Reducing the Strain on the Buenos Aires Electricity Grid:

Rooftop Solar Potential Assessment and Peak-Shaving Analysis

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Abstract

In the past decade, the City of Buenos Aires has experienced recurring power outages due to increased electricity consumption, particularly in the summer. To address this issue, the study assesses the solar potential of residential rooftops in the city as a possible means to lower peak demand. The study utilizes geographical information systems (GIS) and statistical analysis to estimate the available rooftop area in the city in order to calculate the solar potential. Given the size of the city, a sample of 385 residential parcels were chosen to analyze and statistical modeling was used to identify a correlation between rooftop area and parcel area in the sample set. Equations were built from the statistical analysis and were applied to the entire study area to calculate the total rooftop area. Solar photovoltaic potential for the estimated total rooftop area was calculated using equations from Singh and Banerjee (2015) and solar irradiance data, obtained from a meteorological dataset from the Buenos Aires Environmental Protection Agency. The study yielded an estimated annual solar potential of 2,061 GWh, about 17% of the city's total annual electricity use. The solar potential was also calculated by hourly intervals for the months of January and July and compared to daily load profiles to assess the peak-shaving potential of rooftop solar systems. It was found that during the daylight hours from 9 am to 6 pm, rooftop solar generation could potentially shave 61% of the load in January and 19% of the load in July. However, due to the shift between peak demand and peak generation, it is necessary to resort to energy storage systems for effective peak-shaving. That said, an interesting finding was that for season maximum load days in the summer, peak demand occurred during daylight hours and therefore, could be lowered by solar photovoltaic electricity. The methods used in this study can be replicated to obtain the solar potential for other cities in Argentina.

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Introduction

Large-scale power outages have become a regular occurrence in the City of Buenos Aires, Argentina over the last decade, particularly during the summer months. As temperatures rise, electricity demand peaks beyond the ability of the electricity grid to support demand, leading to system failure. With a population of nearly 3 million people living in a densely urbanized area, a few affected neighborhoods can leave thousands, and even hundreds of thousands of residents without power (Instituto Nacional de Estadística y Censo, 2012). In December of 2013, in the midst of a record heat wave, more than ten highly populated neighborhoods lost power for several days up to weeks, affecting an estimated total of 800,000 people, including people from the Greater Buenos Aires area (Giambartolomei, 2013; Rossi, 2013). This was not an isolated incident. Rather, it has been a recurring problem and a growing concern over the years, which is reflected in the increase of blackout frequency and duration. According to Edenor, the electricity distributor that services the northern half of the city, the system average interruption frequency in 2009 was 5.66 interruptions per clientwith an average of 13.04 hours of interruptions per client over the course of the year. However, by 2014 the interruption frequency had risen to 9.55 interruptions per client with an average of 33.03 hours of interruptions per client over the course of the year (Edenor, n.d.). These statistics have dropped slightly from the 2014 numbers, however, power outages due to increased demand continue to be a pressing issue.

While some of the power outages experienced in the city have been due to events of *force majeure*, such as heavy storms, or due to failure in high tension transmission lines, most of the power outages have been a result of increased peak demand overwhelming the system. Although in some cases, this happens during exceptionally cold winter days, it mainly occurs in the summer, during a spell of hot days. A simple analysis of peak consumption records from Cammesa, which is the company in charge of managing the wholesale electricity market in Argentina, along with historical records of temperature highs in Buenos Aires and newspaper articles covering the power outages in the city over the past 6 years, show that for each new electricity consumption peak record there were power outages in the city, which also coincided with recorded temperatures highs above 31°C. (The resulting table can be found in Appendix A of this paper.) Of the 14 registered peak records between 2012 and 2018, only one occurred in the winter during a period of Antarctic cold effecting the region, while the rest occurred during the summer. It is also of interest that, with the exception of the single winter historical peak record, the remaining 13 record electricity peak demands registered by Cammesa have occurred between 2:20 pm and 3:35 pm, during daylight hours. Considering the time frame of the historical record peaks, incorporating electricity from distributed solar systems into the grid could possibly aid in lowering the summer peaks which overload the system, and in this way, avoid massive blackouts.

These peaks in demand seem to be primarily due to the increased use of air conditioning units in homes, which have become a common commodity in the last decade. According to the National Institute of Statistics and Census (INDEC), air conditioning unit sales have increased from $358 million ARS in 2009 to $3.1 billion ARS in 2015 (Instituto Nacional de Estadística y Censo, 2011, 2017). Accounting for the devaluation of the Argentine Peso during that period, this is a 250% increase in sales within six years.[1] Of these numbers, the City of Buenos Aires was responsible for 14% of sales in 2009 and 21% of sales in 2015. In addition, with the utility

[1] 2010 sales were equivalent to USS $93,472,585 at a $3.83 exchange rate, as of December 2009. 2015 sales were equivalent to USS $230,588,235 at a $13.43 exchange rate, as of December 2015.

price tariff freeze of 2002, that had been maintained without changes until 2016, the cost of electricity had become extremely cheap in the City of Buenos Aires, costing 13 times less than the regional average by the end of 2015 (Universidad de Belgrano, 2015). Coupled with the increasing access to air conditioning units, the extremely low cost of electricity has led to unprecedented levels of electricity consumption in the face of high-temperature days.

