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Curriculum: Planning for the Global Urban Agenda

Master Thesis

Energy modeling to investigate ways of improving community energy consumption

---A case study in Temuco (Chile)

Supervisors:
Prof. GUGLIELMINA MUTANI
Prof. GABRIEL FELMER
(Co-supervisor)
FRANCOIN SIMON
(Co-supervisor)

Candidates:
JINGYUAN ZHANG
XIAOSHUANG GUO

CONTENT

Abstract

Urban Building Energy Modelling (UBEM) represents a novel approach aimed at identifying, supporting, and enhancing initiatives for urban sustainable development and measures to improve urban energy efficiency, and as a result, energy efficiency approaches in the residential sector are encouraged. In this paper, this UBEM is applied to Temuco, a city in south-central Chile, using eight typical Chilean residential building models as a basis for a complete geographic information database for Temuco. In addition, one of the solutions to improve the energy performance of buildings is to reduce energy wastage in the building envelope, so this study modeled four building retrofit interventions using ArcGIS tools to assess the impact of these retrofits on the energy performance of the house and to make some policy recommendations for the government; based on modeled solar radiation and using GIS, the solar photovoltaic system in Temuco was assessed for its potential. The results show that Temuco's annual global horizontal solar irradiation exceeds that of other solar-advanced countries. A smooth transition from conventional combustion systems to solar PV systems is expected.

Keywords: Urban Building Energy Modeling(UBEM); energy modeling; ArcGIS; residential buildings; energy performance; energy efficiency; energy saving; retrofit interventions; solar technologies; domestic hot water

1. Introduction

Energy is necessary for human production and life, however, global energy consumption has been growing at an average annual rate of 1.8% in the last decade [1]. The current large amount of energy consumption in cities has led to environmental pollution and social and livelihood problems, highlighting the urgency of improving urban energy efficiency. This issue involves multiple dimensions such as economy, environment, and livelihood. The building sector accounts for a significant share of energy consumption [2]. According to the results of the International Energy Agency's Global Energy Use and Emissions in Buildings report, in 2021, the global end-use energy consumption in the building sector accounted for 37% of the total energy consumption [3], and CO^2 emissions accounted for 28% of the total 40 % of the total emissions in the building operation phase. With the economic and social development and the improvement of the quality of life, the proportion of building energy use in the overall energy use of society will continue to grow, the total energy consumption and CO 2 emissions will increase, energy consumption will play a key role [4]. These indicators show that the urban built environment harbors a huge potential for energy saving[5].

Building energy performance assessment is important for energy efficiency and carbon reduction in the building sector. Real-world energy performance data must be taken into account in the development of large-scale policies to accurately assess energy efficiency and identify potential improvements. Similarly, estimating the energy performance of an entire building complex is challenging due to the numerous factors that influence energy use, including the building envelope, building geometry, occupant behavior, heating and cooling systems, and weather conditions[6]. And, management strategies to improve sustainability in the building sector need to consider the environmental impact of heating systems. It has been estimated that high thermal energy consumption is related to three factors: the quality of the envelope, the low efficiency of the heaters and the low quality of the fuel used [7]. Long-term retrofit strategies are necessary in order to achieve higher levels of sustainability and reduce carbon emissions from buildings.

For Chile, the energy transition is particularly important. About 70% of Chile's energy mix is dependent on imported energy [8]. In terms of heating resources, more than 30 % of Chilean households use fuelwood as their main source of energy, which is the main source of particulate emissions and has a serious impact on human health. Air pollution caused by particulate matter PM10 is one of the biggest environmental and public health problems in Chile [7]. The building sector consumes about 26% of the energy, of which the residential sector accounts for about 78% [4]. In addition, the energy consumed in Chilean houses is mainly used for heating and cooling (53%) and generating domestic hot water (20%) [9]. Improving the energy performance of housing is essential for achieving national energy efficiency goals and reducing environmental impacts. As a result, energy efficiency has begun to play an important role in the government's planning decision-making agenda.

Chile has made gradual progress in public policies for sustainable development and energy efficiency. Since 2000, the Chilean government has implemented thermal codes to improve the energy efficiency of buildings in the operational phase by improving the thermal envelope and replacing old wood stoves used for heating[10]. Mandatory standards were introduced in 2000 for the vertical elements used in housing (wall structures) and in 2007 for roof structures. Also in this context, Chile is committed in its recent Nationally Determined Contribution (NDC) to achieve net zero carbon emissions by 2050, as well as an intermediate carbon target and a reduction of particulate matter by 2.5 (phosphorus 2.5). The main aim of these measures is to reduce carbon emissions during the lifetime of the building. Improving the energy efficiency of buildings and reducing the energy demand is therefore a priority in achieving this goal.

Building energy modeling has been widely used to inform energy-efficient building design, demonstrate code compliance, obtain performance rating credits, evaluate retrofit options and optimize operations[11]. The objective of this study was to develop an energy model based on Temuco to assess the current residential energy consumption rating of the community, as well as to calculate the improvement in energy efficiency and the financial payback time of each retrofit measure as a way to achieve energy savings. The assessment was developed through the energy efficiency of eight typical houses provided in the Household Energy Use Report published by MINVU in 2018, as well as the different thermal zones in Chile. In addition to this, the potential for energy efficiency was estimated by analyzing the most promising options in the region, with this paper focusing on a preliminary assessment of the Temuco solar potential. These measures could significantly reduce the region's dependence on firewood resources and lower CO2 emissions, thus positively affecting air quality and the health of the population.

2. Case study

In this study, we used Temuco, a city in south-central Chile, as a case study. The reason for choosing this city is that Temuco has high levels of air pollution and is one of the most polluted cities in the world in terms of wood smoke. This is because the abundance of local wood biomass makes it the most affordable fuel for residential heating and cooking. However, population exposure to pollutants, particularly PM and fine particulate matter (PM 10 and PM 2.5, respectively), both of which are products of wood biomass combustion, indicates a greater risk of mortality and morbidity from cardiovascular and respiratory diseases [12]. This risk must be addressed by reducing the use of wood as a primary energy source. There is no doubt that improving energy efficiency and reducing energy use in the building stock is crucial. implemented and effective short-term solutions to this end include improvements to the building envelope (i.e., insulation and airtightness) and replacement of old cookers with more efficient ones [2].

Temuco is a city and commune, capital of the Cautín Province and the Araucanía Region in southern Chile. According to the 2017 census by the National Statistics Institute (INE), Temuco had a communal population of 295,839 and a territory of 464,0 km², with a population density of 637.58 hab⁄km²,. Homes are mainly located in low-density urban periphery zones. They are mostly one or two-story constructions of reinforced brickwork (15cm thick brick walls) and/or timber structure (2x4 timber-framed walls and ¾ timber board or sheet facing) with sloping roofs covered in fiber cement or metal sheeting[13].

(1) Araucanía Region (2) Commune of Temuco

Figure 1: Geo-political divisions of the case study.

2.1 Thermal regulation of Temuco

Chile is the longest country in the world from north to south and is characterized by the existence of several climatic zones that vary considerably from one region to another. Chile has an official document that regulates the building codes and materials that should be used in the different geographic regions of the country, called the Thermal Regulation (TR) of the General Regulation of Urban Planning and Construction of the Ministry of Housing and Urban Planning of Chile (MINVU) [14]. In the TR document, construction recommendations have been developed for seven thermal zones, which in turn were determined by the heating degree-days (HDD) method with a base temperature of 15 °C[14]. The Climate and Housing Zoning of the Official Standard is based on the set of meteorological variables that define a climate, including the daily thermal oscillation that occurs in different periods of the year in a locality. Other variables that define a climate are cloud cover, solar radiation, daily hours of sunshine, wind intensity and direction, precipitation, vegetation, and humidity.

As shown in Figure 2, Temuco is located in Zona 5, so this study will follow the energy rules of zona térmica 5 (ZT5). The region experiences an annual range of heating degree days falling within the range of 1,250 to 1,500. This classification is indicative of the climatic conditions and thermal characteristics of the area, informing considerations related to building design and energy requirements.

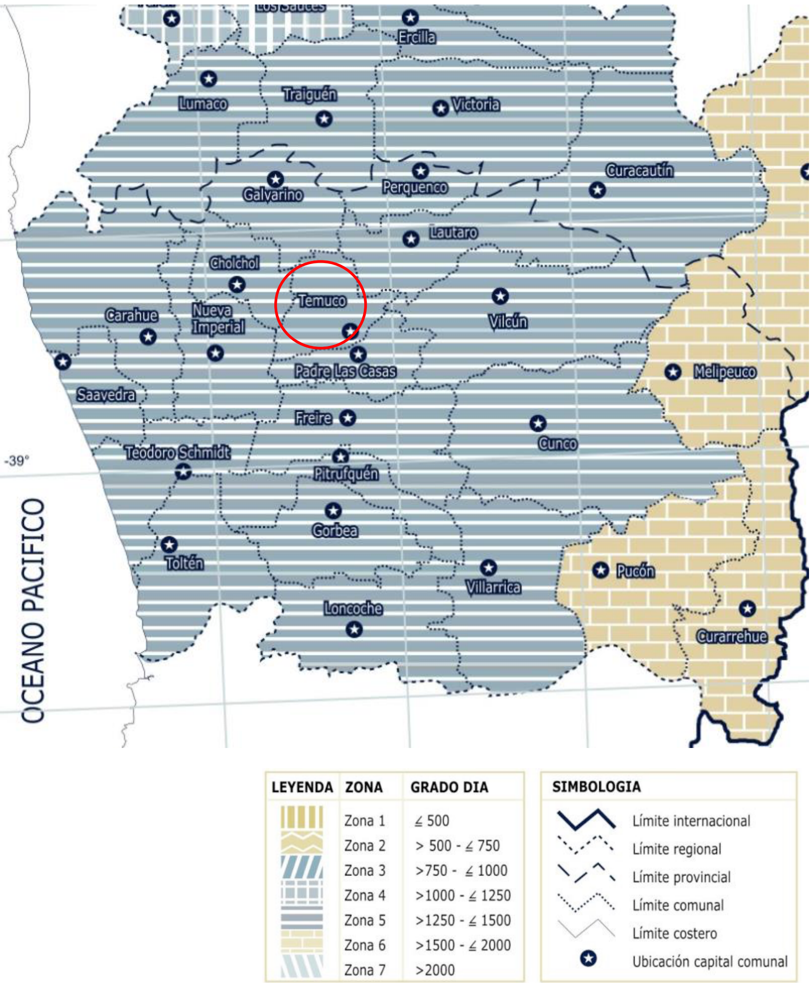


Figure 2. Thermal zone for the commune of Temuco[14]

2.2 Weather in Temuco

The municipality of Temuco is situated within the South Interior climatic zone, renowned for its distinctive attributes of high precipitation and low temperatures, characterized by brief summer periods and moderate solar radiation.

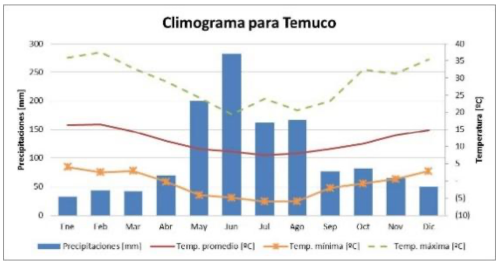


Figure 3: Climogram of Temuco[15]

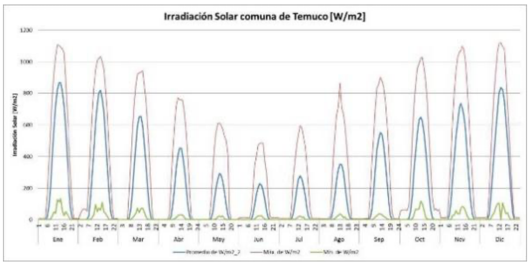


Figure 4: Solar irradiation of Temuco[15]

	Solar irradiation (kWh/ m2)	**Daily Hours of light* (h/day)**	**Temperature (°C)**	**Precipitation (mm)**	**Relative Air Humidity (%)**	**Amount of Covered Sky (in octaves)**
Jun	225.39	14.5	16.0	32.6	78.7	2.7
Feb	160.38	13.5	16.5	60.0	81.4	3.6
Mar	150.49	12.3	13.8	54.0	83.8	3.6
Apr	83.20	11.0	12.4	96.1	88.7	4.9
May	52.06	10.0	8.7	108.6	91.1	6.2
Jun	29.96	9.5	7.5	274.5	93.3	6.5
Jul	42.59	9.8	6.6	107.8	91.0	5.0
Aug	65.18	10.7	7.3	282.2	88.7	6.0
Sep	111.49	11.9	8.3	82.4	84.8	4.6
Oct	137.95	13.1	10.6	182.6	83.9	5.5
Nov	199.89	14.3	12.4	33.2	81.0	3.8
Dec	215.03	14.8	14.3	41.2	81.5	4.0

Table 1. Temuco climate data for the year 2017 (data refer to the weather station of La Araucanía Ad; the data with * refer to weatherspark website)

A comprehensive overview of the climatic characteristics of this locality can be gleaned through the examination of a climograph, exemplified in Figure 3.

The Temuco area has a high level of climate vibration and problems with humidity in the winter. The main problem is reduced comfort due to cold winters. During the winter, temperatures as low as -5°C can be reached. The level of precipitation exhibits a notable disparity between the winter and summer seasons, with June witnessing a substantial increase in precipitation, reaching approximately 280 millimeters. In contrast, during the winter months encompassing December to February, the average precipitation diminishes considerably, typically registering at less than 50 millimeters. Therefore, it can be concluded that the use of air conditioning in summer and heating in winter will account for a significant proportion of household energy consumption.

Chile is located in the southern hemisphere, and the period requiring cooling in summer is from December to February, while the heating period in winter is from May to September. Chile has one of the best solar radiation conditions on Earth, with an average annual radiation equivalent of approximately 1,405 kWh/m^2 for the entire commune, according to the solar radiation map shown in Figure 3 [16].

2.3 Demographic

Based on the 2017 population data obtained from the INE (Instituto Nacional de Estadísticas), we got the following data.

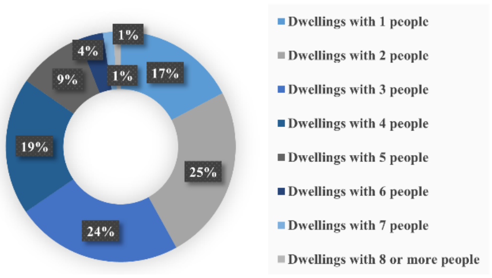


Figure 5. Total private dwellings with residents' present

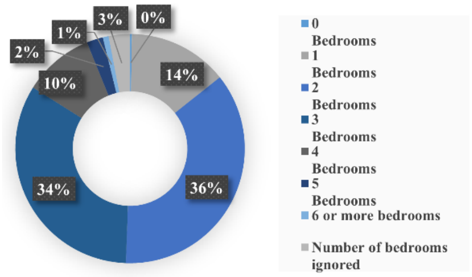


Figure 6. Number of Bedrooms

It can be seen that in Figure 5, a family with two people accounts for the largest proportion, reaching 25%, followed by a family with three people accounting for 24%, and then a family of four accounting for 19%, the proportion of households with more than 6 people in a household is relatively small, accounting for 6% in total.In Figure 6, two- and three-bedroom apartments account for more than half, up to 70%. Next are those with one bedroom and four bedrooms, at 14% and 10% respectively.

According to Table 2, Figure 7 and Figure 8, the 18-65 age group accounts for the largest proportion of the population, reaching 66%. Among them, there are more females than males, followed by the population under 12 years old, accounting for 16%, the proportion of the male population is slightly higher than that of females, then the population over 65 years old accounts for 10%, the number of females is much higher than that of males, nearly 4,800 people, and the population aged 12 to 17 accounts for at least 8%.

