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Research Article

Eco-efficient analysis of thermal regulations applied to thermal envelopes of a dwelling in Chile

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Abstract: The aim of this study is to comparatively evaluate the eco-efficient performance of the only two mandatory thermal regulations applied in Chile: The General Urban Planning and Construction Ordinance (OGUC), and the Atmospheric Decontamination Plans (PDA). Considering the PDA of the communes of Temuco and Padre las Casas, and the system limits of UNE-EN 15978:2012 for the "product" and "use" stages, this study covered the indicators of energy, carbon footprint, economic cost and emissions of fine particulate matter (PM2.5), on thermal envelopes of a house. Applying the PDA over the OGUC, the results indicate that: First, the contained energy increases by 12.4%, the carbon footprint by 8.1% and the economic cost by 7.8% in the stage of product; and second, it reduces the demand for heating, fuel consumption, carbon footprint, and PM2.5 emissions, by 19.4%, in the use stage. Finally, the study concludes that, for Chilean homes to improve their eco-efficient performance, an evaluation with a life cycle cost analysis (LCCA) approach, which allows analyzing their evolution over time, must be included in the mandatory thermal regulations that regulate them.

Keywords: Sustainable construction, environmental indicator, energy efficiency, atmospheric contamination, environmental decontamination plan.

1. Introduction

The construction industry has grown significantly in recent decades, contributing in the economic growth of countries around the world (Acosta 2009). However, this growth has also contributed towards the generation of different global and environmental problems, such as: the energy crisis; global warming; the destruction of the ozone layer; particulate matter emissions; generation of large amounts of solid waste; land erosion; alteration of ecosystems; among other aspects (Seng, Magniont, and Lorente 2019)(Minvu 2018b).

There are studies that show that this industry during construction, generates between 30 and 40% of the world's environmental load (Marrero et al. 2020). In Europe, 36% of carbon dioxide (CO_2) emissions can be attributed to this industry (Cellura et al. 2018), and in Chile, during the entire lifecycle of construction projects, 23% of the total greenhouse gas emissions (GHG) are generated (CChC 2019).

The residential sector is part of the Chilean construction industry (Ministerio de Energía 2020). It is responsible for 66% of the industry's GHG emissions (MMA 2020), consumes more than 15% of the country's entire energy (Minvu 2018d), and generates high levels of thick 10 µm (PM10) and fine 2.5 µm (PM2.5) particulate matter, responsible for the atmospheric contamination, particularly in communes in the center and south of the country (MMA 2014) (Air 2018).

It is important to mention that high concentrations of fine PM2.5 particles cause serious consequences for people's health According to figures from the Chilean environmental authority, during 2018 around 3,640 deaths were associated to cardiopulmonary disease caused by prolonged exposure to this contaminant (MMA 2019b), which now on facing the appearance of the new coronavirus (SARS-CoV-2), also known as COVID-19, has reached alarming figures as this disease is transmitted more quickly when facing high concentrations of fine particulate matter in the air (Cereceda, Díaz, and Seeger 2020). This is alongside the humidity issues, the poor indoor ventilation of dwellings, and intrahousehold contamination -like cigarette smoke and the different contaminating devices-, which also worsen the health of the inhabitants (Armas, M, 2012; MINVU, 2018d).

There are currently two obligatory thermal regulations in Chile that regulate the residential sector: the General Ordinance of Urban Planning and Construction (OGUC, in Spanish), through its article 4.1.10, which organizes the country's regions by thermal zone -with 7 thermal zones in total (Minvu 1992) and the Atmospheric Decontamination Plans (PDA, in Spanish), applicable only in those communes declared as areas saturated by fine particles, which exceed the maximum concentration limits of this pollutant in the air (MMA 2014). It should be noted that the PDAs replace and include higher thermal transmittance requirements than those established in article 4.1.10 of the OGUC (MMA 2014).

Apart from these regulations, there are commitments in place from the Chilean Government, that seek to halt the environmental problems that are being generated at a country level. These include: the Paris Agreement, signed in 2015 for carbon neutrality by 2050 (MMA 2019a); the goals defined in the 2030 Agenda for Sustainable Development as part of the 193 member countries of the United Nations (UN) (MDS 2017); and the goals of strategy 6 of the 2018-2022 Energy Route, where it is expected to reduce at least 30% of the energy demand of the country's dwellings (Ministerio de Energía 2018). However, the obligatory regulations, OGUC and PDA, do not consider any of these commitments.

In Chile, 40% of the country uses firewood as a heating fuel (MMA 2014), which has major repercussions on the levels of atmospheric contamination (Silva and Godoy 2016), and on the economy of each family, who spend US$240 a year on average, to buy it (CDT 2019). At a country level, 97% of the particulate matter emissions generated by residential wood burning, are generated in the communes of Temuco and Padre las Casas, located in the south of Chile, in the Araucania Region, between 37°35' and 39°37' latitude south and from 70°50' longitude west towards to the Pacific Ocean. Both communes are recognized as zones saturated by PM 2.5 (Air 2018), on exceeding the 50 $\mu g/m^3$ maximum daily concentration permitted in the air (MMA 2011).

As for the high PM2.5 concentrations, which Temuco and Padre las Casas are the main responsible parties, these are directly related to the lifestyle, the weather, and the demographic growth of these communes, where 80% of the dwellings, use firewood for fuel to heat and/or cook, on this being inexpensive, readily available, and easier to obtain than other fuels (Emol 2020; Ministerio de Energía 2015; Municipalidad de Padre las Casas 2020; Universidad de Chile 2019). The temperatures vary between 3°C in July to 22°C in January, although the winter temperatures are particular intensive for residential wood-based heating. In the last 15 years, the population of Temuco has grown by 15.1% and Padre las Casas by 26.7%, which has meant an increase in the residential sector, and thus an increase in PM2.5 emissions (Municipalidad de Padre las Casas 2020; Municipalidad de Temuco 2019).

