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Energy modelling to investigate ways of improving community energy consumption

A case study in Santiago (Chile)

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Abstract

Over the last few years, one concept after another has been introduced, such as the heat island effect, carbon peaking, and ocean acidification. All these terms are inseparable from the term "carbon emissions", a problem that plagues the development of human society. The main source of carbon emissions is human activity. Therefore, the issue of how to reduce carbon emissions is a problem we face. On a community scale, saving energy and reducing energy consumption is a fundamental way of reducing carbon emissions.

This work is based on the study of a residential building in the northwest of Santiago, in the Renca. The basic factors such as weather, building material, and volume are taken into account to carry out interventions to reduce energy consumption and thus carbon emissions. The economic factors are also taken into account, with different interventions having different reduction effects and economic costs. Finally, all the data are combined to arrive at the most appropriate measures for the site.

The method for this work is to build a model by collecting geographical information, building information, and temperature. This is used to calculate the energy consumption of the building and to carry out energy classification. By making different interventions, different energy data are obtained and compared with the original data. In addition, economic factors are also taken into account to calculate the amount of investment. This plays an important role in determining the most appropriate measures for the area.

According to this report, there is great scope for upgrading the region's energy classification. By modelling the energy impact of the four measures on the buildings living on the site, and taking into account the economic situation, the best solution is to replace the roofs and walls. Also taking into account the climatic characteristics of the site, the use of clean energy solutions and the collection of energy by solar panels was found to be feasible.

Keywords: energy consumption, energy-saving, interventions, residential community, sustainability, Santiago (Chile)

Introduction

Project description

This research project is the result of a collaboration between Politecnico di Torino and the University of Chile (Faculty of Architecture and Urbanism). The project aims to develop an assessment and a model to assist decision-makers, from the municipal level, in evaluating the effects of urban planning on urban climate, thermal comfort, and energy consumption. The case study is the Community of Renca, located in the North-East of the city of Santiago. Specifically, the aim is the development of a model that will help estimate energy consumption for space heating of residential buildings at an urban scale;

this model is applied to the entire municipal area, based on local cadastral data, weather data, and literature review.

For this project, a residential building in one of the districts of Renca was chosen for the study. Firstly, the characteristics of climate, the number of building floors, the basic residential building types, the relative local thermal regulations, and the local energy classification should be considered. Climate characters enable the analysis of peak periods of energy demand. The number of building floors could give the number of energy demands. The basic residential building types can analyze the characteristics of building energy consumption. In the local thermal regulation, residential buildings can be classified according to the thermal regulation period and energy consumption of buildings in different periods can be calculated according to the thermal regulation period.

According to Chile's thermal regulation [1] there are three periods. The first period for residential buildings is before thermal regulation before 2000 (R0). The second period is during 2001-2007 in which residential buildings have a new-insulated roof (R1). The third period is after 2007 in which residential buildings have new-insulated roofs, walls and floors (R2).

The local energy classification can be used to show the difference in different residential buildings' energy consumption. However, Chile's energy classification is different in different climate zones. There are 7 climate zones which are divided by degree days (It is the difference between the mean daytime temperature for a given location and a base temperature; it can be calculated for a period of time (day, week, month, year), a part or the whole growing season.). The specific degree day data for each climate zone is shown in Table 1, and the regional distribution of the climate zones is shown in Figure 1. Due to Santiago being located in zone 3 [2], our project should obey the energy classification rules in zone 3.

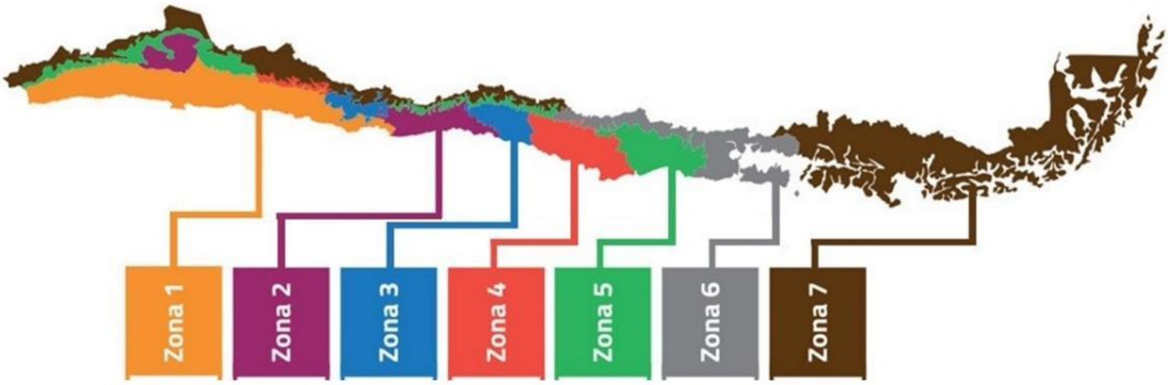


Figure 1: Climate zone in Chile's regulation [3]

ZONE	DEGREE DAYS (°C)
Zone 1	≤500
Zone 2	>500 - ≤750
Zone 3	>750 - ≤1000
Zone 4	>1000 - ≤1250
Zone 5	>1250 - ≤1500
Zone 6	>1500 - ≤2000
Zone 7	>2000

Table 1: The climate zone classification according to degree days

In the energy classification principle, the energy consumption (for space heating and domestic hot water) per square meter of the building is standard, which is also called energy performance (EP, kWh/m^2/year).

Secondly, the new energy consumption was calculated according to the different measures of change, comparing the effects of the measures. Finally, economic factors are taken into account and economic consumption is calculated.

Thesis statement

Together with project teams, the main objective of this thesis is to analyze and study the energy consumption of residential buildings in Santiago and to derive the best energy-saving measures by implementing four different energy measures. The main data analyzed include the type of residential building [2], building energy consumption (MINEN) [4], building energy classifications [5], energy-savings, payback time, and carbon emissions reduced [6].

In addition, discussions are taking place on the economic and technical aspects to reduce energy consumption in residential buildings. For example, the use of clean energy, the improvement of energy efficiency, people awareness and smart technologies, the improvement of energy sharing between energy communities, etc.

The study adopted a bottom-up approach, using the relationship between energy consumption and S/V (surface-to-volume ratio) for different types of buildings in different periods of construction to derive the relationship between energy consumption and S/V to calculate the energy consumption of different buildings on the site [2]. Data comparison and analysis of energy consumption after different measures are carried out. Policy suggestions are also given based on the findings of the data.

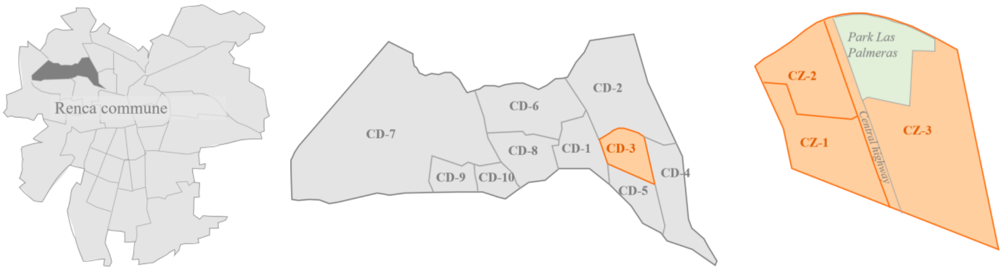
The first chapter focuses on the basic status of the study case site, the weather conditions, and the classification of the residential buildings. The second chapter then presents in detail some basic energy metadata of the site, the energy characteristics of the site, and the overall methodology of the study. Secondly, the third chapter presents the results of the data analysis, including building energy rating, amount of energy saved, economic aspects, and assessment of the solar potential. Chapter 4 then discusses the results of the data to give policy suggestions. Finally, Chapter 5 concludes with a summary of the entire research case.

1. Case study

In these case studies, there are many data that need to be used, for example, AutoCAD file, ArcGIS file and so on. Due to these project mainly focusing on building, in order to obtain as accurate data as possible, other data used in the study should be chosen to be of the same year as the building data as far as possible.

There are hypotheses data:
- The AutoCAD data (2017) is building blocks data.
- The ArcGIS data (2017) is include the shapefile for the city of Renca, and the shapefile of the district and block code.
- The weather data (2017) is include global solar irradiation, diffuse to global solar radiation, cloud cover, average air temperature, wind speed and monthly light hour, from meteorological station Pudahuel, which is the nearest meteorological station.
- The excel data (Manzanas completes 2022) [7] is include block code, number of floors, the function of the building, the period of the building and population.
- The DEM data (2011) [8] is Digital Elevation Model, which is the newest data.
- The energy performance data (2018) is collected by different periods of the building and types in D-3.
- The energy classification rule is collected from a paper which is published at 2
- The retrofit measures data (2018) includes the percentage of energy saved and cost.
- The resources data (2018) is include a share of different types of energy, percentage, cost, efficiency and GHG emission.

1.1 The basic status of Renca



(a) (b) (c)

Figure 2: Relevant geo-political divisions. (a) Metropolitan Region of Santiago; (b) Commune of Renca; (c) Censal District CD-3 José Miguel Carrera (Source: Chilean Open Data website)

Santiago is the capital of Chile and as such is the most densely populated region of the country. The total population is 8 million (The population in Renca is 146341). However, Renca is a low-income community in the North-West of Santiago (see Figure 2). The main function of this community is residential and there are over 40,000 of them, which is located between the southern foothills of Renca Hill and the northern flank of the Mapocho River. This community is characterized by a low building density.

Next, the site of the project is located in the eastern part of Renca - the residential district of José Miguel Carrera, which belongs to census district three CD-3, according to the national census database [9]. As shown in Figure 2, we can see that CD-3, nearly 80 hectares, is divided into three parts: CZ-1, CZ-2, and CZ-3. CZ-1 and CZ-2 are mainly large collective housing developments built after 1970. CZ-2, on the other hand, is an old low-rise single-family residential zone built before 1940.

1.2 The Weather Conditions of Renca

Renca features a fairly mild climate. However, the Renca diurnal temperature fluctuates considerably, so it requires a large amount of space heating energy. As Table 2 shows, the annual average temperature is 14.75°C. The average maximum temperature is 20.5°C (February) and the average minimum temperature is 8.4°C (July). June has the highest annual precipitation with up to 20.8 hours/per month. To sum up, the site has a low variability in temperature and a strong seasonal link in rainfall (April-October will rain, no rain in other months), (Dirección Meteorológica de Chile). On average, based on hourly data from met station Pudahuel, nearby Renca [10], monthly diurnal outdoor temperature fluctuations range above 10K. The peaks of outdoor temperature are between 0–15°C and 15–30°C, during warm and cold days, respectively [10]. Setting the base temperature at 18°C, therefore, gives a total of 1400 annual heating degree days; however, when the base temperature is set at 26°C, the annual cooling degree days barely reach 80 [10].

	Global solar irradiation (kWh/m^2)*	Diffuse to global solar radiation (%)*	Cloud cover (%)	Average air temperature (°C)	Air relative humidity (%)	Wind speed (m/s)	Monthly light hour (h/month)
January	281.86	12	40	21.5	49.7	3.6	450.12
February	212.11	17	39	20.5	55.1	3.2	387.24
March	201.74	16	44	18.8	57.0	2.7	396.80
April	136.99	22	59	14.6	65.8	2.2	348.90
May	86.85	33	75	10.8	73.4	1.7	321.47
June	71.63	30	73	8.6	77.7	1.6	296.10
July	92.21	24	70	8.4	77.4	1.7	303.18
August	111.56	25	64	9.8	75.4	1.9	321.78
September	146.76	28	64	11.6	71.3	2.2	341.40
October	204.83	24	49	15.0	63.0	2.7	387.50
November	234.01	20	32	17.4	55.9	3.2	408.60
December	277.03	16	41	20.0	51.3	3.6	446.40

*Table 2: The Renca climate data for 2017 (from meteorological station Pudahuel [11]) (*PVGIS)*

To sum up, it is a good point that during the hot weather burning season, residents do not have to think about the economic expense of cooling; however, during the three to four months of cold weather, the economic drain of a large amount of heating will be a major problem, as well as the burning of heating fuel, which can affect air quality and living comfort to some extent.

According to the climate classification rule, it belongs to Zone 3, there are seven zones in Chile (Zone 1 is the shortest day grade, and zone 7 is the longest day grade) [2]. Due to the zone number, the basic energy data can be obtained.

1.3 Basic Residential Building Information

In terms of building categories, the buildings in the selected areas are divided into three main types: buildings before thermal conditioning (period R0) (99%) buildings with only treated exposed roofs (period R1), and buildings with treated exposed roofs, walls and floors (period R2) [10]. The site consists mainly of brick mid-basement R0 buildings [12]. In terms of building type, 71% of the housing is one- to two-story detached houses, and almost 29% of the buildings are 4-5 story flat blocks. Moreover, 69% of the housing stock was built on traditional reinforced brick masonry as the predominant wall structural material [10].