Age	Total population	Men	Women
Total Commune	282415	134289	148126
<12	44478	22717	21761
12~17	23078	11759	11319
18~65	186543	88572	97971
>65	28316	11241	17075

Table 2. Temuco Population Statistics

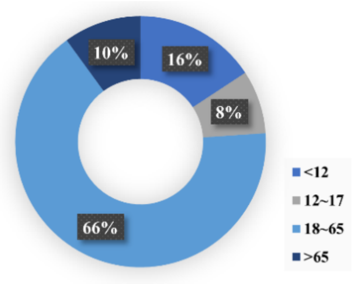


Figure 7. Total population surveyed

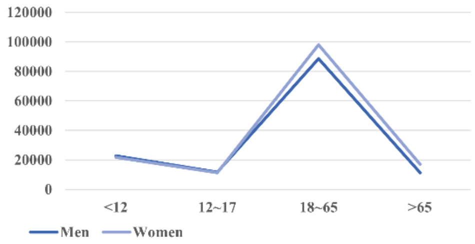


Figure 8. Gender survey for all age groups

3. Materials and methods

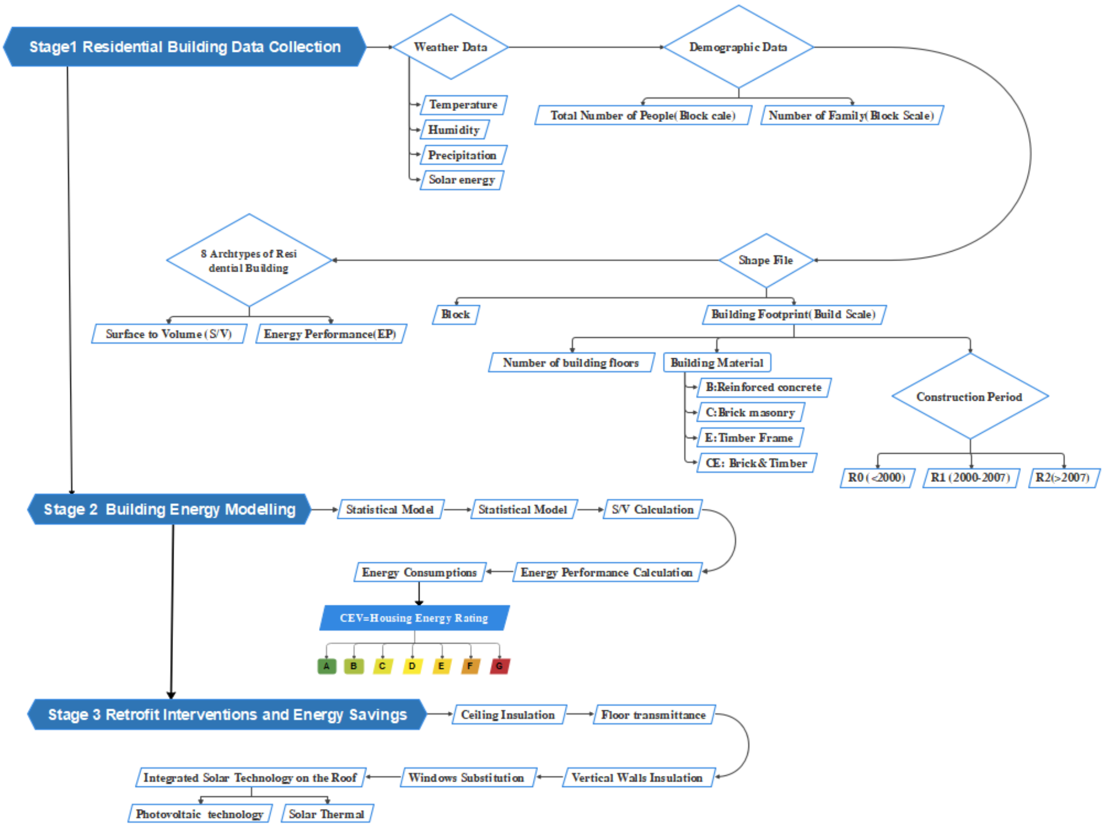


Figure 9. Structure of the methodology for residential building stock in Temuco

This section provides an overview of the data sources and analytical methods used in the study. A bottom-up approach was used in this study to construct the energy equation, and this approach to energy modelling can provide a systematic methodology for simulating energy maps in Chile to be applied to various regions of the country. In addition, the location-based approach is explained in detail for the pre-processing of all the data obtained and the modelling steps are elucidated, using the ArcGIS tool to combine the typical data with Temuco's cadastral information to construct a geographic information database, which allows the calculation of the energy performance. Then, energy retrofit measures were proposed based on the Temuco Local Energy Strategy [14]. Subsequently, the monthly solar irradiation of Temuco was calculated to assess the photovoltaic energy potential of Temuco municipality. Figure 9 visually depicts the methodology used in this study in the form of a flowchart.

Stage 1. Data collection

The following provides information on the calculation of all energy-related variables that can be used to model energy consumption at the city scale:

- The geometries of building stock from the municipality of Temuco(AutoCAD file);
- The geometries of the block from Portal IDE Temuco(Predios Comuna de Temuco);
- The cadastral database of housing from the Internal Revenue Service (Cartografia Digital SII Mapas)[17].
- The energy consumption in Chile and the characteristics of typical building from the Ministry of Energy(Usos de energía de los Hogares Chile 2018)[9];
- The climate data is from Weather Spark;
- The Digital Elevation Model of the territory from 2012.

This work creates a database of geographic information for UBEM with buildings as the basic unit. The building outline data were converted into geometric shapes in order to calculate the footprint and perimeter. In addition, geographic data (population, number of households) and cadastral data (building materials, year of construction, use of the building) are associated with each building in each block, which makes the building model of the city of Temuco a geographic information database with complete cadastral data. This study aims to calculate the energy consumption of existing buildings and to improve their energy efficiency through retrofitting measures.

Since 70% of Temuco's energy consumption quota is attributable to residential buildings, an adjustment was made to the building data and this analysis will only be used for residential buildings. As the revision of the thermal regulations included in the OGUC, which came into force in 2000, and which in the first stage applied exclusively to the roof complex of dwellings. In 2007, limitations were included on the thermal transmittance of walls, floors, and glazed openings[16]. Before the year 2001, buildings lacked any form of insulation, necessitating comprehensive retrofitting measures.

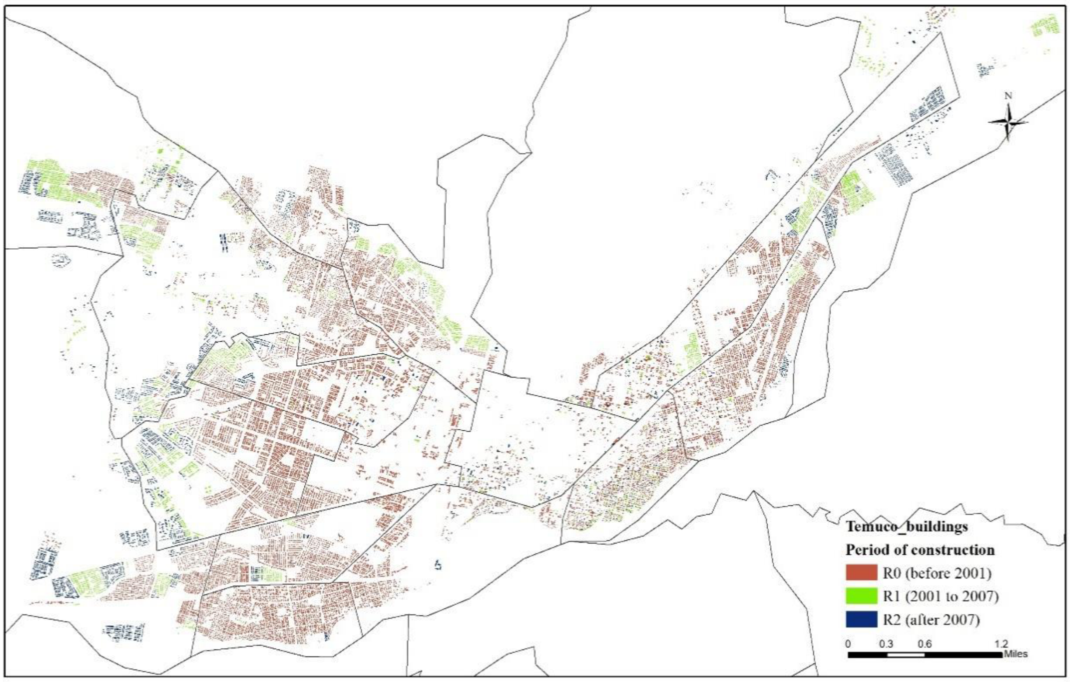


Figure 10. Classification of period of the construction

In Temuco, the construction of residential buildings is shown in Figure 10: 75 % of the buildings were built before 2001 (R1), also before the thermal code; 11% between 2001 and 2007 (R2); and 14 % after 2007 (R2).

Using data on population characteristics in each block of Temuco in Portal IDE Temuco, assigned to each building based on building volume, the population in each building can be calculated. The houses studied had an average of 3.4 permanent occupants per unit, close to the national and regional average of 3.6 occupants per household [18].

Period of Construction	**Number of capitas per building**					**Number of builidings**
	<3	**4-6**	**7-12**	**12-33**	**>33**	
R0	36466	13039	2472	528	63	52568
R1	5776	1566	491	142	7	7982
R2	7742	1601	315	118	52	9828

Table 3. Number of capitas per building in Temuco

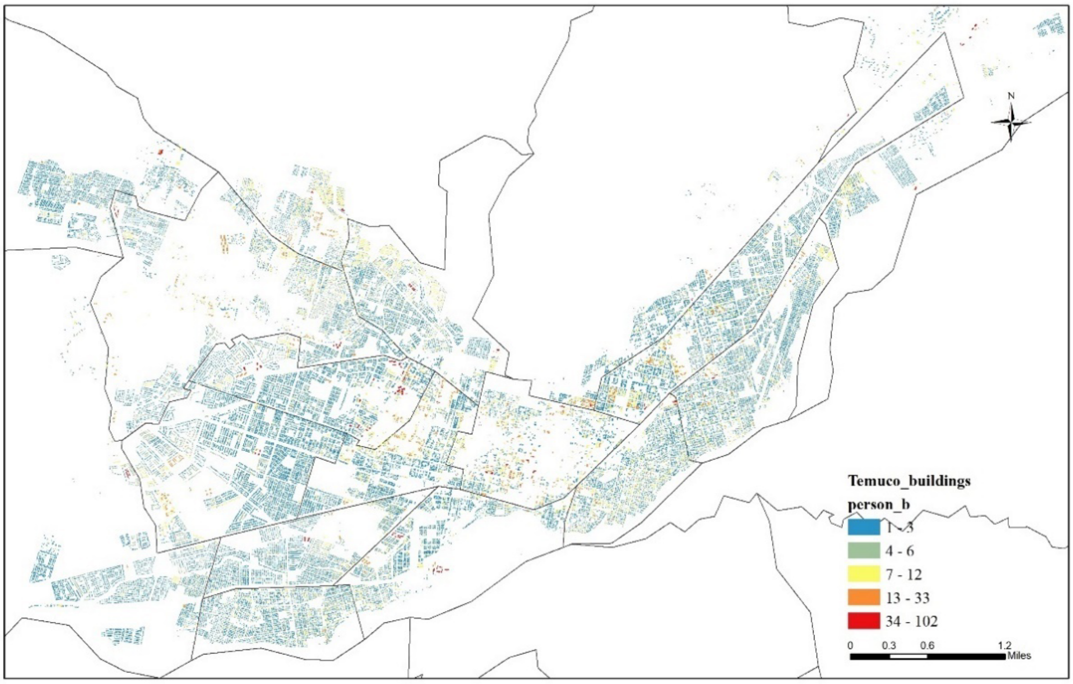
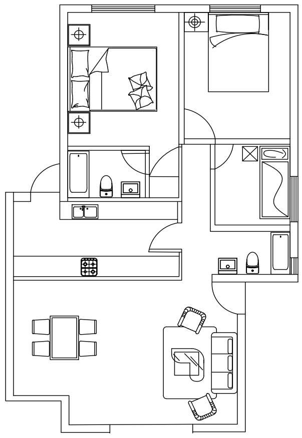


Figure 11. Number of capitas per building in Temuco

Table 3 and Figure 11 reports the population in residential buildings: 71% of them had a capacity of less than 3 persons, which shows that residential buildings in Temuco are dominated by single families; and only 1% of them had a capacity of more than 13 persons, which shows that there are very few apartment-type dwellings in Temuco. It is worth noting that when the actual floor heights are obtained by dividing the building heights by the average Chilean floor height of 2.3 m, we find that 36 % of the houses in Temuco have only one story and 63 % have only two stories. Almost the entire city's residential buildings are detached or semi-detached, with similar styles and layouts.

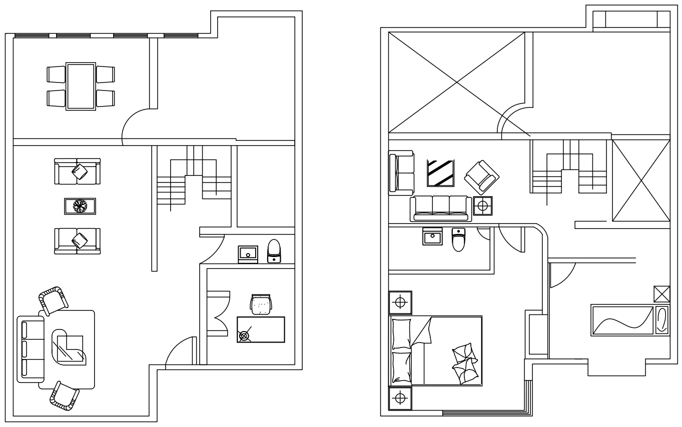
In order to calculate Temuco's energy consumption data, this study will be based on MINVU's 2018 energy data. This report contains 3,500 energy use questionnaires for different climatic regions and social-economic conditions in Chile, as well as eight representative typical dwellings. The report documents the dwelling type, building material, floor area, window area, wall area, roof area, and ceiling height for these eight typical dwellings, which can be found in Table 4. Of the eight types of residential buildings, only Type 4 is a Terrace house, while Type 7 and Type 8 are Condominiums, and the rest of the houses are Detached houses. They have different sizes and materials, and except for Type 8, which is made of reinforced concrete, the material for the remaining seven types of houses is brick masonry.

Archtype 1



Building type	Detached house	Window area (m^2)	17.8
Story	1	Wall area (m^2)	83.8
Material	Brick masonry	Roof area (m^2)	60.2
Useful area (m^2)	56.5	Ceiling height (m)	2.4

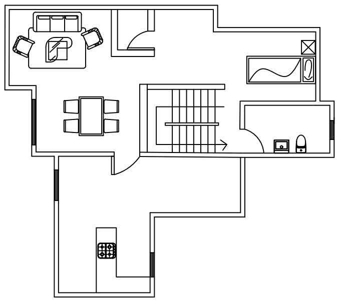
Archtype 2



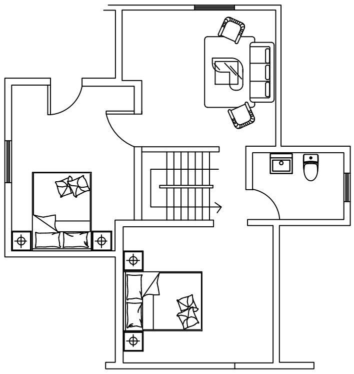
F1 F2

Building type	Detached house		Window area (m^2)		52.4
Story	2		Wall area (m^2)		199.8
Material	Brick masonry		Roof area (m^2)		121.6
Useful area (m^2)	F1	114.7	Ceiling height (m)	F1	2.85
	F2	106.5		F2	2.88

Archtype 3



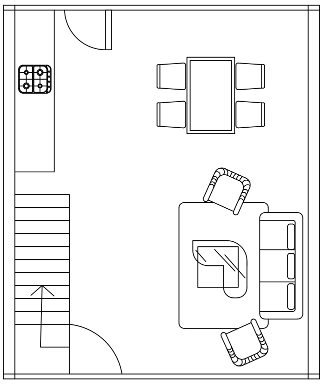
F1



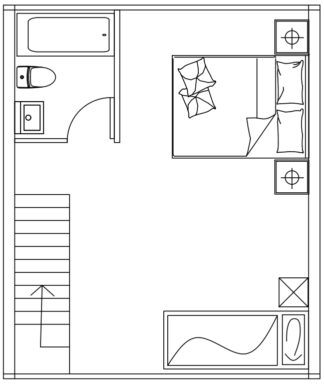
F2

Building type	Detached house		Window area (m^2)		23.7
Story	2		Wall area (m^2)		120.7
Material	Brick masonry		Roof area (m^2)		63
Useful area (m^2)	F1	63	Ceiling height (m)	F1	2.4
	F2	40		F2	2.4