Due to this, a PDA was brought into force as of 2015 for both communes, with the goal of reducing the high PM2.5 emissions concentrated in the air by 67% before 2025. It proposed methods to control the use of firewood, to use energy efficient heating devices, and to incorporate construction strategies focused on improving the thermal standard of dwellings (MMA 2015). However, it is important to highlight that a change of regulation from the OGUC to a PDA, implies at a social level, in the occupation phase of dwellings, that normal heating practices must be changed (Chávez, Gómez, and Briceño 2009), and that in the design and construction phases, thicker thermal insulation or ones that are capable of complying with these requirements must be chosen, or that other materials with better thermal properties must be included (MMA 2015).

Currently, a lot of the environmental problems the construction industry brings into play, and mainly the residential sector in all the phases of its lifecycle -GHG emissions, high energy consumption, high economic expense and particulate matter emissions- are the result of design solutions, the use of environmentally deficient construction solutions and materials, which do not integrate the concepts of sustainability or eco-efficiency, and that have repercussions on the use phase, and thus, on the lifecycle of the dwellings (Minvu 2018a). Most of the materials used, are obtained from petrochemical products or from natural sources processed with high energy consumption, a high carbon footprint and little possibility of reuse, like for example, glass, glass wool, expanded polystyrene or concrete (Dávalos 2013; Fita 2018; Viegas, Walsh, and Barros 2016)

As a result of the aforementioned, the objective of this research is to comparatively evaluate the eco-efficient performance between article 4.1.10 of the OGUC and the PDA of the communes of Temuco and Padre las Casas, based on the study of the indicators of energy, carbon footprint, economic cost and fine particulate matter (PM2.5), of the thermal envelopes of a home. The purpose of the study is to prospect the environmental, energy and economic impacts of a home, with a life cycle approach, to achieve the existing commitments in the Chilean government, considering the limits of the system of the UNE-EN 15978 standard: Sustainability in the construction. Evaluation of the environmental performance of buildings. Calculation methods (AENOR 2012), for the product stage (A1 - Supply of raw materials) and use stage (B1 - Use). In the product stage, the analysis considers only the supply of materials for the constructive solutions, excluding their transportation, machinery, equipment, and labor required to execute each solution. The use stage considers the calculation of the home's heating demand, excluding the energy consumed by electrical appliances and lighting.

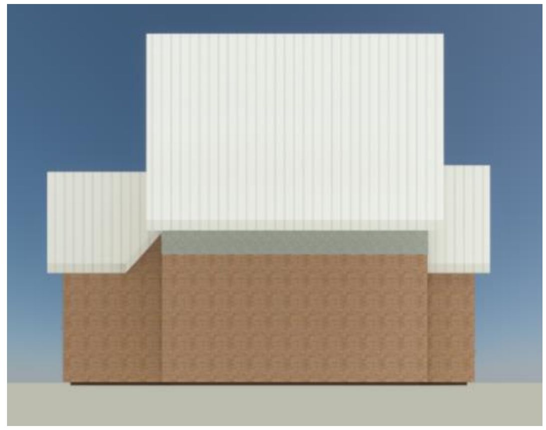
Eco-efficiency corresponds to *a quantitative management tool, capable of providing goods and services at a competitive price, that satisfy human needs and quality of life, while progressively reducing the environmental impact and the intensity of the use of resources throughout the lifecycle, until reaching a level that is compatible with the estimated load capacity of the planet"* (Ponce Kress 2017). *Within the eco-efficiency assessment, the environmental impacts are evaluated using the lifecycle assessment (LCA), as outlined by other international standards (ISO 14040, ISO 14044)* (ISO 14045 2012).

2. Materials and methods

The methodology used in this research has a lifecycle approach, as defined in UNE-EN 15978: Sustainability of Construction Works. Assessment of the Environmental Performance of Buildings. Calculation Method (AENOR 2012) and ISO 14040:2006: Environmental Management – Lifecycle Assessment – Principles and Framework (ISO 14040 2006).

Firstly, a dwelling was chosen, whose construction characteristics are repeatedly used at a national level as well as in the communes of Temuco and Padre las Casas (figure 1):

- Surface area between 50 and 70 m^2 (Minvu 2020).
- Detached house grouping system (Minvu 2020).
- Predominant wall material: masonry (44.4% nationally) and partition with drywall on both faces (60.4% in the Araucania Region) (INE 2018).
- Roof material: metal sheets (65.9% in the country, and 88.8% in the Araucania) (INE 2018).
- Floor material: Tiled reinforced concrete (90% nationally, and 89.1% in the Araucania) (INE 2018).



Detalle Ingreso *Detalle Lateral Derecha.*

Detalle Elevación Posterior. *Elevación lateral Izquierda*

Figure 1. Selected case study. 70 m2 house.

After this a revision of the Official List of Construction Solutions of the Chilean Housing and Urbanism Ministry was made. This provides a database with different construction solutions, starting from the thermal conditioning requirements that article 4.1.10 of the OGUC sets out for each Chilean thermal zone (Minvu 2014). This document allowed choosing the thermal envelopes of the roof, wall, and floor following the thermal transmittance requirements of OGUC for thermal zone 5, and to reassess the same construction solutions, following the PDA requirements of Temuco and Padre las Casas. Table 1 below shows the differences there are in each one of the regulations.

