Potential for producing photovoltaic and solar thermal energy in the Mendoza area (AR)

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Abstract
Argentina is known for its outstanding solar energy resources at a time when the world is making great efforts to develop new energy sources. After that, Argentina's Ministry of Economy approved the 'Guidelines for an Energy Transition Plan to 2030' which call for structural change in the systems of supply and use of energy. The target site is the Mendoza Metropolitan Area, an urban synthesis consisting of 6 components. With the support of ArcGIS, this study proposes a research framework for the assessment of the geospatial potential and feasibility analysis of residential rooftop PV systems. The calculations show that energy production is expected to be very abundant if large renewable energy installations are carried out in the area.

1. Introduction

The vulnerabilities and sensitivities that accompany climate change have long been a hot topic. One notable phenomenon is the sharp increase in energy demand in countries under extreme climatic conditions, which has led to frequent large-scale power cuts. As one way of increasing resilience and reducing carbon emissions, sustainable energy in Argentina needs urgent development. According to the latest climate report of The World Bank, Argentina can attain more robust economic growth by transitioning to a low-carbon economy due to vast renewable energy resources [1]. Solar energy is the primary green energy source available to cities and it often relies on rooftop photovoltaic technology. Thanks to different incentives around the world, the cost of photovoltaic modules is falling, which makes solar technology attractive and acceptable also in developing countries. Nevertheless, the potential for solar energy development varies considerably with time, scale, and building form. Effective development, therefore, requires a high level of knowledge of local conditions.

In terms of energy demand, Argentina is the third largest electricity consumer in Latin America, after Brazil and Mexico. However, solar energy only occupied one percent of total energy production in 2021. Sixty percent of electricity is generated from fossil fuels. According to the latest Climate Action Tracker report, Argentina's nationally determined contribution (NDC) is judged to be highly insufficient [2]. This indicates, to some extent, that clean energy is a low priority in Argentina's future development plans. In order to stimulate political reform in Argentina in the area of decarbonization, the Inter-American Development Bank has provided a loan of US$500 million. Using the loan, Argentina plans to increase the number of renewable energy projects it supports under the Green Productive Development Plan from 17 to 160 by 2024.

Nowadays, there is currently a large gap between Argentina's vast solar resources and the scale of current deployment [3]. Due to geographical factors, the central and northern parts of Argentina are ideal locations for solar energy development. If the Mendoza region can overcome the challenges, it will make significant progress in renewable energy generation. This article is therefore based on GIS data provided by Mendoza Conicet with the aim of calculating the photovoltaic and solar thermal energy potential of the Mendoza region.

2. Literature Review

Research on photovoltaic systems has been going on for some years and is relatively mature. The early case for the sustainable energy contribution of photovoltaic systems was studied in 2003 in Italy[4]. We need to constantly update the calculation of the economic benefits since it is influenced by climate, population, roof slope, PV panel material, and many other factors. Thanks to technological developments, researchers have been attempting many new methods to improve accuracy and ease of use in recent years (Table 1). The range of simulations available also extends from a single building to an entire city.

Authors	Origin	Purpose	Title	Source	Findings
Ubertini and Desideri (2003)	Italy	To install a photovoltaic plant at a high school in central Italy.	Performance estimation and experimental measurements of a photovoltaic roof	Journal of Renewable Energy	The actual power generation is not significantly inaccurate to the simulated data.
Mutani and Vicentini (2013)	Italy	To use the solar irradiation models present in scientific literature to calculate the incident solar energy	Evaluating the potential of integrated solar photovoltaic systems on the roofs of buildings using GIS open source techniques	8th ENERGY FORUM	Areas with a low proportion of houses to buildings are more likely to meet electricity demand than areas with a high proportion
Mutani and Casalengo (2018)	Italy	To implement energy policies based on the real buildings heritage but also to increase transparency and awareness of citizens	The effect of roof-integrated solar technologies on the energy performance of public buildings : The case study of the City of Turin	International Telecommunications Energy Conference (INTELEC)	ArcGIS-based assessment methods can help monitor buildings and can also be used as a tool for decision support.
Kouhestani, Byrne, Johnson, et al. (2018)	Canada	To estimate rooftop photovoltaic potential in an urban environment based on ArcGIS and LiDAR	Evaluating solar energy technical and economic potential on rooftops in an urban setting: the city of Lethbridge, Canada	International Journal of Energy and Environmental Engineering	New methods for calculating roof slope and shading using ArcGIS
Fakhraian, Forment, Dalmau, Nameni and Guerrero (2021)	Spain	Make a systematic review of the PV potential calculation methods that are currently in use.	Determination of the urban rooftop photovoltaic potential: A state of the art	Journal of Energy Reports	Consensus of the previous studies on the use of meteorological data as well as statistical data
Mutani and Todeschi (2021)	Italy	To investigate the benefits, costs, self-sufficiency and self-consumption, of photovoltaic technologies with different roof orientations.	Optimization of Costs and Self-Sufficiency for Roof Integrated Photovoltaic Technologies on Residential Buildings	Journal of Energies	The dimensions, the types of consumer and the orientations of buildings affect energy self-sufficiency
Bragagnolo, Taretto, and Navntoft (2022)	Argentina	To understand solar energy status in Argentina and the drivers that can impact its future development	Solar Energy in Argentina	Journal of Solar	When given the right financial stability conditions, a public–private RE policy leading to PV growth could be implemented successfully in Argentina

Table 1. Findings of the reviewed sources

Geographic Information Systems (GIS) provide excellent solutions for both spatial surveys and data analysis. The digital terrain model (DTM) is frequently used as an input data for extracting urban features and distinguishing environmental shadows. According to the statistic, the error rate based on this method is usually low [5]. The most straightforward method of calculation using ArcGIS is to use the DSM and the 'area solar radiation' tool to generate annual solar irradiation images [6]. Flexible use of the tools in the software can promote diversity in research. For example, the 'Aspect' and 'Calculate Polygon Main Angle' tools are used to distinguish roof orientations to assess the impact on potential [7]. Use the average maximum technique to generate the steepest fall from each cell to its eight surrounding cells as a method to analysis rooftop slopes [8]. Also, ArcGIS hillshade capability was employed to generate a shaded relief based on the local illumination angle (sun’s relative position) and shadows [8].

The data source and its accuracy are also important steps in determining the PV potential and economic benefits of the city. For example, the data from weather stations are real data measured at a specific point in the territory, therefore, depending on the location of the weather station, very different results may be obtained [7]. Some scholars use the Photovoltaic Geographical Information System (PVGIS) to directly capture solar radiation at a specific location [9-10]. In many articles, PVGIS is also often used as a comparison data to determine errors due to its convenient and fast features [7; 11].

Renewable energy is not currently cost-effective in all locations. It is therefore important to determine the potential for solar photovoltaic power [8]. Investors will only consider rooftop PV installations if these facilities are economically reasonable.

3. Methodology

The entire process is divided into six main phases:

- Survey and analysis of the current situation of the selected case to generate a dataset. This includes its architectural characteristics, DTM, and climate conditions at different altitudes (containing temperature, atmospheric transparency, Link turbidity coefficients, etc.). The higher the accuracy of the selected DTM, the more accurate the results, but also the more time-consuming [11].
- The solar radiation tools in GIS were used to generate solar radiation values in Wh/m^2 for 12 months. On this basis, the annual average solar irradiation values were calculated. At the same time, assigning these values to each building provides a more intuitive map.
- When calculating the solar production potential, the efficiency varies depending on the material of the solar panels, so it is necessary to calculate the productivity separately depending on the situation.
- The supply of hot water for domestic use depends on the production of solar thermal energy. Calculations of thermal potential require the efficiency of the collector at different external temperatures.
- Check whether the simulated production results meet the annual energy consumption of the study area.
- Compare the various data of the study area with the EU in order to deduce weaknesses and strengths.