Archtype 4



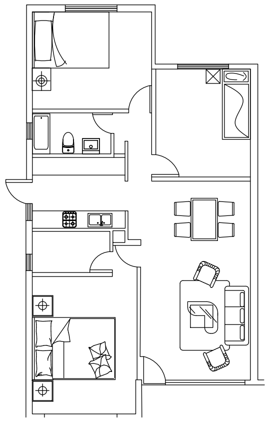
F1



F2

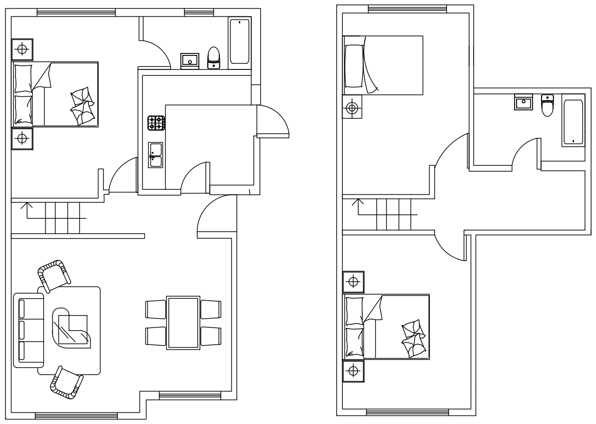
Building type	Terrace house		Window area (m^2)		6.25
Story	2		Wall area (m^2)		82.89
Material	Brick masonry		Roof area (m^2)		26.48
Useful area (m^2)	F1	25.99	Ceiling height (m)	F1	2.44
	F2	25.99		F2	2.355

Archtype 5



Building type	Detached house	Window area (m^2)	5.39
Story	1	Wall area (m^2)	51
Material	Brick masonry	Roof area (m^2)	81.7
Useful area (m^2)	67.7	Ceiling height (m)	2.4

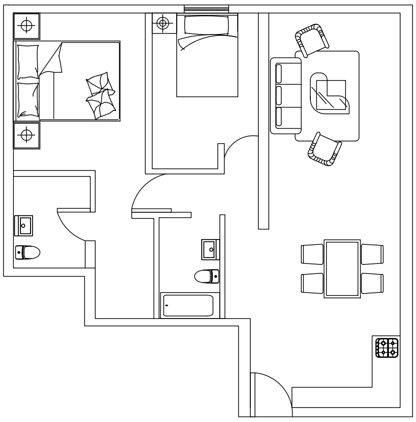
Archtype 6



F1 F2

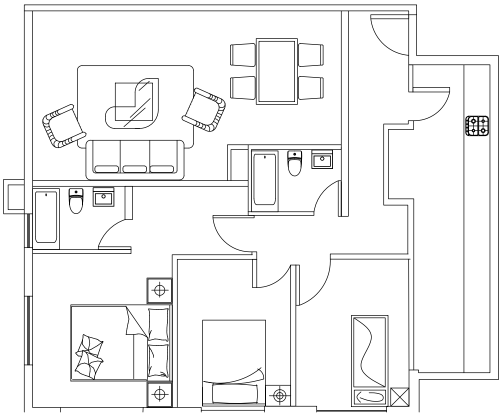
Building type	Detached house		Window area		12.23
Story	2		Wall area		82
Material	Brick masonry		Roof area		56.5
Useful area (m^2)	F1	48.4	Ceiling height	F1	2.3
	F2	36.3		F2	2.3

Archtype 7



Building type	Condominiums	Window area (m^2)	16.3
Story	1	Wall area (m^2)	5.7
Material	Brick masonry	Roof area (m^2)	64.4
Useful area (m^2)	64.4	Ceiling height (m)	2.6

Archtype 8



Building type	Condominiums	Window area (m^2)	21.8
Story	1	Wall area (m^2)	33.2
Material	Reinforced concrete	Roof area (m^2)	109.7
Useful area (m^2)	109.7	Ceiling height (m)	2.6

Table 4. 8 archetypes of residential building

In addition, the more important energy-related variables affecting the energy performance of buildings include climatic conditions, geometric and typological characteristics of the building (volume, surface-to-volume ratio S/V, time of construction, etc.), type of urban environment (building density, height-to-width ratio of urban canyons, H/W, etc.), and socio-economic characteristics of the population (age of the population, number of household members, level of maintenance of the building, etc.)[8]. In particular, S/V reflects the degree of building non-compactness and has a direct impact on building space heating energy consumption, which is shown in the following equation:

$$S\,[m^2] = (Area[m^2] * 2) + (Perimeter[m] * Height[m]) \qquad (1)$$

$$V\,[m^3] = Area[m^2] * Height[m] \qquad (2)$$

where:

S *is heat loss surface* $[m^2]$

V *is heated air gross volume* $[m^3]$

Archetype	**S (m^2)**	**V (m^3)**	**S/V (m^2/m^3)**	**Energy Performance (kWh/m^2/year)**		
				R0	**R1**	**R2**
Type 1	218.3	135.6	1.61	417.5	270.5	206.5
Type 2	488.5	657.2	0.74	244.5	169.5	135.5
Type 3	270.4	302.4	0.89	309.5	225	173
Type 4	141.6	124.6	1.14	322.5	252	177
Type 5	205.8	162.5	1.27	355	189	141.5
Type 6	199.1	222.6	0.89	278	186.5	144.5
Type 7	150.8	502.3	0.30	70	70	55.5
Type 8	274.4	855.7	0.32	101.5	101.5	66

Table 5. S/V((m^2/m^3) and energy performance(kWh/m^2/year) of 8 archetypes

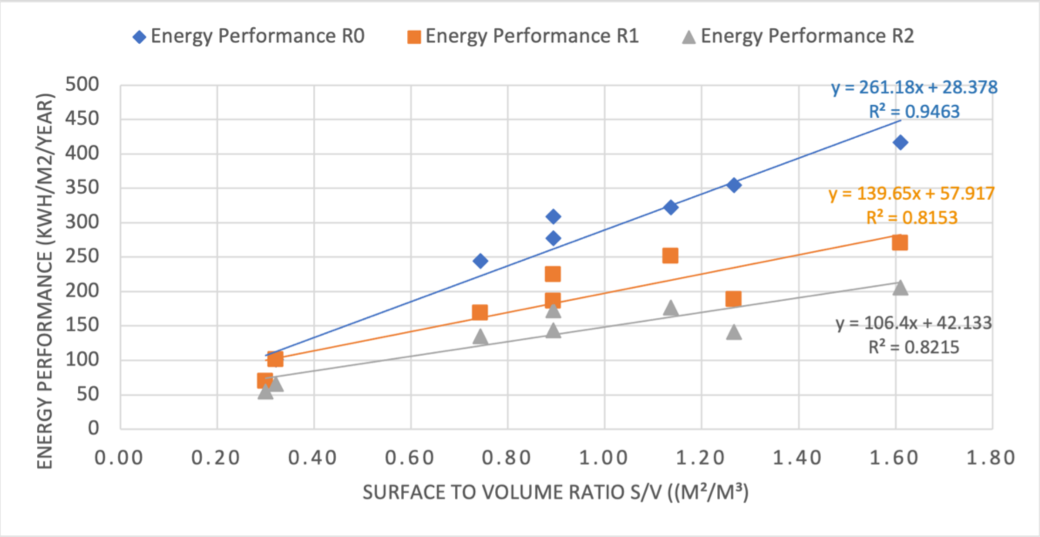


Figure 12. The linear regression between S/V (m²/m³) and EP (kWh/m²/year) by different periods of construction

Based on Table 4, the surface area to volume ratios for these eight buildings can be easily obtained. The MINVU report does not give the energy performance data of ZT5 where Temuco is located, and the energy performance is closely related to the heating degree days, so in this study, the energy performance index of ZT5 in each period is obtained by taking the average value of the energy performance of ZT3 and ZT6 in the report based on the heating degree days.

In order to estimate the space heating energy demand of dwellings at the city level, the ratio of surface area to volume was correlated with the construction age of the building. As shown in Figure 12, the linear regression equations were generated for each regulatory period and the R2 coefficients were well reported: 0.95 (R0); 0.83 (R1); 0.84 (R2). It is easy to see that energy performance is positively correlated with the S/V ratio, the higher the S/V the higher the energy performance of the building This is due to the fact that a higher S/V means a higher heat loss surface and therefore a higher EP. This relationship holds true at the urban scale as well, and these three equations will be used in this calculation.

Stage 2. Pre-processing and energy modeling

In the pre-processing phase of building modeling, the main data usually used are the construction period of the building and the ratio of surface area to volume S/V. However, this always applies to isolated buildings. In cities, most buildings are not always isolated, they sometimes share walls and part of the surface area of this surface will not be exposed and cannot be considered as a heat loss surface. Therefore, it is necessary to subtract the common area of two neighboring buildings when calculating the heat loss surface. The part of the wall shared between the two buildings is calculated by GIS tools and some outliers are counted and removed, which is used to evaluate the true surface area to volume (S/V) ratio of the building.

Next, the Temuco building energy model can be constructed to categorize energy sources and generate energy maps based on the energy classification methodology given by Energy Classification System CEV, a step that helps to assess and visualize buildings with worse energy performance.

Stage 3. Retrofit interventions and projected energy savings

According to the MINVU paper, four energy interventions will be applied to Temuco's energy performance model, including window substitution, vertical wall insulation, ceiling insulation, and floor transmittance. these interventions have different percentages of energy savings for different periods of the building. These interventions have different percentages of energy savings for different periods of the building and are applied to each period of the building through a GIS tool to generate energy savings maps. In addition, the economic cost of the four interventions and the time to report the investment will also be reported. In this phase, the GIS tools will also be used to assess the area's solar photovoltaic potential and solar thermal, with the expected outcome of this work being a pre-feasibility assessment of potential energy consumption.

4. Result and discussion

4.1 Energy Performance Index

In order to simulate the energy performance of the building sites in the city of Temuco, some pre-processing was previously performed on the model. These include the year of construction, which has a strong influence on the energy performance, and the S/V. The period of construction is very important because over the years the buildings have been constructed with different types of envelopes, levels of thermal isolation, window-to-wall ratio, and systems efficiencies[21]. As shown in Table 6 and Figure 10, the year of construction was divided into three categories: R0 (before 2001); R1 (2001 to 2007); and R2 (after 2007).

It's also necessary to determine the geometrical characteristics of the buildings, also known as S/V. Figure 13 shows the true surface area to volume ratio of the buildings of the city of Temuco after pre-treatment. They were classified into four categories:

- Low-rise residential area of one-story single-family houses with S/V ratio higher than 1.09 m^2/m^3 ;
- Terrace houses with two floors with an S/V = 0.9 − 1.09 m^2/m^3;
- Little condominiums of 3–4 floors with an S/V of 0.6–0.9 m^2/m^3;
- Large condominiums with more than four floors with an S/V lower than 0.6 m^2/m^3.

Classes of S/V (m2/m3)	**Period of Construction**			**Number of buildings**
	R0	**R1**	**R2**	
> 1.09	5676	2033	3231	10940
0.9 − 1.09	16565	4266	4095	24926
0.6 – 0.9	28221	1638	2396	32255
< 0.6	2106	45	106	2257

Table 6. Surface to volume ratio S/V(m^2/m^3) of residential building in Temuco

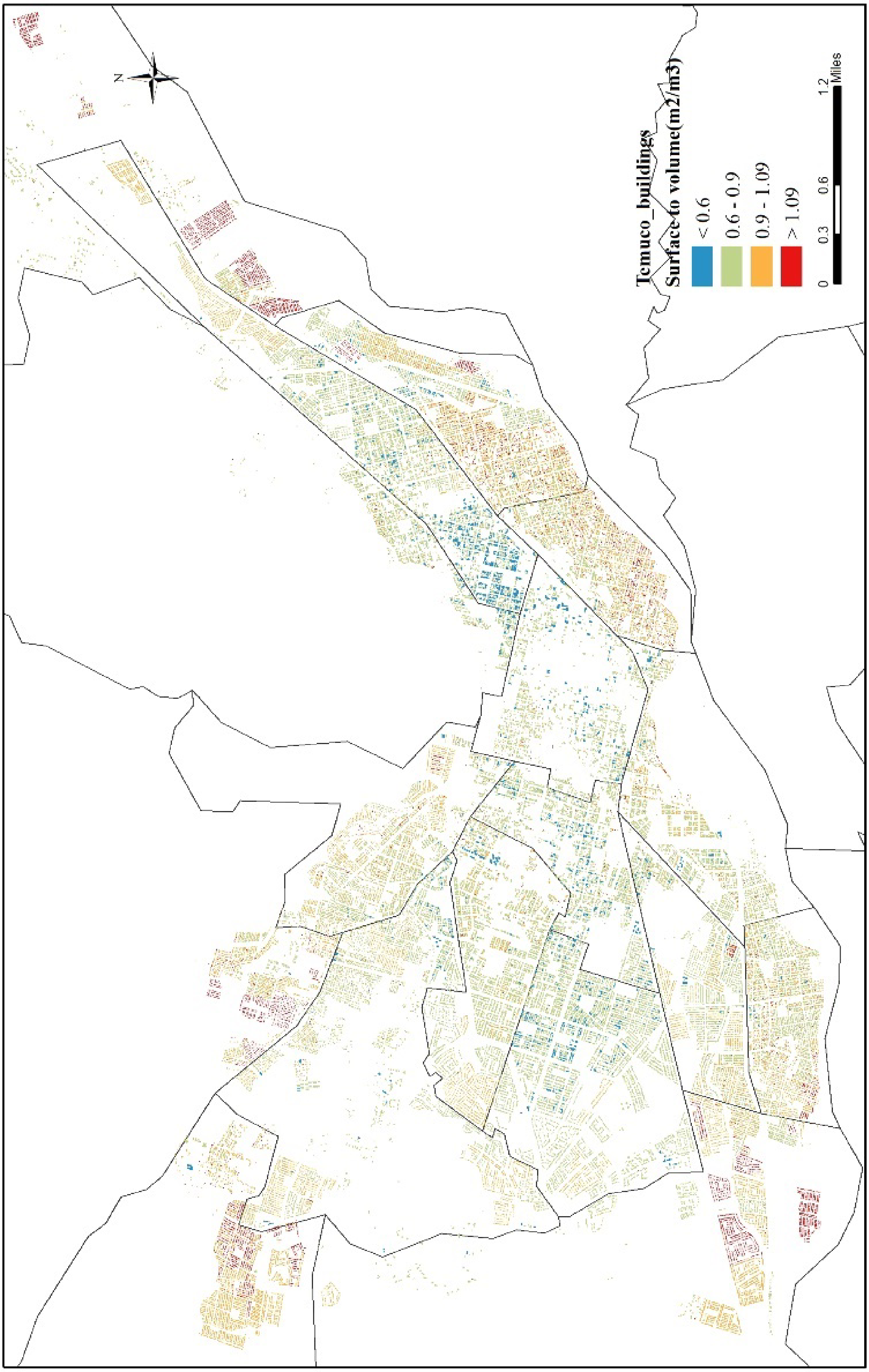


Figure 13. Surface to volume ratio S/V(m^2/m^3) of residential building in Temuco

The same categorization of building groups in the map helps to better observe the distribution of building types in the area. Considering buildings of the same volume V, the higher the S (surface area of heat loss), the higher the energy consumption for space heating. From Figure 13, it can be known that most of the residential buildings in Temuco have a surface area to volume ratio belonging to Little Condominiums (46%) and Terrace houses (35%). While very few buildings belong to Large Condominiums, only 6% of the buildings have S/V less than 0.6.

As a next step, it is necessary to report the equations in GIS to obtain specific energy performance values (EP [kWh/m^2/year]) for the S/V values of the buildings. Table 7 below shows the equations applied for each period, which were derived from the 8 building types above.

Period	**Formula**
R0 (before 2000)	216.18*S/V + 28.378
R1 (from 2001 to 2007)	139.65*S/V + 57.917
R2 (after 2007)	106.40*S/V + 42.133

Table 7. The energy performance (kWh/ m^2/year) formulas using S/V (m^2/m^3) and different periods of construction.

In order to categorize buildings according to their energy efficiency rating, the annual energy performance of each building needs to be calculated. The Chilean Residential Energy Classification System (CEV) is a tool designed by the Minvu in 2012 [12][19]. The system defines the administrative procedures for residential energy rating in Chile. The CEV is used to assess the energy efficiency of a home during its use phase and is designed to be similar to the energy labeling systems used for refrigerators and cars, taking into account factors such as heating, cooling, lighting, and hot water. Eligible homes are assigned labels with colors, percentages, and letters ranging from A to G, where G indicates the lowest efficiency, and the letter E represents compliance with the current building standards set out in Article 4.1.10 of the General Ordinance on Urban Planning and Construction[14]. To calculate the annual energy performance of each building, it is possible to use the evaluation methods provided in the CEV system. Whereas each thermal zone has different criteria for classification buildings, in this study, building energy classification will follow the criteria of ZT5 where Temuco is located.