Table 1. Maximum thermal transmittance differences between the OGUC (thermal zone 5) and the PDA of Temuco and Padre las Casas.

Envelope system	Thermal Transmittance [W/m^{2}K]	
	OGUC (Thermal zone 5)	PDA Temuco & Padre las Casas
Roof	0.330	0.280
Wall	1.600	0.450
Ventilated floor	0.500	0.500
Window	Depends on the maximum window surface percentage on vertical faces of the envelope and the window type (monolithic or HSDG)	3.600
Door	NA.	1.700

Finally, 9 constructive solutions were obtained for the same house described in Figure 1. However, in order to comply with the regulatory requirements indicated in Table 1, different thicknesses were considered for the materials that compose it (as shown in Table 2).

Table 2. Description of the construction solutions for each one of the envelopes selected for the OGUC and the PDA.

Envelope	Quantity [m²]	Description	Thermal Transmittance (U) [W/m² x K]	Regulatory Compliance
Roof	86.36	*Panel with two steel faces attached to an expanded polystyrene insulation core:*		
		OGUC: of 125 mm thick 20kg/m3 expanded polystyrene for thermal zone 5	0.288	Complies
		PDA: 150 mm thick, 20kg/m3 expanded polystyrene	0.242	Complies
Floor N°1	66.34	*29 x 14 x 7.1 cm brick masonry wall, adhered to a drywall plate and an expanded polystyrene insulation core:*		
		OGUC: 10 mm thick and 15kg/m^3 density expanded polystyrene for thermal zone 5.	1.250	Complies
		PDA: 80 mm thick 15kg/m^3 density expanded polystyrene.	0.418	Complies
Floor N°2	47.54	*Perimeter partition wall formed by type C 60 x 38 x 0.85 mm galvanized steel uprights. On the inner face, it considers a drywall sheet and, on the outside, fiber-cement siding. The insulating material is mineral wool.*		
		OGUC: 15 mm thick drywall sheet, 8 mm thick fiber-cement siding and 50mm thick and 40kg/m^3 density mineral wool.	0.880	Complies
		PDA: 15 mm thick drywall sheet, which has an adhered 30 mm thick, 15kg/m^3 density expanded polystyrene sheet. 10mm thick fiber-cement siding and 60mm thick and 40kg/m^3 density mineral wool.	0.406	Complies
Window	14.20	*Sliding window (two and three rails) with up to six mobile sheets. Glazing capacity of 3 to 21 mm.*	2.200	Complies with both regulations
Doors	3.53	*Door made from high density MDF/HDF, 4 mm thick, filled with 45 mm thick 20kg/m^3 density expanded polystyrene.*	0.704	Complies with both regulations
Floor in contact with the ground	37.40	*8 cm thick 170 kg/cem/m^3 reinforced concrete, on a 10 cm thick gravel bed, covered with 7.2 cm thick 45x45 cm tiles.*	1.400	Complies with both regulations

Once the thermal envelopes described in Table 2 were chosen, the lifecycle stages where the eco-efficiency indicators in the dwelling will be evaluated, were determined. According to the system limits established in UNE-EN 15978:2012, the following stages were assessed:

- PRODUCTION: A1 – Supply of raw materials.
- USE: B1 – Use.

2.1. Assessed eco-efficiency indicators

To measure or evaluate eco-efficiency, according to the basic principles established at the Rio Earth Summit of 1992, a series of indicators must be established that allow obtaining tangible results (ONU 1992). The indicators measured in this research, are some of those that the report developed by the United Nations Conference on Trade and Development (UNCTAD) (Unctad 2004) (Rincón 2011) state and that those described by (Leal 2005) (see Table 3).

Table 3. Eco-efficiency indicators measured according to the lifecycle stage.

Eco-efficiency indicator	Measurement	Lifecycle stage
Energy consumption	Energy consumed by the materials [MJ]	Stage A1
	Energy demand [MJ/m^2/year]	Stage B1
Greenhouse gas emissions	Carbon footprint of the materials [kgCO_2eq]	Stage A1
	Carbon footprint of the fuels [kgCO_2eq]	Stage B1
Acid emissions in the air	Particulate matter emissions from fuels [gr$PM_{2.5}$]	Stage B1
Financial	Economic cost of materials [$]	Stage A1
	Economic cost of fuels [$]	Stage B1

2.2. System Limits

For the production stage, the environmental data included on the ABACO-CHILE platform was used. This is the only Chilean platform for public, scalable, and open-access digital platform, with a cost database and environmental indicators which focus on making the application, evaluation, and monitoring process of public and private construction projects more efficient in Chile (ÁBACO-CHILE 2020). The carbon footprint and embodied energy indicators were taken from ABACO-CHILE, broken down for each construction solution and material that forms part of each envelope. In the case of the materials not included in the database of this platform, the environmental indicators were taken from the Carbon and Energy Inventory of the University of Bath, whose production process is similar to Chile's (Hammond and Jones 2011). For the economic cost, the base unit cost of each material was considered.

In order to evaluate the use stage, the carbon footprint and heating value (HV) of the three fuels used as heating systems in Chile: firewood, LPG, and pellets, were considered, through which it was possible to obtain the carbon footprint and the PM2.5 emissions for this stage. It is worth mentioning, that at a country level, from the total energy consumed in this stage, 39.6% corresponds to firewood, 31.4% to gas (LPG), and the pellet is considered as one of the replacement fuels that the PDA establishes (MMA 2015) (CDT 2019). For the energy demand, a dynamic simulation was made using the Revit 2021 software, which allowed calculating the heating demand through an integrated tool, using the architectural model of the dwelling, defining the location, placing spaces, and assigning areas (AUTODESK 2021). Finally, the economic cost was determined using the base unit cost per kilogram of fuel.