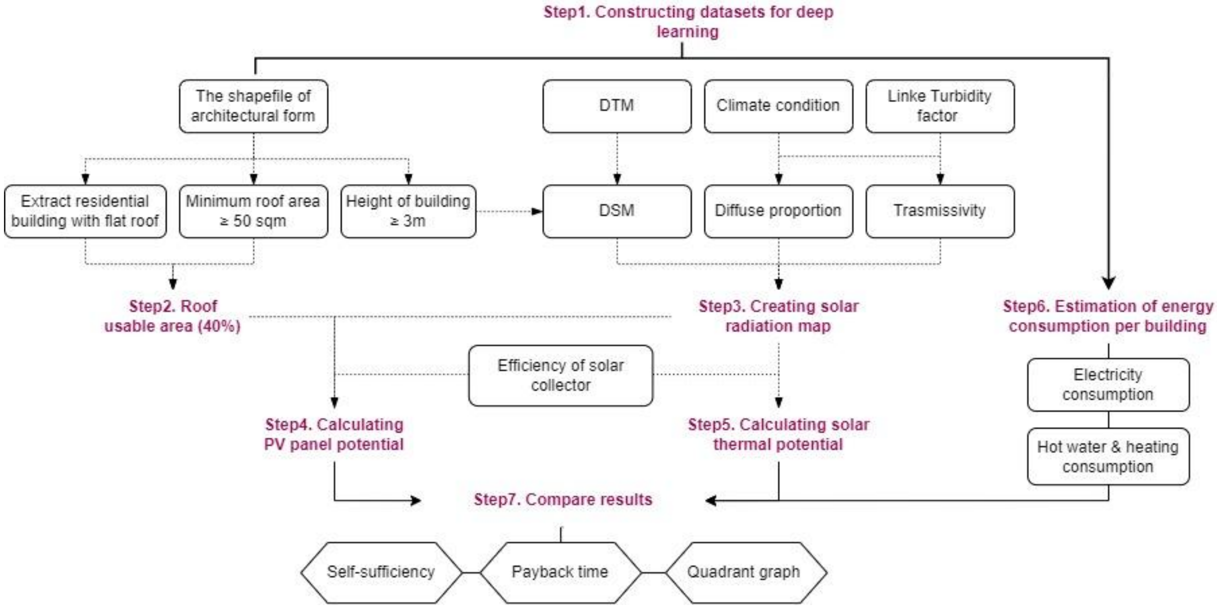


Chart 1. Flowchart of research

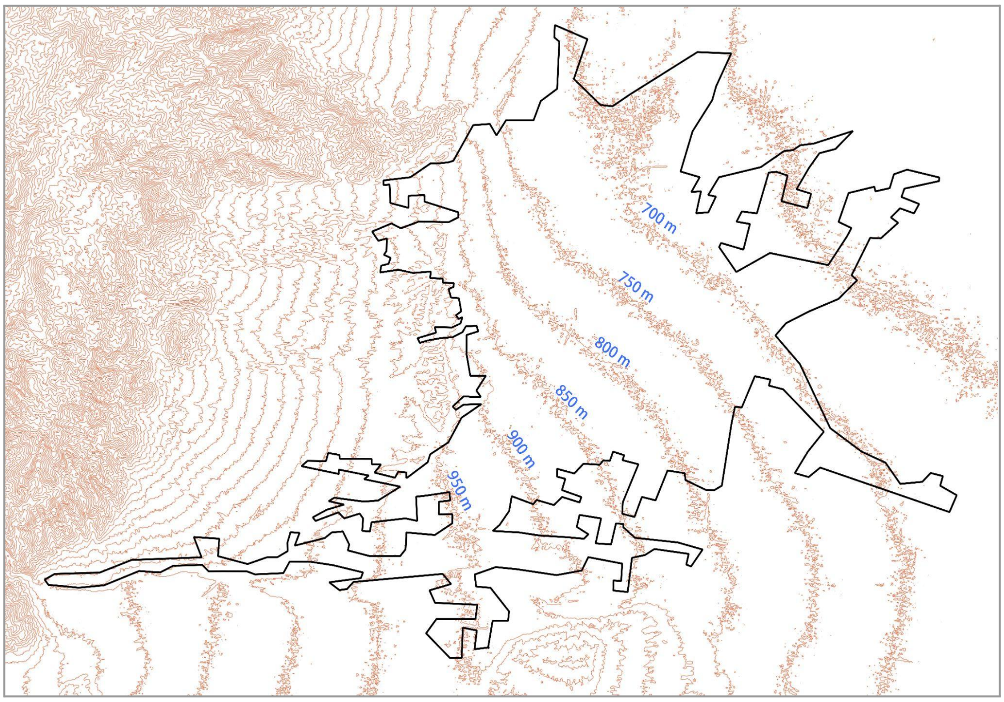
4. Data collection and preparation

4.1 Current situations

The Mendoza Metropolitan Area (MMA) is an urban complex with a population of close to one million, located in the dry lands of west-central Argentina. The MMA is the result of an integration process in which six municipalities were physically integrated into one urban synthesis.

Mendoza has hot summers and cool winters. It has about 300 sunny days per year. Precipitation amounts to 235 millimeters per year which is a low value. The main city reaches an average altitude of 874 meters above sea level. The topography is high in the west and low in the east, with a maximum of 1,000 meters. Also, the MMA area is surrounded by steep hillsides to the west. The average daily solar radiation reaches 4.8 kWh per square meter, which shows that Mendoza has great potential for the installation of photovoltaic roof panels and is worth studying.

DTM contains the elevation data of the terrain in a digital format that relates to a rectangular grid. Vegetation, buildings, and other cultural features are removed. Mendoza Conicet offers DTM files with a precision of 30 meters and annual parameters of 2017. In general, the use of lower precision and older years will make the results less accurate [7].



Picture 1. Elevation map

4.2 Population

Based on census data from the National Institute of Statistics of Argentina (INDEC), the number of people and households in the MMA area can be obtained.

	Capital	Godoy Cruz	Guaymallen	Las Heras	Luján	Maipu	MMA
Population	110,993	190,632	283,803	202,436	118,761	171,776	1,078,401
Density [ab/km2]	3162	6758	3548	2946	1414	1870	1870
Households	39,136	57,375	79,770	53,978	32,233	46,569	309,061
Density [hou/km2]	1118	2207	1140	885	384	665	893

Table 2. Population and households in the six departmentos and MMA

4.3 Building data processing

Based on the study objectives and the associated methodology [6-7], it was possible to identify the range of buildings suitable for the installation of rooftop solar panels. In the shapefile documentation provided by Mendoza Conicet, there are 583,291 buildings in the MMA area. These buildings were extracted and categorized into four directions: region, building type, roof area, and height. Before doing so, it is necessary to unify the coordinate system of all files: POSGAR_1998. It's obvious that Guaymallen and Godoy Cruz regions have more residential buildings.

Residential Buildings 89.8%	Roof area ≥ 50 m² and height ≥ 3 m	Capital	Godoy Cruz	Guaymallen	Las Heras	Luján	Maipu
523788	215419	30617	46329	58355	33023	21036	26059

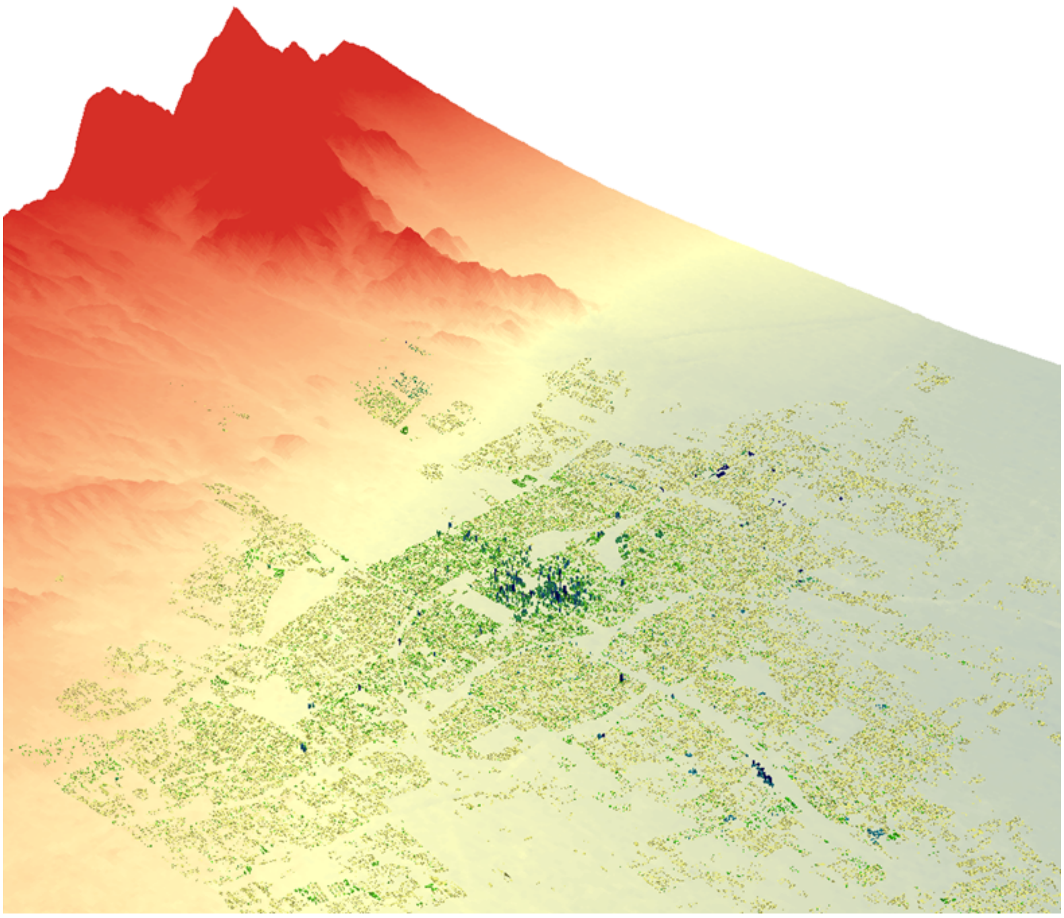
Table 3. Residential buildings in the six departmentos in Mendoza

Radiation decreases with increasing atmospheric distance, so high-rise buildings usually have higher radiation values. Statistics show that of the 215,419 available residential buildings in the MMA, the share of low-rise buildings is huge. Mid-rise occupies 7.3%. The percentage of buildings above 21m is only 0.1%.