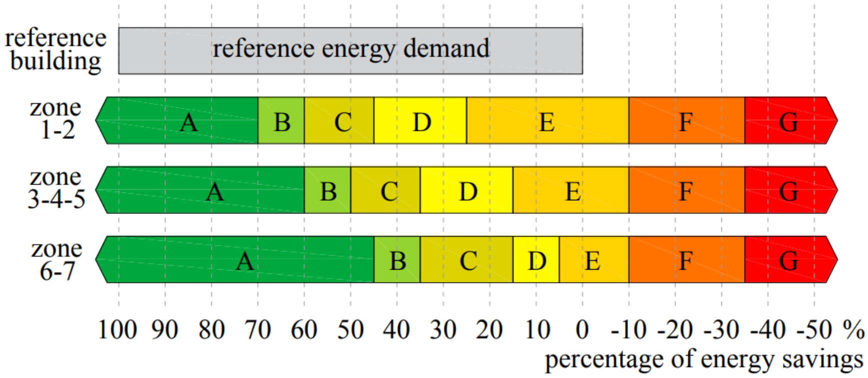


Figure 14: Energy classification of dwellings in Chile [16]

In the CEV file, the average energy demand (in kWh/m^2/year) is divided according to type and thermal zone. These values are used to compare the energy efficiency of the projected house with the energy efficiency of an average house built in a regional capital. In Temuco, for example, The average energy demand of the building varies between periods: 268 kWh/m^2/year in period R0; 159 kWh/m^2/year in period R1; and 111 kWh/m^2/year in period R2[8]. As this energy rating is based on the percentage of energy savings of the house, it does not allow for easy comparison of buildings with similar energy performance, it is necessary to calculate the energy performance of each building using the following formula:

$$EP_{classification}\ [kWh/m^2/year] = EP_{reference}\ [kWh/\ m^2/year] \times (1\ \text{-}percentage\ of\ energy\ savings\ [\%])\quad (3)$$

where:

$EP_{classification}$ *is energy performance of energy classification [kWh/ m^2/year]*

$EP_{reference}$ *is reference energy performance [kWh/ m^2/year]*

Based on the above equation, buildings can be classified into eight classes based on energy performance. Table 8 shows the energy performance classification based on CEV.

Classification of energy	Energy Performance (kWh/m²/year)		
	R0	**R1**	**R2**
A	EP <107.2	EP <63.6	EP <44.4
B	107.2 ≤ EP < 134	63.6 ≤ EP < 79.5	44.4 ≤ EP < 55.5
C	134≤ EP < 174.2	79.5≤ EP < 103.4	55.5≤ EP < 72.2
D	174.2≤ EP < 227.8	103.4 ≤ EP <135.2	72.2≤ EP < 94.4
E	227.8 ≤ EP < 294.8	135.2 ≤ EP < 174.9	94.4 ≤ EP < 122.1
F	294.8 ≤ EP < 361.8	174.9 ≤ EP < 214.7	122.1 ≤ EP < 149.9
G	EP ≥ 361.8	EP ≥ 214.7	EP ≥ 149.9

Table 8: Energy classification of residential buildings of ZT5

The same classification can be used in ArcMap to display the results on the map. The average energy performance of residential buildings in Temuco is 204.8 kWh/m²/year, and it is easy to see from this Figure (labeled as Figure 15) that since most of the buildings in Temuco are detached houses, with high S/V values, the majority of the buildings in the area fall into the Class D and Class E in terms of energy performance grading, with 38 % and 28 % respectively. A smaller number of buildings are in Class F, accounting for 15% of the total. It can be seen that the buildings in this area have a high potential for energy savings and could be retrofitted with a range of measures to reduce energy demand.

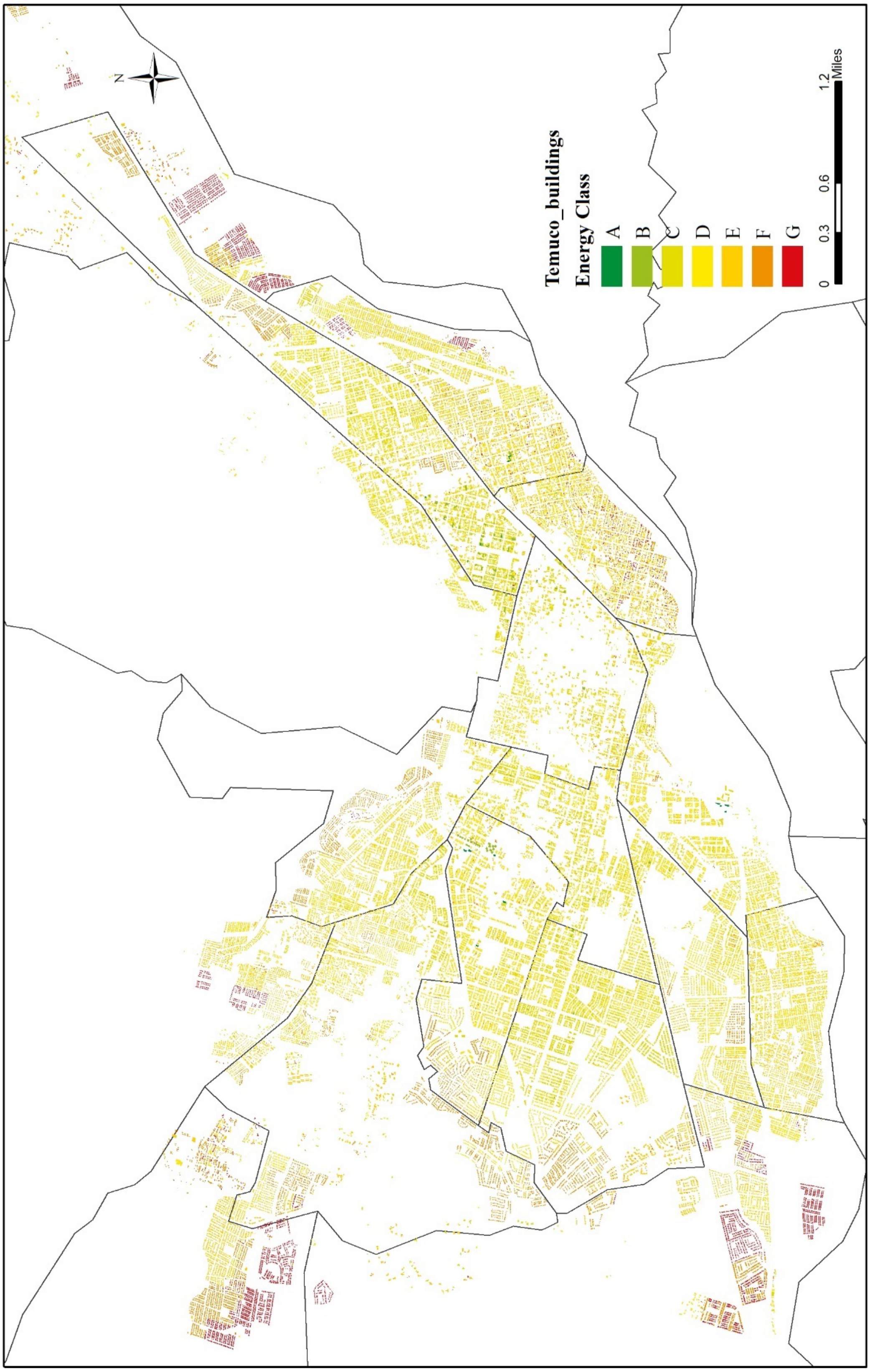


Figure 15 : Energy classification of residential buildings in Temuco

Energy classes	**Period of Construction**		
	R0	**R1**	**R2**
A	36	0	0
B	197	0	0
C	6006	3	16
D	27005	26	25
E	18153	993	668
F	1164	5680	3788
G	7	1280	5331

Table 9: Number of EPCs by period of construction and energy classes.

4.2 Conceiving energy retrofit

Once the main characteristics of the energy performance of the existing building stock have been identified, the evaluation of interventions and retrofitting of energy saving and emission reduction measures can be continued. According to the recommendations given by Minvu [9], there are four types of measures that require investment but have a high energy-saving potential for the country:

- Installing 20cm of insulation in the walls;
- Installing 15cm of insulation in the ceiling;
- Installing tightly glazed windows for the building;
- Installing insulation on the floor.

The percentage of energy savings from these retrofits varies depending on the period of the house. Table 10 shows that wall retrofits have high energy savings for each period of the building, while floor retrofits have relatively low ES. The economic cost spent on each retrofit measure is also shown in the document, with window retrofits costing the most at $\$158.6/\text{m}^2$ and ceiling retrofits costing the least at only $\$8.52/\text{m}^2$[9].

Retrofit interventions	Percentage of energy saving			Cost
	R0	R1	R2	($/m²)
Window substitution with U=1,1 [W/m2ºC]	12%	19%	21%	158.6
Vertical wall insulation with 20cm	32%	51%	44%	36.42
Ceiling insulation with 15cm	40%	7%	8%	8.52
Floor transmittance with 1cm	2%	4%	5%	18

Table 10: Percentage and cost of energy saving after different retrofit.

In order to calculate the energy efficiency gains after the four retrofit interventions (window substitution, vertical walls insulation, ceiling insulation, floor transmittance), the area of the retrofitted area will be calculated using the following formula:

$$\text{Total surface of the window } [m^2] = 1/7 \times S_{\text{useful heated surface}}\ [m^2] \qquad (4)$$

$$\text{Total surface of the wall } [m^2] = S_{\text{heat loss surface}}\ (m^2) - [(\text{area of the building } (m^2] \times 2) + \text{surface of the windows } (m^2)] \qquad (5)$$

$$\text{Total surface of the roof } [m^2] = \text{total area of the building } [m^2] \qquad (6)$$

$$\text{Total surface of the floor } [m^2] = \text{total area of the building } [m^2] \qquad (7)$$

Figure 16 and Figure 17 show the energy performance classification of residential buildings in Temuco at different times before the retrofit interventions and after modeling four different retrofit interventions.

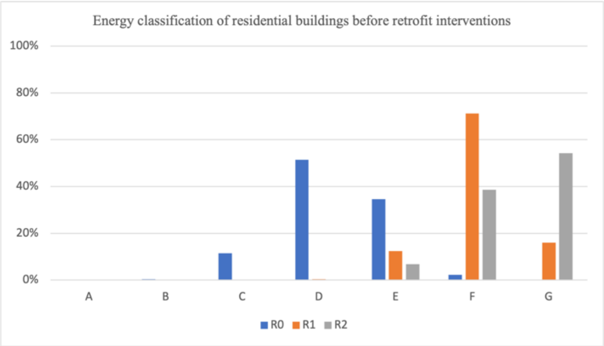


Figure 16: Energy classes of buildings before retrofit interventions

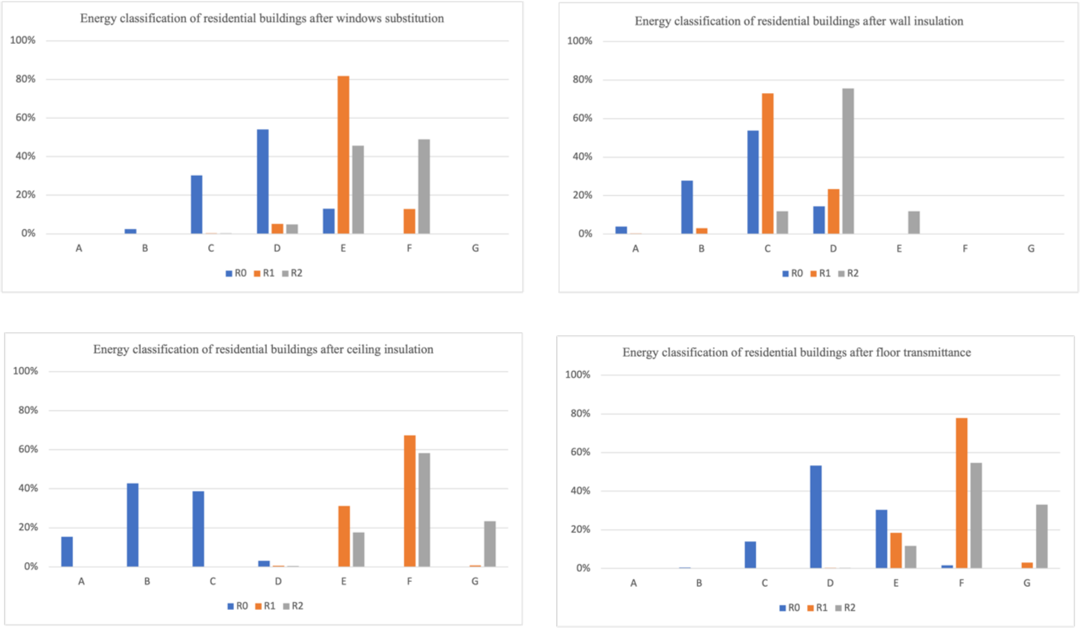


Figure 17: Energy classes of buildings after 4 types of retrofit interventions

- Before the retrofit, the average energy performance of Temuco residential buildings was 204 kWh/m²/year. Most of the buildings in the R0 period were in Class D and Class E, and 71% of buildings in the R1 period are in Class F. Most buildings in the R2 are in Class F and Class G. Overall, the energy rating of buildings is low and there is a huge potential for energy savings.
- After window substitution, the average energy performance of Temuco's residential buildings improves to 176 kWh/m²/year, with buildings in the R0 period performing in Class C and D, and most of the energy classes of buildings in the R1 period are upgraded to Class E. The energy ratings of buildings from the R2 period are predominantly classified as Class E, which remains relatively low.
- After wall insulation, there is a very significant improvement in building performance, with an average performance of 132 kWh/m²/year. The majority of the buildings have reached EP values of Class C and Class D. Half of the buildings in the R2 period have performance in Class D. Most of the buildings in the R0 and R1 periods are in Class C.
- The most significant energy savings after ceiling insulation are in R0 residential buildings, where 97 % of the buildings are in Class A, B, and C, compared to 11 %

before the retrofit. However, the retrofit seems to have had a relatively insignificant impact on R1 and R2 buildings, which have been upgraded from Class E to Class F. The average EP has also been reduced to 136 kWh/m²/year due to the significant uplift in the R0 period.

- Finally, there is the retrofit for floors, which has the lowest energy savings of the four measures, and the energy performance of the residential buildings does not change much between the periods.

When calculating energy savings, it is necessary to calculate Temuco's current total energy consumption. Energy consumption is the amount of energy required per square meter of a building per year, which is a direct reflection of the level of energy demand in the building. To calculate the amount of energy used for heating per year, the energy performance must be multiplied by the useful heating surface. The calculation of useful heating surface needs to consider the average thickness of the vertical walls of the building, which is related to the material of the building and the age of construction. Table 11 shows the number of buildings of different materials in each period.

Building material	**Average wall thickness (m)**	**R0**	**R1**	**R2**
Reinforced concrete	0.12	217	56	1466
Brick masonry	0.14	30997	6378	6712
Timber frame	0.09	21354	1548	1650

Table 11: Number of buildings of different materials in each period

Most of the visible building materials are a mixture of brick masonry and wood construction, both of which are typical of the area. By calculating the weighted averages, the average thickness (dm) of the building walls for each period is given as 0.12m for period R0, 0.13m for period R1, and 0.13m for period R2. The average annual energy consumption for each building can be calculated using the following formula:

$$S_{gross\ heated\ surface} = the\ base\ area * floors\ [m^2]\ (8)$$

$$S_{uesful\ heated\ surface} = fn \times S_{gross\ heated\ area}\ [m^2]\ (9)$$

$$fn = 0.9761 - 0.3055 \times dm \quad (10)$$

$$EC = EP \times S_{useful\ heated\ surface}\ [kWh/year] \quad (11)$$

where:

EC is energy consumption [kWh/year]

EP is energy performance [kWh/ m^2/year]

dm means the mean thickness of the wall [m]

At this point, the use of annual consumption can be used to calculate the cost of energy, that is, how much is spent each year to heat the building. According to Minvu [9], if only thermal energy consumption is taken into account, Table 12 shows that the main source of heating energy in Temuco is Firewood, with a share of 86.5 %, followed by electricity and Kerosene with 11.4 % and 10.3 %, respectively. The paper also gives the average cost per kWh of the different energy sources. By calculating the weighted average of the costs, it is known that the average price of energy from Temuco fuels is 0.05 $/kWh. The energy prices in this study use the Chilean energy prices of 2018 and didn't take into account the increase in the unit price of energy after covid-19.