3. Results

The results obtained were differentiated following the stages of the dwelling's lifecycle, as established in UNE-EN 15978:2012.

3.1. Evaluation of the indicators in stage A1

3.1.1. Embodied energy evaluation in stage A1

The embodied energy of the materials that each one of the envelopes comprises, considers the energy consumed in obtaining the raw materials, their manufacturing, distribution, use and the end of life of the element analyzed. This is measured in MJ/kg (ISO 14045 2012). In this sense, the results obtained for each one of the regulations are shown in Table 4.

Table 4. Results of the evaluated envelopes contained energy for each of the regulations in [MJ/m2].

	Contained Energy [MJ/m^2]					
	Roofing	1° Floor Wall	2° Floor Wall	Windows	Doors	Ground contact floor
OGUC	323	327	116	14.007	741	187.221
PDA	367	420	195	14.007	741	187.221

From Table 4 it is seen that, on applying the PDA requirements, the roof envelope increases its embodied energy by 12.1%; the first-floor wall, by 22. %; and the second-floor wall, by 40.2%; compared to the envelopes with the OGUC requirements. The first-floor wall stands out from these three elements since it has a higher embodied energy, mainly due to the inclusion of hollow reinforced brick as a material, which has a high embodied energy percentage due to its manufacturing process -from all the embodied energy of this envelope, 64% is attributed to the brick; 25% to the 80 mm thick expanded polystyrene; and 6% to the cement sacks used for the mortar-. The rest of the envelopes do not have changes since the same construction system was considered to assess both regulations, on meeting the requirements outlined in Table 1.

The second-floor wall solution has a higher difference between both regulations -40% difference between the embodied energy results-. This is mainly due to the incorporation of an additional sheet of expanded polystyrene on its inner face, and an increase in thickness of the existing materials (see Table 2).

3.1.2. Carbon footprint assessment in stage A1

The carbon footprint of the materials corresponds to the *quantification of the direct and indirect emissions of Greenhouse Gases, hereinafter GHGs (CO_2, CH_4, N_20, HFCs, PFCs and SF_6), which are released into the atmosphere as a result of activities of a company, of the product's lifecycle, the organization of an event, or the activity of a person"* (García Sardina 2013), and it is considered as an environmental impact category as per ISO 14045 (ISO 14045 2012). The results obtained for each one of the regulations are shown in Table 5.

Table 5. Results of the evaluated envelopes carbon footprint for each of the regulations in [kgCO2eq/m2]

	Emissions GEI [kgCO_{2eq}/m^2]					
	Roofing	1st Floor Wall	2nd Floor Wall	Windows	Doors	Ground contact floor
OGUC	19	22	12	984	68	17.009
PDA	21	25	16	984	68	17.009

According to Table 5, on applying the PDA requirements, a higher carbon footprint (CF) is seen in each one of the envelopes studied, compared to the requirements of the OGUC. This is mainly due to the increase in the thickness of the materials considered in this case (see Table 2). What was seen in the embodied energy evaluation is repeated, where the highest difference between both solutions appears on the second floor wall with 26.56%, followed by the first floor wall with 13.85%, and the roof with 7.99%. These percentages show that the choice of insulating materials can have a positive or negative impact on polluting emissions into the atmosphere (Ulutaş et al. 2021). For example, the process to manufacture expanded polystyrene -a material commonly used as thermal insulation- consists of a polymerization to convert the styrene -raw material- into expandible polystyrene beads. For this, a chemical mixture of several components that allow this expansion must be applied, at temperatures of around 220°C – 260°C (Unión Europea 2009).

3.1.3. Evaluation of the economic cost of stage A1

The economic cost of the materials of each envelope, was determined using a unit cost analysis of each construction solution. For this, each solution was broken down and the base costs were obtained through quotations made to local suppliers in the communes of Temuco and Padre las Casas. The results obtained are shown in Table 6.

Table 6. Results of the evaluated envelopes economic cost for each of the regulations in US$/m^2.

	Costo Económico (US$/m2)					
	Roofing	1st Floor Wall	2nd Floor Wall	Windows	Doors	Ground contact floor
OGUC	20	21	25	186	114	37
PDA	23	26	30	186	114	37

In Table 6, it is possible to see that the unit economic cost increased. For the PDA, it increased by 7.8% on average. From the same analysis, the first-floor wall stands out, which saw the cost of the envelope increase by 20.1% in regard to the OGUC case. This is mainly related to the 15 kg/m^3 density expanded polystyrene, some 87% more expensive, on significantly increasing its thickness from 10mm to 80 mm.

3.2. Evaluation of the indicators in stage B1

3.2.1. Evaluation of the energy demand in stage B1.

The lower the thermal transmittance of a construction element is, the better thermal performance the building will have from a heating demand point of view (Bustamante 2009). In this sense, on applying the PDA requirements outlined in Table 2, the dwelling's behavior improved by 19.4%, as shown in Table 4.

Table 7. Results of the heating demand of the dwelling.