In light of these issues, the incorporation of solar photovoltaic (PV) technologies in buildings could provide a significantly effective and sustainable path towards reducing the strain on the Buenos Aires electricity grid. Buenos Aires has great solar resources, receiving about 1,800 kWh/m2 annually (SolarGIS, n.d.-a). Compared to the current state of the art in Germany, which has an extremely high level of penetration of distributed solar systems in its electricity grid with only 1,200 kWh/m2 of annual radiation in its southernmost part, Buenos Aires has an even greater potential for electricity generation from solar technology (SolarGIS, n.d.-b). Unfortunately, without specific regulations and incentives in place for the development of solar energy, and with heavily subsidized utility prices, solar energy has been considered too expensive to implement with no prospect of a return on the investment in the lifetime of the installation (Vegas, 2015). However, with the change in administration at the end of 2015, the government subsidies for utilities, which had remained intact since 2002, were partly removed in 2016 with plans to completely remove all subsidies in the subsequent years. This may open a way for PV installations to potentially become viable (do Rosario, 2016).

Purpose of This Study

Taking advantage of the changing political tides, it is of interest to consider the potential electricity production from residential rooftop PV systems in Buenos Aires in the face of the electricity crisis in the city. To the best of my knowledge, there is currently no existing solar map of the city or an estimation of the total solar potential of its rooftops. With this in mind, this study seeks to answer the questions: *What is the solar photovoltaic potential of residential rooftops in the City of Buenos Aires, Argentina, and to what extent can residential rooftop photovoltaic systems contribute to peak-shaving?* In this study, solar potential refers to the total possible amount of electricity that can be generated from rooftop PV systems, and peak-shaving refers to reducing the electricity consumption from the grid during periods of maximum demand through the use of solar-generated electricity from rooftops.

The aim of the study, therefore, is to gain insights into the solar potentials for residential rooftop PV systems in Buenos Aires and to examine the possibility of peak-shaving, particularly during the summer months. Specifically, the study seeks to:

1. Develop a methodology for the estimation of the residential rooftop solar PV potential on a city scale when data availability is limited;
2. Analyze the peak-shaving potential during daylight hours through a comparative analysis of the city's load profile and the rooftop solar electricity production profile; and
3. Formulate recommendations to drive regulation and incentives to promote the incorporation of distributed solar systems in the city.

Scope and Limitations of the Study

While the issue of peak demand and power outages affects a much larger area, the geographic scope of this analysis is focused on the City of Buenos Aires, which alone is responsible for 12% of the nation’s electricity consumption (Buenos Aires Ciudad, 2014). Within the city, only the residential sector is considered, which is responsible for 36% of the city’s electricity consumption (Buenos Aires Ciudad, 2014). Although the commercial and industrial sectors are not included in this research, given the large share of the residential sector in the total electricity consumption of the city, it alone accounts for 4.32% of the nation's total consumption of electricity. Considering that 61% of electricity in Argentina is generated through thermal energy using fossil fuels, lowering electricity demand through the use of solar energy could not only lower the risks of power outages in the city, but could also lower the electricity industry's release of carbon dioxide from electricity generation, which amounted to 44 million tons of carbon dioxide in 2014, a steep increase from the 16.3 million tons in 2002 (Cammesa, 2016b; Subsecretaría de Ambiente y Desarrollo Sustentable, n.d.). Although the reduction of carbon emissions is not the focus of this study, it is worth mentioning, as it pertains to the effects of climate change in increasing temperatures, which are then associated with the blackouts in the city.

Due to the size of Buenos Aires, the time constraints of this study, and the lack of certain data, the analysis of the available residential rooftop area and its solar potential was limited to a stratified sample of buildings. An estimation of the citywide available rooftop area and its solar potential was done based on this sample, using statistical analysis. In addition, while some of the reviewed literature included the financial aspects of solar system installations, due to time constraints, this study only focused on the technical aspect in relation to the city's electricity consumption and the possibility of peak shaving during daylight hours. While economic potential was briefly addressed, in-depth economic analysis was left to be pursued in further studies.

Overview of the Study

The following section includes a background on the Buenos Aires electricity grid and the state of solar energy in the city, followed by the literature review section, which gives an overview of existing literature relating to different methodologies for available rooftop area estimation and solar potential calculation from solar radiation. The section that follows outlines the methodology adopted for this research based on the material discussed in the literature review. Next, the results are presented and discussed, and finally, the last section provides the conclusions and recommendations.

Background

The electricity crisis in Buenos Aires has been a growing concern over the last decade. In order to address the issue through this research, it is necessary to first understand the situation of the electricity grid in Buenos Aires and the state of solar energy.

The Deterioration of the Electricity Grid

After the economic crisis of 2001, Argentina was left with a growing fiscal deficit and no access to international credit to finance that deficit due to the high levels of public debt accumulated during the presidency of Carlos Menem in the 90's. With the resulting default, the Argentine Peso devalued, and bank deposits and credits were forcibly converted from dollars into pesos. The Minister of Economy, Roberto Lavagna, then froze the public utility tariffs in order to mitigate the burden on household economies from the currency devaluation, inflation, and the pesofication of the deposits in dollars (Cachanosky, 2017).