In terms of building energy consumption, the dominant energy sources for domestic space heating are LPG (40%), kerosene (35%), electricity (12%), natural gas (NG) (7%), and firewood (4%) [13], according to regional statistics at the national scale.

The residential buildings database was adjusted considering only buildings with space heating systems, then buildings with a footprint area higher than 50 m^2 and a height higher than 2.3 m were utilized in this analysis (as heated residential buildings). This information is reported in Table 3.

	Commune of Renca			**Censal District CD-3 José Miguel Carrera**		
	R0 (before 2001)	R1 (during 2001-2007)	R2 (after 2007)	R0 (before 2001)	R1 (during 2001-2007)	R2 (after 2007)
Number of residential buildings	21,012	1,668	2,584	1,724	0	2
Number of analyzed buildings	27,764	1,694	2,739	1,812	0	3

Table 3: Number of residential buildings used by periods of construction

2. Material and Methods

2.1 Cadastral and energy data of residential buildings

Cadastral and energy data of residential buildings were given in CAD format so to use this data in the project CAD file were exported in a GIS format. AutoCAD files about the buildings in Renca were obtained from the Renca City Council website, containing the building shape, building code, period of construction, and building use [14]. The number of floor data was obtained from the Renca City Council website in an Excel format [16] and it was merged with the GIS table of content to have the information about the height of buildings.

No information about the energy consumption of Renca residential buildings was reported. Thus, data on typical buildings were obtained from the latest national report on household energy use by the Ministry of Energy (MINEN [4] for its Spanish acronym) in Chile.

MINEN's energy consumption data was obtained from questionnaires from 3,500 households living in different climatic zones in Chile, for various socioeconomic backgrounds, and different housing types. Specifically, the database includes.

1. Building features
2. Building a technological system
3. Electrical devices and appliances
4. Energy consumption, energy-saving, potential, and economic expenses for energy services.

Figure 3 shows the specific operations about combining cadastral and energy data to build the GIS buildings database and energy model. The collected data is explained below.

- Weather data is used for the analysis of the energy consumption characteristics, which is from meteorological station Pudahuel [11].
- Shape file data shows the plan of the residential building, which is collected from Chile's municipal website.
- Building stock features could show the specific energy consumption of each kind of building, which is collected from SII in National residential energy characterization [2]. And residential buildings are classified into 8 categories, depending on the number of floors, building materials, and useful area. Type 1 is one story detached house with brick masonry, and the useful area is 56.5 m^2. Type 2 is a two-story detached house (double-family house) with brick masonry, and the total useful area is 221.2 m^2. Type 3 is a two-story detached house (single-family house) with brick masonry/light, and the total useful area is 103 m^2. Type 4 is a two-story terrace house (apartment) with brick masonry, and the total useful area is 51.8 m^2. Type 5 is a one-story detached house (single-family house) with brick masonry, and the total useful area is 67.7 m^2. Type 6 is a two-story detached house (double-family house) with brick masonry/light, and the total useful area is 84.7 m^2. Type 7 is a one-story condominium (single-side apartment) with brick masonry, and the total useful area is 64.4 m^2. Type 8 is a one-story condominium (single-side apartment) with reinforced concrete, and the total useful area is 109.7 m^2.
- Energy consumption data is collected from MINEN, which is used to calculate the energy consumption of each residential building.

- Energy classification rule [5] is used to compare the energy consumption of different residential buildings easily.

Using the collected residential building data, the energy model can be built to calculate the energy performance indicator EP and which is energy consumption per m^2, energy classes, energy consumption (EC) and energy savings after retrofit interventions.

For the energy performance calculation, the EP values can be obtained by using eight types of residential buildings in different periods of thermal regulation to three formulas for the energy performance of the buildings in periods R0, R1 and R2 respectively, which can be used to get each residential building of energy performance.

Energy consumption, it means the total energy that the building needs. Hence, energy consumption can be obtained by multiplying the useful area by the energy performance.

For the energy classes, a pre-and post-retrofit interventions energy classification makes it easy to tell how effective a measure is.

According to National residential energy characterization [2], residential buildings in Chile can be divided into eight categories and data on them are available (dwelling type, story, quality of material, useful area, window area, wall area, roof area and ceiling height). As can be seen from Table 3, the residential buildings have different orientation characteristics, building materials, and different areas; in addition, these materials are mainly traditional brick masonry, with a small proportion mixed with lightweight timber or steel framing. Based on the above basic data, the authors estimated the surface-to-volume ratio (S/V) of each building for the study of energy consumption in the Renca area (see also Figure 6).

The percentage of energy savings for different measures (see Table 5) [2] can be used to calculate energy savings after retrofit interventions. In other words, it gives a visual indication of the amount of energy that can be saved by retrofitting different types of buildings in different ways over time.

Table 4 also shows variations in space-heating ED (energy demand) for the eight residential building archetypes selected by MINEN [4]. As can be seen, large variations in space-heating ED can be found between the dwelling with the lowest and that with the highest S/V ratio ranging from 50–300 $kWh/m^2/year$ from Type 1 (detached house) to Type 6 (terrace house), respectively. It can also be noted that if the period of construction was changed to comply with the minimum thermal transmittance requisites of each building regulatory period the energy demand of the dwellings can be reduced in the order of 20-50% depending on the building type.

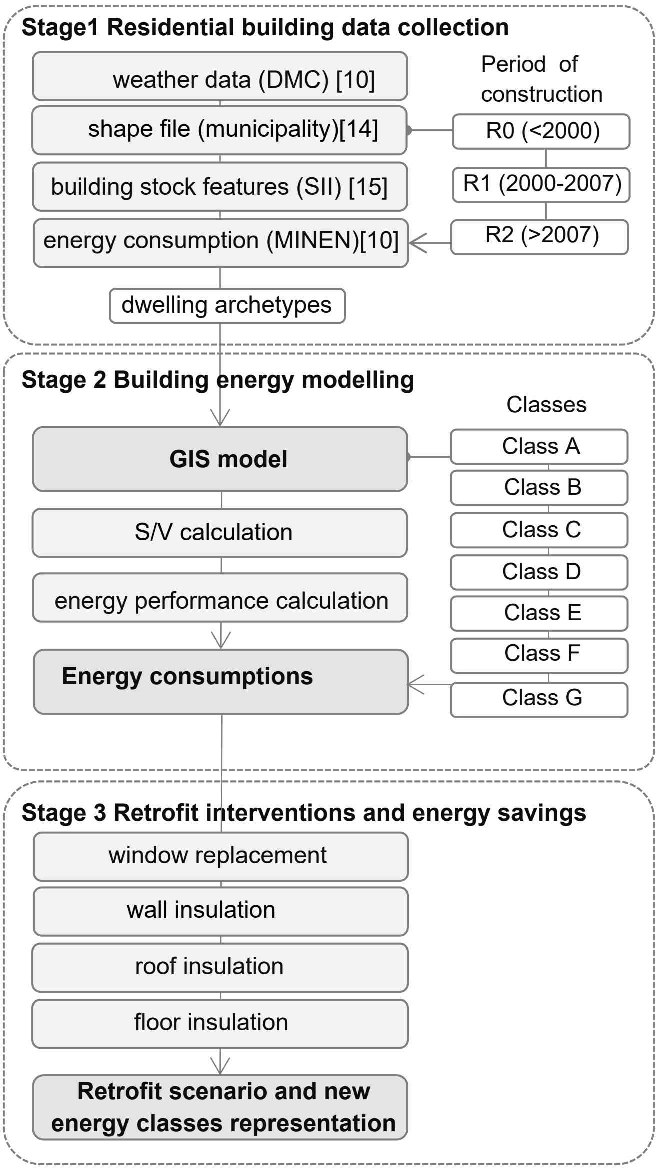
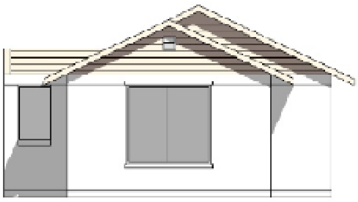


Figure 3: Methodological workflow

The different residential building typologies can be seen in Table 4 (namely, detached houses, terrace houses and condominiums). They can be explain as follows:

- Detached house: a building that is isolated from the other buildings.
- Terrace house: a little building that is adjacent to the same type of building.
- Condominium: a row house with 5-10 apartments and a maximum of 5-6 floors.
- Towers: big and compact condominiums with more than 10 apartments.

Type 1:



Dwelling type	Detached house			**R0 (<2000)**	R_1 (2000-2007)	**R2 (>2007)**
Stories	1		**EP (kWh/m^2/year)**	326	216	194
Quality of material	brick masonry		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	56.5		**Net heated floor area (m^2)**	52.31	52.31	51.44
Window area (m^2)	N-W	5.4	**Energy-use (kWh/year)**	17,053	11,299	9,979
	N-E	7.8				
	S-W	0.5	**Energy demand (kWh/m^2/year)**	11,255	7,457	6,586
	S-E	3.8				
Wall area (m^2)	83.8		**Fuel**	Natural gas	Primary.coeff.	1.05
Roof area (m^2)	60.2		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height (m)	2.4		Window substitution (U=1.1 W/m^2/year)	2,046	2,147	2,096
			Wall thermal insulation with 20 cm	5,457	5,762	4,391
S/V (m^2/m^3)	1.28		Roof thermal insulation with 15 cm	6,821	791	798
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	341	452	499

Type 2:

Dwelling type	Detached house: double family house			**R0 (<2000)**	R_1 (2000-2007)	**R2 (>2007)**
Stories	2		**EP (kWh/m^2/year)**	196	140	128
Quality of material	brick masonry		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	F1	114.7	**Net heated area (m^2)**	204.78	204.78	201.4
	F2	106.5				
Window area	N-W	28.7	**Energy-use (kWh/year)**	40,137	28,669	25,779
	N-E	16.4				
	S-W	0	**Energy demand (kWh/m^2/year)**	26,490	18,922	17,014
	S-E	7.3				
Wall area (m^2)	199.8		**Fuel**	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	121.6		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height	F1	2.85	window substitution (U=1.1W/m^2/year)	4,816	5,447	5,414
	F2	2.88	Wall thermal insulation with 20 cm	12,844	14,621	11,343
S/V	0.61		Roof thermal insulation with 15 cm	16,055	2,007	2,062
(m^2/m^3)						
System efficiency (-)	0.66		Floor thermal transmittance with 1 W/m^2/K	803	1,147	1,289

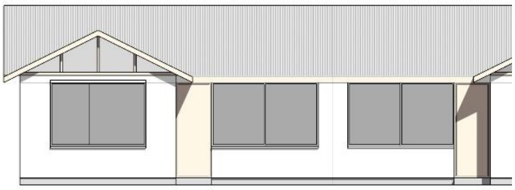
Type 3:

Dwelling type	Detached house: single family house			**R0 (<2000)**	**R1 (2000-2007)**	**R2 (>2007)**
Stories	2		**EP (kWh/m^2/year)**	240	177	159
Quality of material	brick masonry/light		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	F1	63	**Net heated floor area (m^2)**	95.35	95.35	93.78
	F2	40				
Window area (m^2)	N-W	10.1	**Energy-use (kWh/year)**	22,884	16,877	14,911
	N-E	5.9				
	S-W	7.7	**Energy demand (kWh/m^2/year)**	15,103	11,139	9,841
	S-E	0				
Wall area (m^2)	120.7		**Fuel**	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	63		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height (m)	2.4		window substitution (U=1.1W/m^2/year)	2,746	3,207	3,131
			Wall thermal insulation with 20 cm	7,323	8,607	6,561
S/V (m^2/m^3)	0.93		Roof thermal insulation with 15 cm	9,154	1,181	1,193
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	458	675	746

Type 4:

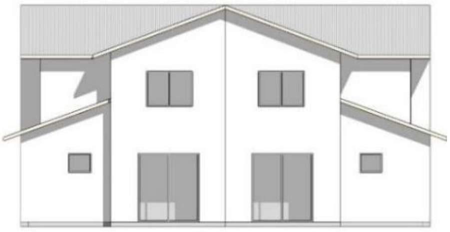
Dwelling type	Terrace house: apartments			**R0 (<2000)**	**R1 (2000-2007)**	**R2 (>2007)**
Stories	2		**EP (kWh/m^2/year)**	250	197	171
Quality of material	brick masonry		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	F1	25.9	**Net heated floor area (m^2)**	48.12	48.12	47.33
	F2	25.9				
Window area (m^2)	N-W	3.3	**Energy-use (kWh/year)**	12,030	9,480	8,093
	N-E	2.9				
	S-W	0	**Energy demand (kWh/m^2/year)**	7,940	6,257	5,342
	S-E	0				
Wall area (m^2)	82.8		**Fuel**	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	26.4		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height (m)	F1	2.44	window substitution (U=1.1W/m^2/year)	1,444	1,801	1,700
	F2	2.36	Wall thermal insulation with 20cm	3,850	4,835	3,561
S/V (m^2/m^3)	0.89		Roof thermal insulation with 15 cm	4,812	664	647
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	241	379	405