	Heating demand	
	[kWh/m²/year]	[MJ/m²/year]
OGUC	121.420	437.110
PDA	97.880	352.370

With the results obtained in Table 4 and the heating value of the fuels (LPG 14.07 kWh/kg, pellet 4.8 kWh/kg and firewood 4.94 kWh/kg (Kairies-Alvarado, Muñoz-Sanguinetti, and Martínez-Rocamora 2021)), it was possible to determine the fuel consumption generated, on considering each one of the regulations studied (see Table 5).

Table 8. Fuel demand by type of heating system.

	Fuel demand per year [Kg/year/m^2]		
	Firewood	Pellets	LPG
OGUC	24.580	25.300	8.630
PDA	19.810	20.390	6.960

From Table 5, it is seen that the greater the heating value of the fuels, the lower the demand is that is produced during the use stage. This information will be the basis for the calculation of the rest of the eco-efficiency indicators.

3.2.2. Evaluation of the carbon footprint in stage B1.

The carbon footprint for this stage, was determined using the fuel demand results of Table 5, and the carbon footprint indicators that each kilogram of fuel generates (see Table 9).

Table 9. Carbon footprint of fuels [kgCO_2eq/Kg] based on references from (POCH 2008) (Kairies 2020).

	Carbon Footprint (CF) [kgCO_2eq/Kg]
Firewood	1.721
Liquefied Petroleum Gas (LPG)	2.9575
Pellet.	0.059

Finally, the carbon footprint results that are generated annually by built m^2 are those outlined in Figure 2.

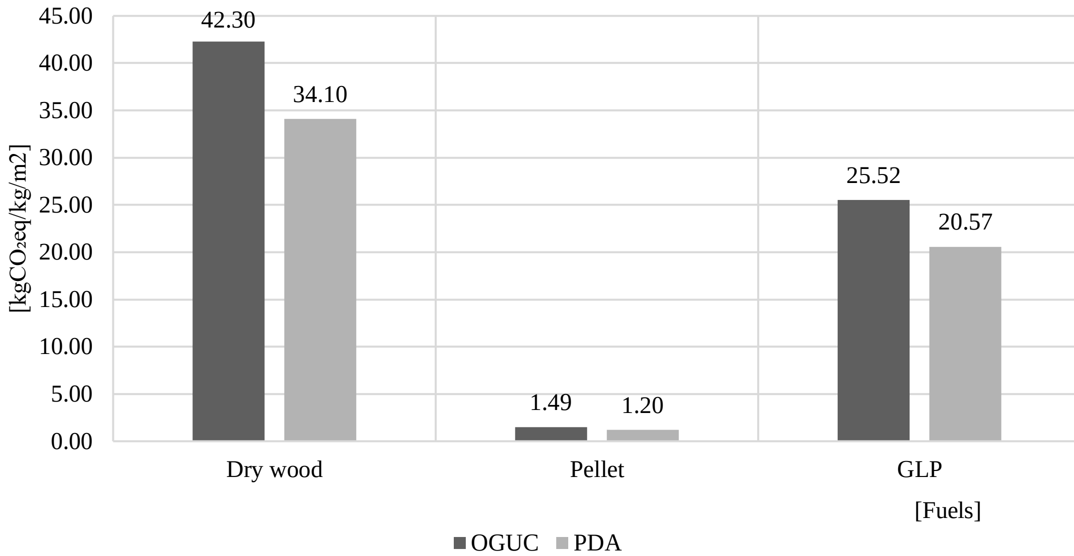


Figure 2. Carbon footprint results of the fuels evaluated in $kgCO_2eq/kg/m^2$/year.

From Figure 4, it is possible to deduce that comparing the three analyzed fuels, the best evaluated, from the carbon footprint point of view, is the pellet because it emits 59% less carbon footprint per m2 than firewood and a 35% less than liquefied petroleum gas. At the same time, comparing the OGUC and PDA regulations, the PDA norm implementation generates 19% less emissions to the environment, in the use of fuels for heating.

3.2.3. Evaluation of the economic cost in stage B1.

The results of the economic cost of the fuels evaluated for each one of the regulations (see Figure 3), were taken from the results obtained in Table 5.

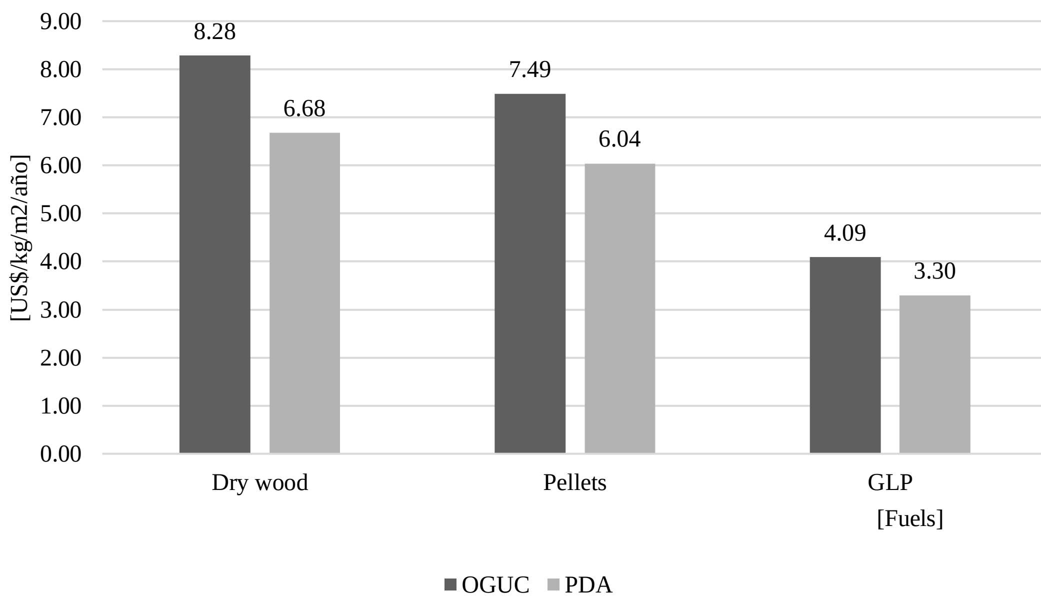


Figure 3. Results of the economic cost of the fuels evaluated in US$/kg/$m^2$/year.