Height = 3	6 ≤ h ≤ 9	9 < h ≤ 21	21 < h ≤ 30	30 < h ≤ 42	42 < h ≤ 57
196447 91%	15984 7%	702 0.3%	259 0.1%	45 0.02%	16 0.007%

Table 4. Number and percentage of different heights

Due to the effect of altitude on solar radiation, the height of the buildings had to be added to the original DTM raster map to form the Digital Surface Model. However, it does not include the slope of the roof due to the limitations of the unit. In terms of urban form, the tallest residential buildings are concentrated in the central area, namely the Capital Region.



Picture 2. Height distribution of buildings in 3D map

4.4 Weather data processing

Solar radiation traveling through the atmosphere is affected by topography and other surface characteristics and is finally received as direct, diffuse, and reflected irradiance components. In the photovoltaic geographical information system (PVGIS: https://re.jrc.ec.europa.eu/pvg_tools/en/), the monthly weather data of MMA can be obtained directly after entering the coordinate system and time.

The Linke turbidity factor (TL) expresses the degree to which light is attenuated by scattering. It was then a profitable way to assess the effect of aerosols. Higher values mean the atmosphere is cloudier and the light from the sky is attenuated more. The number of TL is equal to 1.0 for a perfectly transparent atmosphere and 3.0 as the average annual value for rural and urban areas [12]. The GeoTIFF file for the Global Link Factor is available on the SoDa website (https://www.soda-pro.com/help/general-knowledge/linke-turbidity-factor). The TL factor for Mendoza ranges between 3.5 and 5.5 throughout the year, with low values in winter and high values in summer. This confirms that the air is moist and rainy in the summer. In contrast, the winter months are less snowy and drier.

Atmospheric transmissivity(τ) is a critical factor in climatology. It influences the surface energy balance by determining the fraction of incoming solar radiation reaching the surface to the one at the top of the atmosphere [13]. Since only some weather stations can monitor τ, estimates of transmissivity are needed:

$$\tau = \left(\frac{G_{b,h}}{solar\ cost}\right)^{1/TL} \quad with \quad G_{b,h} = \frac{H_{b,h}}{Light\ hours} \times (1 - Diffuse)$$

$$H_{b,h}\text{: } direct\ solar\ irradiation\ on\ horizontal\ plane\ (b = beam)\ [Wh/m2\ ]$$

$$Solar\ constant\text{: } average\ extra\ atmospheric\ solar\ irradiance\ =\ 1367\ [W/m2\ ]$$

			kWh/m2/mo	[-]	°C				W/m2	[-]
Year	**Month**	**Days**	**H(h)_m**	**Diffuse**	**T2m**	**h/d**	**h/m**	**TL**	**Gbh**	**τ**
2020	Jan	31	260.6	0.17	25.4	14.07	436	5.24	490.0	0.82
2020	Feb	29	191.09	0.21	23.2	13.25	384	5.02	387.9	0.78
2020	Mar	31	185.02	0.19	21.8	12.28	381	4.44	393.6	0.76
2020	Apr	30	143.28	0.2	14.2	11.25	338	3.72	339.6	0.69
2020	May	31	110.61	0.19	10.2	10.42	323	3.56	263.8	0.63
2020	Jun	30	89.08	0.21	7.7	10.00	300	3.78	234.6	0.63
2020	Jul	31	113.8	0.25	5.4	10.20	316	3.63	284.3	0.65
2020	Aug	31	134.51	0.2	8.4	10.92	338	3.86	294.1	0.67
2020	Sep	30	175.5	0.17	13.1	11.90	357	4.46	388.4	0.75
2020	Oct	31	218.65	0.16	16.8	12.90	400	4.92	442.9	0.80
2020	Nov	30	235.91	0.18	20.2	13.83	415	5	454.8	0.80
2020	Dec	31	266.62	0.16	23.2	14.32	444	5.34	492.6	0.83

Table 5. Climate data from PVGIS. (H(h)_m: Irradiation on horizontal plane; H(i_opt)_m: Irradiation on optimally inclined plane; Hb(n)_m: Monthly direct irradiation on a plane always normal to sun rays; T2m: 24-hour average of temperature).

5. Solar radiation

5.1 Calculation method

The Regional Solar Radiation tool in ArcGIS can be used to generate radiation for an input raster file at a specific time. This tool uses Viewshed, SunMap, and SkyMap to overlay the raster map for the total radiation in wh/m². The total radiation ($Globaltot$) is calculated by:

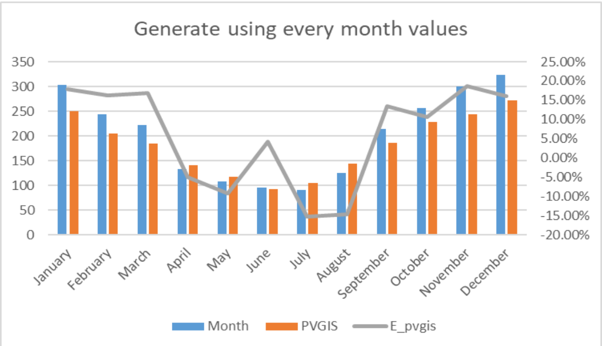
$$Globaltot \;=\; Dirtot \;+\; Diftot$$
$$Dirtot\text{: } direct\ radiation\ of\ all\ sun\ map\ and\ sky\ map$$
$$Diftot\text{: } diffuse\ radiation\ of\ all\ sun\ map\ and\ sky\ map$$

Due to the large size of the MMA, the DSM files are separated and associated climate values for each of the six departments. The remaining parameters are 7 of day intervals, one-hour interval, 32 calculation directions, 8 zenith divisions, 8 azimuth divisions, and a standard overcast sky(the diffused radiation varies together with the zenith angle). In order to separate accurately the energy performance of different months, 12 times simulations were run for all departments.