Type 5:



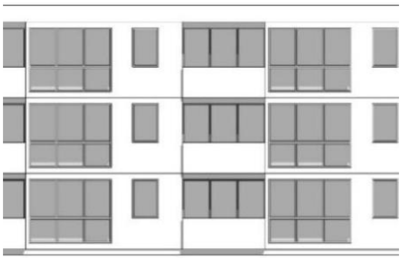
Dwelling type	Detached house: single family house			R0 (<2000)	R1 (2000-2007)	R2 (>2007)
Stories	1		EP (kWh/m^2/year)	275	151	128
Quality of material	brick masonry		Gross➡net area coeff: f_n	0.93	0.93	0.91
Useful area (m^2)	67.7		Net heated floor area (m^2)	62.67	62.67	61.64
Window area (m^2)	N-W	3.9	Energy-use (kWh/year)	17,234	9,463	7,890
	N-E	1.4				
	S-W	0	Energy demand (kWh/m^2/year)	11,375	6,246	5,207
	S-E	0				
Wall area (m^2)	51		Fuel	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	81.7		Energy savings (kWh/year) after retrofit interventions			
Ceiling height (m)	2.4		window substitution (U=1.1W/㎡ /year)	2,068	1,798	1,657
			Wall thermal insulation with 20cm	5,515	4,826	3,472
S/V (m^2/m^3)	1.03		Roof thermal insulation with 15 cm	6,894	662	631
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	345	379	394

Type 6:



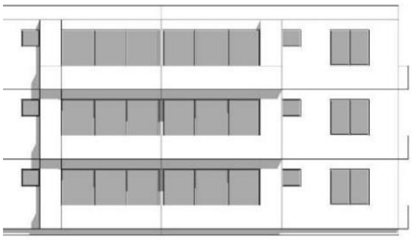
Dwelling type	Detached house: double family house			R0 (<2000)	R1 (2000-2007)	R2 (>2007)
Stories	2		EP (kWh/m^2/year)	215	147	132
Quality of material	brick masonry/light		Gross➡net area coeff: f_n	0.93	0.93	0.91
Useful area (m^2)	F1	48.4	Net heated floor area (m^2)	78.41	78.41	77.12
	F2	36.3				
Window area (m^2)	N-W	5.8	Energy-use (kWh/year)	16,858	11,526	10,180
	N-E	4.7				
	S-W	1.6	Energy demand (kWh/m^2/year)	11,126	7,607	6,719
	S-E	0				
Wall area (m^2)	82.89		Fuel	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	26.48		Energy savings (kWh/year) after retrofit interventions			
Ceiling height (m)	F1	2.3	window substitution (U=1.1W/m^2/year)	2,023	2,190	2,138
	F2	2.3	Wall thermal insulation with 20cm	5,395	5,878	4,479
S/V (m^2/m^3)	0.81		Roof thermal insulation with 15 cm	6,743	807	814
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	337	461	509

Type 7:



Dwelling type	Condominium: single side apartment			R0 (<2000)	R1 (2000-2007)	R2 (>2007)
Stories	1		**EP (kWh/m^2/year)**	53	53	48
Quality of material	brick masonry		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	64.4		**Net heated floor area (m^2)**	59.62	59.62	58.64
Window area (m^2)	N-W	16	**Energy-use (kWh/year)**	3,160	3,160	2,815
	N-E	0				
	S-W	0	**Energy demand (kWh/m^2/year)**	2,086	2,086	1,858
	S-E	0				
Wall area (m^2)	5.7		**Fuel**	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	64.4		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height (m)	2.6		window substitution (U=1.1W/m^2/year)	379	600	591
			Wall thermal insulation with 20cm	1,011	1,612	1,238
S/V (m^2/m^3)	0.09		Roof thermal insulation with 15 cm	1,264	221	225
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	63	126	141

Type 8:



Dwelling type	Condominium: single side apartment			R0 (<2000)	R1 (2000-2007)	R2 (>2007)
Stories	1		**EP (kWh/m^2/year)**	76	76	59
Quality of material	reinforced concrete		**Gross➡net area coeff: f_n**	0.93	0.93	0.91
Useful area (m^2)	109.7		**Net heated floor area (m^2)**	101.56	101.56	99.88
Window area (m^2)	N-W	9.8	**Energy-use (kWh/year)**	7,719	7,719	5,893
	N-E	0				
	S-W	12	**Energy demand (kWh/m^2/year)**	5,094	5,094	3,889
	S-E	0				
Wall area (m^2)	33.2		**Fuel**	Natural gas	Primary coeffi.	1.05
Roof area (m^2)	109.7		**Energy savings (kWh/year) after retrofit interventions**			
Ceiling height (m)	2.6		window substitution (U=1.1W/m^2/year)	926	1,467	1,238
			Wall thermal insulation with 20cm	2,470	3,936	2,593
S/V (m^2/m^3)	0.15		Roof thermal insulation with 15 cm	3,087	540	471
System efficiency (-)	0.66		Floor thermal transmittance of 1 W/m^2/K	154	309	295

Table 4: Eight archetypes of residential building

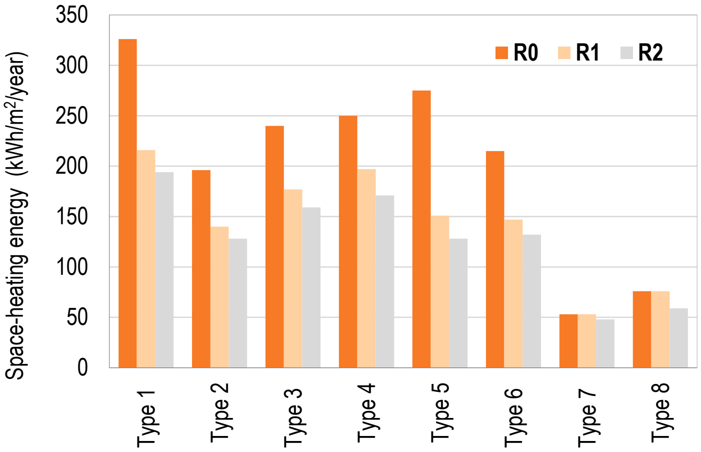


Figure 4: EP (kWh/m^2/year) of different building types(Notes: Municipality of Renca, "Plan Regulador Comunal 2022," 2022. https://renca.cl/unidades-municipales/secretaria-comunal-de-planificacion/prc/ (accessed Sep. 13, 2022) [13])

According to Figure 4, energy performance is related to the period of the building, with the highest energy performance in the R0 period, followed by R1 and R2. And building performance is also affected by building type, the government should pay attention to the use of type in new buildings.

	R0 (<2000)	R1 (2000-2007)	R2 (>2007)
Window substitution (U=1.1W/㎡/K)	12%	19%	21%
Wall thermal insulation with 20cm	32%	51%	44%
Roof thermal insulation with 15 cm	40%	7%	8%
Floor thermal transmittance of 1 W/m²/K	2%	4%	5%

Table 5: Percentage of energy savings after different retrofit measures [2]

2.2 Geographic information system (GIS) modelling

2.2.1 Types of residential building modeling (8 types)

According to MINEN [14], the eight types of building basic information can be obtained (namely, dwelling type, stories, quality of material, useful area, window area, wall area, roof area, and selling height). With these data, it is easy to calculate the S/V, and it can be explained below.

$$S = S_{foot\ print\ area} + S_{window} + S_{roof} + S_{wall}\ [m^2] \qquad (1)$$

$$V = S_{foot\ print\ area} \times H\ [m^3] \qquad (2)$$

During Figure 5, it is clear to see that most of the S/V of residential is during 0.5-0.6 m^2/m^3. Besides, the rest of other buildings of S/V is during 0.07-0.5 m^2/m^3, mostly. However, the west part of the residential building has smaller number of S/V, comparing with the other side.

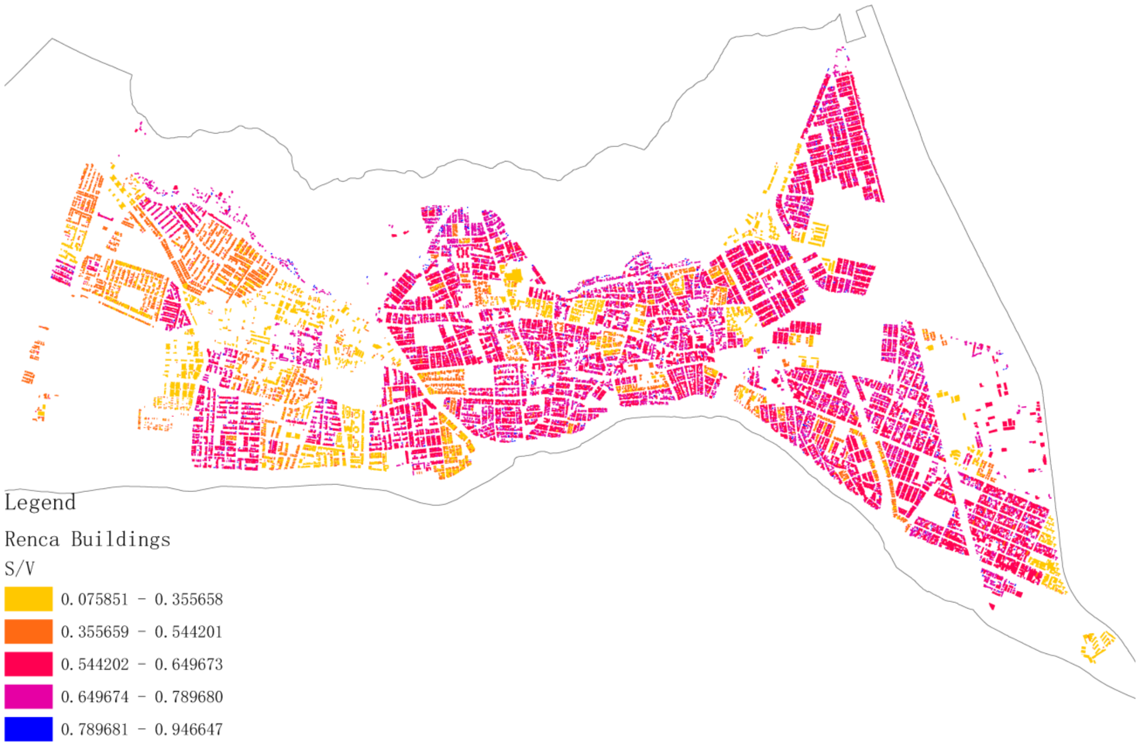


Figure 5: The surface to volume ratio of residential building in all Renca

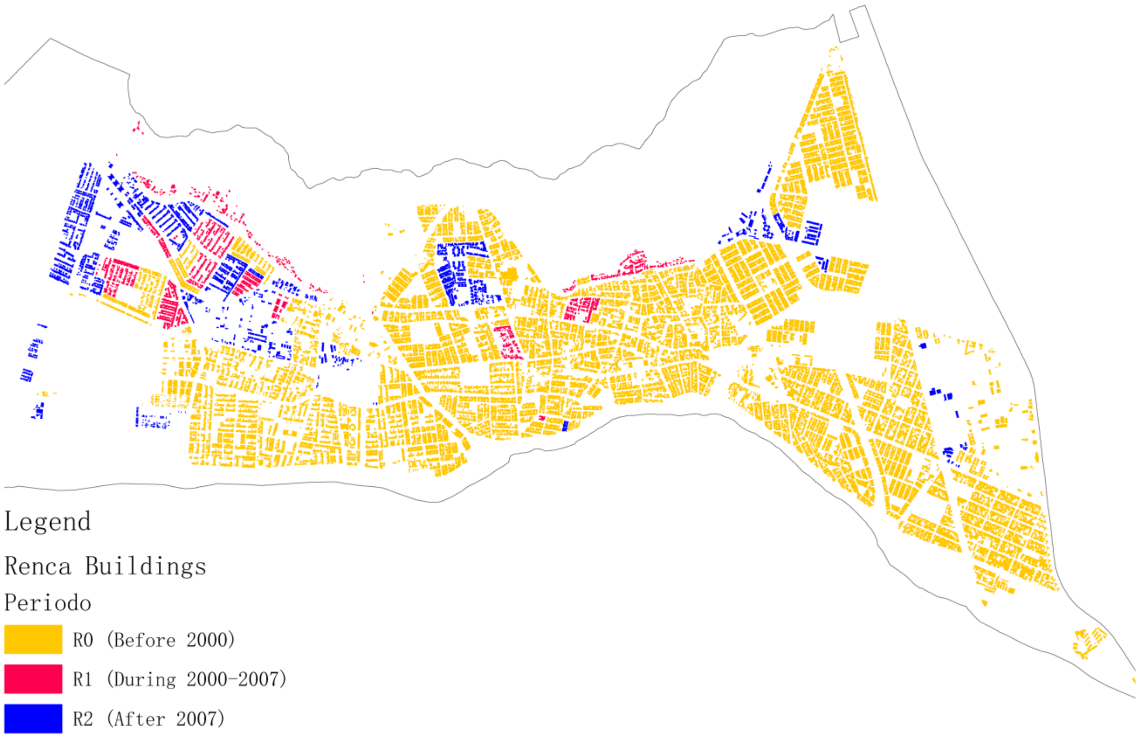


Figure 6: The different periods of residential building in all Renca

Next step, energy performance in different periods of different archetypes can be obtained [2]. Energy consumption means the amount of energy a building needs to consume per square meter per year and it gives a direct expression of the amount of energy demanded by the building. To know the actual annual energy consumption of each building, we need to find the energy consumption. The energy consumption EC was calculated knowing the energy performance index EP according to:

$$EC = EP \times S_{useful\ heated\ area}\ [kWh/year] \tag{3}$$

$$S_{uesful\ heated\ area} = fn \times S_{gross\ heated\ area} \times number\ of\ floors\ [m^2] \tag{4}$$

$$fn = 0.9761 - 0.3055 \times dm \tag{5}$$

Where:

