean one has not been carried out and therefore represent future work that can be tackled to improve the precision in energy modelling but also to verify the effectiveness of the grouping of geographic spaces in “representative climatic zones”.

In this work, it was assumed that the house built to the Passivhaus standard would use only electricity to satisfy the energy demand. It was also assumed that the typical house uses a mixture of energy sources following the Chilean matrix, based principally on fossil fuels. This has an impact on quantifying carbon dioxide emissions and certainly leads to a result which favours the Passivhaus. However, the optimised houses could also use electricity as an energy source and reduce carbon dioxide emissions.

## 4. Conclusions

The aim of this work was to compare the performance of different energy-efficient housing solutions for the context of Chile, considering both life cycle energy use. A typical house was optimised for different climate zones in Chile with different energy-efficient housing solutions. Furthermore, fourteen cities located in different climate zones of Chile are considered, to verify the results’ variation depending on the climate variables. A workflow was developed using REVIT-CYPETHERM and JEPlus to determine if only with passive measures it is possible for a traditional Chilean house to achieve the same energy performance as a Passivhaus and to test optimal combinations of thermal insulation. Additionally, a life cycle analysis is carried out for both houses to determine the associated environmental impacts of the materials’ manufacturing, construction, and operational phase.

The results of the energy demand in the operational phase show that, in most cases, the traditional housing required 10% more energy than a house built with the Passivhaus standard in hot climates and 90% in cold climates. On the other hand, it is observed that in hot climates it is possible to equal the energy consumption of a Passivhaus using minimal thermal insulation measures in traditional houses. The demand of an optimised traditional house in cold climates is 27% higher than the energy demand of a Passivhaus. This show that only with insulation measurement it is possible to reduce the energy demand and to achieve thermal performances that meets Passivhaus standards.

This work additionally shows the efficiency of the proposed workflow in energetically evaluating a home using multiple solutions. In this case, more than 1000 combinations of construction solutions are tested in parallel to determine which option offers the possibility of reducing energy demand in the operational phase. It is observed that most of the results obtained achieve an equal or close thermal performance of a traditional house optimised to a Passivhaus.

From the life cycle analysis, the results show that in the home construction phase the environmental impacts based on the contained energy and $CO_2$-eq emissions in the Passivhaus are between two and four times more than those involved in building a traditional house. This environmental impact is offset in the operational phase in which the Passivhaus, due to its lower energy demand, also has lower environmental impacts. However, this difference is not so substantial in hot areas. It is also observed that from an environmental point of view, in hot climate zones lower greenhouse gas emissions are reported when building a thermally optimised house instead of a Passivhaus.

## CRediT authorship contribution statement

**Aner Martinez-Soto:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Marco Iannantuono:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Paolo Macaya-Vitali:** Methodology, Writing – original draft. **Emily Nix:** Writing – review & editing, All authors have read and agreed to the published version of the manuscript.

## Declaration of competing interest

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

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