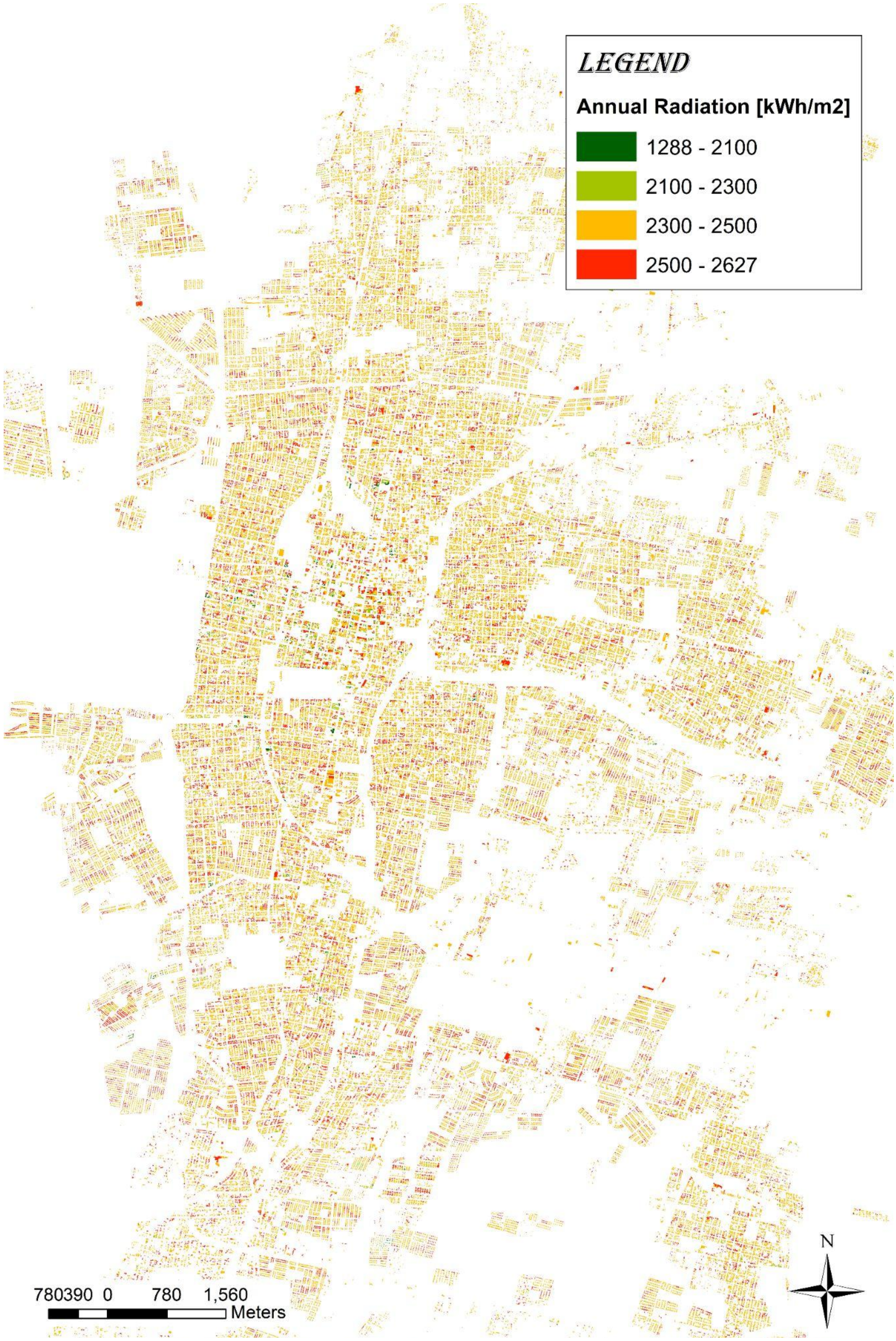
The values of the final radiation map show that the Las Heras area buildings have relatively lower annual radiant values, mostly in the 2100-2400 kWh/㎡. Maipu and Guaymallen area in the east has a slightly lower value, due to its lower elevation compared to the other areas. The Capital district is characterized by a high number of high-rise flats and commercial and residential buildings with radiation values above 2550 kWh/m2 compared to other districts. However, there are also a number of below-average buildings that are clustered together with high radiation; Lujan has more mid-rise buildings, so it is the second highest in average radiation of all the districts.

5.2 Comparison of results

Compared to the processing time of ArcGIS, PVGIS is a fast and simple tool. Its data results are considered to be reasonably accurate, although it is less sensitive to changes from month to month [7]. Summer time with the highest incidence of rain and clouds, so the irradiance indices can vary from the simulated results. Also, as can be seen from the chart, the error varies more significantly in the months when the seasons change (e.g. June, and November).



Charts 2. Comparison of monthly generated data with PVGIS



Picture 3. Annual radiation values for residential buildings [kWh/m²]

6. Energy production

6.1 Photovoltaic production

To calculate the photovoltaic potential, it is required to speculate numerous technological solutions, each of them having a different efficiency and panel size. The conversion efficiency means the ratio of light energy converted into electricity. Currently, the most popular technique on the market is Monocrystalline silicon. Monocrystalline cells are solar cells made from silicon crystallized into a single crystal with good heat resistance. Their efficiency is 15%–24%, but their manufacturing is complex and expensive. Considering that the efficiency of PV panels is also affected by air dust and aging, the final efficiency is assumed 20%.

The equation for the calculation of energy that can be produced on buildings' PV rooftops:

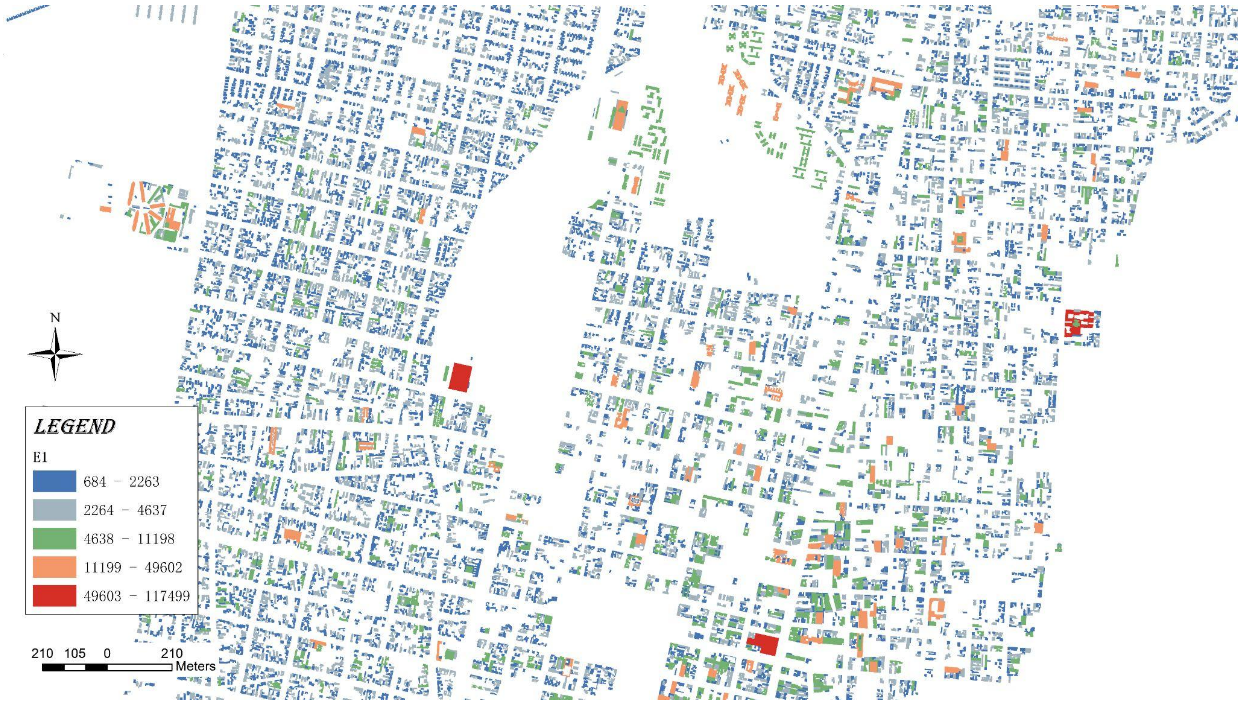
$$E = PR \cdot Hs \cdot S \cdot \eta$$

$$PR: \ the\ performance\ index\ of\ the\ system\ (\approx 0,75)$$

$$Hs: \ the\ solar\ radiation\ [kWh/(m^2 a)]$$

$$S: \ the\ flat\ roof\ surface\ of\ the\ panel\ [m^2]\ (40\%\ of\ roof\ area)$$

$$\eta: \ Monocrystalline\ efficiency\ (assumed\ 20\%)$$



Picture 4. Production in January for single buildings [kWh]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Capital	956	748	643	325	220	172	200	297	553	713	897	998
Godoy Cruz	1219	954	821	416	282	221	256	380	705	909	1143	1271
Guaymallen	1586	1241	1067	539	364	285	331	491	916	1183	1487	1654
Las Heras	822	642	552	278	188	147	170	253	473	612	771	858
Luján	636	497	427	216	146	115	133	198	366	474	597	664
Maipu	576	451	387	195	132	103	120	178	332	429	541	602

Table 6. Daily production in each month [GWh]

6.2 Thermal production

Solar thermal system uses the energy from the sun to heat up water to use in the home. Mainly produces hot water and heating. The solar collector is the main working structure in a thermal system. It works by reflectors capturing and focusing sunlight onto an optical receiver, then transferring this heat to a thermo-vector fluid. Estimating the potential is, therefore, a matter of calculating how much of the incident solar energy is converted into usable thermal energy (Q_u).

Collector efficiency(η_{coll})is a key factor in the calculation of the available thermal energy. It was influenced by optical receiver efficiency(η_o), reduced temperature difference(x), heat loss coefficient(a_1), and temperature dependence(a_2). Optical receiver efficiency does not depend on the mean fluid temperature, but only on the optical properties of the material. Meanwhile, the heat loss coefficient also represents the quality of the collector. High quality corresponds to a low value and low quality to a high value.