From Figure 5, it can be deduced that on applying the PDA, the fuels used to heat a dwelling, are 19.4% cheaper, as the fuel demand is reduced on thermically improving the envelope, that is to say less demand, leads to less fuel use. Likewise, on analyzing the fuels separately, the liquefied gas is 18% and 22% cheaper than pellets and firewood, respectively

3.2.4. Evaluation of the fine particulate matter 2.5 µm emissions in stage B1.

To evaluate the fine particulate matter 2.5 µm, the emission factors (EF) of each fuel are considered (see Table 7). The EF, correspond to the statistical average of the contaminant flow, emitted by processed fuel unit or consumed energy unit, and are generally measured in grPM2.5/kg of fuel (Pereira 2012).

Table 10. Emission factors for residential combustion of fine particulate matter, 2.5 µm (SICAM 2015) (SINCA 2011).

	Particulate matter emissions [grPM$_{2.5}$/kg of fuel]	
	Dry firewood (% Moisture < 25%)	Moist firewood (% Moisture > 25%)
Wood stove	7.00	13.00
Slow combustion without baffle	5.80	11.00
Slow combustion with baffle	4.90	10.20
Salamander stove	11.80	34.10
Fireplace	9.20	26.60
Pellet heater	1.80	0
LPG	0.17	0

In this way, analysis is made for the use stage, starting from the annual demand data of each fuel per meter squared of the dwelling (see Table 5), multiplied by the emission factor of each fuel (Table 7). The results are shown in Figure 4, considering the use of dry firewood.

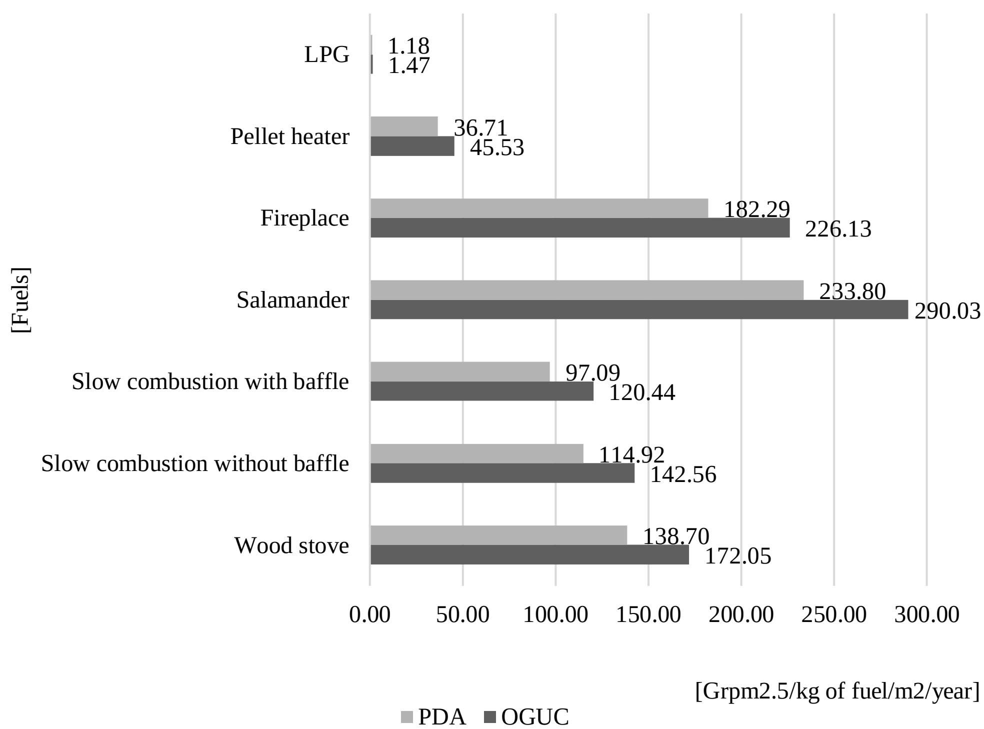


Figure 4. Annual particulate matter, PM2.5 emissions, considering dry firewood.

From figure 6 it can be seen: (i) salamander-type stoves, with dry firewood, generate the greatest amount of emissions of fine particulate matter; (ii) the fuels with the lowest emissions are pellets and LPG.

4. Discussion

From the results obtained, it is shown that the envelopes evaluated under the Temuco and Padre las Casas PDAs conditions, during stage A1 - Production, increase on average: the embodied energy by 12.4%; the carbon footprint, by 9.1%; and the economic cost of the materials the envelopes comprise by built m2, by 7.8%. On verifying this, by applying this regulation, there is a negative impact on stage A1 of the dwelling, as such, it becomes relevant to consider materials with a low environmental load on designing the envelope.