EC is energy consumption [kWh/year]

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

dm means the mean thickness of the wall [m]

To calculate fn, the three eras of buildings are needed to do the corresponding average thickness of the walls. Table 6 shows the wall thicknesses of buildings of different materials, and the percentage of buildings of different materials in the three periods, respectively. It can be observed in green, that old buildings use mainly brick masonry, a building built in 2001-2007 use concrete and newer buildings use lightweight materials. Froe Table 6 (Calculation of weighted average scores based on the percentage and thickness of different wall materials), the average thickness of the walls of the buildings in the different eras can be obtained (namely, the average thickness of the wall in R0, R1 and R2 are 0.15 m, 0.2 m and 0.2 m separately).

Building material of walls	dm (m)	R0 (<2001)	R1 (2001-2007)	R2 (>2007)
Brick masonry	0.15	97%	-	25%
Concrete	0.1	2%	67%	25%
Lightweight	0.08	1%	33%	50%

Table 6: The wall thickness of buildings of different materials and the percentage of buildings of different materials in the three periods of construction

Hence, energy consumption can be obtained with the specific data using the data and formulas above. Now, the total energy consumption of each type of building is shown by the ability of the building to use energy. The energy is translated by a variety of resources, like natural gas, liquefied gas (LPG), firewood, kerosene, and electricity. Different resources have different translation efficiency, which is shown in Table 7. It is clear to find that liquefied and kerosene are occupied a large proportion, separately, 40.3 % and 35.6 %. To get the real energy using - energy demand, we need to get the average energy efficiency (namely, 66 %) using the data which is shown in Table 7.

Energy sources	Natural gas	Liquefied gas	Firewood	Kerosene	Electricity	Another
Percentage (%)	0.30	40.30	12.20	35.60	11.40	0.20
Efficiency (%)	70	65	55	60	100	70

Table 7: Share of different types of energy, percentage, and efficiency, etc. (at Santiago level).

Energy demand can be get using the formula below:

$$ED = EC \times \eta \ [kWh/year] \qquad (6)$$

where:

ED is energy demand [kWh/year]

EC is energy consumption [kWh/year]

η is the average system efficiency [-]

The systems efficiency was taken from the National Commission of Energy [3] and these data are reported in Table 4 for all archetypes.

2.2.2 Urban scale building energy model

To further understand the exact energy consumption of the residential buildings on the site and to understand the actual conditions of the site, an energy model needs to be constructed using ArcGIS. Flowing the flow chart (Figure 3), the CAD file and the number of floor data are input in the energy model together to build the basic model framework. In this step, each building is shown on the map, with the building height, material, age, code, area, length, and width.

The next step is to get the S/V of each building. S is the exposed surface area of the building and V is the volume of the building. Volume is easy to get (area multiplied by height). However, for the exposed building surface, a point should not be ignored that building with bordering surfaces, which means the face of the building bordering the building should not be taken into account in the surface area. In other words, this surface needs to be excluded from the exposed surface area. After that, the S/V of each building can be obtained to calculate the energy data.

To get energy performance (energy consumption per m^2) for each of the buildings on the urban scale, the relationship of EP with S/V should be obtained from the 8 types of buildings, which means this relationship also can be used at the urban scale. The energy performance of different types of buildings over three periods is obtained by MINEN [3], and S/V data is calculated by the authors (Table 8).

According to Figure 7, the formulas are obtained which are shown below (Table 9). These can be used in the energy model to get the energy performance of residential buildings at the urban scale.

Archetype	S/V (m^2/m^3)	Energy Performance ($kWh/m^2/year$)		
		R0	R1	R2
Type 1	1.28	326	216	194
Type 2	0.61	196	140	128
Type 3	0.93	240	177	159
Type 4	0.89	250	197	171
Type 5	1.03	275	151	128
Type 6	0.81	215	147	132
Type 7	0.09	53	53	48
Type 8	0.15	76	76	59

Table 8: The energy performance and S/V of different types of residential building

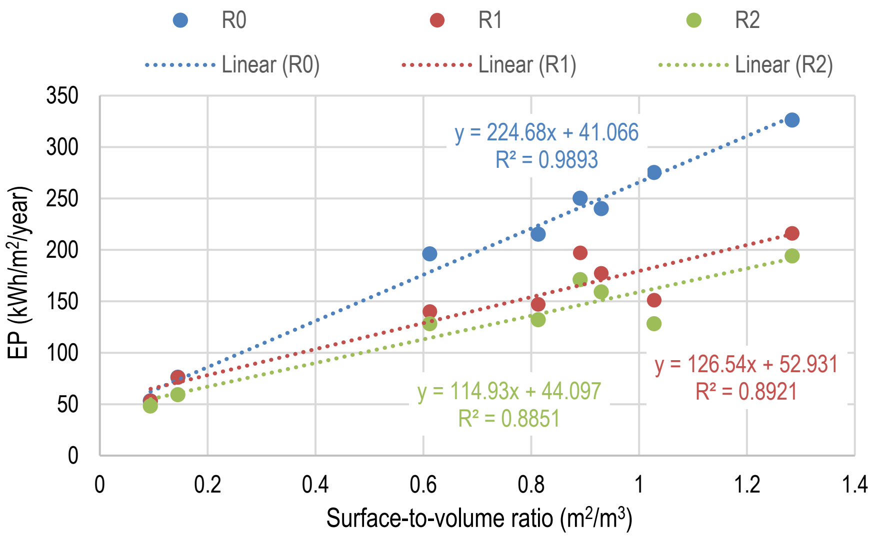


Figure 7: The linear relationships between S/V (m^2/m^3) and EP ($kWh/m^2/year$) by different periods of construction (R0<2001; R1=2001 - 2007; R2 >2007)

Periods	The formula
R0 (before 2000)	$EP_{R0} = 224.68 * (S/V) + 41.066$
R1 (during 2000-2007)	$EP_{R1} = 126.54 * (S/V) + 52.931$
R2 (after 2007)	$EP_{R2} = 144.93 * (S/V) + 44.097$

Table 9: The energy performance ($kWh/m^2/year$) formulas using S/V (m^2/m^3) and different periods of construction

By the energy performance index of a building, it is possible to evaluate the energy consumption, knowing its period of construction (i.e., the higher the S/V, the more energy the building consumes per square meter and the more energy intensity is). As a result, we can obtain a map (Figure 8) of the energy performance of buildings throughout the Renca region.

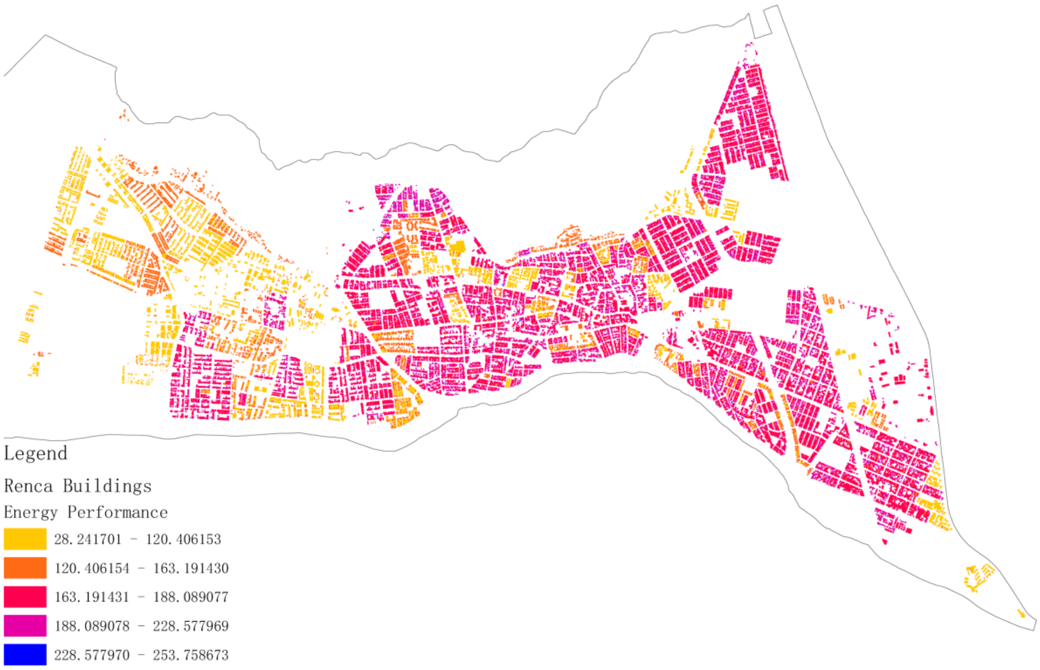


Figure 8: The energy performance map of the residential buildings at all Renca

In this map, we can see that blue represents a large number for energy performance, which means that more energy is needed, and yellow represents a small number for energy performance, which means that less energy is needed. In this map, it is clear to see that most of the buildings are red and pink, which means that energy performance is relatively large. This means that there is more room for energy improvement at the site.

2.2.3 District scale model

In the above article, the energy performance of the entire Renca has been obtained and a detailed picture of the venue was obtained. However, due to the size of the site, it was difficult to do a detailed analysis, so a representative area was chosen for further study and exploration. The district energy model is extracted from the urban energy model, and the energy performance at the district scale is shown below (see Figure 9).

As with the map of Figure 8, most of the residential buildings in the city of Renca on the district 3 site have larger values for Energy performance. There is a lot of room for improvement through building-appropriate measures.

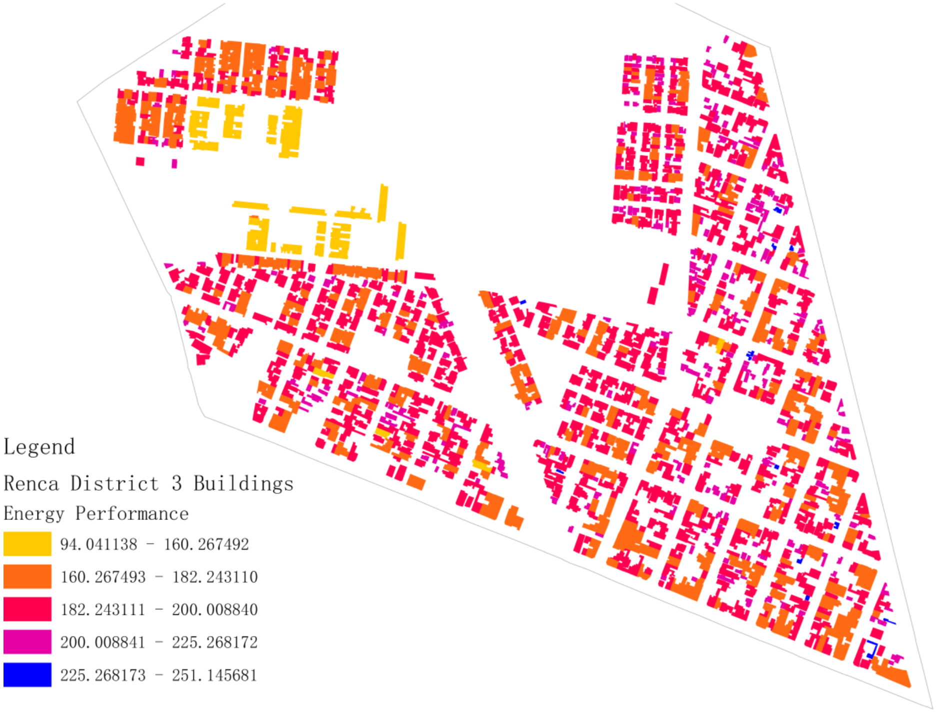


Figure 9: The energy performance (kWh/m^2/year) map of the residential buildings at the district scale

2.3 Identification of energy-related variables and data-driven model

As previous figures show, the energy performance of each building has been obtained. To derive the annual energy consumption of the site for subsequent energy-saving measures, the energy consumption and energy demand are derived in turn. Energy consumption means the net energy required by the building in a year, in other words, energy consumption can be obtained by multiplying energy performance by the useful heated area. And energy demand means the total energy that needs to be supplied to the building (here the energy lost to heat is included). These steps are similar to the steps calculating energy consumption and energy demand for each type of building. These data are shown in Table 10.