In the midst of one of the worst moments in history for Argentina, Néstor Kirchner was elected president in 2003. His presidency (2003-2007), followed by his wife's Cristina Fernández de Kirchner (2007-2015), became known as the "*Década K*." In the beginning of *Década K*, the Argentine economy showed signs of strong recovery amid a favorable global economic climate with high prices for Argentine exports, particularly of soy (Wylde, 2011). However, even after the economic recovery of the country, the freeze on the public utility tariffs continued, creating distorted relative prices for electricity to the point where, by the end of 2015, the average residential users in Argentina were paying seventeen times less for electricity than counterparts in the neighboring Chile (Universidad de Belgrano, 2015). Cheap electricity spurred consumption, which rose to 3.09 MWh per capita in 2014 from 2.17 MWh per capita in 2003, a 42% increase in a decade (International Energy Agency, 2016).

The tariff freeze also led the electricity distributing companies to fall into debt with Cammesa, the government-controlled company that manages the wholesale electricity market. With the increasing annual inflation and the unaltered electricity revenues, the distributors were unable to pay for the electricity they were providing and also cover their own operating costs. By 2014, the distributing companies owed the government over $18 trillion ARS (P. F. Blanco, 2014).[2] With a growing debt, rising costs, and insufficient income in relation to the inflation, the distributing companies were unable to maintain the local grid. The already deteriorated grid fell into a cycle of constant deterioration. In addition, misallocation of resources during the *Década K* led to a halt in investment in energy and infrastructure, causing Argentina to go from being a net exporter of energy to a net importer by the end of the Kirchner era in 2015. (Thomas & Cachanosky, 2016).

The year 2015, however, marked the end of the Década K policies with the election of Mauricio Macri of the opposition as the new president of Argentina. One of Macri's platforms was to reduce public spending in order to turn the fiscal deficit around. One way he did so was by ending the tariff freeze and cutting down on energy subsidies (do Rosario, 2016). The government even sanctioned a project in 2017 that would allow residents to produce their own

[2] The companies reportedly owed $18 trillion ARS, which equals to $2.09 billion USD at an exchange rate of $8.58 as of December 2014.

energy based on renewable sources. With the changing legislation and the restructuring of the utility tariffs, the distributing companies in Buenos Aires started updating the grid and installing meters that will allow clients to sell electricity back to the grid, should they decide to invest in their own PV systems (P.F. Blanco, 2017). Thus, the end of the tariff freeze opened a door to a world of new possibilities for rooftop solar systems.

The Situation for Solar Photovoltaics in Argentina

Even though Argentina is one of the most important economies within South America, it has been lagging behind in solar energy investment compared to its neighboring countries. Within South America, Chile is leading the way with 1,802 MW of installed capacity, which makes up 8% of the country's total installed capacity (Generadores de Chile, n.d.). Brazil follows with 1,266 MW of installed capacity, although this only makes up 0.8% of the total installed capacity in the country (ANEEL, 2018). Uruguay also has significant installed solar capacity at 78 MW, 2% of the nation's total installed capacity (Administración del Mercado Eléctrico, 2016). In contrast, with an installed capacity of 8 MW, electricity derived from solar energy accounted for only 0.0002% of the total installed capacity in Argentina (Cammesa, 2016b).

Nonetheless, there is a growing interest in renewable energies in the country. In 2015, Law 27,191 was published in the Official Gazette, which promotes the use of renewable energy sources for electricity generation (Ley N° 27191, 2015). The law establishes the goal that by 2025, 20% of electricity generated in the country would come from renewable sources. In step with this goal, at the beginning of 2017, President Mauricio Macri signed 16 contracts for renewable energy projects, four of which are for solar PV plants in the provinces of Jujuy and Salta ("Energías renovables: el Gobierno firmó 16 nuevos contratos por 818 megavatios," 2017). In addition, the construction of a new solar panel production facility is underway in the province of San Juan, which will be the first to completely produce solar panels nationally (Schmid Group, 2015).

In terms of small-scale applications, the provinces of Santa Fe, Salta, and Mendoza have already had regulations for net metering for some time. This allows residents to inject the surplus of electricity generated from their rooftop PV systems into the grid and in turn, receive credit from the utility companies to offset the cost of the electricity drawn from the grid when their rooftop PV systems are not generating power. However, Buenos Aires has been lagging behind. Only recently did Congress pass a law to allow the integration of distributed solar energy into the grid nationwide. This will now allow Buenos Aires residents to become "user-generators" if they choose to install PV systems on their rooftops (Ley N° 27424, 2017). There is also a growing number of public buildings in Buenos Aires with rooftop solar panels installed, such as the Environmental Protection Agency (AFRA) building, the Buenos Aires Legislature building, and the Ministry of Science and Technology, among others (Buenos Aires Ciudad, n.d.). The latest installation was on the Metrobus stations roofs (along 9 de Julio Avenue), which generate enough electricity to power 190 homes (Ensinck, 2017).