In the use stage, which begins when a family starts to live in the dwelling, the assertiveness that the application of this regulation is confirmed, as the fine particulate matter PM2.5 emissions (the main goal of the PDA), the energy demand, carbon footprint and economic cost of the fuels are reduced by 19.4% on average. With regard to this percentage, this does not meet the goal set out by the PDA, where expects that by 2025, at least 67% of fine particulate matter emissions are reduced. Considering this, the application of more demanding regulations than the current ones and the constant monitoring of the construction solutions used, becomes a transcendental aspect.

Also, on averaging the carbon footprint and embodied energy indicators obtained on evaluating the dwelling following the OGUC and PDA requirements, considering the total surface area of the dwelling (70m2), and a service life of 50 years (SII 2003), it is possible to confirm that in stage A1, the dwelling consumes a higher amount of energy and emits a higher carbon footprint (see Figure 5).

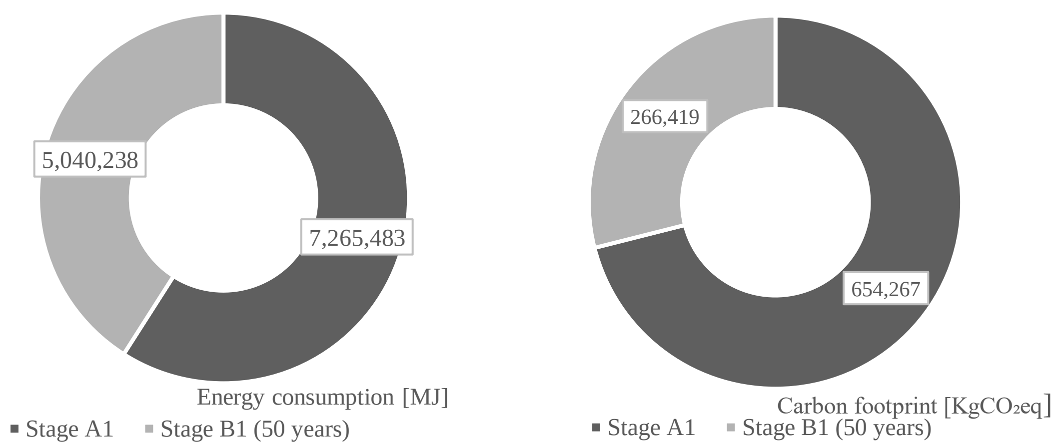


Figure 5. Energy consumed and carbon footprint during the life cycle of the home.

From Figure 5, it is seen that in the production stage, the materials the envelopes comprise and that are used during the construction phase of a dwelling, emit 71% of the total carbon footprint emissions and consume 59% of all the energy, through which it can be seen that, in their manufacturing, the highest environmental load of its entire cycle is generated, due to the processes used in them (León-Velez and Guillén-Mena 2020). Likewise, it is seen that, in the use stage, this corresponds to 29% and 41% of the total GHG emissions and energy consumption, respectively. These percentages are important, since in the commitments of the Chilean State, it is expected that carbon neutrality is reached by 2050, and energy consumption is reduced by 30%. However, using the results of this study, it could be forecast that these commitments would not be met under any of the regulations evaluated.

On one hand it is worth stating, that both indicators are directly related with thermal improvements considered in the envelopes, which favor the heating demand and, therefore, fuel demand. In this way, a lower heating demand is equivalent to a lower fuel demand (see Table 5), but at the same time this means, that a lower heating demand, also implies considering the use of thicker insulation materials (see Table 2) and higher environmental loads (see Figure 1 and 2), negatively affecting the production stage.

On the other hand, regarding the fuels considered in the use stage of the dwelling with a surface area of 70m2, evaluated over 50 years of service life, it is seen that pellets are the fuel with the lowest impact on the carbon footprint, compared to firewood and LPG -with more than 1000% of difference-, i.e., for this study, firewood is the most expensive fuel from the economic point of view, and LPG is the one that emits the lowest amount of PM2.5. As an example, the results that are obtained by evaluating the dwelling under the demands of the PDA, considering dry wood, are shown (see Figure 6).