Scale	Total energy consumption (kWh/year)	Total energy demand (kWh/year)
Renca	884,249,350	1,339,771,742
Censal District CD-3 Josè Miguel Carrera	59,446,482	90,070,428

Table 10: The energy demand (kWh/year) and consumption (kWh/year) of residential buildings in Renca

2.4 Place-based GIS methodology

After the basic energy data is obtained, further studies need to be carried out (considering: energy classification, energy-savings, energy-saving measures, calculation of carbon emissions, solar energy harvesting, etc.). A bottom-up approach is used here, that is, moving from the local to the whole, from specific data analysis to overall policy recommendations. And the specific steps are shown at the below part.

3. Results

3.1 Performing building classification and energy-saving interventions

The data of the average heating energy demand of Chilean dwellings before and after the TR (Thermal Regulation) and the percentage of energy savings used are shown below (Figure 10 and Figure 11) [16]. Due to Santiago belongs to Zone 3, the project energy classification should obey Figure 9.

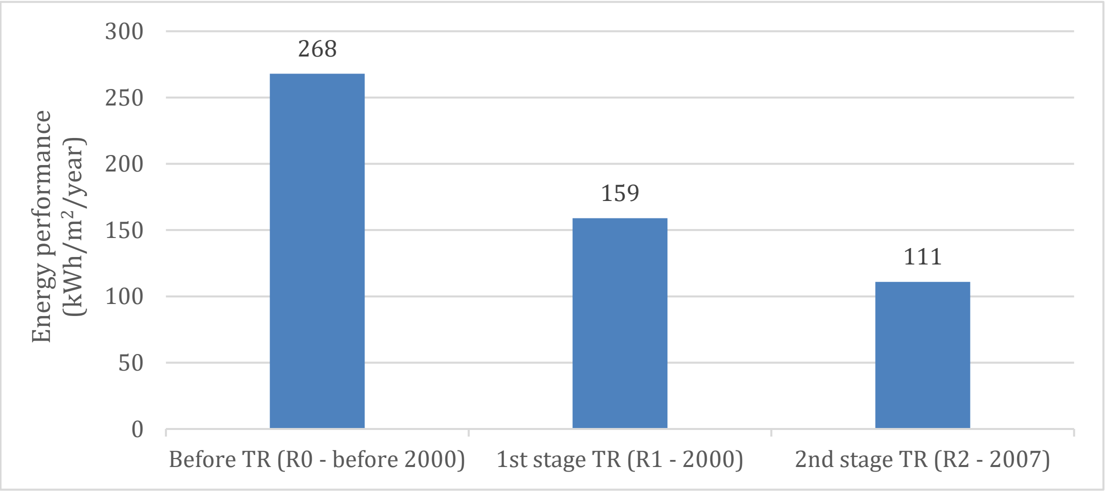


Figure 10: Average heating energy performance of Chilean dwellings before and after the TR

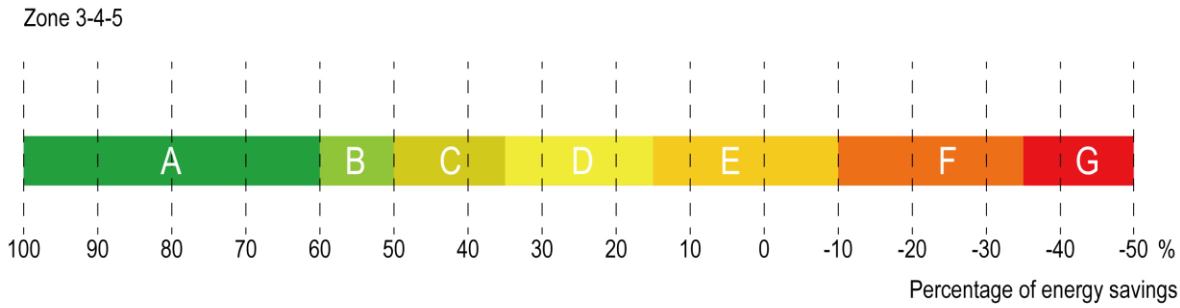


Figure 11: Percentage of energy savings used in the Chilean energy qualification of dwellings system when comparing the energy demand between the assessed and the reference building

Using the data in Figure 10 and Figure 11, by the formulas below, the energy performance in different classifications during different periods can be get, which is shown in Table 11.

$$EP_{classification}\ [kWh/m^2/year] = EP_{period}\ [kWh/m^2/year] \times (1 - \text{percentage of energy savings } [\%]) \qquad (7)$$

where:

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

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

However, in this graph, we can only distinguish trends in energy performance and cannot easily compare buildings with similar energy performance. Therefore, according to the Chilean energy classification for buildings [17], we can classify buildings into seven classes (see Table 11).

Period		R_0	R_1	R_2
Energy performance (kWh/m²/year)	***Class A***	X<107.2	X<63.6	X<44.4
	Class B	107.2≤X<134.0	63.6≤X<79.5	44.4≤X<55.5
	Class C	134.0≤X<174.2	79.5≤X<103.4	55.5≤X<72.2
	Class D	174.2≤X<227.8	103.4≤X<135.2	72.2≤X<94.4
	Class E	227.8≤X<294.8	135.2≤X<174.9	94.4≤X<122
	Class F	294.8≤X<361.8	174.9≤X<214.7	122≤X<149
	Class G	X≥361.8	X≥214.7	X≥149

Table 11: Energy classification in Renca by different periods of residential building

Hence, according to this classification table, it is used in the energy model to get the results map (Figure 12) it is easy to find that most of the buildings' classifications are Class D (the middle class). The buildings located on the northwest side have a poor situation with low class, which means there are many red buildings here.

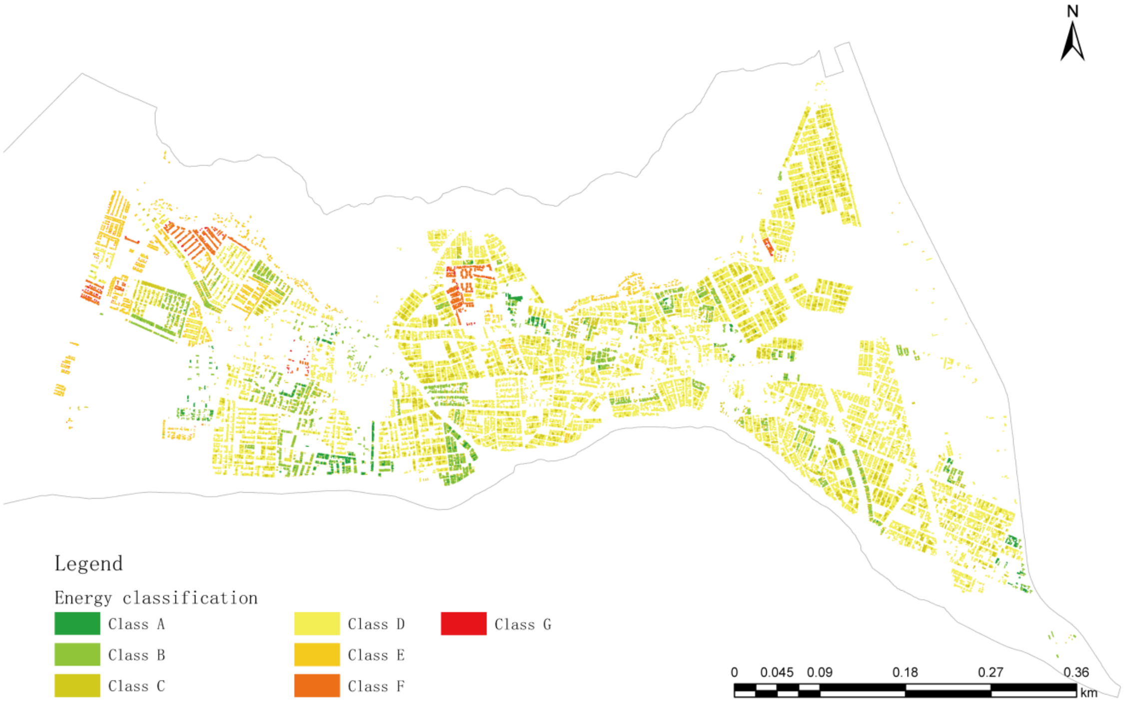


Figure 12: The existing residential building classification map at Renca

3.2 Consider economic issues - cost-benefit analysis and payback time

With regard to interventions, in addition to the amount of energy saved it is also necessary to consider the cost of the intervention. The combined amount of energy saved and the costs consumed by the intervention can be compared more visually by the payback time. And the result is shown below (Table 12).

There are four interventions [2], which are window substitution (U=1.1W/㎡/K), wall thermal insulation with 20cm, roof thermal insulation with 15 cm and floor thermal transmittance of 1 W/m2/K. The cost of the interventions for windows, walls, roofs and floors are 216 $\$/\mathrm{m}^2$, 120 $\$/\mathrm{m}^2$, 80 $\$/\mathrm{m}^2$ and 105 $\$/\mathrm{m}^2$ respectively [18]. Besides, each renovation area can be get from ArcGIS mode and they are calculated by the formulas below:

$$\textit{Total surface of the window } (m^2) = \textit{ 1/10 the useful heated area } (m^2) \tag{8}$$

$$\textit{Total surface of the wall } (m^2) = \textit{heat loss surface } (m^2) - [(\textit{area of the building } (m^2) \times 2) + \textit{surface of the windows } (m^2)] \tag{9}$$

$$\textit{Total surface of the roof } (m^2) = \textit{total area of the residential building } (m^2) \tag{10}$$

$$\textit{Total surface of the floor } (m^2) = \textit{total area of the residential building } (m^2) \tag{11}$$

Since cost and area are known, the costs required for the four retrofit measures are also known.

$$\textit{The useful heated area } (m^2) = \textit{gross heated surface } (m^2) \times fn \tag{12}$$

$$\textit{Gross heated surface per building } (m^2) = \textit{foundation area of the residential building } (m^2) \times \textit{ the number of heated floor} \tag{13}$$

Where:

The useful heated area means that due to the different thicknesses of the walls (fn), the degree of heat loss is not the same and thus the area that is really effectively heated.

The gross heated surface means the area heated in an ideal state.

Fn means the actual heating efficiency, according to different degrees of heat loss depending on the thickness of the wall.

Heat loss surface means all surfaces where the exchange of energy is possible (heat loss).

Hence, since the cost of each intervention ($\$/\mathrm{m}^{2)}$ and each renovation area are known, the total costs of the four interventions ($) are also known (It can be seen inTable 12). Besides, using the formula below, the total energy demand saving (kWh/year) can be get.

$$\textit{The total ED saving (kWh/year)} = \textit{ total energy demand (kWh/year) } \times \textit{ percentage of energy saving (\%)} \tag{14}$$

Where:

The percentage of energy saving data is in Table 5.

Intervention	Window	Wall	Roof	Floor
Content[(a)]	*Window DHV[(b)] U=1.1 w/m²/K*	*Thickness of insulation over 20 cm*	*Thickness of insulation = 15 cm*	*floor insulation, k=1*
Cost (\$/m²) [16]	216	120	80	105
Renovation area (m²)	90,254	82,926	342,238	371,607
Cost of intervention (\$)	19,494,864	9,951,120	27,379,040	39,018,735
Total ED Saving (kWh/ year) [(c)]	29,667,894	79,042,471	98,521,429	4,953,638

Table 12. Four interventions' specific content, cost, renovation area, cost of intervention and total energy saving at D-3. (Notes: (a) The data from national residential energy characterization, 2018. (b) DHV is a double-glazing window. (c) The proportion of savings from the interventions came from national residential energy characterization, 2018.)