While positive changes have recently been taking place in favor of solar energy, there is still a great lack of awareness and a lack of tools and resources to implement these changes. For this reason, the present study will be particularly relevant in bringing to attention the potentially vast solar resource available simply on residential rooftops in Buenos Aires.

Literature Review

Numerous studies attempt to estimate the rooftop solar PV potential of different cities or regions around the world. In the absence of prior attempts at estimating the solar potential of

Buenos Aires' rooftops, it is necessary to review existing literature on the solar potential of other cities around the world in order to define the proper methodology for this research in consideration of the needs and limitations of Buenos Aires.

Studies vary across different levels of geographic coverage and spatial resolution as presented by Mainzer et al. (Kai Mainzer et al., 2014). In general, studies that cover larger areas have a lower spatial resolution, depending on census data and statistical techniques to calculate solar potential. These studies estimate the rooftop solar potential on a regional or national scale. Small-scale studies, on the other hand, rely on more precise data that can be obtained through remote sensing technologies, such as Light Detection and Ranging (LiDAR), allowing for higher spatial resolution, down to the individual roof. However, these studies require extensive computational capacities and large datasets that can be expensive to acquire.

Regardless of the level of precision and scope, there are three main factors that influence solar PV potential: available rooftop area, incoming solar radiation, and the technical aspects of solar photovoltaic systems, which include module efficiency, performance ratio, etc. The following subsections below review the existing literature addressing these three factors.

Available Rooftop Area

The methodologies for the estimation of available rooftop area vary greatly, depending on the scale and the availability of data. Mainzer et al. (Kai Mainzer et al., 2014) assessed the available rooftop area for Germany using statistical data about the number of residential buildings per building type and municipality. The average roof area per building type and roof type were calculated taking into account the mean size per apartment, the average number of apartments per building, the average number of floors, additional floor area to account for common areas, and average roof slope. The study adopted a fixed utilization factor based on literature to calculate the available roof area for solar installation. Izquierdo, Rodrigues, and Fueyo (2008) also used statistical data such as population, land use, and building density to estimate total roof area in the provinces of Spain. Their study was based on stratified statistical sampling, where stratification was based on average building typologies in urban areas in Spain.

For smaller scale studies, such as block, neighborhood, or city-level studies, more specific data is generally used, such as LiDAR data and high-resolution satellite imagery, to estimate the available rooftop area. According to Jakubiec and Reinhart (2013), LiDAR is the best tool to accurately measure an entire urban area. In their study of rooftop solar potential in Cambridge, Massachusetts, LiDAR data was used to create a 3D model of the entire city, which was used to estimate the available rooftop area and the annual irradiation. Using 3D models has the advantage of being able to include detailed roof forms and slopes, as well as the landscape into the study. Rodríguez, Duminil, Ramos, and Eiker (2017) also used 3D models to determine the potential roof area of Ludwigsburg county in Germany. In addition, Rodríguez et al. performed an exhaustive literature review on different reduction coefficients that determine the actual suitability of rooftops for solar system installations, taking into account voids, shadows, rooftop equipment, etc., and incorporated nine different reduction coefficients into their study in order to increase the accuracy of the estimation of available rooftop area.

In some cases, LiDAR data and building footprint data are not available. Such is the case in the study by Luqman et al. (2015) that estimated the available rooftop area of a housing society in Lahore, Pakistan by digitizing rooftops using Google Earth imagery as a base map in geographic information systems (GIS) software. Only rooftops that met certain criteria and were favorable towards PV installations were digitized. Elevation data was manually collected using

Global Positioning System (GPS) technology. This was possible because of the small scale of the study area.

When high-resolution data is unavailable and manual digitization is not feasible for citywide estimations, studies resort to hybrid methodologies. Byrne, Taminiau, Kurdelashvili, and Kim (2014) demonstrated a methodology used to estimate the citywide solar potential for Seoul, South Korea. In the study, Byrne et al. used statistical data sets that included the total floor area and the number of floors of buildings to estimate the average area per floor. Roof suitability factors were calculated and used to estimate the final available roof area. Another study used a sample set of buildings under different land-use types to estimate the building footprint area and the available rooftop area for the city of Mumbai using satellite images in GIS software (Singh & Banerjee, 2015). The ratios obtained from these estimations were then used to estimate the total rooftop area. Carl (2014) also used a hybrid methodology using GIS tools and statistical analysis to estimate the rooftop area for Kailua Kona, Hawaii. Satellite imagery was used to manually digitize the rooftops of a sample set of buildings. Then, statistical analysis was used to analyze the correlation between roof size and lot size to estimate the total roof area in the study area.

Given the similarities in limitations with the studies by Carl (2014) and Singh and Banerjee (2015), the present study adopted a hybrid methodology to estimate rooftop area, including aspects of GIS analysis on a sample set of buildings, the use of statistical data on the city’s buildings and parcels, and statistical analysis to extrapolate the data to the rest of the study area.