There are two main types of solar collectors on the market today, each with its own advantages and disadvantages. Flat plate collectors tend to be more cost-effective due to their low cost and relatively easier installation. However, it has strict requirements for the angle of the collector and has a higher heat loss coefficient. In the case of vacuum tubes, the efficiency remains optimal regardless of the angle of installation. For further study, this product has been selected as an example according to type:

Collector type	Name	Manufacturer	η_o $[-]$	a_1 $[\frac{W}{m^2K}]$	a_2 $[\frac{W}{m^2K^2}]$
Flat-Plate HQ	VFK 140VD	Vaillant GmbH	0.855	2.1698	0.039

Table 7. Relevant data for collector

This study used the formula for calculating efficiency from *European Standard EN 12975-2*:

$$\eta_{coll} = \eta_o - a_1 \cdot x - a_2 \cdot I \cdot x^2 \quad with \quad x = \frac{T_m - T_a}{I} \, [\frac{m^2K}{W}]$$

$$T_m : mean\ fluid\ temperature\ (assumed\ at\ 30°C)$$

$$T_a : the\ external\ air\ temperature\ of\ each\ month$$

External temperature and daily solar irradiance (I) depend on local conditions and the data generated by Arcgis are used directly here. Seasonal temperature variations in the Mendoza area affect Collector efficiency, but this difference is very small. Incident irradiation has a greater impact on the final production, being at its peak in summer and dropping significantly in winter.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Efficiency	0.854	0.853	0.853	0.852	0.850	0.847	0.847	0.850	0.852	0.853	0.854	0.854

Table 8. Monthly collector efficiency

The monthly thermal energy production in the MMA area can be calculated as follows:

$$Q_u = A_c \cdot H_{sol} \cdot \eta_{coll}$$

$$A_c : 40\%\ of\ the\ roofs\ surface\ [m^2]$$

$$H_{sol} :\ monthly\ solar\ incident\ irradiation\ from\ ArcGIS [\frac{Wh}{m^2}]$$

From the table, it was concluded that Guaymallen and Godoy Cruz areas, which have more total built area, have more production capacity. Lujan and Maipu areas have relatively low total production even during the summer months when sunshine conditions are optimal.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Capital	5282	3347	2805	1945	1505	1173	1304	1932	2729	3644	5152	5552
Godoy Cruz	6646	4211	3530	2447	1894	1476	1640	2431	3434	4584	6482	6986
Guaymallen	8699	5512	4620	3203	2479	1932	2147	3182	4495	6001	8485	9144
Las Heras	4506	2855	2393	1659	1284	1001	1112	1648	2328	3108	4395	4736
Luján	3467	2197	1841	1277	988	770	856	1268	1792	2392	3382	3645
Maipu	3710	2350	1970	1366	1057	824	916	1357	1917	2559	3618	3899

Table 9. Daily thermal production of the total residential building in different months

Picture 5. Production for single buildings in July [kWh]

7. Energy consumption

7.1 Electricity consumption

Through the MMA's electric company, the power consumption of the consumers in each two months is provided. Thus the total electrical energy consumption of each district can be obtained. The total electricity consumption of residential buildings in the MMA area in 2020 is 998 GWh.

	Jan_Feb	Mar_Apr	May_June	July_Aug	Sep_Oct	Nov_Dec
Capital	24049	21879	18578	23039	19074	17409
Godoy	34839	30670	24857	32650	28156	23833
Guaymallen	48398	46342	37368	45261	38516	37617
Las Heras	53870	50342	42994	52220	42226	43384
Luján	44219	43768	45714	55610	43159	41799
Maipu	55876	51931	49189	59928	48691	48813

Table 10. Monthly electricity consumption in 6 departmentos [MWh]

In order to make finer predictions and comparisons, the data from these users were converted into coordinate points to connect to buildings. It is worth noting that some buildings that failed to connect their data were removed as they do not contain data for the whole city. The consumption of condominiums was multiplied by the number of households in them to roughly simulate whole building energy consumption.

7.2 Natural gas consumption

7.2.1 Domestic hot water consumption

Natural gas is used in a wide range of ways within the home, including cooking, heating water, heating, etc. In these facilities, hot water is the most significant energy consumption.

For the estimation of daily domestic water consumption per capita, the following formula was applied:

$$Q = V \cdot \rho \cdot c_p \cdot \Delta T / \varepsilon$$

$$V: \ volume\ of\ water\ assumed\ at\ 50l = 0.05/(24 * 3600)\ m^3/s$$

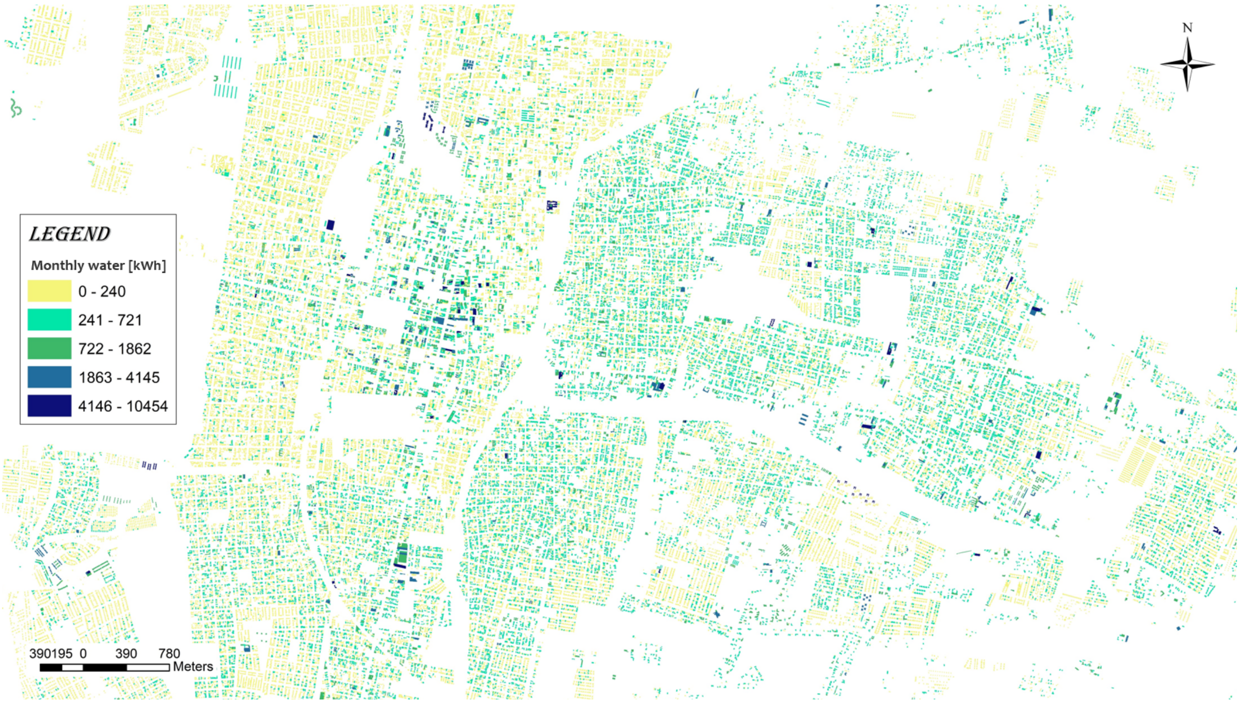
$$\rho: \ water\ density = 997\ kg\ /\ m^3$$

$$c_p: \ water\ specific\ heat\ (assumed\ at\ 1.163\frac{Wh}{kgK})$$

$$\Delta T: \ temperature\ difference\ between\ the\ outlet\ and\ inlet\ water\ (assumed\ at\ 30K)$$

$$\varepsilon = 0.9\ is\ the\ efficiency\ of\ a\ heat\ exchanger$$

Therefore, the per capita electricity consumption for hot water is approximately 1.98 kWh. This gives a total daily consumption of 2156 MWh in the MMA area and a total average monthly consumption of 65782 MWh.



Picture 6. Hot water consumption for single buildings [kWh]

7.2.2 Space heating consumption

In order to estimate the energy consumption of space heating, Heating degree days(HDD) are essential. It represents the total temperature at which the house needs to be heated at a specific time. The higher the HDD, the more heating is required. The HDD is calculated by comparing the outside air temperature and the inside air temperature. In general, the inside temperature is set at 18℃. If the result is positive, that is the HDD for that day. If the result is zero, that means no heating was needed. Therefore, in the MMA area, May to September are the months that need to be heated.