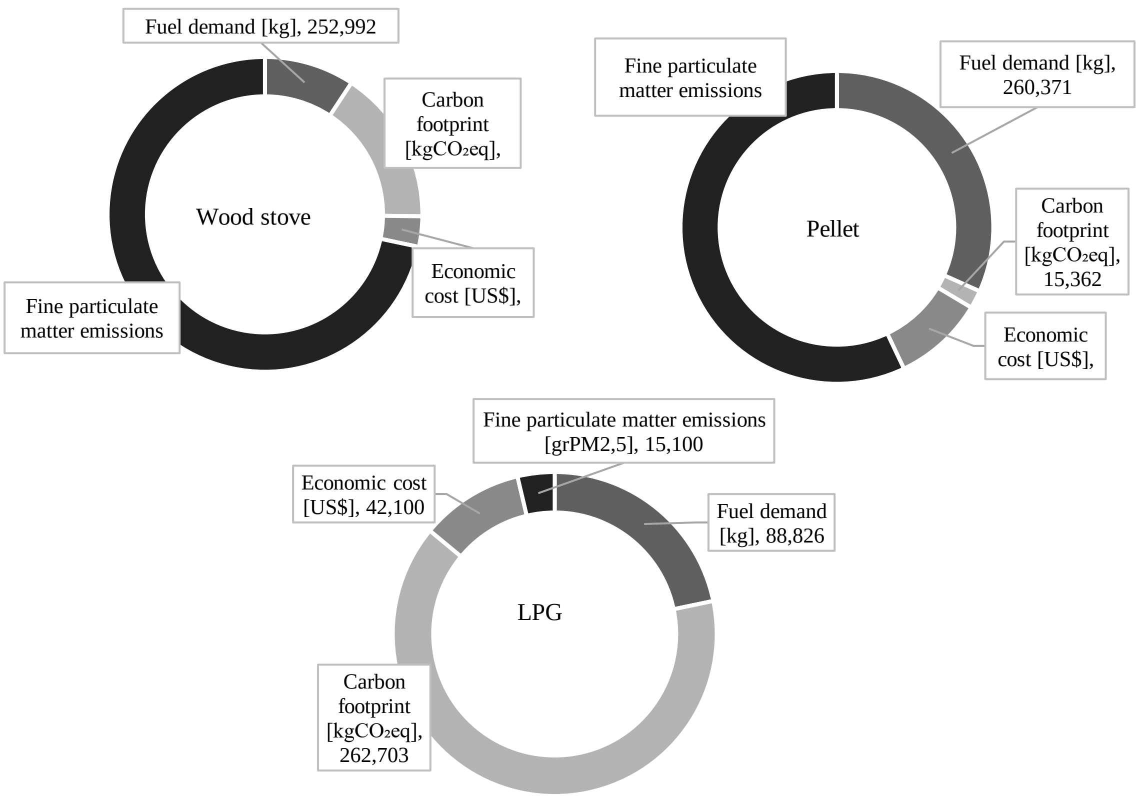


Figure 6. Evaluation of the eco-efficiency indicators for firewood, pellet and LPG fuels for USE stage – B1, under the PDA requirements.

In Figure 6, it is seen that firewood, despite being the most commonly used fuel in central-southern Chile, the result of practices passed on from generation to generation on being easy to obtain (Ministerio de Energía 2012), this is the least eco-efficient fuel of the three, in the study of each one of the indicators. It has a lower heating value, i.e. that 1 kg of firewood emits less heat than 1 kg of pellets or LPG. Therefore, to heat a home, a more kilos of firewood are required than kilos of pellets or LPG. This has a direct repercussion on the economic situation of the families that use this fuel to heat and/or cook, who have to pay out more money to buy firewood to reach the energy demand of the dwelling. In addition, it is the fuel that contaminates most -higher CF and fine particulate matter emissions-, a determining factor that should be considered in the current public policy of the country, bearing in mind people's health and the environmental quality of the air component (MMA 2011)(Ministerio Secretaría General de la Presidencia Norma 1998).

Likewise, the pellet which is the alternative fuel proposed by the Chilean government in the “Wood-burning device change program” for the communes of Temuco and Padre las Casas (Pereira 2012), by using the results obtained in this study, it was found that this is the fuel with the lowest carbon footprint of the three, and second, it produces a low amount of fine particulate matter 2.5 µm emissions, along with a lower economic expense, during the use stage of the dwelling.

Regarding the vision that is held worldwide, the World Health Organization (WHO) has calculated that every year, exposure to air pollution causes 7 million premature deaths and is responsible for a series of health problems. such as reduced lung function and growth in children, ischemic heart disease, stroke, diabetes, and neurodegenerative diseases in adults (WHO 2021). That is why the European Union (EU) has proposed to reduce premature deaths due to suspended particles by at least 55% to the year 2030, and achieve zero air pollution no later than the year 2050, based on periodic monitoring and the creation of new regulations (European Commission 2022).

5. Conclusion and policy implications

Based on the results obtained, it is possible to conclude: Firstly, none of the two mandatory regulations in Chile are having an eco-efficient impact on the life cycle of the dwelling studied, because they present a negative impact on the product stage, increasing the indicators by 12.4%, of contained energy, 8.1%, the carbon footprint and 7.8%, the economic cost.Secondly, despite the 19.4% decrease in the indicators in the use stage, produced by the incorporation of the PDA (including the upper thermal transmittance limits of article 4.1.10 of the OGUC), this percentage does not meet the objectives in the Country Agenda, in relation to the carbon neutral month for 2050.

From the above it is shown that, making modifications in the thermal conditioning of a dwelling, through the thermal transmittance limits, is not enough to solve the environmental issue the Chilean residential sector is responsible for, regarding energy consumption and greenhouse gas emissions.

Finally, it is proposed that, when creating or modifying mandatory thermal regulations for the Chilean residential sector, such as article 4.1.10 of the General Urbanism and Construction Ordinance, and the Environmental Decontamination Plans, they should incorporate requirements for the eco-efficiency indicators studied in this research (carbon footprint, energy consumption, economic cost and emissions of particulate matter).This, with the objective that the houses can be analyzed in their evolution during the time of use, through a life cycle cost analysis approach (ACCV), which would have a real positive impact on the quality of life of the people who live in the house.

This will also allow sensitization regarding the use of natural materials or ones with a lower environmental load, which are on the Chilean and international market, for the creation of databases, with recommendations of eco-efficient construction solutions, similar to those already present in Chile, on the List of Construction Solutions of the Ministry of Housing and Urbanism.

6. Limitations and findings

Some of the limitations and findings found during the development of this research are:

- Currently, ÁBACO-CHILE is the only platform for public use that exists in Chile, which allows obtaining eco-efficiency indicators for the product stage (contained energy and carbon footprint). However, this only includes the material resources that are part of a construction budget, and leaves out labor, machines and equipment, resources that are also responsible for consuming and emitting energy and carbon footprint respectively.

- There are no available Environmental Product Declarations (DAP) of Chilean origin, which allow obtaining the real impact of the materials used in the construction sector.

- Existing regulations in Chile do not include the eco-efficiency indicators that were analyzed in this research, which makes it more difficult to evaluate construction projects globally.

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