Incoming Solar Radiation

In order to calculate the photovoltaic potential of rooftops, it is necessary to estimate the incoming solar radiation. To generate electricity, PV systems use “Direct Normal Irradiance” (DNI), “Diffuse Horizontal Irradiance” (DHI), and “ground-reflected irradiance,” which together make up “global solar irradiation” (Esri, n.d.). DNI is the solar energy that reaches the earth’s surface uninterrupted, while DHI is the energy that is scattered by atmospheric gases and aerosols before reaching the earth. The reflected irradiation is the energy reflected from surrounding surfaces, such as the terrain.

There are a number of different models that are used to estimate solar radiation. Freitas, Catita, Redweik, and Brito (2014) performed an exhaustive review of the existing models in the literature, ranging from empirical solar radiation models to web-based solar maps. Empirical solar radiation models use data from local weather stations or solar radiation raster images to calculate the transposition of horizontal radiation onto tilted surfaces using mathematical equations. These models produce a solar radiation constant that assumes that every point on a rooftop receives an equal amount of solar radiation (Jakubiec & Reinhart, 2013). Singh and Banerjee (2015) use such a model in order to estimate total solar radiation in Mumbai with data from the Climate Design Data 2009 ASHRAE Handbook, which averages data from a period of 30 years from a variety of locations around the world (American Society of Heating, Refrigerating and Air Conditioning Engineers, 2009). Another study by Mainzer, Killinger, McKenna, and Fitchner (2017) used radiation data from the Copernicus Atmosphere Monitoring Service (CAMS) in their transposition model to estimate the incoming solar radiation for Freiburg, Germany (European Commission, 2017). In each of these studies, reduction coefficients are also employed to account for shadowing from the local urban context, which is not accounted for when using a constant value.

Other types of models found in literature include computational solar radiation models, which are basically simulation tools that consider topography and shadows in the estimation of incoming solar radiation. Among these tools are the ESRI's ArcGIS Solar Analyst tool and the r.sun tool in the open source GRASS GIS program (Freitas et al., 2014). The Solar Analyst plugin relies on a digital elevation model (DEM) in order to calculate incoming solar radiation. Luqman et al. (2015) used the Solar Analyst plugin to calculate solar radiation on rooftops in government housing in Lahore, Pakistan. Carl (2014) also used this tool to estimate solar radiation for a study on rooftop solar potential in Kailua Kona, Hawaii. However, there are some limitations to this tool, including the inability to model reflected radiation from the local urban context and the effects of cloud coverage (Jakubiec & Reinhart, 2013).

Like Solar Analyst, r.sun uses DEMs to calculate solar radiation. It is useful for modeling radiation in large geographic areas that have different climate zones as the ratio between direct and diffuse radiation can be manipulated, rather than it being fixed, as is the case in Solar Analyst. R.sun also accounts for ground-reflected radiation, unlike Solar Analyst. Bergamasco and Asinari (2011) used PVGIS, which is based on r.sun, for their solar radiation values. The outputs are raster maps with the desired solar radiation data, which is why this tool seems most appropriate for large geographic areas (Jakubiec & Reinhart, 2013).

Finally, there are studies that used 3D modeling to analyze solar radiation. One such study is from Jakubiec and Reinhart (2013) that used DAYSIM daylighting analysis software to simulate solar radiation on a 3D urban massing model of Cambridge, Massachusetts. While this study showed the high accuracy of its model, high-quality LiDAR data is not always available to create accurate 3D models.

Considering the lack of certain data for Buenos Aires, it was decided that this study would use a solar radiation constant for its solar potential calculations. While many studies that used solar constants used transposition models to recalculate incoming solar radiation onto an inclined plane, this study was simplified and the values of incoming solar radiation on a horizontal plane were used. This use is further explained in the methods section.

Solar Potential

A simple calculation of solar potential consists of multiplying the incoming solar radiation, the surface area of the PV panels receiving the radiation, and the power conversion efficiency coefficient for the PV panel chosen. Many web-based GIS tools, such as PVGIS, use this equation to estimate annual total electricity production of PV panels (Choi, Rayl, Tammineedi, & Brownson, 2011).

Some studies use more complex equations to account for other factors, such as losses related to temperature variation, azimuth angle, inverter efficiency, etc. Bergamasco and Asinari (2011) estimated the solar potential for Piedmont, Italy using an equation that multiplies the incoming solar radiation, solar panel surface area, the panel efficiency, and a number of coefficients that represent losses from temperature variation, losses from incorrect azimuth angle, and other accessory losses. These coefficients are constants that the authors predetermine through assumptions. Rodríguez, Duminik, Ramos, and Eiker (2017) also used a similar equation employing losses coefficients to estimate the solar potential in Ludwigsburg, Germany. They obtained the coefficients from literature. While these equations consider many factors to estimate solar potential, they are restrictive, as they rely on fixed coefficients, particularly regarding losses from temperature variation and orientation losses.

Singh and Banerjee (2015) used a different set of equations to calculate solar potential by hourly output in Mumbai, India. The equation takes into account the number of effective sunshine hours along with solar radiation, surface area, panel efficiency, and inverter efficiency. In addition, they calculated losses from temperature variation from a separate equation that takes into account the Power Temperature Coefficient, which is the percentage change in the output of a panel for every degree Celsius of temperature variation from the standard 25°C used to test the PV panels. Another equation calculates the temperature of the panel according to the ambient temperature and the incoming solar radiation. Given the completeness of this method, the present study adopted these equations in order to calculate the solar potential in Buenos Aires. The details of the equations are given in the methods section below.

