Are high-rise residential buildings rising to future weather scenarios?

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Abstract. Evaluating the energy and thermal performance of existing buildings during their lifetime brings about uncertainty, since there is strong evidence suggesting that climate change (CC) will affect indoor environment quality. CC has been reflected, among other phenomena, in a temperature rise that is necessarily related to the indoor temperature of buildings. Recognizing possible future climate scenarios and their possible effects will allow improving the resilience of existing buildings. Today's buildings are sources of high energy demand. In the case of Chile, an ordinary house, due to its poor thermal performance, requires between 40% and 60% of its energy consumption for heating or cooling, depending on the location. On the other hand, a constructive phenomenon has been seen in Latin American cities over the last three decades, where city centres are densified with high-rise residential buildings. These are characterized by very small apartments, which affect indoor environment quality, solar gains, ventilation, etc. Thus, the proposal of this paper is to evaluate this residential typology. The aim of this research is to prospectively study the effects produced by CC on the energy-thermal performance of high-rise residential buildings, using an exploratory research, in three different thermal zones of Chile through to 2080. The analysis consists in comparing the performance of the same case built in three cities, using the Design Builder software for dynamic simulations. The results show a temperature increase that affects apartments in different ways. In the northernmost city, Iquique, the heating demand would disappear in 60 years; in Santiago, it will be reduced by half and in the south, while in Puerto Montt, it will represent only 62% of current demand; however, the cooling demand will increase in all cases. While hours within the comfort range will increase in the southernmost cities, in the northernmost and central cities, the risk of overheating will increase significantly. This provides great challenges in terms of improving thermal comfort for the coming years, incorporating possible CC impacts into housing design to prevent negative results, such as overheating.

1. Introduction

Buildings are sources of high energy demands and producers of large emissions of carbon dioxide into the atmosphere due to the need of heating and cooling. In Chile, 16% of households suffer energy poverty [1]. Dwellings require an average of 111 kWh/m² per year of total energy consumption for heating [2], especially in the southernmost areas of the country where the climate is cold and the consumption of fuelwood is high. According to the National Energy Balance [3], the residential sector in Chile represents 26% of the country's energy consumption. As a result, recent governments have introduced several measures and regulations to mitigate the increase of energy consumption and...
environmental pollution. Regarding the residential sector, the Thermal Regulation [4] and the Energy Rating Tool for Housing [5] have been implemented. The first one has defined insulation standards for housing envelopes since 2000, while the second objectively rates the energy performance of new houses.

Although these measures have improved energy performance in terms of heating, it is unknown how useful they will be in future decades considering the consequences of Climate Change (CC), with extreme weather events, global temperature rises, among other expected phenomena, that will directly affect buildings without air conditioning or energy efficiency and environmental comfort strategies [6] [7]. This brings about great challenges in terms of improving the building’s performance for the coming years without increasing power consumption and the release of GHG [8]. Anticipating the energy-thermal performance of buildings using future meteorological data can help prevent negative results such as overheating and high humidity [9], as well as mitigate or adapt strategies and solutions for a better indoor performance and user comfort.

1.1. International Scenario

Several research projects have evaluated the influence of CC on indoor comfort and the energy demand of buildings [10] [11] [12], all of them concluding that the temperature increase is a fact. It is assumed that the combination of CC and heatwaves may lead to a potential effect on indoor temperature, making thermal conditions inhospitable for human comfort and implying a higher energy consumption for air conditioning [13]. A vicious cycle of rising exterior temperatures and the consequent increase in CO$_2$ emissions, associated with the elevation of energy demands for cooling in warm seasons, especially during summer heatwaves [14], is assumed. Meanwhile, in Spain, it was predicted that the energy demand for heating will decrease by 36% on average and that required for cooling will increase [15]. Research in the United States and Germany and in other latitudes conclude the same dominant trend, indicating that cooling and heating demand will generally go in opposite directions [16][17][18].

However, there is a limited level of detail for a global model due to the lack of mass-scale regional models, making the development of diagnoses at regional scale [19] to detect the levels of influence of CC on different buildings built in different realities, necessary. Understanding how the thermal-energy performance of a building will change in the future will allow proposing future strategies that can contribute to CC adaptation and mitigation.

It is anticipated that the temperature will increase by 4°C to 5°C in Chile by the end of the century, from the highest increases in the north and the mountains and the lowest in the south and the ocean [Error! No se encuentra el origen de la referencia..], given the country’s geography. It is necessary to define strategies that will allow CC adaptation in Chile, by diagnosing its effect on the thermal and energy performance (heating and cooling) of existing housing, also considering that the national housing regulations do not involve the risk of overheating, but are focused solely on heating needs [21].