Month	Days	External air temperature	DT (18°C)	Total	Occupation
Jan	31	24.3	0	0	0%
Feb	28	20.1	0	0	0%
Mar	31	20.2	0	0	0%
Apr	30	14.8	0	0	0%
May	31	10.8	7.2	223.2	15%
Jun	30	5.8	12.2	366	24%
Jul	31	4.9	13.1	406.1	27%
Aug	31	7.4	10.6	328.6	22%
Sep	30	12.2	5.8	174	12%
Oct	31	15.7	0	0	0%
Nov	30	19.1	0	0	0%
Dec	31	20.9	0	0	0%

Table 11. HDD in each month [℃]

The specific heat capacity formula is used to calculate the amount of heat energy needed to change the temperature of the object. The heating of the building is still affected by heat loss, proportion, solar radiation, and other factors. In order to simplify the calculation, this study assumes that heat loss or gain is proportional to the temperature difference between the inside and outside of the buildings and there are no other sources of heat energy besides the heating system.

The calculation uses two formulas:

$$Q = m \cdot c \cdot \Delta T$$
$$m: total\ air\ mass$$
$$c: specific\ heat\ capacity\ of\ air\ at\ room\ temperature\ 1030\ J/kg$$
$$\Delta T: total\ temperature\ to\ be\ heated$$
$$m = V/Density$$
$$V:\ Volume\ of\ each\ building$$
$$Air\ density\ of\ 800\ meters\ from\ U.S.\ STANDARD\ ATMOSPHERE\ 1976:\ 1.134\ kg/m^3$$

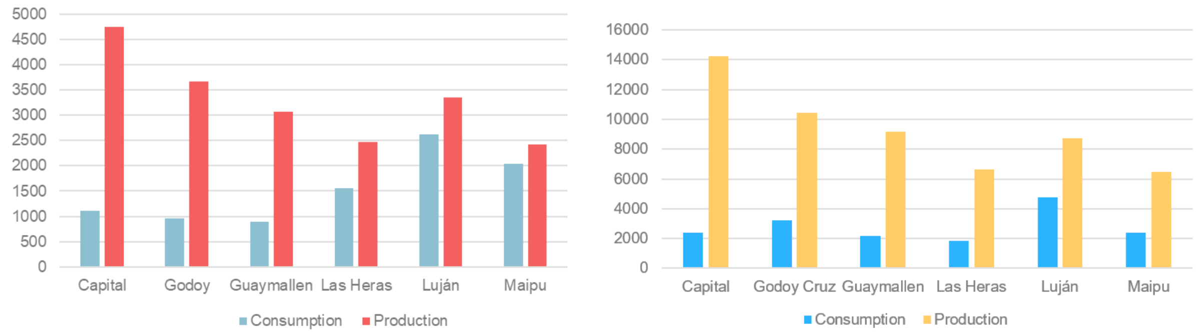
[kWh]	Capital	Godoy Cruz	Guaymallen	Las Heras	Luján	Maipu
May	955,760	854,016	1,073,974	546,070	428,918	376,585
June	1567140	1,400,203	1,760,273	894,947	703,334	617,125
July	1,738,990	1,553,833	1,953,310	993,327	780,365	684,874
August	1,407,044	1,257,382	1,580,692	803,817	631,484	554,231
September	745,065	665,574	837,367	425,826	334,343	293,589

Table 12. Space heating consumption [kWh]

8. Result discussion

8.1 Comparison of per capita data

The results show that both electricity and thermal energy are produced in surplus in all departments. However, in the less densely populated regions, their per capita consumption of electricity is higher, due to the fact that there is more living space. Thus the gap becomes narrowed. The same happens with thermal energy, but it is not very significant.



Charts 3&4. Production per capita vs consumption per capita [kWh]

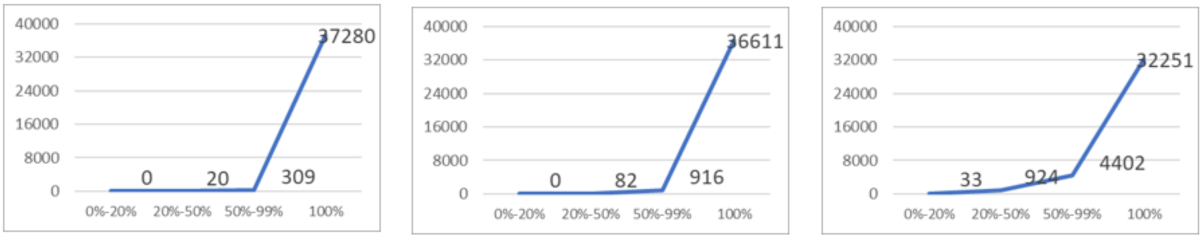
8.2 Self-sufficiency ratio

The self-sufficiency ratio measures the degree to which a city can meet its own energy needs from local resources. A value of 100% means that the building is completely self-sufficient, while a value below 100% means that it needs to draw energy from the grid.

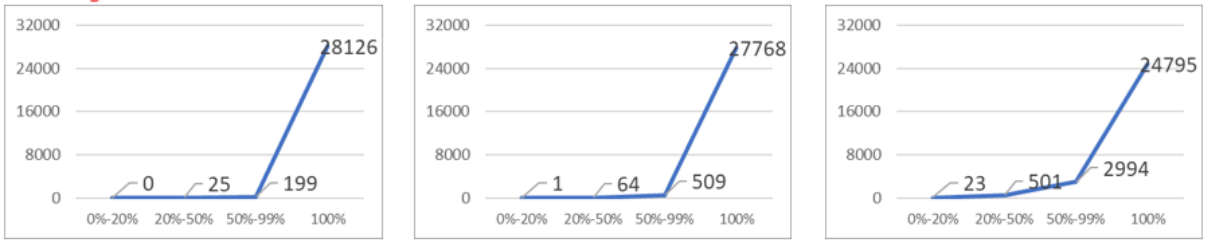
$$Self\ sufficiency = Self\ consumption\ /\ Energy\ Consumption$$
$$Self\ consumption = Minimum\ value\ between\ consumption\ and\ production$$