Methods

The purpose of this study is to assess the residential rooftop solar potential in the City of Buenos Aires and its contribution to peak shaving as a potential means to lower the strain on the electricity grid. In order to do so, the study adapted different methodologies from the existing literature to the needs and limitations of the city, creating a hybrid methodology, which uses GIS analysis, public-domain secondary data, and statistical analysis.

One of the biggest challenges for Buenos Aires is the lack of publically available data. Many city-scale studies use LiDAR data, satellite imagery, and data sets, such as building footprint data, to estimate the available rooftop area for the city (Jakubiec & Reinhart, 2013; Redweik, Catita, & Brito, 2013; Rodríguez et al., 2017). When building footprint data is not available, manual digitization of rooftops is an option for small-scale studies (Luqman et al., 2015). In the case of Buenos Aires, LiDAR data and building footprint data are not publically available. In addition, given the size of the city, manual digitization of rooftops was not a feasible option due to time constraints. For this reason, this study worked on a representative stratified sample set of residential rooftops for its analysis, which was then extrapolated to estimate the city total solar yield. Figure 1 shows the flowchart for calculating the photovoltaic rooftop potential in this study. The following sections describe in detail the methods and procedures used. Details on the data sources used are found in Appendix B of this study.

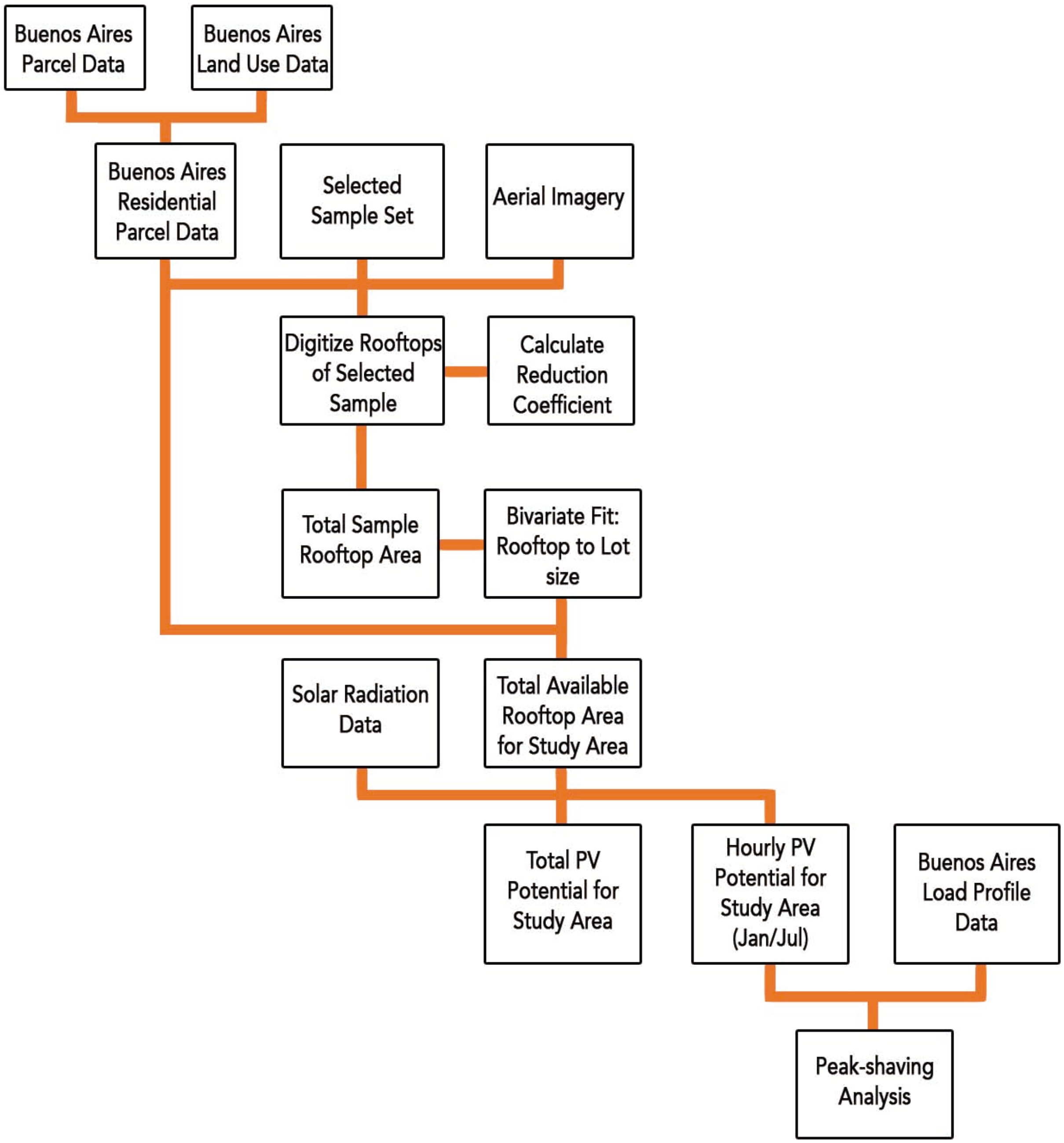

Figure 1. Flowchart for Calculating Residential Rooftop Solar Potential in Buenos Aires