Since the 90s, Chile’s public urban renewal strategy has been based on a subsidy policy, promoting the demand for new affordable housing located in the central areas of the largest cities. The application of this subsidy has generated a housing market which is preferably targeted at medium and medium-high socio-economic groups [Error! No se encuentra el origen de la referencia.., resulting in a housing densification in high-rise buildings as a profitable residential alternative for real estate development. As a result of this situation, this paper looks to evaluate the performance of a typical high-rise building replicated in three different cities under four future climate scenarios (TMY 2020, 2050 and 2080).

2. Materials and methods

The methodology is predictive, comparing the results of thermal and energy performance on real case studies of representative typology apartments, carried out using Design Builder (Energy and Thermal Analysis Software) due to its efficiency and reliability [23]. A unique high-rise building typology is selected as a case study. This could have been built in different cities and their envelope’s characteristics represent the majority of the existing stock per location.

2.1. Climate scenarios in Chile
Chile has a great extension in terms of latitude (from 17º 30’ to 90º and a length of 4,300 km), with several different characteristics and phenomena (mountain ranges, Humboldt cold water stream, Pacific anticyclone, polar front, among others) that cause a stark contrast in climate from north to south and east to west. Because of this context, three regional capitals with climatic diversity (according to the national regulation, NCh 1019) and location (north, center and south), with high populations and long distances between them, are chosen: Iquique, Santiago and Puerto Montt (Table 1).

Iquique is characterized by abundant cloud cover, low thermal oscillation during the whole year, less in summer where temperatures double within the same day, making it the hottest and most humid coastal city during the summer period. In Santiago (capital of Chile), the climate is temperate with rainfall concentrated between June and August. Temperatures vary during the year, with summer being very hot, and temperatures easily reaching 33°C, while in winter they drop to 0°C. Puerto Montt presents abundant and constant rainfall that decreases between October and April. With a little annual oscillation, the maximum temperatures in summer do not exceed 25°C.

| Table 1. Selected locations and corresponding characteristics. |
|---|---|---|
| **Density (inhab/km²)** | Iquique | 8978.18<br>(NC) | Santiago | 7468.18<br>(IC) | Puerto Montt | 3331.42<br>(SC) |
| **Climatic Zone NCh** | Tropical and Subtropical Desert | 20°13’ S<br>70°10’ W | 33°12’8” S<br>70°38’ W | 41°46’ S<br>72°94’ W |
| **Latitude** | 20°13’ S | 33°12’8” S | 41°46’ |  |
| **Longitude** | 70°10’ W | 70°38’ W | 72°94’ W | 14 |  |
| **Elevation (m)** | 570 |  |  |  |

The Climate Change World Weather File Generator (CCWorldWeatherGen) [9] is used to create climate files of the cities in different future years. This tool provides a consistent basis of predictive models to calculate energy demand variations for buildings. It is developed based on the 3rd data report from the Met Office Hadley Center Coupled Model (HadCM3) of the Intergovernmental Panel on Climate Change [6] [7] and is widely used in research that investigates varied performances under the prediction of future climates [13]. The HadCM3 model uses two socio-economic scenarios: A (pessimistic) and B (optimistic), both estimated for 2020, 2050 and 2080. Both scenarios were developed by the Atmospheric Stabilization Framework Model from ICF Consulting in the USA [24] and have subcategories based on possible storylines, each corresponding to scenarios of social, economic and technological developments.

This research considers the A2 scenario because it is closer to the Chilean context, which presents a slow population growth, with a lack of adaptation through correct environmental measures, while economic development tends to be regional (due to their work sources) and per capita. Technological change is fragmented and slow, with a relative improvement in supply efficiency and end energy use [25].

The average temperature change in scenario A2, regarding the current climate over continental Chile, is expected to vary between 2 and 4°C, being more accentuated towards the Andes regions and decreasing from north to south [26]. It is observed that, on evaluating future climatic scenarios of the three cities under the supposed A2 development and for 2020, 2050 and 2080, and using the CCWorldWeatherGen, all maximum, minimum and average temperatures will increase (Figure 1). The maximum temperature rises 5°C on average for all cases, while the minimum increases by 1.6°C in Puerto Montt, 2.3°C in Santiago and 5.4°C in Iquique. This means that the need for heating inside buildings in the south of Chile will continue but without high risks of overheating, contrary to what happens in the other two cities, where overheating will be greater and for more days of the year.
Important differences are observed on comparing temperatures obtained from the TMY weather file with those of 2020. All the temperature values in the 2020 file are higher than in TMY. This suggests that we are using weather files which do not necessarily respond to real weather patterns, since they represent previous meteorological data, omitting all phenomena caused by global warming.