Once we have obtained the total energy savings, we need to consider the economic factor (Namely, payback time.). Therefore, it is necessary to calculate the energy consumption that can be saved. According to the ministry of energy [19], the share of different energy sources can be obtained.

According to the National Commission of Energy [3], the capacity of the different energy sources to convert electricity can be obtained. The unit price of energy can be obtained from Natural gas [20] in Chile. The Ministry of Environment [21] Chile, gives the value of carbon emissions. The final data available is in Table 13.

In this table, it is clear to see that liquefied and kerosene are occupied a large proportion, separately, 40.3% and 35.6% (in green). However, firewood is the cheapest energy source (0.054 \$/kWh), with the lowest system efficiency (55%). For the GHG emission column, natural gas is the best environmental friendly, which has the lowest number (0.252 $kgCO_2$/kWh). And according to the data, the average cost of delivered energy can be get, which is 0.106 \$. The average efficiency is 0.66, and the average greenhouse gases (GHG) emission index is 0.303 $kgCO_2$/kWh (in blue).

Energy sources	Percentage	Cost of energy fuels (\$/kWh)	GHG emission ($kgCO_2$/kWh)	Systems efficiency
Natural gas	0.30%	0.086	0.252	0.70
Liquefied gas (LPG)	40.30%	0.110	0.254	0.65
Firewood	12.20%	0.054	0.395	0.55
Kerosene	35.60%	0.104	0.270	0.60
Electricity	11.40%	0.154	0.480	1.0
Another	0.20%	0.102	0.330	0.70
Average	-	0.106	0.303	0.66

Table 13. Share of different types of energy, conversion rates, carbon emission value, etc (referring to 2018).

Based on the above data, the reduction in energy costs due to the reduction in energy can be calculated:

Cost of energy saving (\$/year) = energy consumption saving (kWh/year) × average cost (\$/kWh) (15)

Energy consumption saving (kWh/year) = energy demand saving (kWh/year) / average system efficiency (16)

And, thus the simple payback time can be calculated:

Simple payback time [years] = cost of intervention [\$] / Annual economic saving [\$/year] (17)

Besides, the number of greenhouse gas emission savings can be calculated (The basic data comes from the Ministry of Environment [21]). This data provides a better visualization of the impact of reduced carbon emissions in terms of environmental protection, in other words, it can be compared with data on carbon emissions generated in other areas. The result is shown below (Table 14).

In this table, according to the formulas above, it is easy to get the total energy consumption saving, annual economic savings and simple payback time. However, for the GHG emission saving, due to Table 13, the average number of resources GHG emission for 1 kWh is getting (namely, 0.303 $kgCO_2/kWh$). Hence, using the formula below, the GHG emission saving can be get for each intervention.

GHG emission saving (t/year) = total energy consumption saving (kWh/year) / average GHG emission (kgCO2/kWh) /1000 (unit changed) (18)

Intervention	Total EC saving (kWh/year)	Annual economic saving (\$/year)	Simple payback time (year)	GHG emission saving (t/year)
Window	19,580,810	2,075,566	9.39	64,623
Wall	52,168,031	5,529,811	1.79	172,171
Roof	65,024,143	6,892,559	3.97	214,601
Floor	3,269,401	346,557	112.59	10,790

Table 14. The data about energy consumption savings, annual economic savings, payback time and GHG emission saving

3.3 Evaluation of solar energy potential

This section presents an approach to assess solar energy potential at the city level using ArcGIS tools and the PVGIS portal [24]. By analyzing the available roof area, to evaluate the solar potential, consider only residential buildings of Renca, consider the optimized slope is 35°and no consider shadow between buildings.

Annual and monthly solar radiation values were calculated at the building level using ArcGIS, using the ‘Area Solar Radiation’ tool to determine solar photovoltaic potential. Download the DEM 2011 (Digital Elevation Model) [25] base map, with an accuracy of 30 m × 30 m. To get the annual solar radiation simulation to obtain the monthly, annual cumulative and average annual solar radiation.

To simulate solar radiation in ArcGIS, the tool "Area solar radiation" can be used to characterize the sun and sky with the following monthly input data: ratio of diffuse to global irradiation K_d and sky transmissivity T . Indeed, the sun and sky change during the year with higher K_d and T in the summertime, then is very important to simulate correctly these variables. The values of these variables for each city can be found on online webtools (i.e., PVGIS [24], SODA [26], ENEA for Italy [27]) and calculated by the following equations:

$$T^{FDL} = G_{b,h} / \text{Solar constant} \tag{19}$$

$$T = (G_{b,h} / \text{Solar cost})^{1/FDL} \tag{20}$$

$$G_{b,h} = H_{b,h} / M_{l,h} \text{ with } M_{l,h} = M_d \times D_{l,h} \text{ and } H_{b,h} = H_{h,m}(1 - K_d) * 1000 \tag{21}$$

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) [Wh/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 [%]*

The calculation of the monthly Transmissivity of Renca was done by collecting the variables of equations (20) and (21) from the webtools for the reference 2017. There use the formula (21) can calculate $G_{b,h}$ (Table 15).

Month	$D_{l,h}$ (h/d)	$M_{l,h}$ (h/mo)	M_d (d)	$H_{h,m}$ (kWh/m^2)	K_d (%)	$H_{b,h}$ (Wh/m^2)	$G_{b,h}$ (W/m^2)
Jan	14.52	450.02	31	281.86	12	248037	551.2
Feb	13.83	387.33	28	212.11	17	176051	454.5
Mar	12.8	396.80	31	201.74	16	169462	427.1
Apr	11.63	349.00	30	136.99	22	106852	306.2
May	10.37	321.47	31	86.85	33	58190	181
Jun	9.87	296.00	30	71.63	30	50141	169.4
Jul	9.78	303.28	31	92.21	24	70080	231.1
Aug	10.38	321.88	31	111.56	25	83670	259.9
Sep	11.38	341.50	30	146.76	28	105667	309.4
Oct	12.5	387.50	31	204.83	24	155671	401.7
Nov	13.62	408.50	30	234.01	20	187208	458.3
Dec	14.4	446.40	31	277.03	16	232705	521.3

Table 15: Database monthly radiation from PVGIS of Renca in 2017

Then the Linke Turbidity Factor FDL was downloaded by the online site of SODA [26], obtaining the FDL values for each month in Renca needed by Area solar radiation (of ArcGIS); The formula (20) consents to calculate monthly transmissivity T (in Table 16).

Month	Gb,h (Wm/m^2)	FDL(-)	1/FDL(-)	T(-)
Jan	551.2	3.4	0.29	0.77
Feb	454.5	3.7	0.27	0.74
Mar	427.1	3.3	0.30	0.70
Apr	306.2	3.0	0.33	0.61
May	181.0	3.1	0.32	0.52
Jun	169.4	3.3	0.30	0.53
Jul	231.1	2.7	0.37	0.52
Aug	259.9	2.8	0.36	0.55
Sep	309.4	3.0	0.33	0.61
Oct	401.7	3.5	0.29	0.70
Nov	458.3	3.2	0.31	0.71
Dec	521.3	3.7	0.27	0.77

Table 16: Monthly atmosphere turbidity FDL and transmissivity [T] data for the city of Renca in 2017

There has a ratio of diffuse to global irradiation and transmissivity, input the annual average of the two data into the "Area Solar Radiation" tool of ArcGIS to obtain the annual solar radiation simulation of the Renca area (in Figure 13).

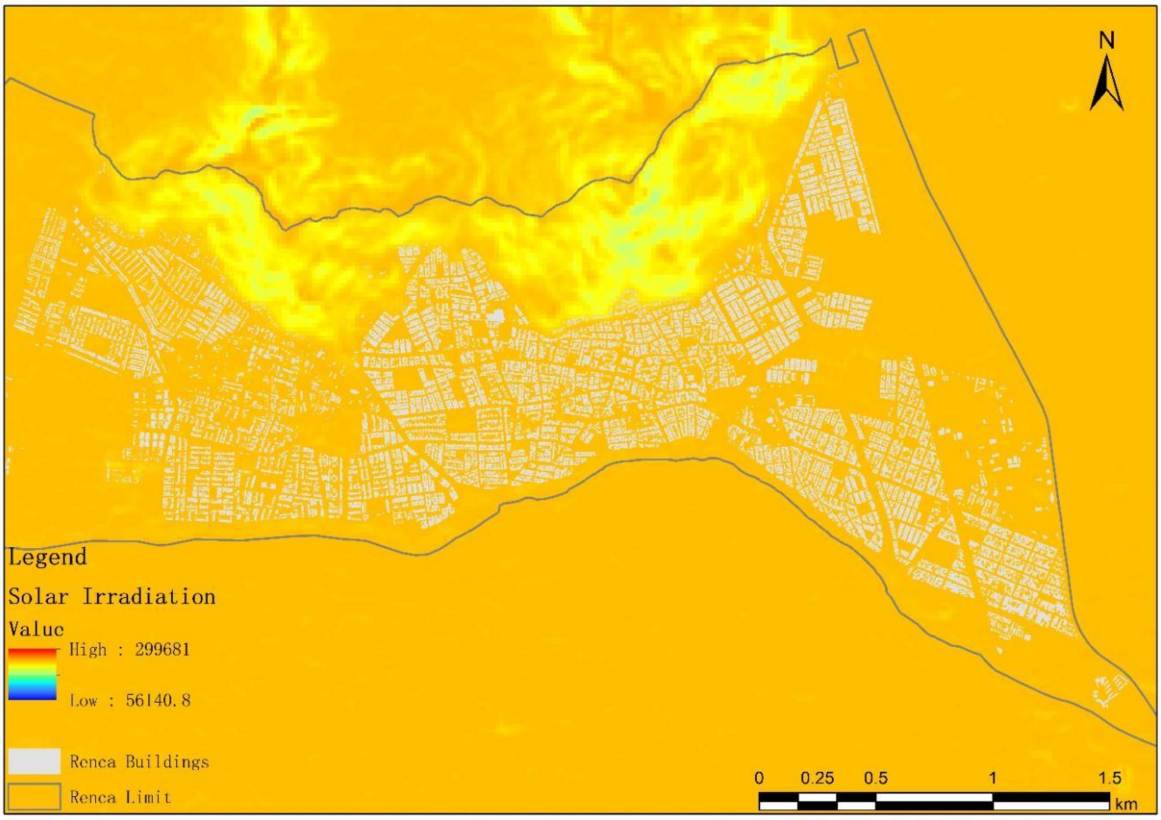


Figure 13: Annual Solar irradiation simulation of the municipality Renca (DEM in 2011 with the accuracy 30m × 30m)

The northern part of Renca city is covered with hills, and most of the city buildings, especially the city residential buildings, are 1-3 stories, and most of them are 1-2 stories, as can be seen in Figure 13, where the DEM file gives good results.

To create a data table associated with the image, it is necessary to convert the raster file into a shapefile, use "Conversion Tools" to convert all the monthly data, and then add the monthly data to obtain the annual cumulative solar radiation in the Renca area.

Annual cumulative radiation (Wh/m^2, sum of the monthly), to convert in kWh/m^2 (divide the value by 1000). Finally, the annual solar irradiation is 1,899.6 kWh/m^2 in Renca. Chile has one of the highest solar potential in the world, through the calculation of renca city, the solar irradiation value in the Renca area also is high and suitable for the use of solar energy.

4. Discussion (technical and economical feasibility)

4.1 The conclusion from project energy data

Firstly, the energy savings from the four different interventions are compared and contrasted. The data is made into bar charts (Figure 12) to give a good visualization of the results. According to the bar chart, this has an interesting phenomenon the measure of changing the floors saves very little energy, compared to the other three interventions. Besides, wall intervention and roof intervention should be considered. Because they save a huge amount of energy.

The second point Is that payback time also requires comparative analysis, as it combines the amount of energy saved with economic factors. The bar chart (Figure 13) below shows the data directly. This table gives the exact opposite result to the previous one, with the window, wall and roof interventions paying for themselves very quickly. However, the floor intervention takes upwards of 115 years. Clearly, this is not in line with sustainable urban development in Chile.