Selection of Sample Set

As mentioned above, one of the challenges for this study was the lack of building footprint data. Without it, it was not possible to calculate the rooftop area of each individual building. Digitizing each rooftop was also not feasible given the size of Buenos Aires and the time constraints for this study. In addition, due to the high urban density of the city, it was not possible to extract building structures from satellite imagery using ArcGIS image classification tools. The software had difficulty differentiating between buildings and other urban structures. As a result, it was decided that a stratified sample set of rooftops would be used to represent the entire city, following similar methods used by several other studies (Carl, 2014; Izquierdo et al., 2008; Wiginton, Nguyen, & J.M. Pierce, 2010). The hypothesis is that a correlation exists between the parcel area and the rooftop area in each stratum, which can be used to extrapolate out to the entire city to estimate the total rooftop area.

A representative sample set was selected based on available data, which includes Buenos Aires parcel and land-use datasets, obtained from the Public Data and Transparency of the City of Buenos Aires Initiative. The land use dataset revealed that there is a total population of 260,182 residential buildings in the city. For this population size, the sample size n_0 was calculated using the following formula from Izquierdo et al. (2008):

$$\boldsymbol{n_0 = t_\alpha^2 (\mathrm{CV})^2 / e^2} \qquad \mathbf{(1)}$$

Assuming a margin of error of e = 0.05; a confidence-level coefficient of $\propto = 0.05$, and therefore a z-score of $t_{0.05} = 1.96$; and a coefficient of variation of CV = 0.5, the sample size is 385.

In order to ensure that the samples chosen represent the different rooftops in the study area, it was necessary to create strata according to building typology as available rooftop area varies greatly between a single-family home and a multi-family high-rise building. For example, a single-family home may only have a small water tank on their roof as a limiting factor, while a residential high-rise building may have other obstructions such as an elevator mechanical room or a pool on the roof, in addition to a larger water tank. Furthermore, different building types may have different correlations between their rooftop size and the size of the parcel in which they are located.

The land-use dataset differentiates between houses (*casa*), single residence (*vivienda* única), undefined residence (*vivienda*), and apartment building (*departamentos*), and includes the number of floors for each building. However, the criteria for classification in the dataset is not clear. For example, the single residence class has floor quantities ranging from 1 to 23. Due to this uncertainty, it was decided for this study to reclassify the buildings by the number of floors. Table 1 displays the number of buildings corresponding to the new classification and the resulting sample size per class. The final 385 parcels were chosen at random for each class using the Research Randomizer tool (www.randomizer.org).

Table 1. Stratified sample calculation

Classification	Number of Floors	Number of buildings	Percentage of total	Sample size
0	1-3 floors	224,897	86.44%	**333**
1	4-10 floors	28,593	10.99%	**42**
2	11-17 floors	6,071	2.33%	**9**
3	18+ floors	621	0.24%	**1**
	TOTAL	260,182	100%	**385**

Estimation of Sample Set Rooftop Area

The first step in estimating the available residential rooftop area in Buenos Aires is to locate and digitize the sample rooftops in ArcGIS. Unfortunately, the land-use dataset is not accurately geo-referenced to align with the corresponding residential parcels. However, it does specify the parcel identification codes, which can be used to join the land use dataset to the parcel dataset. In this way, the residential building information from the land use dataset can be linked to their corresponding parcel. Joining the two datasets yielded many “null” entries, mostly caused by differences in the capitalization of the parcel identification codes between one dataset and the other. After correcting this issue, 2,786 entries were still resulting in “null” entries. Upon closer inspection, it was found that the issue was due to inconsistencies between the parcel dataset and the land-use dataset. This can be explained by the fact that the two datasets were compiled in different years. The parcel dataset was last updated in February of 2018, while the land-use data is from 2011. Considering that the "null" entries only make up 1% of the total number of residential parcels, it was decided that removing these entries would be acceptable.

Once the land-use dataset and the parcel dataset were successfully joined, the samples were located and each rooftop was manually digitized using the built-in World Imagery satellite map from ESRI’s online catalog. The resulting rooftop feature class includes the area of the digitized rooftops. For each of the sample rooftops, the available rooftop area for solar photovoltaic systems was then calculated. In order to do so, a corrective coefficient was adopted. This coefficient was obtained through the ratio between the actual available rooftop area, which excludes, water tanks, elevator machine rooms, ventilation shafts, etc., and the total rooftop area. An average of the coefficient was then calculated for each class to be used when extrapolating rooftop areas to the rest of the study area.

Given the lack of data, roof structure types are not considered in this study. While in countries with colder climates roof inclination must be taken into account when estimating available rooftop area, with a warm and temperate climate, Buenos Aires very rarely sees snowfall. As a result, roofs are generally flat. Therefore, it is considered acceptable not to include roof slope in this study.