![Figure 1. Max., min., and average annual temperatures of selected cities (TMY-2020-2050-2080).](image)

2.2. Comfort Criteria

The thermal susceptibility varies according to very low or elevated temperatures, geographic location, climate, building type and their function, in addition to the vulnerability of dwellers [27], hence the temperature where users are in comfort varies among people. As a result, this research uses the ASHRAE 55:2017 adaptive comfort model [28], setting a comfort zone, or range, to find the most favourable operative air temperature in free-run buildings (naturally conditioned spaces). The comfort zone is around the neutrality/comfort line. It represents the comfortable upper and lower temperature and corresponds to 90% acceptability limits. According to the standard method, the comfort zones corresponding to the selected cities are: 21-26°C for Iquique, 20-25°C for Santiago and 18-23°C for Puerto Montt.

Comparing comfort zones with the maximum and minimum temperature values of Figure 1, it is noted that there is a risk of overheating for all cities and in all the scenarios evaluated, though, this is much higher in Santiago, where the maximum temperature would reach 37.9 °C in 2080. On the other hand, observing that future minimum temperatures increase, a lower use of energy in terms of heating is expected.

Since the climates of cities are diverse, the performance analysis is not done by seasons (heating and cooling for example), but rather it is evaluated throughout a full year to make the study comparable.

2.3. Residential high-rise buildings

The decision to study high-rise apartment typology buildings was made because Chile has seen an exponential growth of 9-floor residential buildings, especially since 2002. The housing building process in the country has been progressively distributing the residential sector between two polar types of height in construction: one or two level houses and high-rise buildings [29]. This event does not occur solely in large Chilean cities, but in others in Latin America too. It represents an urban renewal boom that, after a generalized economic crisis in the southern cone (1998-2002), has become an area prone to intensifying strategies for attracting private financial capital (undermining State participation), turning to private Property Developers and maximizing profits by delivering apartments that tend to dwarf the city [22].

Chilean cities are suffering homogenization caused by the increase of poor identity high-rise construction. Identical buildings are replicated from north to south, causing an urban development imposed by real estate activity. With this in mind, the decision was made to use a unique high-rise building typology built in the three evaluated cities, whose envelope’s characteristics represent the
majority of the existing stock per location. The information about existing residential high-rise buildings is obtained from national websites like the Observatorio Nacional [30] and Portal Inmobiliario [31], which provide information on the characteristics of buildings, such as materials, surface, year of construction, location, among others. The most representative building built in three cities (Figure) is chosen based on this data. Although this building is identical in form and space, it has differences in the physical-constructive characteristics of the envelope, for example, masonry versus reinforced concrete, related to the Thermal Regulation (TR) requirements (Table 2).

![Referential images of the case study (building and apartment).](image)

### Table 2. Simulation assumption and characteristics of case study.

| Model input parameters                  | Value  | Unit       |
|-----------------------------------------|--------|------------|
| Net conditioned building area           | 56.12  | m²         |
| Infiltration rate                       | 1      | ach        |
| Number of people                        | 0.071  | p/m²       |
| Metabolic factor                        | 0.9    |            |
| Occupancy rate                          | 50 (of 24/7) | % |
| Lighting                                | 3      | W/m²       |
| Orientation                             | 90     | °          |
| Exterior Walls U-value                  |        | [W/m²K]    |
| Iquique (Reinforced Concrete): 4        |        |            |
| Santiago (Reinforced Concrete): 1.9     |        |            |
| Puerto Montt (Masonry): 1.1             |        |            |
| Roof U-value                            | Iquique: 0.84 |        |
|                                        | Santiago: 0.47 |        |
|                                        | Puerto Montt: 0.28 |        |
| Windows Value                           | 2.7    |            |

### 2.4. Building models

To estimate the energy and thermal performance of apartments, a Design Builder (powered by EnergyPlus) model of the case studies in their current situation is built using TMY, and future weather files (.epw) are created. This annual weather data file extension has a resolution of at least one hour as input data, which is much more detailed than the predicted monthly change.

Simulations are made with two modalities, one in free running mode (without an HVAC system) to observe the thermal performance, depending on comfort zones obtained for each city, and another with the activation of HVAC mode to know the energy performance of each apartment, using comfort zone values as heating and cooling set points. Table 2 shows modelling assumptions which remain the same for all cases, except for the conditions required by the regulations.

After the diagnosis, it is possible to determine retrofitting strategies for a better thermal performance and energy efficiency, but these results will be the subject of another article.

### 3. Results and discussion

The analysis of the results is divided into two categories: (i) percentage of time under, within and over acceptable comfort zones and (ii) associated energy demand, in terms of heating and cooling needs.
The results obtained reflect an obvious CC impact on the indoor thermal environment and energy performance of the evaluated cases, increasing the risk of overheating and thus the associated energy demand (Table 3). However, there are differences between the analysed climates.