Jan-Feb	Mar-Apr	May-Jun

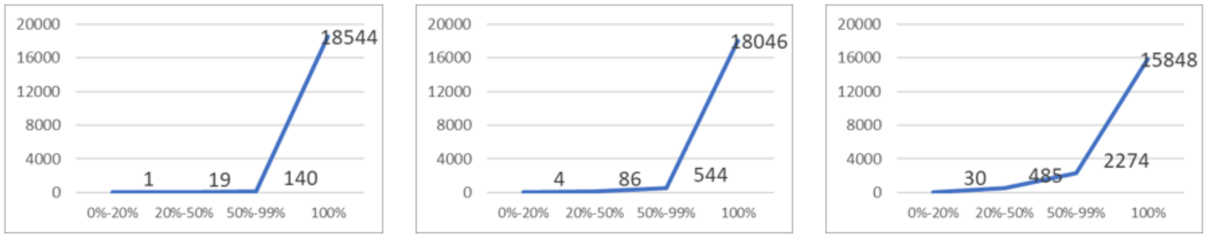
Guaymallen



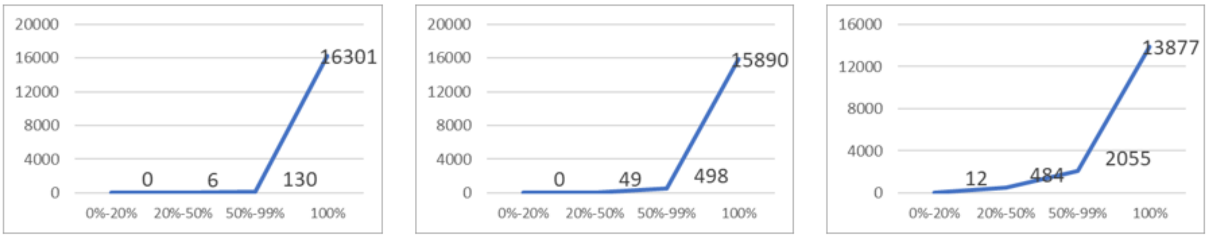
Godoy Cruz



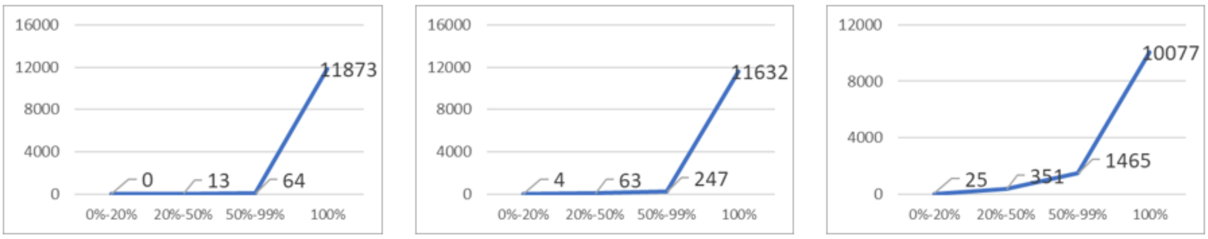
Las Heras



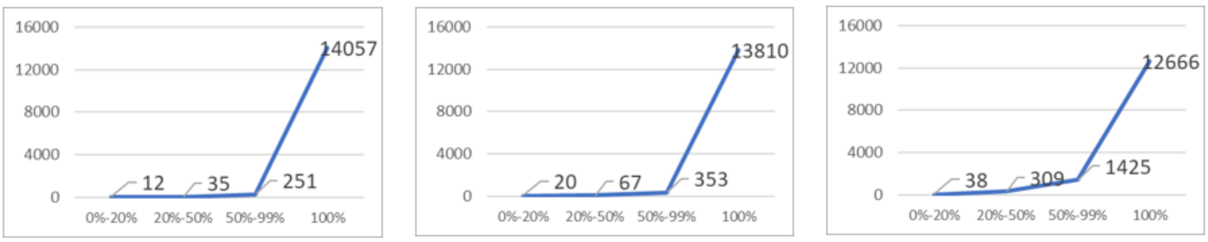
Maipu

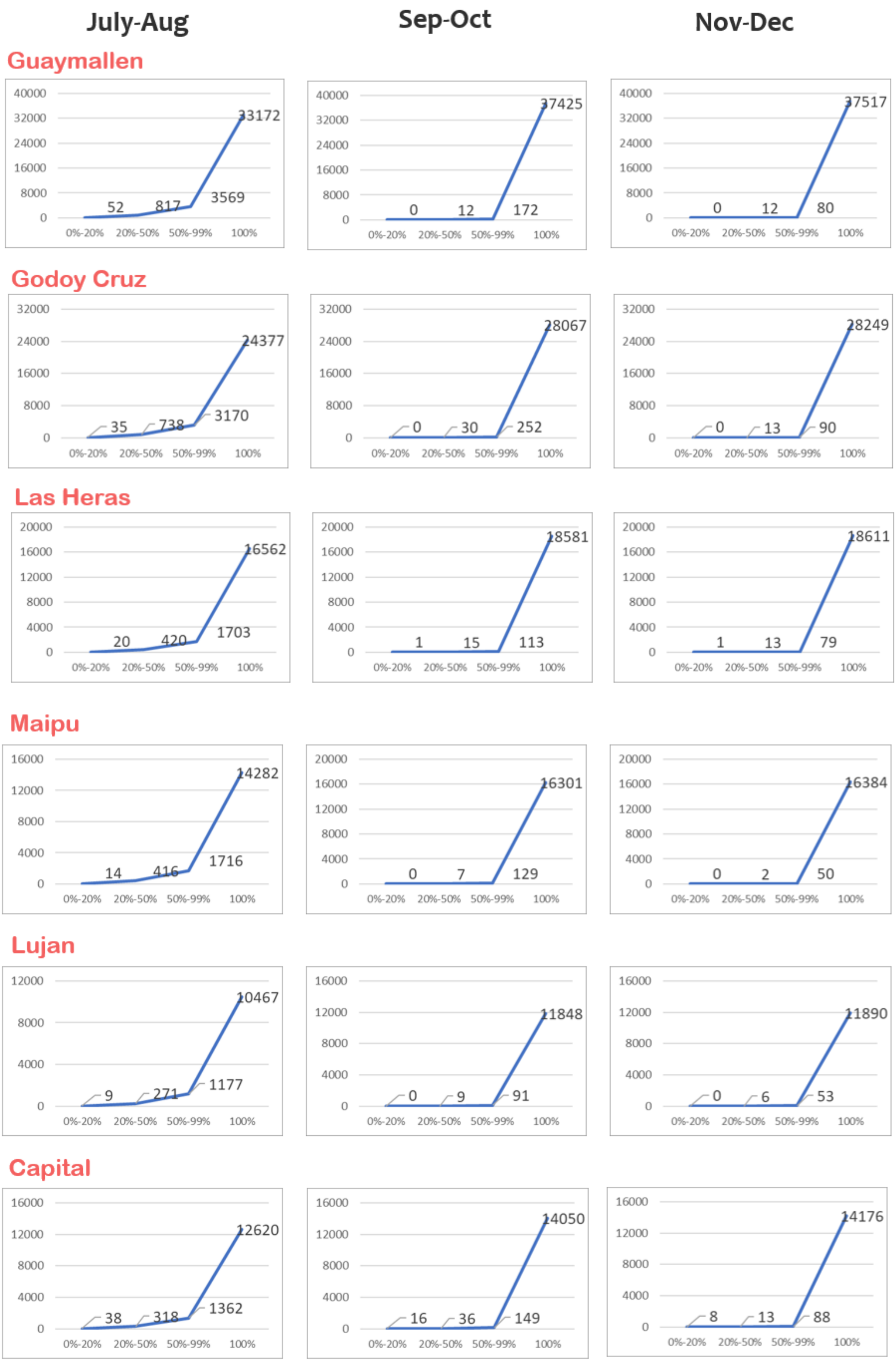


Lujan



Capital





Charts 5. Frequency analysis of self-sufficiency

In all departments, the majority of buildings are self-sufficient in the summer, however, in the winter their rate falls to a certain degree. In the Capital, which contains a certain number of high-rise buildings, they need to draw more energy from the grid throughout the year. In the Godoy Cruz and Guaymallen areas, the total number of dwellings is two to three times higher than in the other departments, and it contains more mid-rise dwellings. As a result, it is somewhat self-sufficient but still requires support from the grid.

8.3 Simple Payback Time

Law 27424 was passed by the Argentinean Congress in December 2017, with the aim of promoting distributed renewable energy generation connected to the grid[19]. Mendoza is one of the provinces that joined the national framework in 2019.

It regulates[20]:

- Users-generators can offset their consumption with their generation on a monthly basis, using a bidirectional meter that records the energy injected and withdrawn from the grid.
- Users-generators receive credits for any surplus they export to the grid, which can be used to pay for future consumption or transferred to other users within the same distribution area.

The energy payback time is the time it takes for the energy savings from a system to equal the energy invested in its installation and operation[21]. Therefore, it is possible to assess the future economy and establish policies by calculating the payback time for electricity and thermal energy in each department. It is calculated using the following equation:

$$SPT = Cost/Revenue\ [years]$$

8.3.1 Electricity payback time

The investment costs depend on the power of the PV systems. This step assumes 1800 €/kW for PV systems and the peak power needs 7 m² areas.

$$C = 1800 \cdot \frac{A_c}{7}\ [€]$$

$$A_c:\ Collector\ gross\ area\ assumed\ to\ 40\%\ roof\ surface$$

The primary revenue is determined by the amount of PV panels used power and the price at which electricity is drawn from the grid. However, due to local policies, selling surplus electricity to the grid can add additional revenue. Thus the formula can be obtained:

$$R = E_{user} \cdot 0,22 + (E_{PV} - E_{user}) \cdot 0,10\ [€]$$

$$Withdrawn\ from\ the\ network:\ 0.22\ EUR/kWh$$

$$Injected\ to\ the\ network:\ 0.10\ EUR/kWh$$

	Capital	Godoy Cruz	Guaymallen	Las Heras	Luján	Maipu
C_invest [€]	372764674	470839886	613903269	317972880	244696937	262192526
C_family	9525	8206	7696	5891	7592	5630
R [€/year]	67560929	88274664	117796609	79398638	67949451	75043756
R_family	1726	1539	1477	1471	2108	1611
SPT[year]	5.52	5.33	5.21	4.00	3.60	3.49

Table 13. SPT of each department

8.3.2 Thermal payback time

The payback calculation for thermal energy is simpler compared to electricity. This is because its production cannot be stored. Natural Gas cost is assumed at 0.018 €/m³.