Fuels	**Distribution of thermal energy**	**Average price per $/kWh**
Gas Natural	0.3%	0.146
Liquid Gas(GLP)	7.7%	0.097
Electricity	11.4%	0.110
Firewood	86.5%	0.010
Kerosene	10.3%	0.119
Pellet	5.9%	0.340
Weighted average	-	0.050

Table 12: Percentage and price of different fuels in Temuco[22][23][24]

Based on previous studies, the annual energy consumption and energy prices are known, and the following formula can be used to find out how much is spent annually on heating energy in the region:

$$\text{Annual Heating Cost} = 0.05 * EC\ [\$/year] \qquad (12)$$

where:

EC is energy consumption [kWh/year]

In addition, the following equation will be used to calculate the energy performance, after the four interventions. financial savings, energy saving, investment, and simple payback time.

$$EP_n\ [kWh/m^2/year] = EP[kWh/m^2/year] \times (1\text{-}ratio\_s) \qquad (13)$$

$$ES[kWh/year] = EC[kWh/year] \times ratio\_s \qquad (14)$$

$$FS\ [\$] = ES\ [kWh/year] \times 0.05\ [\$] \qquad (15)$$

$$\text{Payback Time [years]} = \text{Cost of Intervention [\$] /Annual Economic Saving [\$/year]} \qquad (16)$$

where:

EP_n *is New Energy Performance [kWh/m²/year]*

EP is Energy Performance [kWh/m²/year]

ES is Energy Saving [kWh/year]

EC is Energy Consumption [kWh/year]

FS is Financial Saving [\$]

Using the prices in Table 10 and Table 12 it is possible to estimate the energy consumption and economic costs of residential buildings throughout Temuco, as well as to compare the payback time, discuss the most favorable options, and identify the most appropriate building retrofit policy for the municipality.

Comparing the results of the four different retrofit interventions (labelled as Table 13), Ceiling insulation is retrofit with the lowest investment cost of $8.52/m² and the highest energy savings, with a payback time of just 2 years. Windows substitution and wall insulation have a payback time of 19 and 14 years respectively, but the area of window retrofitting is much smaller than wall retrofitting, and the corresponding investment amount is much less. Floor retrofits are the least recommended because of the high cost of investing in them and the relatively small energy savings. In addition, the payback time for investing in a floor retrofit is longer, taking 53 years

Retrofit interventions	Windows	Vertical walls	Ceiling	Floor
Cost (\$/m^2)	158.6	36.42	8.52	18
Renovation area (m^2)	1,385,051	11,283,853	6,022,018	6,022,018
Cost of intervention ($)	219,669,089	410,957,926	51,307,593	108,396,324
Energy Saving (kWh/year)	228,568,212	594,685,232	609,542,673	41,089,832
Financial saving ($)	11,428,411	29,734,262	30,477,134	2,054,492
Payback Time (years)	19	14	2	53

Table 13: Data of retrofit area, cost of intervention; energy saving; financial saving; and payback time

4.3 Evaluation of rooftop integrated solar technology

4.3.1 Background analysis

According to data provided by Genadoras de Chile[25], the installed capacity of the National Electricity System (SEN) as of December 2022 (referring to the amount of energy generated based on a certain technology) is 33,218 MW. 62.0% of the installed capacity corresponds to renewable energy sources (22.3% hydro; 24.1% solar; 13.0% wind; 2.3% biomass; 0.3% geothermal), while 38.0% 0% corresponds to thermal sources (13.0% coal, 15.1% natural gas and 9.8% oil). In addition, the growth of renewable energy power generation has been very important in recent years. The national energy policy goal is to achieve renewable energy power generation accounting for 60% of the country's power generation by 2035 and 70% by 2050 [25]. The largest increase is in solar photovoltaic and wind energy technologies, with a significant increase from 0 to 0.5% in 2011 and reaching 28.0% in 2022. In Temuco, on the other hand, high household electricity prices and a high dependence on fossil fuels have made Temuco the most polluted city in Chile and the world. According to the survey, among the total energy used for space heating in 2020, the average share of Temuco's wood biomass will be 78%, kerosene 7%, electricity 8% and natural gas 7%, followed by electricity, natural gas, oil and other energy sources, each accounting for 2% share[26].

In terms of location, due to the development of urbanization, the building density in Temuco is getting higher and higher, and the ground space is crowded and scarce. However, there is still a lot of unused space on the roof surface of the building where solar photovoltaic equipment can be directly installed. Secondly, in terms of transportation, since the places where energy is generated are generally located in suburbs far away from cities and a large amount of energy is lost during transportation and distribution, so if this kind of transportation can be reduced, energy costs can be greatly reduced, and energy efficiency improved. Finally, solar photovoltaic thermal systems can reduce fuel consumption and reduce carbon dioxide emissions, with excellent economic value and low-cost systems, resulting in clean and environmentally friendly systems.

In terms of policy, the Temuco government also implemented a tax exemption for the purchase of solar thermal systems for domestic hot water in 2009. Although it is applicable to new houses, it does not include houses built in previous years. However, such economic incentives can foresee that solar photovoltaic power generation systems will be gradually extended to urban residential buildings in the future. In 2020, the Department of Energy announced the Residential Energy Transition Strategy, with the overall aim of transitioning to a cleaner, safer and more efficient residential heat matrix and providing alternatives to firewood that are accessible to all and promoting efficient buildings and equipment. . It can be seen that the government hopes to support efficient and clean technologies to replace the use of wood heating technologies through a series of policies, regulations and financial incentives.

To sum up, we believe that the solar photovoltaic thermal system (PVT) can convert solar radiation into electrical energy and thermal energy at the same time. It is one of the most effective, environmentally friendly and sustainable systems and will be the most reliable option to overcome the energy crisis. Regeneration system. Temuco has great development potential to transition these fossil fuel combustion systems to efficient equipment such as solar photovoltaic systems to meet household energy needs.

4.3.2 Survey on Temuco’s electricity usage

This assessment of the potential development of solar energy is primarily based on residential single-family systems. We obtained data on community annual electricity consumption and number of customers from 2015 to 2022 from the Energía Abierta[27]website (in Table 14).

Year	**Billed clients**	**Annual electricity consumption（kwh）**
2015	98,644.00	17,148,249
2016	100,696.00	18,474,810
2017	104,537.00	18,512,440
2018	107,624.00	18,929,874
2019	107,165.00	18,568,774
2020	113,792.00	20,795,508
2021	117,901.00	23,936,707
2022	119,470.00	23,793,321

Table 14: Number of annual electricity customers and annual electricity consumption in the community from 2015 to 2022[27]

According to Table 14, it can be seen that the amount of electricity used as household energy in the community has been increasing from 2015 to 2022, and the annual electricity consumption is also gradually increasing. It will start to surge in 2020, and 2021 and 2022 have already arrived relatively speaking. highest value and remains unchanged.

According to data on Global Petrol Prices[28], we can know that in 2023, the average price of global household electricity will be US$0.157 per kilowatt hour. The average price of household electricity in Chile is US$0.168 per kWh (in Table 15).

Electricity prices per (kWh)	Time	Electricity prices per (kWh)
Households	01.03.2023	0.168
Business	01.03.2023	0.125

Table 15. Household and commercial electricity prices in Chile in 2023

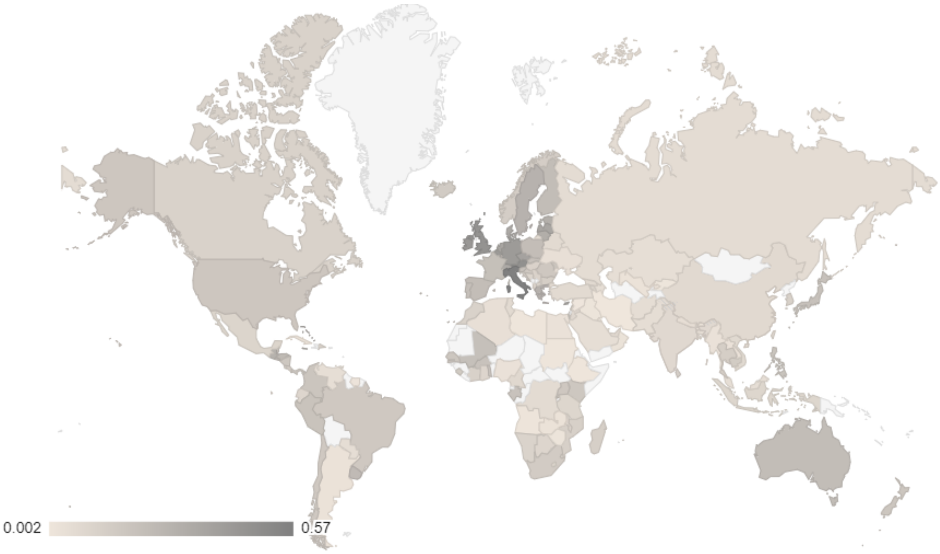


Figure 18: Household electricity prices per kWh in 148 countries, Q1 2023

Figure 18 shows household electricity prices per kWh for 148 countries in the first quarter of 2023. Prices are calculated based on average annual household electricity consumption in each country and are expressed in US dollars using the current exchange rate of 8. It can be seen that even across the world, electricity prices in Chile are relatively high.

4.3.3 Methodology

We used ArcGIS to calculate the annual and monthly solar radiation values at the building level, and then used photovoltaic geographic information system tools and related formulas to determine the solar photovoltaic potential. We downloaded the DEM 2012 (Digital Elevation Model) base map on the Earthdata website[29], The accuracy is 12.5m×12.5m (Figure 20). Temuco is located in a valley in south-central Chile, between the western Pacific and the Andes Mountains in the east. The northwest side of the city is close to the mountains and the terrain is higher. The southwest is plain so the terrain is low.

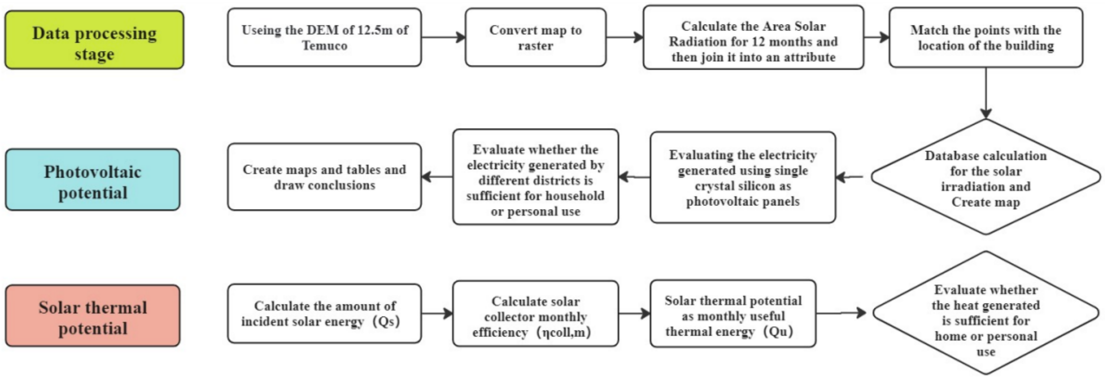


Figure 19. Methods for assessing urban distributed solar potential

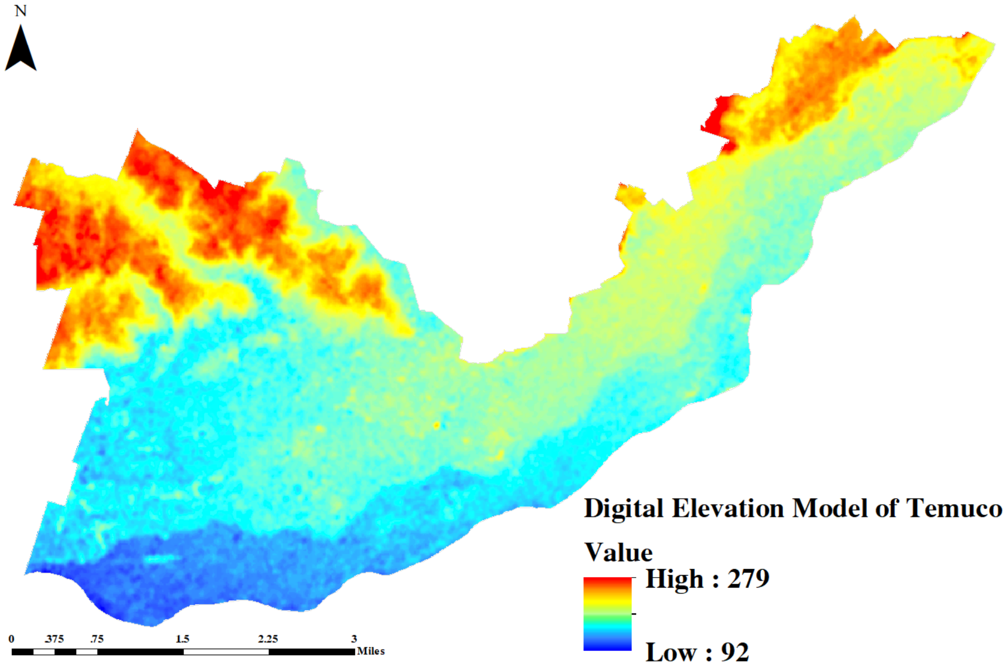


Figure 20.Digital Elevation Model of Temuco

Then, we performed solar radiation simulations for 12 months to obtain monthly, annual cumulative, and annual average solar radiation. Daily sunshine duration can be obtained from the website Weather Atlas [30] (labelled as Figure 21).

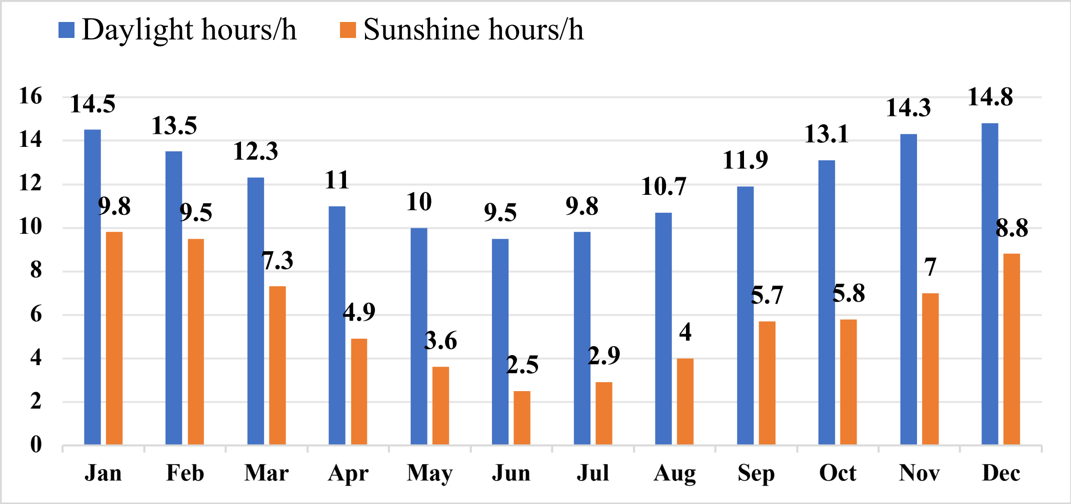


Figure 21.Average daylight / Average sunshine Temuco, Chile

As shown in Figure 21, the month with the longest days is December (average daylight: 14 hours and 48 minutes). The month with the shortest days is June (average daylight: 9 hours and 30 minutes). The sunniest month is January (average daylight: 9 hours 48 minutes). The month with the least sunshine is June (average daylight: 2 hours and 30 minutes).

To model solar radiation in ArcGIS, the "Area solar radiation" tool can characterize the sun and sky using the following monthly input data (labelled as Table 17): the ratio of diffuse to total radiation, K_d, and the sky transmittance, T. Indeed, the sun and sky change during the year with higher K_d and T in the summertime, then it is very important to simulate correctly these variables. The values of these variables for each city can be found on the PVGIS (PHOTOVOLTAIC GEOGRAPHICAL INFORMATION SYSTEM) official website [20]. For the evaluation of Link turbidity, it can be obtained in the Meteonorm software and calculated by the following formula:

$$T^{FDL}=G_{b.h}/\text{Solar constant} \qquad (17)$$

$$T=(G_{b.h}/\text{Solar cost})^{1/FDL} \qquad (18)$$

$$G_{b.h}=H_{b.h}/M_{l,h} \quad \text{with} \quad M_{l,h}=M_d*D_{l,h} \quad \text{and} \quad H_{b,h}=H_{h,m}(1-K_d)*1000 \qquad (19)$$

where:

T: *atmosphere transmissivity [-]*

FDL: Linke turbidity factor [-]

$G_{b,h}$: direct solar irradiance (b=beam) [W/m^2]

Solar constant: average extra-atmospheric solar irradiance = 1367 [W/m^2]

$H_{b,h}$: direct solar irradiation on the horizontal plane (b=beam) [kWh/m^2]

$M_{l,h}$: monthly light hours [h/month]

$D_{l,h}$: daily light hours [h/day]

M_d: monthly days [d]

$H_{h,m}$: global irradiation on the horizontal plane (kWh/m^2 /month)

K_d: ratio of diffuse to global irradiation [%]

Temuco's monthly transmittance is calculated through the variables of equations (1) and (2). Then use formula (19) to calculate the direct solar irradiance. (labelled as Table 16).