### Table 3. Results of thermal and energy performance.

|                  | Time under, within and over the Comfort range [%] | Energy Demand [kWh/m²/year] |
|------------------|--------------------------------------------------|------------------------------|
|                  | <21°C | 21-26°C | >26°C | Heating | Cooling | <21°C | 21-26°C | >26°C | Heating | Cooling |
| **Iquique**       |       |         |       |         |         |       |         |       |         |         |
| 2080 TMY         |       |         |       |         |         |       |         |       |         |         |
| Time             | 58.5  | 41.1    | 0.4   | 29.03   | 0.34   |
| 2050 TMY         | 45.7  | 54.3    | 0.1   | 13.13   | 5.54   |
| 2020 TMY         | 20.3  | 71.4    | 8.3   | 3.76    | 7.92   |
| 2000 TMY         | 0.1   | 78.8    | 21.1  | 0.01    | 22.17  |
|                  | <20°C | 20-25°C | >25°C | Heating | Cooling |
| **Santiago**     |       |         |       |         |         |       |         |       |         |         |
| 2080 TMY         | 63.4  | 32.9    | 3.7   | 62.97   | 3.05   |
| 2050 TMY         | 58.2  | 34.9    | 6.9   | 50.26   | 3.13   |
| 2020 TMY         | 52.3  | 36.2    | 11.5  | 43.01   | 6.9    |
| 2000 TMY         | 46.3  | 36.2    | 17.5  | 33.37   | 13.44  |
|                  | <18°C | 18-23°C | >23°C | Heating | Cooling |
| **Puerto Montt** |       |         |       |         |         |       |         |       |         |         |
| 2080 TMY         | 91.7  | 8.3     | 0.0   | 71.06   | 0.17   |
| 2050 TMY         | 82.5  | 17.4    | 0.1   | 59.64   | 0.31   |
| 2020 TMY         | 78.6  | 21.0    | 0.4   | 51.18   | 0.31   |
| 2000 TMY         | 70.0  | 28.2    | 1.7   | 44.96   | 0.92   |

Regarding the climate of Iquique, almost all the energy required for heating with the TMY file would become energy for cooling in 2080 (29.03 and 22.17 kWh/m²/year respectively). This demand is obviously reflected in the percentage of time below the comfort range, reaching a value close to zero. Although the time within the comfort range goes up 78.8% in 2080 (37.7% more than today), the risk of overheating increases from 0.4% to 21.1%.

In cities at the extremes of the country, it is necessary to focus only on one season of the year. In Iquique, strategies aim to avoid overheating, while in Puerto Montt, buildings must be designed for the cold season. However, in Santiago, the design must consider heating and cooling seasons, making it difficult to juggle them. In this city, the heating demand does not disappear, but it decreases by almost half. While the percentage of time within the comfort range remains almost the same (32.9 – 36.2%) and the time under the range decreases by 17%; the risk of overheating increases at least 4.7 times. The cooling demand is lower than in Iquique, but the poor ventilation conditions and urban heat islands that Santiago has, suggest that the thermal sensation would affect overheating even more.
As for Puerto Montt, the energy demand for cooling also increases, but it is negligible (just under 1 kWh/m² in 2080), which suggests that passive strategies could solve the risk of overheating (1.7%). In contrast, the time under the comfort zone will continue to exist, but to a lesser extent (from 91.7 to 70%), which manifests itself in a high level of energy for heating (98% of the total demand).

It is noteworthy that although the risk of overheating increases in all cases, total energy demands are always lower than the energy demand required today (or in TMY). This is explained by the decrease in time under the comfort zone and a moderate increase in the demand for overheating. However, as mentioned, it is expected that the demand in real use of dwellings could increase due to the micro-climatic conditions of locations. Regarding thermal performance, all cases present a positive scenario, since hours within the comfort range increase. In Iquique, the percentage of time is almost double; in Santiago, it is very slightly higher, while in Puerto Montt, it is 3.4 times more.

4. Conclusions

All the case studies show variations in their indoor thermal conditions, presenting a tendency towards overheating that corresponds to the evaluated progressive climate scenarios; however, the time within the comfort zone increases in all three cities and for the three future scenarios. It is observed that apartments are a good option in climates like those of Santiago and Puerto Montt, mainly due to the compactness of the high-rise typology which is more protected from climatic conditions (less surface area in contact with the exterior and lower glazing percentage).

Although energy efficiency requires not only improvement in building design, it is also necessary to understand the user’s behaviour and to clarify which thermal objectives the building is designed for. In Chile, for example, there is no regulatory framework that identifies requirements to avoid the risk of overheating; the norm is made for cold climates. Although weather files are a theoretical approach to this research topic, with different economic, social, cultural and environmental projections, they have certain limitations because they are, in fact, theoretical, and practice, they can vary quite a lot due to the sociological components.

It seems interesting to compare the results obtained from the weather files today (TMY) with the results of 2020. The difference is only one year and the results are quite different, urging the question, ed

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