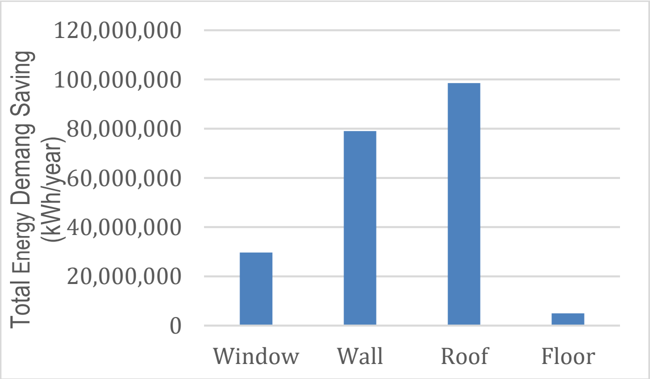


Figure 14. Total energy saving with four different interventions

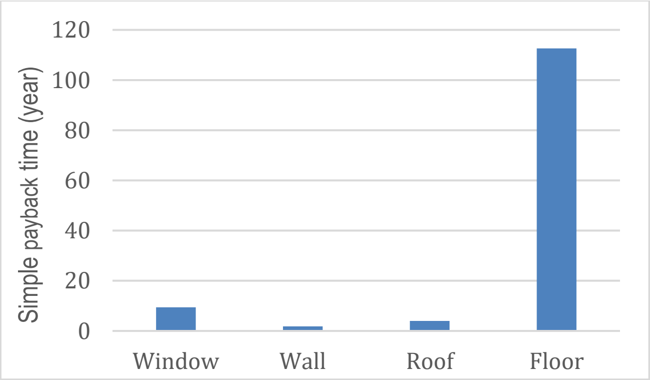


Figure 15. Payback time with four different interventions

Besides, in international energy, the amount of carbon emissions is commonly used to measure energy. Therefore, it is necessary to calculate the carbon emissions saved by the site through different interventions. For these, the data also need to be compared (Figure 14). It is clear from the bar chart that the roof intervention reduces carbon emissions by a very large amount, almost twice times as much as the window intervention. And the floor interventions reduce carbon emissions very little, compared to the other three. The roof and wall interventions are therefore the more recommended choice in terms of carbon emissions.

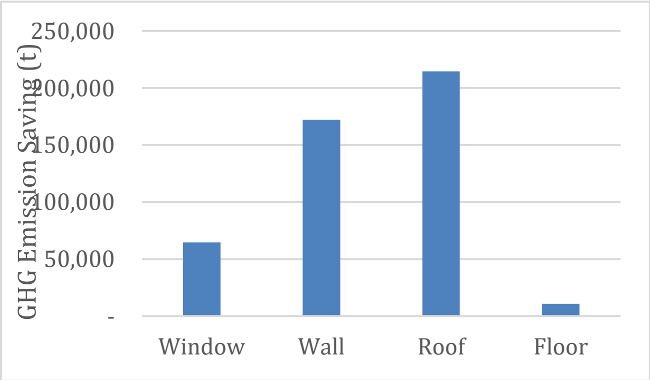


Figure 16. The relationship between GHG emission saving and interventions

To sum up, combined energy savings, payback time and reduced carbon footprint, the interventions strongly recommended for the Renca area are roof and wall replacements and, to a lesser extent, wall replacement. The least recommended intervention is the replacement of window and floor.

4.2 Policy suggestions

This section focuses on five main perspectives: save energy with energy efficiency measures, using clean energy, people awareness and smart technologies， reach energy (self-sufficiency) and climate (self-consumption with RES) target, improving energy conversion rates and ways to save energy.

a. **Save energy with energy efficiency measures**

First, increasing the energy conversion rate is an important point. Reducing the heat loss in energy conversion reduces the economic pressure and the number of carbon emissions. For example, a good way to utilize set-up losses is to use the energy lost from heat in the heating system during the heating season. As Chile is a long strip of country and the transportation of electricity is a problem. This is because it can be long from where the electricity is produced to where it is used. Therefore, extra high voltage technology should be considered so that the loss of electricity can be reduced.

Technical synergies have been further analyzed in a recent working paper by the International Renewable Energy Agency (IRENA) and the Copenhagen Centre on Energy Efficiency (C2E2) to demonstrate the effect renewable can have on energy efficiency [28]. The increased deployment of renewable could reduce energy intensity in some countries by 5 to 10 per cent by 2030, compared to business as usual. When energy efficiency and renewable energy potentials are considered in parallel, total global energy demand could be reduced by 25 per cent by 2030.

b. Use clean energy-solar energy

- Electrical Energy

Chile is rich in solar and wind energy. But Santiago is landlocked and most of the wind energy is in the coastal areas. Therefore, the clean energy source for Renca is mainly solar energy.

Due to the strong solar radiation in the Renca area, photovoltaic panels (PV roofs) are a clean source of energy well suited to the Renca region. In order to calculate the photovoltaic potential, it is necessary to compare the various solutions most widely used on the market, each technical solution has a specific efficiency and panel size: monocrystalline silicon (MC), polycrystalline silicon (PC) and thin film (FS).

Calculation of photovoltaic energy production for different solutions according to two formulas:

$$E = PR\ Hs\ S\ \eta\ [22] \qquad (22)$$

(22 – equation to use for the calculation of the energy that can be produced on every building)

Where:
E is the electrical energy produced by year [kWh/a];
PR is the performance index of the system ($\approx 0,75$).
H_s is the cumulative annual solar radiation [kWh/(m^2a)];
η is the conversion efficiency, that is the ratio of incident solar energy to produced energy:
• Monocrystalline silicon: $\eta_{MC}=20\%$
• Polycrystalline silicon: $\eta_{PC}=16\%$
• Thin film: $\eta_{FS}=10\%$.
$\eta = Wp/(S*I_{stc})$ (23) where:
*Wp is the peak power output of the panel (equal to 1 kWp) **
S is the working surface of the panel [m^2]
I_{stc} is the tested irradiation under standard conditions (1 kW/m^2)

Consider that the surface area of panel "S" is about the 40% of the roof area.
** for 1 kWp installed, corresponding 6-8* m^2 *of panel surface*
With the combination of the relations (1) and (2) the electrical energy yearly produced is obtained:

$$E = PR\ Hs\ Wp/Istc \tag{24}$$

(24 – equation to use to compare the calculated energy that can be produced with 1 kWp and the PVGIS values)

Calculate the annual energy production of different materials according to the formula on ArcGIS. On this part, only consider the residential building the surface area of the panel is about the 40% of the roof area (in Figure 17).

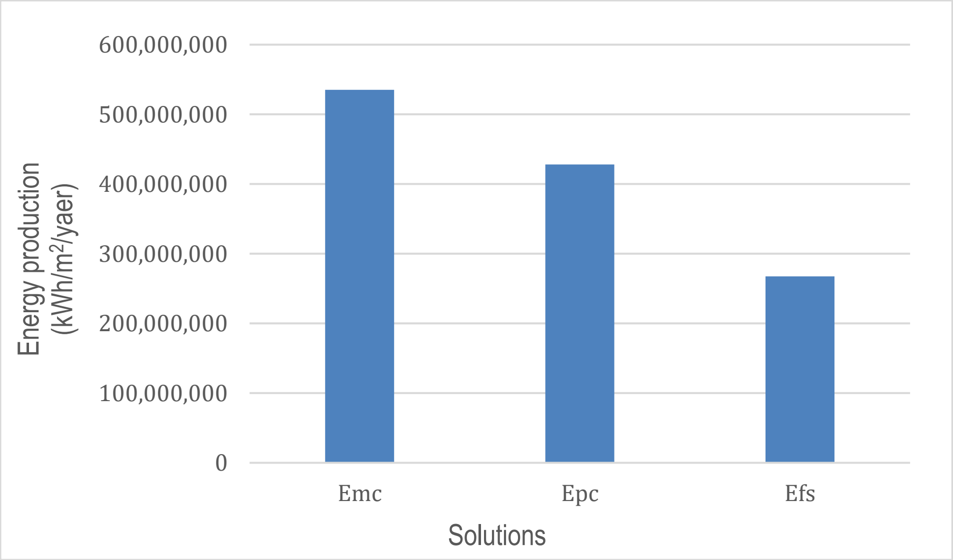


Figure 17: Annual energy production of different solution

According to the chart (Figure 17), it can be easily seen that MC produces the highest energy per year, followed by PC, FS. The following energy production maps can be exported in ArcGIS according to Renca residential buildings by use solution monocrystalline silicon MC (Eq.22) (in Figure 18). The energy produced by PV roof-integrated technology with 1kWp on residential buildings in Renca (Eq.24) (in Figure 19).

According to Figure 18 and Figure 19, it can be seen that the solar potential is higher in the east and southeast of the Renca area, and according to Figure 19, when energy production is with 1 kWp, not consider the roof area. It can be seen that the energy production does not change significantly, and does no a distribution pattern. Finally, the energy production it can be observed that the area of the roof has an impact on solar energy production.

According to the calculation results and the energy distribution map, the urban area of Renca can consider installing photovoltaic panels in the south and southeast of houses with larger roof areas.

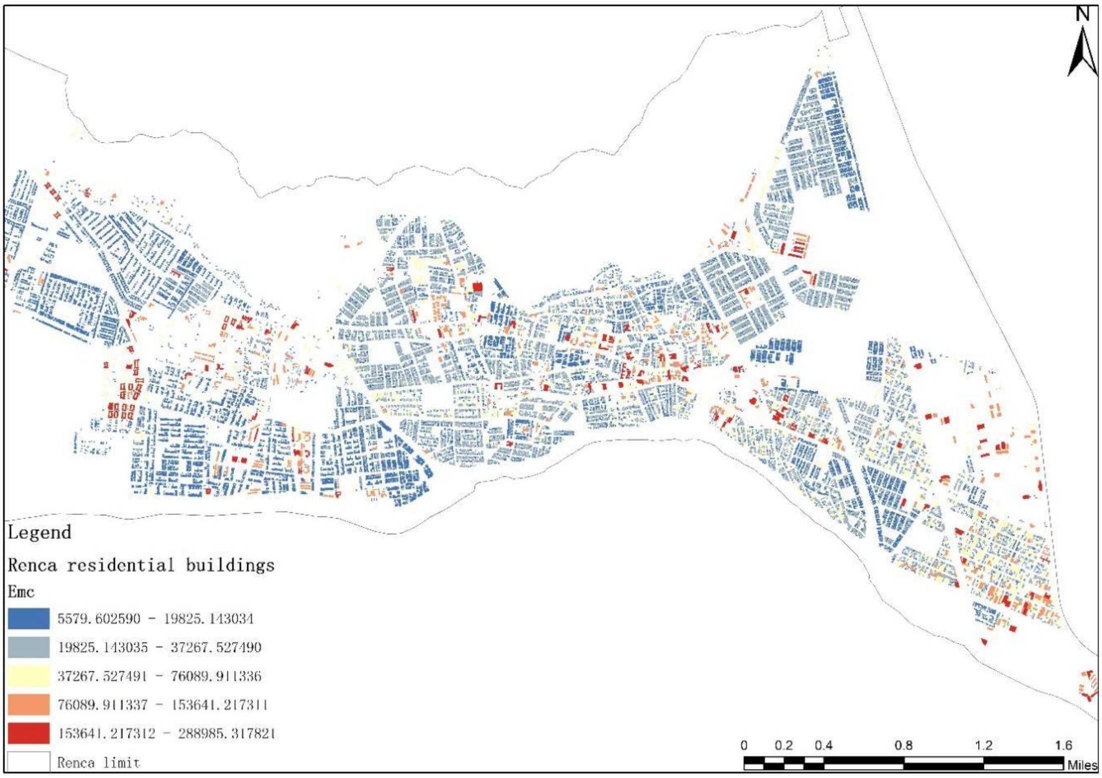


Figure 18: Energy produced by PV roof-integrated technology on residential buildings in Renca from eq22 (considering 40% of roof surface)