Month	$D_{l,h}$ (h/d)	$M_{l,h}$ (h/mo)	M_d (d)	$H_{h,m}$ (kWh/m^2)	K_d (%)	$H_{b,h}$ (kWh/m^2)	$G_{b,h}$ (W/m^2)	FDL (-)	T (-)
Jan	10.5	325.5	31	242.4	21	191.5	588.31	2.69	0.73
Feb	10.3	288.4	28	176.5	24	134.1	465.12	2.83	0.68
Mar	8.3	257.3	31	152.9	27	111.6	433.8	2.68	0.65
Apr	6.9	207	30	86.3	37	54.4	262.65	2.72	0.55
May	4.7	145.7	31	69.2	36	44.3	303.97	2.85	0.59
Jun	3.9	117	30	40.2	50	20.1	171.79	2.7	0.46
Jul	4.2	130.2	31	58.3	37	36.7	282.1	2.67	0.55
Aug	5.7	176.7	31	74.6	43	42.5	240.65	2.8	0.54
Sep	6.4	192	30	120.7	36	77.2	402.33	2.78	0.64
Oct	8.3	257.3	31	149.2	36	95.5	371.12	2.72	0.62
Nov	9.7	291	30	203.9	28	146.8	504.49	2.68	0.69
Dec	9.5	294.5	31	231.8	24	176.2	598.19	2.75	0.74

Table 16: Temuco’s PVGIS database monthly radiation and Linke turbidity factor and atmosphere transmissivity data in 2017

With the values for the ratio of diffuse to total radiation and transmittance, the monthly average of these two data is input into the "Area Solar Radiation" tool of ArcGIS, and the annual solar radiation simulation results of the Temuco area can be obtained .and the annual solar radiation simulation results of the Temuco area can be obtained.

In order to obtain a more accurate result, it would be better to use one average value for the winter months, one for the summer months, and one for the others. The following tables contain both the average and seasonal values:

Parameter	**Summer**			**Spring-Autum**				**Winter**				
	Dec	**Jan**	**Feb**	**Mar**	**Apr**	**Oct**	**Nov**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Kd	21	24	27	37	36	50	37	43	36	36	28	24
	24			40				33.4				
T	0.73	0.68	0.65	0.55	0.59	0.46	0.55	0.54	0.64	0.62	0.69	0.74
	0.69			0.54				0.65				

Table 17: The average ratio of diffuse radiation to total radiation and the average atmospheric transmittance in Temuco during the four seasons

Using the ArcGIS tool Area Solar Radiation, we obtained a map of simulated annual solar radiation for the Temuco area in 2017. Then use the raster layer tool to select the corresponding monthly data to obtain a raster file for 12 months.

In order to create the data table associated with the image, the raster file needs to be converted to a Shapefile, using the "Convert Tool" to convert the 12 months of data. The output is a point layer containing the values of the cells from the raster file. To associate the total radiation values accumulated over different months to each point, a series of join by attribute operations are used. We make all connections on the January shapefile and proceed in chronological order. The join will be based on the field [POINTID].

After completing 12 connections, we have an attribute table containing solar radiation data for all months. Now, we are able to calculate the annual cumulative radiation, average monthly radiation and average annual radiation, with the following equations. Then summarize all the data into Table 16.

$$ACR=\Sigma 12_{n=1}\ Month_n/1000 \qquad (20)$$

$$ACRM_n= Month_n/days_n*1000 \qquad (21)$$

$$ACRY=\Sigma^{12}_{n=1}\ ACRM_n/12 \qquad (22)$$

Where:

ACR: annual cumulative radiation [kWh/m^2]

Month$_n$: radiation of the nth month [Wh/m^2]

ADRM$_n$:average daily radiation by month [kWh/m^2]

ADRY: average daily radiation by year [kWh/m^2]

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
ADRM$_n$ (kWh/m^2)	8.51	7.27	4.98	3.3	2.71	2.13	2.42	3.67	5.71	5.92	7.25	8.8
ADRY (kWh/m^2)	5.22											
Average monthly radiation (Wh/m^2)	263.7	210.8	154.5	99.04	83.91	63.77	75.1	113.7	171.4	183.6	217.4	272.8
ACr (kWh/m^2)	1909.6											

Table 18: Daily/monthly average radiation and annual cumulative radiation in Temuco

- Annual cumulative radiation (Wh/m^2, sum of the 12 GRIDCODE), to convert in kWh/m^2 (divide the value by 1000);
- Average daily radiation by month [GRIDCODE/n° of days of the month considered], to be calculated for all 12 months, in Wh/m^2 (to convert in kWh/m^2 by dividing the value by 1000);
- Average daily radiation by year [average of 12 average daily radiation by month calculated], in kWh/m^2.

Then, we can compare the results with the data from PVGIS website[20]（labelled as Table 19、Figure 22）.

Month	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average monthly radiation(Wh/m^2)	263.7	210.8	154.5	99.0	83.9	63.8	75.1	113.7	171.4	183.6	217.4	272.8
PVGIS values	181.1	146.3	121.4	75.4	47.7	33.3	41.4	59.8	94.3	131.2	159.2	184.4
Relative error	0.5	0.4	0.3	0.3	0.8	0.9	0.8	0.9	0.8	0.4	0.4	0.5

Table 19. Compare different Average monthly radiation.

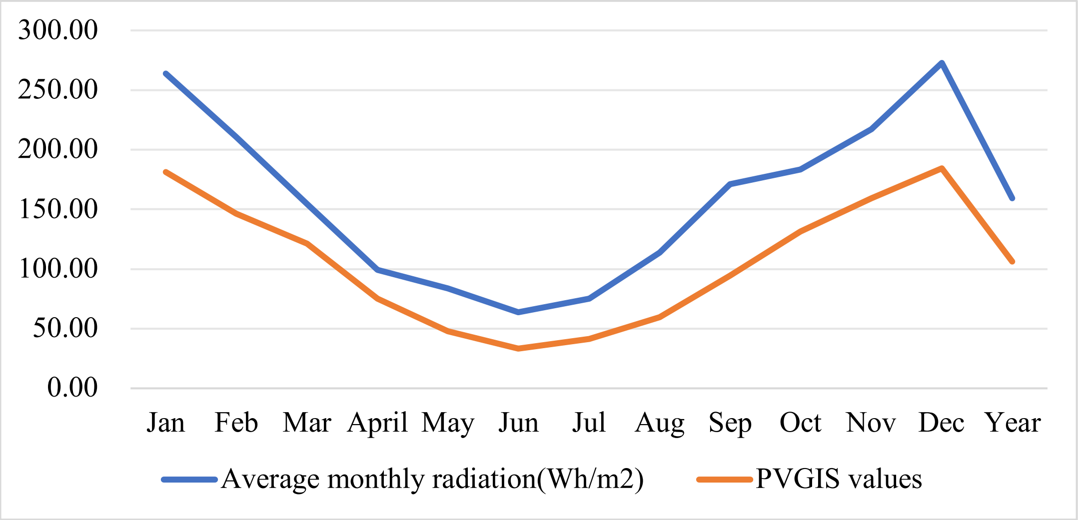


Figure 22. .Compare different Average monthly radiation

We evaluated the potential of Temuco solar photovoltaic systems based on simulated solar radiation and using GIS. The results show that Temuco's annual global solar radiation reaches 1909.6 kWh/m^2, exceeding the levels of other advanced solar countries. Therefore, we believe Temuco has the potential to become an ideal location for the promotion of solar photovoltaic systems.

Combining Table 19 and Figure 22, we can know that although the two data have a large relative error, their monthly average solar radiation trends are almost the same each month. They all reached their peak in December, followed by January, and the lowest in June, followed by July. Therefore, we believe that the average monthly radiation data we calculated through GIS is relatively accurate.

All in all, in the development of sustainable energy technologies, solar photovoltaic thermal systems are gradually becoming a popular clean energy solution. And we evaluated the potential of solar photovoltaic systems in Temuco based on simulating solar radiation and using geographic information systems. According to our calculations, Temuco's global solar horizontal radiation reaches 1909.6 kWh/m^2, which far exceeds the levels of other solar advanced countries. For example, Germany, which has the largest installed capacity of solar photovoltaic power generation in the application of solar energy, has an average annual solar radiation lower than that of Temuco. The average annual solar radiation in Freiburg, a German city known as the Little Sun, is 1117 kWh/m^2. Therefore, we believe that Temuco has the potential to become an ideal promotion location for solar photovoltaic systems.

4.3.4 Assessment of Photovoltaic Potential

In order to calculate the photovoltaic potential, it is necessary to assume various technical solutions, each with specific efficiencies and panel dimensions.

The most widely used types of photovoltaic panels on the market are monocrystalline silicon (MC), polycrystalline silicon (PC), or thin film (FS).

The following efficiency values can be used as standard parameters:

- Monocrystalline silicon: η_{MC}=23%
- Polycrystalline silicon: η_{PC} =15%
- Thin film: η_{FS} =8%.

The choice of technology type affects not only the space required for the installation (with the same possible power for the installation), but also the support costs and payback period, so we need to calculate the consequences of incident solar radiation to get the potential PV value.

Equation (23) is used to calculate the energy generated by each building.

$$E = PR\ H_s\ S_{net}\ \eta \qquad (23)$$

$$S_{net}=S_{grosss}*82\% \qquad (24)$$

where:

E is the electrical energy produced by year [kWh/a];

PR is the performance index of the system (≈ 0,75).

Hs is the cumulative annual solar radiation [kWh/m^2];

S_{net} is photovoltaic panel net surface [m^2]

S_{grosss} is total surface of photovoltaic panels [m^2]

η is the conversion efficiency, that is the ratio of incident solar energy to produced energy:

$$\eta = Wp/(S*I_{stc}) \qquad (25)$$

where:

*Wp is the peak power output of the panel (equal to 1 kWp) **

I_{stc} is the tested irradiation under standard conditions (1 kW/m²).

** for 1 kWp installed, correspond 6-8 m^2 of panel surface*

With the combination of the relations (23) 、(24) and(25) the electrical energy yearly produced is obtained:

$$E = PR\ Hs\ Wp/I_{stc} \qquad (26)$$

Equation (26) to use to compare the calculated energy that can be produced with 1 kWp and the PVGIS values)

In order to represent and compare the achievable potential in relation to the area considered, previously obtained data on average annual cumulative radiation can be compiled. Consider the only roof surface of the buildings to consider roof-integrated solutions with scarce visual effect. The tool to use is a join by location of the available areal layers and the point layer of the solar radiation, using the average value of the point layer (summarized value: average). The output is a shapefile containing the average values detected in each area.

Then annual power generation capacity of monocrystalline silicon photovoltaic panels can be calculated.

Parameter	Value	Unit
Number of buildings	70378	-
Population	276391	-
Roof surface	6022018.9	m^2
Photovoltaic panel gross surface	2408807.6	m^2
Photovoltaic panel net surface	1975222.2	m^2
E_{mc}	650766083.56	$kWh/m^2/year$

Table 20: Photovoltaic solar panel related data

In this assessment, We only consider the residential building the surface area of the panel is about 40% of the roof area. Therefore, we can use formulas (23) and (24) in GIS to calculate the photovoltaic cost of monocrystalline silicon. Panels for residential buildings produce year-round electricity (labelled as Figure 23). The average annual electricity production is 650766083.56 $kWh/m^2/year$.

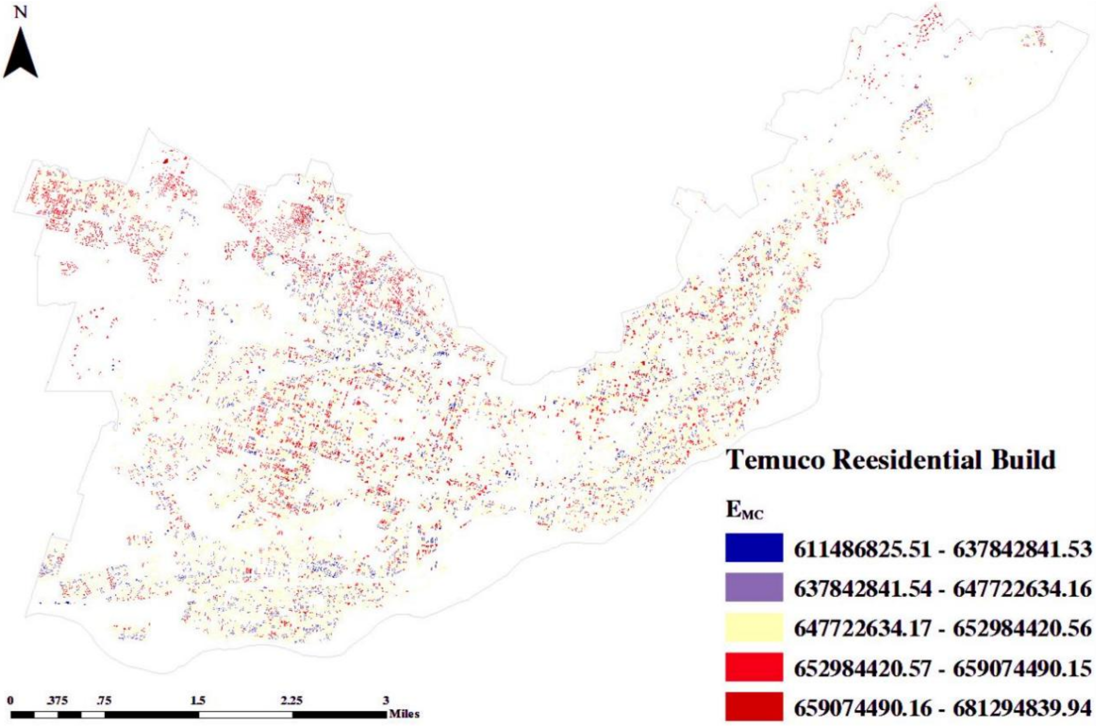


Figure 23. Electricity produced by PV roof-integrated technology on residential buildings in Temuco (considering 40% of roof surface)

Parameter	Value	Unit
Electricity consumption per capita	730	kWh/m^2/year
Total energy consumption per capita	4380	kWh/m^2/year
Electricity consumption per household	2130	kWh/m^2/year
Total energy consumption per household	12710	kWh/m^2/year

Table 21: Temuco's energy indicators are based on the energy consumption of the residential sector as reference consumption.

Parameter	Electricity consumption per household	Electricity consumption per capita	Unit
E_{mc}	9246.5	2354.5	kWh/m^2/year

Table 22: The electricity generated by single-crystal silicon photovoltaic panels used by households and per capita per year

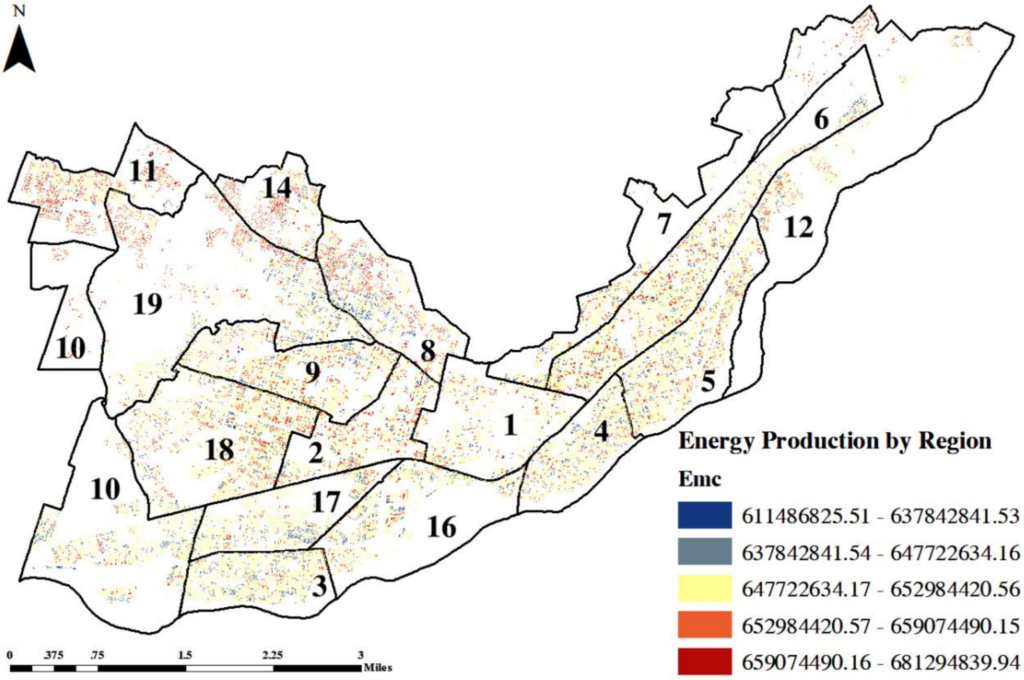


Figure 24: Annual solar radiation simulation of residential buildings in different districts of Temuco

By comparing Table 21 and Table 22, we can clearly understand that the power produced by monocrystalline silicon photovoltaic panels far meets the annual power supply of individuals and families. In order to more accurately analyze the electricity generated by photovoltaic solar panels, we divided Temuco into 17 areas for more specific analysis. As shown in Figure 24.