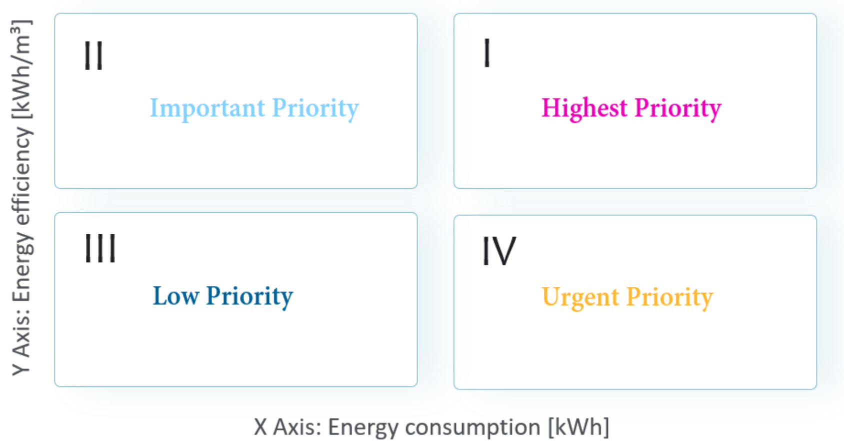
$$R = Production \cdot 0.189\ [€/kWh]$$

	Capital	Godoy Cruz	Guaymallen	Las Heras	Luján	Maipu
Consumption[kWh]	264770417	587598729	618526624	336917531	498192417	369514119
Production [kWh]	1,578,658,341	1,994,006,847	2,599,880,252	1,346,615,100	1,036,291,493	1,110,385,308
Revenue [€]	298366426	376867294	491377368	254510254	195859092	209862823
SPT [year]	0.88	1.55	1.25	1.32	2.54	1.76

Table 14. SPT of each department

8.4 Interventions priority of electricity

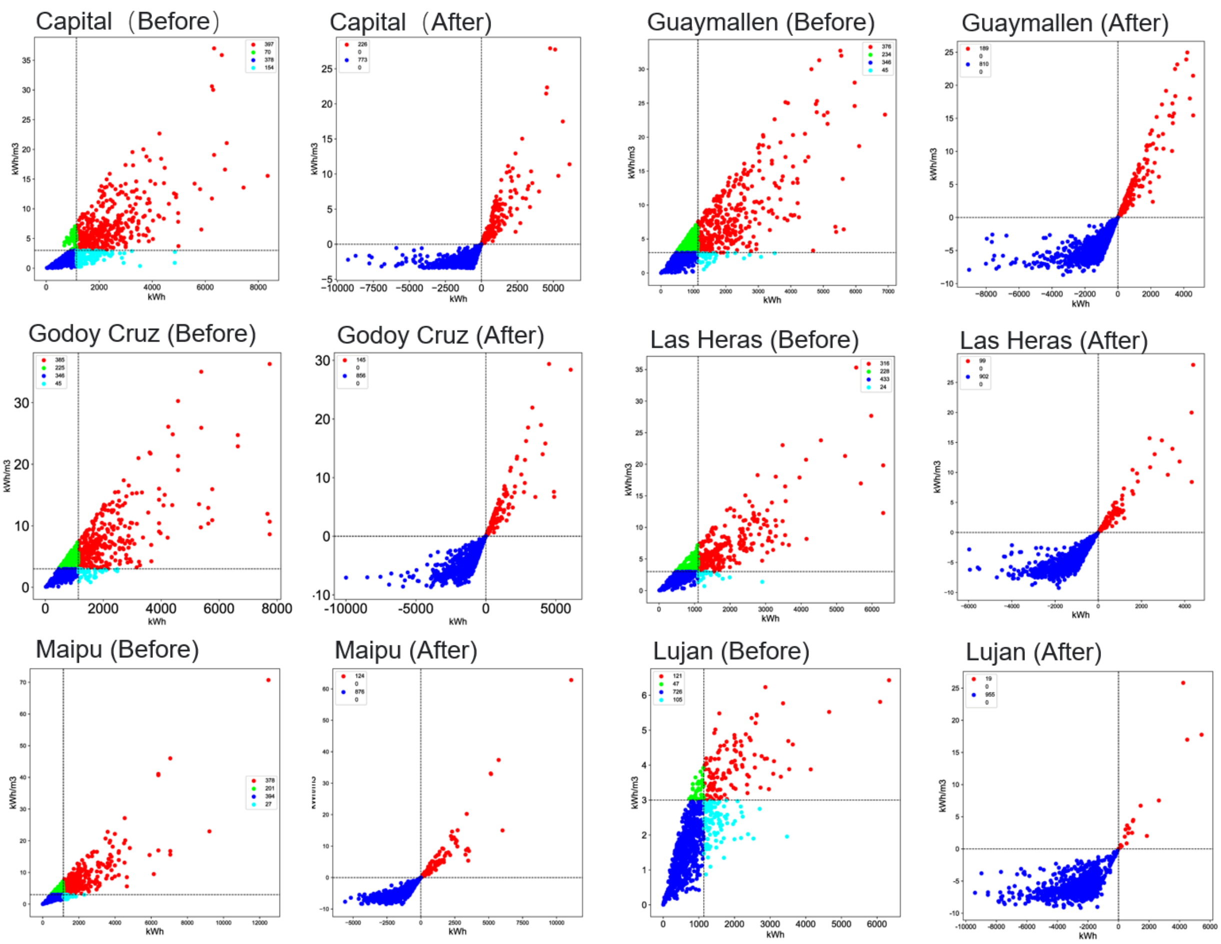
The Covey matrix is a framework for establishing priorities based on the urgency and importance of time and tasks. In this study, it can help decide which departments to proceed with new energy development first and which departments can slow down. The x-axis is the energy consumption of each building and the y-axis is the energy efficiency of each building. The position of the axes is determined by the mean value.



Charts 6. The Covey matrix

Quadrant I: These are groups that consume a lot of energy and have low efficiency. They may have a large potential for energy savings and emissions reduction.
Quadrant II: These are groups that consume little energy but have low efficiency. They may have a small potential for energy savings and emissions reduction, but they may also face challenges in accessing or affording energy services.

Quadrant III: These are groups that consume little energy and have high efficiency. They may have a low potential for energy savings and emissions reduction, but they may also have a high level of energy security and sustainability.
Quadrant IV: These are groups that consume a lot of energy and have high efficiency. They may have a high potential for energy savings and emissions reduction, but they may also face challenges in managing their energy demand and supply.



Charts 7. Comparison of original data and new data

In terms of numbers in quadrant 1, Capital, Guaymallen, and Godoy Cruz need to be given priority for new energy installations. However, even after installation, these regions still have a certain number of buildings that need to purchase energy from the grid. It can also be observed that regardless of the department, there is a microscopic amount of buildings that do not achieve the desired energy efficiency. In Guaymallen there are more buildings of this type. Therefore, the other three regions could sell their excess power to them.

9. Conclusion

Based on all the above data and current information, a SWOT methodology about installing solar energy in the Mendoza area is used here:

Strengths

- The Mendoza region has approximately 91% low-rise buildings. The high-rise buildings are concentrated in the capital area, with a small number in the other areas. The energy efficiency impact of the shadows from the surrounding tall buildings is greatly reduced. At the same time, low-rise buildings are easier to install and maintain in the future.
- The installation ratio of green energy in Mendoza is still relatively low, so new products with higher conversion efficiency can be installed over a large scale.
- Compared to other regions in Argentina, the price of electricity in Mendoza is relatively high. According to a report by the World Bank, the average residential electricity price in Argentina in 2020 was 0.15 USD/kWh. However, Mendoza has some residential customers paying up to 0.25 USD/kWh. The installation of photovoltaic panels can help to reduce electricity bills and save money.
- Current energy production in the Mendoza area is dominated by traditional fossil fuels. The installation of PV panels will reduce the carbon footprint, save on building operating costs and reduce the environmental impact.
- The payback time for thermal energy is very short and the vast majority of residents can install it.

Weaknesses

- There are some informal settlements in Mendoza that cannot be installed with PV panels [1]. Local government needs to improve legal frameworks.
- Although Argentina is a large country in South America, it has a relatively low level of economic development and GDP per capita compared to the world. According to Gifex, Mendoza Province has a GDP per capita of US$9,000 in 2018, which was slightly below the national average of US$9,800 [17]. The willingness of local residents to install PV will not be very strong due to the cost price.
- There is a limited number of skilled professionals in Mendoza who are qualified to design and install PV systems.

Opportunities

- Regulatory reforms of solar energy could help to increase employment opportunities in the region and attract foreign companies to the area. At the same time, more local expertise will be developed, which will allow the Mendoza region to benefit in the future, both economically and technologically.
- There are various routes that can be taken in the allocation of spillover resources:
    - Installing the battery. When solar energy is sufficient during the day, the intelligent controller stores the extra power in the battery. When it is night, cloudy, or when the power grid is out, the intelligent controller will send the stored power in the battery to the user load.

    - Creating renewable energy communities. If people in an area join an energy community, they will sell their unused energy to other consumers or to the national grid. This could help to reduce energy bills and strengthen social cohesion.
- Government policy and financial support: Argentina has a national target of reaching 20% of renewable energy in its electricity mix by 2025 [18].

Threats

- We know from experience in previous years that the Argentine government has several times reduced subsidies for renewable energy [16]. This has not only resulted in many PV installations not being connected to the grid but has also led to a loss of investor confidence in the country's PV industry. The government needs a more stable policy to convince the population.
- In the case of Mendoza, which requires a large number of solar panels to be installed, the panels currently used in Argentina are mainly imported from other countries. This will hit local businesses and cause higher maintenance costs in the future.

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