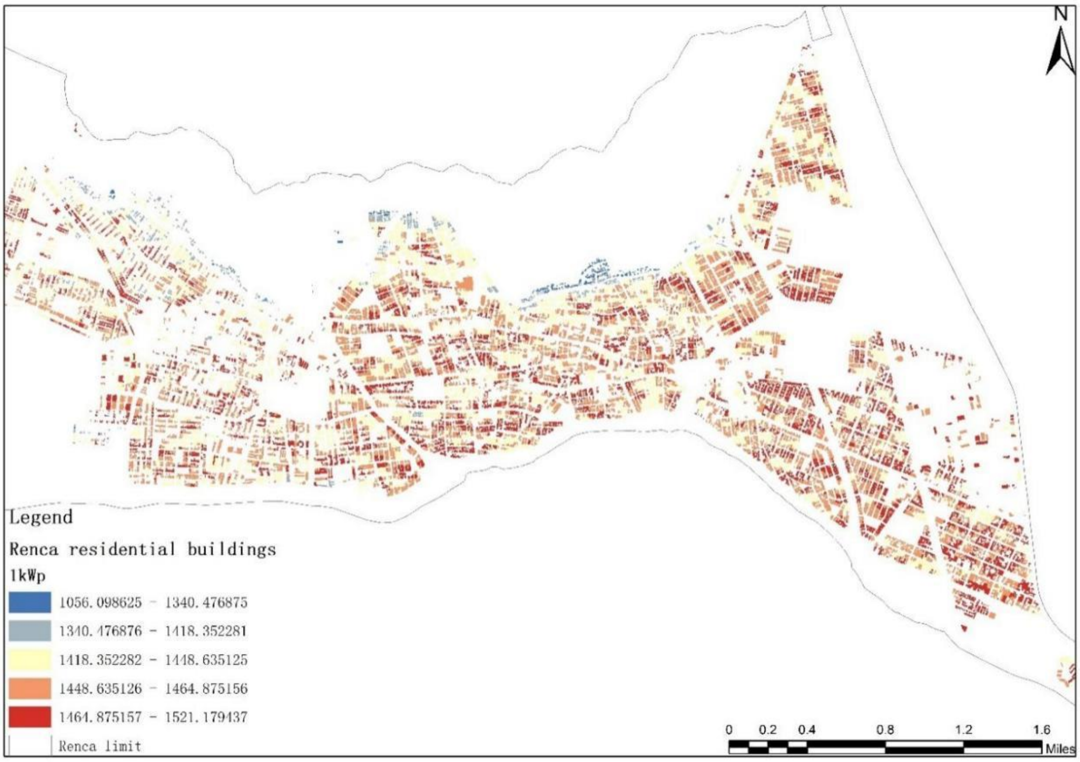


Figure 19: Energy produced by PV roof-integrated technology with 1kWp on residential buildings in Renca from eq24

With an average of 3.1 people per household and an average annual consumption of 7,869 (kWh/year) per household [2], it is possible to calculate an average annual consumption of 2,538 (kWh/year) per person, and based on the energy production of the three solutions, it is possible to caculate the number of people that can be used by each solution. The population of Renca city residents is 146,341 (Manzana Excel data 2022), among these three solutions, that solutions of Emc and Epc is sufficient for residential use, the energy produced by Efs is not enough to meet the needs of the population of Renca for one year(Table 17).

	Emc	Epc	Efs
Energy production ($kWh/m^2/year$)	535,150,190.8	428,120,152.7	267,575,095.4
Use of population	210,855.0791	168,684.0633	105,427.5396

Table 17: Population analysis of the use of energy produced by the three solutions

- Thermal Energy

Values for assessing the heat energy produced by solar thermal systems, In this section, the aim of this simulation process is to evaluate the energy performance of a solar thermal system used to produce domestic hot water. The solar collector thermal efficiency is the most useful parameter in order to predict the yearly energy produced and to choose the best collector with reference to the system location and boundary conditions.

$$\eta_{coll,m} = \eta_o - a_1 \cdot x - a_2 \cdot I \cdot x_2 \qquad (25)$$

$$x = T_m - T_a / I = \Delta T_m / I \; [\, m^2 K/W \,] \qquad (26)$$

The mean fluid temperature(T_m) 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:

$$T_m = (T_{IN} + T_{OUT})/2 = 30\ °C = 303{,}15K. \qquad (27)$$

$\eta_{coll,m}$: solar collectors' monthly efficiency

η_o : optical collector efficiency;

x (m^2K/W): reduced temperature difference;

a_1 (W/m^2K): heat loss coefficient;

a_2 (W/m^2K^2): temperature dependence of the heat loss coefficient;

I [W/m^2]: solar irradiance that can be calculated by dividing the solar irradiation by the hours of light in each month: $I = H_{h,m}/h_m$ (W/m^2) (PVGIS) [24]

Then, after this calculation, the last parameters necessary for the $\eta_{coll,m}$ evaluation are the optical and heat losses coefficient η_o , a_1, a_2 described in the previous section.

In this section, that these tree different solar collector types (eta1[29], eta2[30], eta3*11300-4) are selected for calculation and analysis(see Table 18). The quality of a solar collector strongly depends on η_o, a_1, a_2 coefficients.

Description	eta1	eta2	eta3(11300-4)*
Optical collector efficiency η_0	0.70	0.785	0.90
Heat loss I order a_1 (W/m^2k)	1.15	3.594	1.80
Heat loss II order a_2 (W/m^2k)	0.013	0.014	0.008

*Table 18: Numerical example of a value to evaluate the thermal energy generated by a solar thermal system(eta 1 [29], eta2[30], *eta311300-4)*

Then, knowing the monthly values of the solar collectors' efficiency and the solar collector gross area values, it is possible to evaluate the monthly thermal energy by applying this equation (Table 19):

$$Q_u = S \cdot H_{h,m} \cdot \eta_{coll,m} [kWh] \tag{28}$$

	Global solar irradiation (kWh/m^2)*	Average air temperature (°C)	h/day	h/month	I (W/m^2)	X (m^2K/W)	X^2	eta1	eta2	eta3
January	281.86	21.5	14.52	450.12	626.19	0.0136	0.00018	0.68	0.73	0.87
February	212.11	20.5	13.83	387.24	547.75	0.0173	0.00030	0.68	0.72	0.87
March	201.74	18.8	12.8	396.8	508.42	0.0220	0.00049	0.67	0.70	0.86
April	136.99	14.6	11.63	348.9	392.63	0.0392	0.00154	0.65	0.64	0.82
May	86.85	10.8	10.37	321.47	270.17	0.0711	0.00505	0.60	0.51	0.76
June	71.63	8.6	9.87	296.1	241.91	0.0885	0.00783	0.57	0.44	0.73
July	92.21	8.4	9.78	303.18	304.14	0.0710	0.00504	0.60	0.51	0.76
August	111.56	9.8	10.38	321.78	346.70	0.0583	0.00339	0.62	0.56	0.79
September	146.76	11.6	11.38	341.4	429.88	0.0428	0.00183	0.64	0.62	0.82
October	204.83	15	12.5	387.5	528.59	0.0284	0.00081	0.66	0.68	0.85
November	234.01	17.4	13.62	408.6	572.71	0.0220	0.00048	0.67	0.70	0.86
December	277.03	20	14.4	446.4	620.59	0.0161	0.00026	0.68	0.72	0.87

Table 19: Three different type of solar collectors monthly efficiency

As shown in Table 19, all the parameters needed to evaluate the efficiency of the solar collector are determined. The results for the different three efficiencies can now be compared according to the bar chart (Figure 20).

Here type eta3 is an ideal energy efficiency that is too idealized and too different from the real data, so eta3 is not considered in this analysis. Comparing the type eta1 and the type eta2, the type eta1 also has good energy efficiency in winter and the data is smooth throughout the year, so the type eta1 is considered to be the most effective efficiency.

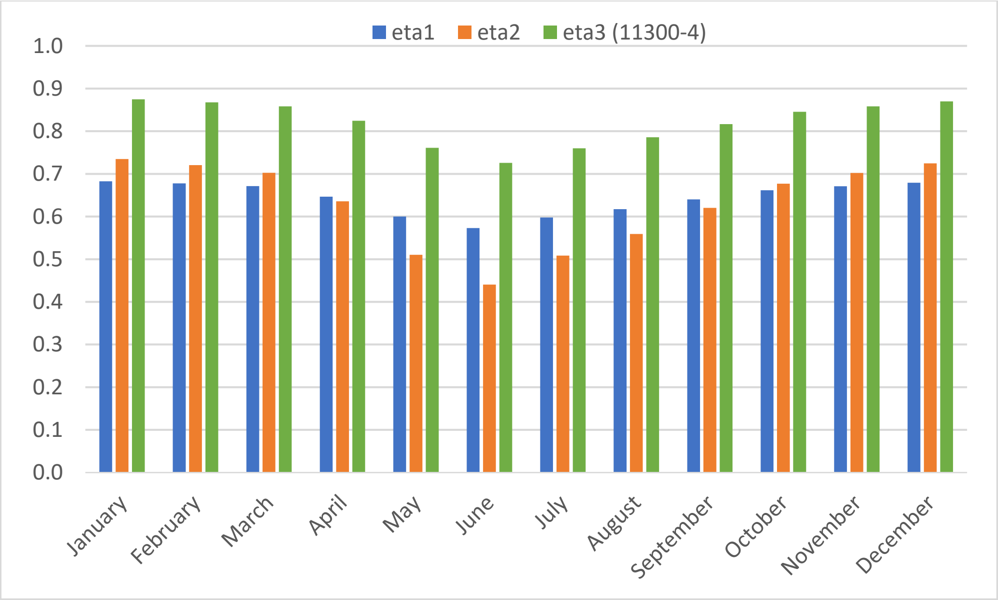


Figure 20 Three results with different solar collector efficiency

Now using type eta1 solar collector monthly efficiency, 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 (Table 20):

$$Q_{u,TOT} = \sum^{12}{}_{i=1} Qu,i \ \ [kWh] \tag{29}$$

	40 % of the roof area (m^2)	Global solar irradiation (kWh/m^2)*	eta1	Energy production ($kWh/m^2/month$)	Monthly thermal energy (kWh)
January	1,839,109	281.86	0.682889739	192.48	353,990,391
February		212.11	0.677912751	143.79	264,449,278
March		201.74	0.671459038	135.46	249,125,957
April		136.99	0.647042079	88.64	163,015,473
May		86.85	0.60053374	52.16	95,921,216
June		71.63	0.573658433	41.09	75,571,105
July		92.21	0.598385611	55.18	101,476,762
August		111.56	0.617695968	68.91	126,733,290
September		146.76	0.640538151	94.01	172,886,126
October		204.83	0.661832678	135.56	249,315,461
November		234.01	0.671095614	157.04	288,819,330
				Global useful thermal energy (kWh)	2,487,437,700

Table 20: The monthly thermal energy and the global useful thermal energy (kWh)

The daily pro-capita energy consumption is for domestic hot water:

$$Q_{u,d} = V \cdot \rho \cdot c_p \cdot \Delta T = V \cdot \rho \cdot c_p \cdot (T_{OUT} - T_{IN}) \tag{30}$$

$V = 50 - 70\ l/d$ *is the daily volume of water consumed by a single person (consider 70)*
$\rho = 1\ kg/l$ *is the water density*
$cp = 4.186\ kJ/kgK$ *or* $1.163\ Wh/kgK$ *is the water specific heat*

According to the Manzana excel data [9], the residential population of Renca is 146,341. Calculated the daily pro-capita energy consumption for domestic hot water according to the formula (30) is 2.44kWh/d. Annual pro-capita energy consumption is 890.6kWh/y. Then using global useful thermal energy 2,487,437,700kWh, it is possible to calculate how many people can be used throughout the year, the result of the people number is 2,792,990.

This section shows the energy production from the conversion of photovoltaic panels into electricity and thermal, both of which are sufficient for the residents of the city of Renca to live. PV panels can be considered for installation within reasonable limits.

c. People’s Awareness and smart technologies

The substitution of energy awareness into people's lives, the guidance of campuses, the development of community rules for residents' lives, government policies, the restrictions on travel by the relevant authorities, and especially the city's plans to renovate energy-intensive buildings such as stores.

The introduction and use of new technologies, while respecting high conversion rates and low costs, these reductions will be achieved in part through increased implementation of electrification technologies, increased deployment of modern, more efficient stoves, and accelerated transition to solar and wind energy, which are more efficient than technologies requiring thermal conversion. In many developing countries, efficiency measures will also be needed in off-grid hybrid systems and distributed renewables.

d. Reach energy (self-sufficiency) and climate (self-consumption with RES) targets

Retrofitting energy-intensive buildings to make the most of Chile's natural resources. For example, install fans and solar photovoltaic panels on the roof to supply clean energy to meet the electricity needs of indoor air conditioners, office equipment, and exterior walls. Heat recovery systems and electric energy storage systems can be installed to achieve energy self-sufficiency and intelligent regulation, and achieve zero carbon emissions. Recyclable, removable and mobile materials can be used.

Using renewable energy technologies. Technical synergies have been further analyzed in a recent working paper by the International Renewable Energy Agency (IRENA) and the Copenhagen Centre on Energy Efficiency (C2E2) to demonstrate the effect renewables can have on energy efficiency [26].

The increased deployment of renewables could reduce energy intensity in some countries by 5 to 10 per cent by 2030, compared to business as usual. When energy efficiency and renewable energy potentials are considered in parallel, total global energy demand could be reduced by 25 per cent by 2030.

e. Improve energy sharing with energy communities

Finally, the government should encourage energy conservation in all regions. New policies should be created. For example, the creation of a carbon market. The carbon market operates by encouraging companies with low abatement costs to exceed their abatement targets and sell the remaining carbon credits or GHG emission reductions to companies with high abatement costs through trading, helping companies with high abatement costs to achieve the set abatement targets and effectively reducing the abatement costs of achieving the targets.

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