DN	Number of Family	Population	EP	$EC_{household}$	$EC_{per\ capita}$
1	5660	11450	28177561	4978	2461
2	4636	9471	35891372	7742	3790
3	4925	14384	36750017	7462	2555
4	4807	14010	36117184	7513	2578
5	6965	20554	53340358	7658	2595
6	7118	19086	70510069	9906	3694
7	2157	5081	18021859	8355	3547
8	5967	18036	37403612	6268	2074
9	6630	14718	48797740	7360	3316
10	16523	45210	34365710	2080	760
11	5826	16177	29134717	5001	1801
12	3423	9912	19967638	5833	2014
14	5806	16789	16182518	2787	964
16	3724	9961	31520347	8464	3164
17	4504	12056	31355110	6962	2601
18	6990	19059	71139063	10177	3733
19	8193	22840	51380993	6271	2250
Total	103854	278794	650055868	114819	43896

Table 23: Energy production per district in Temuco

where:

DN:*District Number*

EP:*Energy Production with PV (kWh/m^2/year)*

$EC_{household}$:*Electricity consumption per household (kWh/m^2/year)*

$EC_{per\ capita}$:*Electricity consumption per capita (kWh/m^2/year)*

Combining Figure 26 and Table 23, it can be seen that the energy generated after installing solar photovoltaic panels in most areas is sufficient for households and individuals. In particular, the household energy production in Districts 6 and 18 far exceeds the energy indicator issued by the government of 2130 kWh/m^2/year. Individual energy production in Districts 2 and 18 far exceeds the government-issued energy target of 730 kWh/m^2/year. Due to the dense population in District 10, the energy generated by installing solar photovoltaic panels is not enough for households, and there is not much value exceeding the per capita standard. Although District 14 meets the energy production indicators for households and individuals, it is only a little more, because the energy generated in this area is the least of all areas. Because for areas with insufficient energy, we will increase the installation area of photovoltaic solar panels to meet the energy use of households.

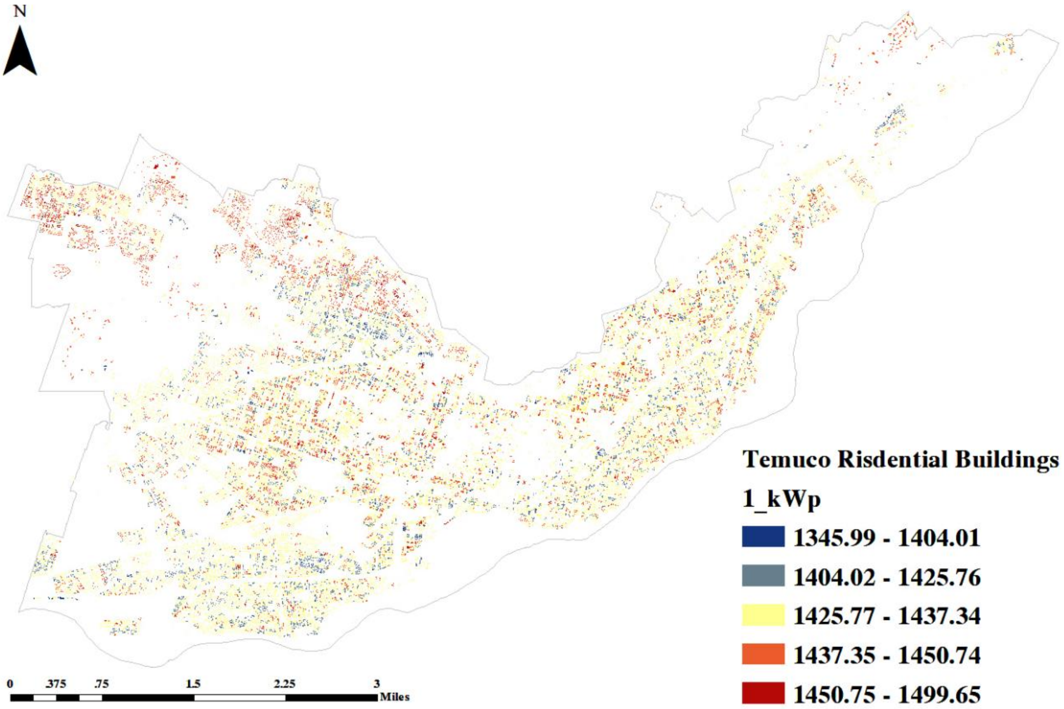


Figure 25.Energy generated by 1kWp of integrated photovoltaic roof technology in a Temuco residential building (from Equation 24)

According to equation 24, the energy generated by the 1kWp photovoltaic roof integration technology of Temuco residential building can be obtained (labelled as Figure 25).

According to the analysis figure 25, when the power generation is 1kWp, the roof area is not considered. The energy production value of most buildings does not change much.

However, the northwest and northernmost parts of the city, near the mountains, are on higher ground and therefore generate higher energy than the rest of the region. Therefore, the annual solar radiation of the building is high, and the terrain in other places is flat, so the annual solar radiation is relatively evenly distributed. So, after analyzing the map, we concluded that the amount of energy generated is proportional to the height difference of the terrain. The higher the terrain, the higher the energy generated. In addition, roof area also has a significant impact on solar power generation. All in all, we believe that Temuco has huge development potential in solar photovoltaic systems and is expected to achieve a smooth transition from traditional combustion systems to solar photovoltaic systems to meet the growing demand for clean energy in households.

4.3.5 Assessment of solar thermal potential

Today, increasing access to electricity and energy consumption through distributed energy solutions in developing countries necessitates the search for a range of energy-saving strategies. Therefore, solar thermal systems (STS) have been extensively developed to improve their performance and deployment. An STS system is a system that uses solar energy to heat water and usually consists of a solar collector, a hot water storage tank, and a piping system. These systems are widely installed in buildings to provide energy for heating and cooling spaces.

Solar collectors are key components of active solar heating systems because they collect the sun's energy, convert its radiation into thermal energy, and then transfer this heat to a thermal vector fluid (in this case, water). In this section, we simulate the energy performance of a solar thermal system to produce domestic hot water (DHW). We will mainly analyze the thermal efficiency of solar collectors, as this is the most useful parameter for predicting annual power generation and selecting the best collector with reference to system location and boundary conditions.

it is possible to evaluate the Solar Thermal Potential as the monthly useful thermal energy, hence the fraction of the solar irradiation (H) converted in thermal energy for each month, as shown in the following equation:

$$\eta_{coll,m}=Q_u/Q_s \qquad (27)$$

$$Q_s=A_c*H \qquad (28)$$

$$Q_u=A_c*H*\eta_{coll,m} \qquad (29)$$

where:

$\eta_{coll,m}$ *:solar collector monthly efficiency*

Q_s *: the amount of incident solar energy*

Q_s*: solar thermal potential as monthly useful thermal energy*

$Ac(m^2)$*: collector gross area assumed equal to 17% of the roofs surface (calculated with GIS for each roof);*

$H(Wh/m^2)$*: Average monthly radiation (calculated with GIS for each month on each roof);*

Finally, the global useful thermal energy required by the user can be determined by considering the summation of each useful thermal energy for each specific month:

$$Q_{u,TOT}=\Sigma_{n=1}^{12} \ Q_{u,i} \quad [kWh] \qquad (30)$$

The quality of a solar collector strongly depends on η0, a_1, a_2 coefficients. These values depend on the type of solar collector. Generally, evacuated tube solar collectors are more expensive than flat plate solar collectors. Moreover, flat solar thermal collectors are easy to manufacture and require little maintenance. Therefore, we only consider Flat-plate Solar Collectors in this evaluation. These values we can obtain from the website Kloben, we use the FSK 2.0 version[33] with a total area of 2.02 m^2 as our flat plate solar collector due to its high quality, performance, reliability and functionality and its evaluated according to the European Standard EN 12975-2.

Its several coefficients are:

$$\eta 0= 78.5\%$$

$$a_1 = 3.594 \ W/m^2K$$

$$a_2 = 0.014 \ W/m^2K^2$$

where:

$\boldsymbol{\eta_0}$*: optical collector efficiency*

$a_1[W/m^2K]$*: heat loss coefficient*

$a_2[W/m^2K^2]$*: temperature dependence of the heat loss coefficient*

We can also know that the energy production rate of FSK 2.0 is 1115 kWh/ year (Test in Würzburg, 3m^2), so according to the Temuco Local Energy Strategy promulgated by the Temuco government in 2016, the thermal energy and total energy consumption of the residential sector are used as a reference Energy indicators (in Table 20), based on the statistics of population and number of households in Table 19, it can be calculated that each household needs to install at least 10 square meters of solar collector panels to meet the domestic hot water use of each household. . We estimate that the total area that needs to be installed is 1,038,540 square meters, accounting for 17% of the total roof area. Therefore, we considered using 17% of the roof area as the area for installing flat-panel solar collectors.

Parameter	Value	Unit
Heat energy consumption per capita	3640	kWh/m^2/year
Total energy consumption per capita	4380	kWh/m^2/year
Heat energy consumption per household	10580	kWh/m^2/year
Total energy consumption per household	12710	kWh/m^2/year

Table 24.Energy indicators of thermal energy and total energy consumption of residential buildings in Temuco

Table 24 shows the energy indicators based on the thermal energy and total energy consumption of the residential sector in the Temuco Local Energy Strategy promulgated by the Temuco government in 2016.

$$\eta_{coll,m} = \eta_0 - a_1 * x - a_2 * I * x^2 \qquad (31)$$

$$x = (T_m - T_a)/I \qquad (32)$$

For simplicity, the mean fluid temperature can be calculated as the arithmetic average between the inlet fluid temperature (T_{IN}=15 °C) and the outlet fluid temperature (T_{OUT}=45 °C). Hence, it is a constant value:

$$T_m = (T_{IN} + T_{OUT})/2 = 30°C = 303.15K \qquad (33)$$

$$I = H/M_{l,h} \qquad (34)$$

where:

$x[m^2/W]$*: reduced temperature difference.*

$I\ [W/m^2]$*: solar irradiance that can be calculated by dividing the solar irradiation by the hours of light in each month:*

$M_{l,h}[h/month]$ *: monthly light hours*

$H[kw/m^2]$*: Average monthly solar irradiance*

Then, knowing the monthly solar collector efficiency value and the total solar collector area value, you can apply formula (29) to evaluate the monthly thermal energy (labelled as Table 25), and then use formula (30) to get the total thermal energy usage for the whole year (labelled as Table 26);

Month	T_a **°C**	T_m **°C**	$M_{l,h}$ **(h/mo)**	**H kWh/m²**	**I W/m²**	**x** m^{2k}/W	x^2	**FSK2.0** n_{coll}	**FSK 2.0** Q_u**(kWh)**
Jan	16	30	449.5	263.7	586.7	0.02386	0.00057	0.69924	188789517.8
Feb	16.5	30	378	210.8	557.6	0.02421	0.00059	0.69798	150605462.6
Mar	13.8	30	381.3	154.5	405.2	0.03998	0.0016	0.6413	101439171.9
Apr	12.4	30	330	99	300.1	0.05864	0.00344	0.57419	58217901.05
May	8.7	30	310	83.9	270.7	0.07869	0.00619	0.5021	43131216.39
Jun	7.5	30	285	63.8	223.8	0.10056	0.01011	0.42346	27645056.81
Jul	6.6	30	303.8	75.1	247.2	0.09466	0.00896	0.44467	34187516.14
Aug	7.3	30	331.7	113.7	342.8	0.06622	0.00439	0.54693	63662672.2
Sep	8.3	30	357	171.4	480	0.04521	0.00204	0.6225	109211071.5
Oct	10.6	30	406.1	183.6	452	0.04292	0.00184	0.63072	118523985.3
Nov	12.4	30	429	217.4	506.7	0.03474	0.00121	0.66014	146902688.3
Dec	14.3	30	458.8	272.8	594.5	0.02641	0.0007	0.69008	192702901.1

Table 25. FSK 2.0 solar collector monthly efficiency (considering 20% of roof surface)

Month	**FSK 2.0 Qu(kWh)**	**Heat energy consumption per household kWh/m^2/year**	**Heat energy consumption per capita kWh/m^2/year**
Jan	188789517.84	1817.84	677.16
Feb	150605462.63	1450.17	540.20
Mar	101439171.88	976.75	363.85
Apr	58217901.05	560.57	208.82
May	43131216.39	415.31	154.71
Jun	27645056.81	266.19	99.16
Jul	34187516.14	329.19	122.63
Aug	63662672.20	613.00	228.35
Sep	109211071.50	1051.58	391.73
Oct	118523985.28	1141.26	425.13
Nov	146902688.25	1414.51	526.92
Dec	192702901.09	1855.52	691.20
Total	1235019161.08	11891.88	4429.86

Table 26.FSK 2.0 solar collector for Temuco residential buildings for domestic and personal heat production

We compared the annual heat energy consumption per household and per person (Table 22) with the reference energy indicators for heat energy consumption in the residential sector in the Temuco Local Energy Strategy promulgated by the Temuco government (Table 20) and found that the installed roof area 17% of the solar collector panels are enough for the whole year and personal annual consumption, especially from September to March, which far meets the heating needs. However, due to the low solar radiation from April to August, it cannot meet the needs of families and individuals.

Integrating renewable energy not only reduces carbon emissions but also enables communities to reduce their dependence on foreign energy sources, thereby reducing countries' vulnerability to energy price fluctuations and geopolitical uncertainty. It fosters a distributed energy production system that is better able to cope with unforeseen challenges, making it a critical step towards a greener, more resilient future.

4.3.6 Evaluation of the total energy consumption and costs

4.3.6.1 Economic Analysis referred to Electrical Energy

We obtained Chile's per capita electricity consumption data from 2011 to 2022 from the website IEA Data Services[31], as shown in Figure 26.

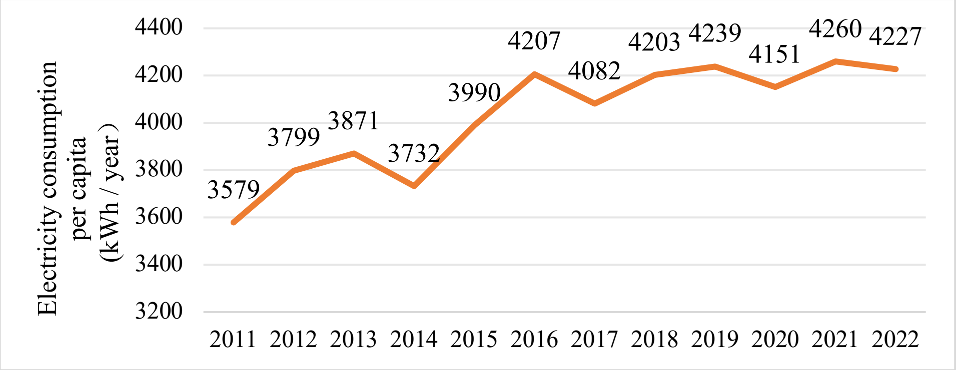


Figure 26 .Electricity consumption per capita, Chile, 2011-2022

It can be seen that per capita electricity consumption has tended to a relatively stable value since 2016. In our subsequent evaluation, we mainly use 4227 kWh/Capita in 2022 to conduct an economic analysis of electric energy.

$$E_{el,pro\ capita}=4227\ kWh/year \qquad (35)$$

The global yearly electrical consumption for the families (i.e. users) of a Municipality can be calculated as:

$$E_{el,user}=E_{el,pro\ capita}*Number\ of\ families \quad [kWh/year] \qquad (36)$$

We obtained from the website Helius Energy[32]that 5kwp (10 panels, 500W each) costs $5,751 including tax (19%), so we assume that the cost of installing 1 1kWp Photovoltaic (PV) Panels is 1150.2$.

The investment costs are:

$$C_{inv,PV=}\ C_{pv}*kWp\ [\$] \qquad (37)$$

$$kWp=A_c/6\ [kW] \qquad (38)$$

where:

$C_{inv,PV:}$ *The investment costs*

C_{pv} *:Cost of installing 1kWp Photovoltaic (PV) Panels。(about 1150.2$)*

Wp [W]:Peak/Nominal Power of PV system (general lkWp corresponds about 6m^2*for standard monocrystalline-polycrystalline modules*

$A_c[m^2]$*: collector gross area assumed equal to 40% of the roofs surface*

Cost of Electrical Energy taken from the network:0.168$/kWh

We then estimate the annual revenue generated from using photovoltaic panels:

$$R=E_{el,user}*0.168 \quad [\$] \qquad (39)$$

According to data on Global Petrol Prices[28], we can know that in 2022, the average price of household electricity in Chile will be 0.168$/kWh

We can then perform a simple payback period (SPT) analysis, which is defined as the time (in years) required to recoup the cost of an investment (without considering discounted cash flow methods). SPT can be evaluated as the ratio of investment cost to annual return:

$$SPT=C_{inv,PV}/R \quad [years] \qquad (40)$$

Finally, we summarize the data calculated by formulas (35) to (40) into Table 27.

Parameter	Value	Unit
$E_{el,pro\ capita}$	4227.00	kWh/year
$E_{el,user}$	438990858.00	kWh/year
C_{pv}	1150.20	$
Ac	2408807.60	m^2
kWp	401467.93	kW
$C_{inv,PV}$	461768416.92	$
R	73750464.14	$/year
SPT	6.26	years

Table 27.Cost Assessment of Monocrystalline Silicon Photovoltaic Systems

It can be seen that the return on investment time for installing solar photovoltaic panels is 6.26 years, so we believe that Temuco is very suitable for promoting solar photovoltaic panels.

4.3.6.2 Economic Analysis referred to thermal collectors

We need to first calculate the daily per capita domestic hot water energy consumption:

$$Q_{u,d}=V*\rho*C_\rho*\Delta T \quad [Wh/d] \qquad (41)$$

where:

$Q_{u,d}$*(Wh/d) :Daily per capita energy consumption for domestic hot water*

$V=50\text{-}70(\ l/d\ )$*is the daily volume of water consumed by a single person*

$\rho=1\ (kg/l)$ *is the water density*

C_ρ *is the water specific heat (1.163 Wh/KgK)*

$\Delta T=(T_{OUT}=T_{IN})=(45-15)℃=30℃=30\ K$ *is the temperature difference between the outlet and the inlet temperature of the water passing through the solar collectors.*

Then we can get the annual domestic hot water energy consumption of Temuco based on the daily per capita domestic hot water energy consumption multiplied by the number of days in the year and then multiplied by the number of residents in Temuco, that is:

$$E_{th,user}=Q_{u,d}*278794*365 \quad [kWh/m^2/year] \qquad (42)$$

According to Table 22, we know that the amount of heat produced in a year by a household with solar collectors is 11,891.88 kWh/m2/year, so we can know that the heat that can be produced by the whole residential building in Temuco is:

$$E_{th,ST}=11891.88*\text{Number of families} \quad [kWh/m^2/year\ ] \qquad (43)$$

We know from the website Kloben that the cost of installing a flat-panel solar collector of FSK version 2.0 [34]with a total area of 2.02 m^2 is 634,90 €. In Chile, we calculate costs mainly in US dollars, so the exchange rate is based on 1 EUR = 1.07 USD on April 25, 2024, which gives a cost of 634,9€= 679.34$ for the flat plate solar collector.

$$C_{inv,ST=}\ 679.34*\ (Ac/2.02) \quad [\$] \qquad (44)$$

where:

A_c *is the area of the flat-panel solar collector, which is 20% of the total building area, which is* $1023743.21m^2$.

$C_{inv,ST}$ *is the cost of flat-panel solar collectors for residential buildings in Temuco.*

We have learned in table 8 that the main heating energy source in Temuco is wood, followed by electricity, Keroseney, etc., and the average weight of these fuels is 0.05$/kWh. Since the energy production from using solar thermal collectors ($E_{th,ST}$) is much higher than the energy consumption from using natural gas or wood ($E_{th,user}$), we can calculate the annual income from installing ST panels and the annual income required to use traditional fuels for domestic hot water by following formula:

$$R_{user}=E_{th,user}*0.05\ [\$] \qquad (45)$$

$$R_{ST}=E_{th,ST}*0.05\ [\$] \qquad (46)$$

Also in this case, it is possible to calculate the so-called Simple Payback Time (SPT) defined as the amount of time (years) necessary to recover the investment cost (not considering the discount cash flow methods). The SPT can be evaluated as the ratio between the investment cost and the yearly revenues:

$$SPTuser=Ruser/Ruser \quad [years] \qquad (47)$$

$$SPTST=Cinv,ST/RST\ [years] \qquad (48)$$

Finally, we summarize the data calculated by formulas (41) to (48) in Table 28.

Parameter	Value	Unit
C_{ST}	679.34	$
Ac	1023743.21	m^2
$C_{inv,ST}$	344291936.77	$
$E_{th,ST}$	650055868.00	kWh/m^2/year
$Q_{u,d}$	2093.40	Wh/d
$Q_{u,y}$	764.09	kWh/year
$E_{th,user}$	213023986.25	kWh/year
$C_{inv,user}$	10651199.31	$
R_{user}	10651199.31	$
R_{ST}	61750965.28	$
SPT_{user}	1	$/years
SPT_{ST}	5.58	$/years

Table 28. Cost assessment of flat panel solar collectors

If traditional fuels are used as the energy required for domestic hot water, the return on investment will only take one year. However, Temuco has always used wood or natural gas as the main energy source for domestic hot water, which has led to very poor local air quality. In the long run, it will also reduce the quality of life of residents, affect their health, and cause irreversible damage to the environment. However, if we can promote the use of solar collectors, we can ensure that the energy required for domestic hot water can be met most of the time of the year. The return on investment is 5.58 years, which is relatively short, and this method is more environmentally friendly and sustainable. Therefore, we believe that Temuco is very suitable for promoting solar collectors.

5. Discussion of Energy Planning

5.1 Chile's role and policy objectives in the global renewable energy process

Chile ratified the Paris Agreement in 2017 and pledged to develop policies to address climate change and transition to a more sustainable energy system. To achieve this goal, the world must reduce greenhouse gas emissions by 2050, ideally reaching net zero emissions. In today's global energy landscape, solar energy is gradually becoming a key energy source. Although fossil fuels still dominate energy supply, renewable energy, especially solar energy, is developing rapidly and will play an increasingly important role in the foreseeable future. It is expected that by 2050, solar power generation will increase to 48% of global energy supply, reflecting its key role in promoting the transformation of the global energy system to a more sustainable direction[35].As of the end of 2016, the total installed capacity of photovoltaic technology in the world was estimated to have reached 303 GW, with an increase of 75 GW throughout the year[36].

In Latin America, as early as the 1970s, renewable energy was incorporated into the national energy structure, becoming a prelude to the transition from fossil energy to a low-carbon energy supply model[37]. As Latin America's energy markets expand, the upward trend in newly installed capacity is expected to continue in the coming years[38]. Chile is one of the largest installers of solar PV in Latin America. Since 2014, the country has made significant progress in solar technology, mainly due to its abundant solar resources and favorable market conditions. Chile has the highest level of solar irradiance in the world, especially in the Atacama Desert. Chile's solar PV power generation is growing rapidly even without government financial incentives. Chile is considered one of the most stable energy investment markets in Latin America, attracting investors and obtaining favorable financing conditions from banks[39][40]. Chile's energy policy goal is to have renewable energy account for 60% of the country's electricity generation by 2035 and 70% of the country's electricity generation by 2050[25].

In summary, the promotion of renewable energy and energy efficiency has become an important strategy for Chile to reduce emissions and achieve energy and environmental goals, which are covered in various government studies. The promotion of solar photovoltaic technology and the installation of solar thermal systems not only meets the goals of Chile's national energy policy, but also can provide Temuco with clean energy, reduce dependence on traditional energy, reduce carbon emissions, improve air quality, and protect the environment. We believe that with the joint efforts of the government, financial institutions, enterprises and the public, Temuco is expected to become a model city for renewable energy and sustainable development in the future.

5.2 Policy and Regulatory

5.2.1 Energy Efficiency Standards

Formulating building energy efficiency standards requires new and renovated buildings to achieve certain energy performance levels. Buildings with good insulation can maintain a more stable indoor temperature, reducing the need for heating and cooling, thereby lowering energy consumption. Improving the insulation of walls, roofs, and floors, and ensuring proper sealing of doors and windows, can minimize heat loss or gain. Based on the research, installing roof insulation is identified as the most efficient and cost-effective home improvement measure. Renovating houses is a primary task for energy conservation.

5.2.2 Renewable energy incentives

Providing tax incentives, subsidies, or grants can promote the development and application of renewable energy, encouraging the use of solar, wind, and other renewable energy sources. Tax credits, such as the Investment Tax Credit (ITC) and the Production Tax Credit (PTC), can be offered to individuals or businesses that invest in and install renewable energy equipment. Additionally, the government can reward projects based on the amount of clean energy they produce, similar to Germany's renewable energy subsidy program. By implementing these policies, the government can not only drive the transition in energy structure but also create job opportunities, stimulate economic growth, reduce environmental pollution, and achieve sustainable development goals.

5.3 Technological and Infrastructural

Globally, achieving emission reduction targets fundamentally depends on the electrification of energy systems and the development of renewable energy. Therefore, Chile, as a country rich in renewable resources, should leverage its abundant natural resources to develop extensive solar, wind, hydro, and geothermal energy projects. According to the calculations presented in this paper regarding the solar potential in Temuco, it is demonstrated that the region possesses abundant solar resources, providing an ideal environment for large-scale photovoltaic power plants. Additionally, installing solar collectors on homes with large roof areas to achieve community energy self-sufficiency is also a viable solution.

Renewable energy installations encompass various devices and technologies that utilize renewable energy (we chose to use solar energy) for energy production. In this paper, we employed solar photovoltaic systems and solar collector systems. A solar photovoltaic system is a device that uses solar photons to excite photovoltaic cells to generate electricity, typically installed on rooftops or solar fields. Solar collectors are devices that use solar thermal energy to heat water, providing hot water for households.

5.4. Community Engagement

5.4.1 Education and Training

Providing education and training on energy conservation and renewable energy is a key step in raising public energy awareness and promoting sustainable development. This can be achieved through school and university curricula, community education programs, online resources and tools, as well as professional training and certification. Basic education courses can introduce fundamental energy knowledge at the elementary and secondary school levels, while specialized university courses can offer practical opportunities. Communities can disseminate knowledge through lectures, demonstration projects, and workshops, and share resources via social media and online platforms. The content to be communicated includes concepts of energy, energy-saving measures, and renewable energy technologies. Additionally, showcasing successful cases and demonstration projects can help the public understand the practical application and benefits of energy conservation and renewable energy more intuitively, thereby promoting societal progress towards sustainability.

5.4.2 Stakeholders

Stakeholders play a crucial role in providing education and training on energy conservation and renewable energy, and their collaborative efforts can achieve broader impacts and results. Key stakeholders include government agencies, educational institutions, non-governmental organizations, businesses and industry organizations, investors, media, and the public.

To elaborate, government agencies can promote energy conservation and renewable energy education through policy formulation, funding support, and public awareness campaigns. Educational institutions can design and implement curricula, advance technological innovation through research and practice, while non-governmental and community organizations can drive grassroots education through community involvement and advocacy.

Businesses and industry organizations can foster the professional development of energy-saving technologies and renewable energy through corporate responsibility initiatives, employee training, and collaborative projects. Investors can support the development of relevant technologies and projects through funding and incubation. Media and communication organizations can enhance public awareness and interest by disseminating information and educating the public on energy conservation and renewable energy.

The public can actively participate in education and training activities organized by community and local government bodies, applying the learned energy-saving measures and renewable energy technologies in daily life to enhance personal knowledge and skills.

Finally, through the concerted efforts of these stakeholders, a comprehensive and effective education and training system can be established, promoting the widespread adoption and application of energy conservation and renewable energy technologies, thus advancing sustainable development in society.

5.4.3 Community energy projects

Community energy projects are crucial for achieving economic, environmental, and social sustainability. Effective community energy projects can leverage renewable energy to reduce carbon emissions and costs, enhance energy autonomy, create jobs, promote economic development, improve environmental quality and living standards, strengthen community cohesion, and drive technological innovation.

For example, projects can be funded through community crowdfunding, ensuring that community investment and benefits circulate within the community. Energy facilities can be collectively owned and managed by community members, increasing community income through energy sales while reducing residents' energy costs. Additionally, such projects can yield social benefits by strengthening community cohesion and raising awareness and support for clean energy among residents. Environmentally, they contribute to reducing fossil fuel use and lowering carbon emissions, helping to achieve carbon neutrality goals.

6 Conclusion

Urban Building Energy Modelling (UBEM) is important for energy efficiency testing and implementation of energy efficiency measures in buildings. The model can predict energy demand and supply and implement decarbonised energy policies. Creating a

UBEM requires a large amount of data, which is relatively easy to obtain in developed countries and is mostly open data. In developing countries such as Chile, where data is not always available for many cities, the availability of data is a major barrier.

In this study, the GIS data of the buildings were provided by the government of Temuco, which contains the geometric characteristics and geographic location of the buildings, where important information such as height, material, year of construction, and purpose of use need to be combined with the codes of the buildings on the SII website, corresponding to the files, and then manually entered into the GIS database. The process is time-consuming but essential, but provides Temuco's urban planners and energy developers with a complete database. On the other hand, due to the missing energy characteristics of the buildings, eight building prototypes from Chile were used for the model development, a bottom-up approach typical of UBEM, which is also applicable to other Chilean cities and provides a new way of thinking for other cities that lack energy consumption data.

In addition to this, different energy saving and emission reduction scenarios for the Chilean energy system were simulated. These scenarios include energy savings and emission reductions through retrofitting measures for existing houses as well as the development of new energy sources to replace traditional biomass energy sources. Combining the two approaches can add significant value as it provides a different perspective on potential transformation and decarbonisation pathways in Chile up to 2050. In the case of Temuco, for example, enhancing the thermal envelope by improving the insulation of the façade is the easiest retrofit measure to construct and is a cost-effective option for both older and newer buildings, with a payback time of only seven years; for pre-2001 buildings, ceiling retrofits would be a good measure to achieve energy savings in the house; window replacements, while more costly, are small in terms of overall square footage; and floor retrofit is the least recommended because of the very long payback time and high investment cost.

From a global perspective, the realization of emission reduction targets essentially relies on the electrification of the energy system and the development of renewable energy. Therefore, Chile, as a country rich in renewable energy resources, must actively promote existing policies and encourage investors to develop new photovoltaic panels, photovoltaic and wind farm projects. In the development of sustainable energy technologies, solar photovoltaic power generation and solar thermal systems have gradually become a popular clean energy solution. Integrating renewable energy can not only reduce carbon emissions, but also enable residents to reduce their dependence on wood, making them Becoming a critical step towards a greener, more resilient future. And we evaluated the potential of solar photovoltaic systems and solar thermal in Temuco based on simulated solar radiation combined with geographic information systems. The results show that the two types of energy generated by converting solar photovoltaic panels into electricity and heat are sufficient in most cases to meet the needs of local households and residents. However, there are still a small number of areas where the population is so dense that the electricity generated by installing solar photovoltaic panels in a small area is not enough for household use. Also, we must take into account that the low irradiance from April to August results in insufficient heat generation for the residents. But overall, especially from an economic and environmental perspective, solar thermal systems are more cost-effective, green and sustainable. Therefore, we believe that Temuco has the potential to become an ideal promotion location for solar photovoltaic systems. The Temuco government has also provided strong support for the promotion of solar photovoltaic technology in cities through its supportive policies and incentives. Looking to the future, Temuco has huge development potential in solar photovoltaic systems and is expected to achieve a smooth transition from traditional combustion systems to solar photovoltaic systems to meet the growing demand for clean energy in households.

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