Estimation of Incoming Solar Radiation

Raw measurements of solar radiation were obtained from a meteorological dataset from the City of Buenos Aires government database, as detailed in Appendix B. This dataset records the measures of hourly incoming solar radiation in Watts per m^2 from 16 different monitoring stations located around the city at different elevations. The measurements are from April 2011 to July 2012. This was the most recent data publicly available.

Given the large volume of data, the dataset was condensed into a manageable table in Excel. It was found that some of the entries were either errors of measurement or errors in the transmission of the data from the measuring stations. For example, some entries recorded high levels of solar radiation for time periods that should not have exposure to solar radiation, such as night-time hours. Other questionable entries recorded levels that were not comparable to other station readings for the same time frame. This may either be due to an error in the measurement or due to the effects of shadowing of the measuring instruments from neighboring structures, particularly during the morning and afternoon time frames when the sun is lower on the horizon. To determine the incoming solar radiation levels for the solar potential estimation, the entries from stations with questionable levels of radiation that seem to be due to measurement error or shadowing were removed from the dataset. The remaining entries were averaged by hour for each day of each month, and a monthly average of hourly solar radiation was subsequently calculated for each month of the year. This calculation is necessary for the estimation of solar potential on an hourly basis, particularly for the months of January and July, in order to analyze the peak shaving potential of rooftop solar photovoltaic systems. Annual solar radiation was also calculated from the daily averages in order to estimate the total annual solar potential of the residential rooftops in the City of Buenos Aires. Table 2 summarizes the solar radiation data.

Table 2. Average Hourly Solar Radiation by Month for Buenos Aires

Hour	January	February	March	April	May	June	July	August	September	October	November	December
6:00	1	0	0	0	0	0	0	0	0	0	1	4
7:00	45	21	4	1	0	0	0	0	2	26	24	66
8:00	174	129	78	24	4	2	0	7	32	100	100	210
9:00	380	312	217	140	53	25	18	62	71	199	234	411
10:00	553	453	359	294	136	88	54	125	193	405	489	560
11:00	708	554	498	409	216	176	134	249	400	527	683	682
12:00	804	667	544	505	323	281	209	312	517	594	708	752
13:00	758	741	617	568	365	330	294	330	540	577	480	763
14:00	774	707	635	542	348	335	299	313	573	565	654	773
15:00	760	651	560	463	287	246	271	238	485	509	571	699
16:00	636	528	441	367	206	159	180	152	335	362	305	622
17:00	504	374	300	235	111	81	66	96	210	224	199	463
18:00	287	198	159	91	26	15	17	39	94	108	76	255
19:00	142	78	35	11	0	0	0	3	14	25	31	128
20:00	30	9	1	0	0	0	0	0	0	0	4	24
Daily Total	6,555	5,423	4,448	3,651	2,075	1,738	1,543	1,926	3,465	4,219	4,559	6,413
Monthly Total	203,192	151,842	137,894	109,535	64,312	52,144	47,835	59,721	103,964	130,797	136,766	198,802
											Annual Total Solar Radiation	**1,396,806**

(Source: Agencia de Protección Ambiental, 2016)

Extrapolation of Sample Rooftop Area to Study Area Through Statistical Analysis

The underlying hypothesis was that a correlation exists between roof size and parcel size. To test this hypothesis, this study relies on correlational analyses using R statistical computing software to enable extrapolation.

The first analysis performed was a bivariate correlation analysis using Pearson's method in R. This analysis generates a coefficient between -1 and 1 that expresses the measure of linear correlation between two variables, where -1 is a perfect negative linear correlation and 1 is a perfect positive linear correlation (PennState, n.d.-a). Once an existing correlation was established, a simple linear regression was run for rooftop size and parcel size for each building class and for the total sample set. The analysis was divided into building classes to see whether correlations are stronger or weaker depending on the class. A linear fit equation was identified through this analysis to use as a basis for extrapolation in order to estimate the total available rooftop area based on the city's parcel data. In addition, the previously calculated reduction coefficient was included in the linear fit equation to account for unsuitable rooftop areas for solar installation. Given the size of the dataset, these calculations were done in ArcGIS.

Calculation of the Photovoltaic Potential of Rooftops

Once the total available rooftop area was identified, its solar photovoltaic potential could then be calculated. To do this, there are many factors to take into account, such as panel efficiency, performance ratio, ambient temperature, etc. For this study, the methodology from Singh and Banerjee (2015) was adopted to calculate solar photovoltaic potential. Singh and Banerjee used Equation 2 to calculate the hourly solar energy generation for a typical day for each month of the year in Mumbai, taking into account the available sunshine hours.

$$\sum_{N_{sh}} \boldsymbol{E_{PV}} = \sum_{N_{sh}} \boldsymbol{E_{sol} \times A \times \eta_{PV} \times \eta_{PCU}} \quad \textbf{(2)}$$

where E_{PV} is the energy output of the solar photovoltaic panel for one hour (kWh); E_{sol} is the incident solar energy in one hour on a unit area (kWh/m^2); A is the area of the panel (m^2); η_{PV} is the rated efficiency of the panel; η_{PCU} is the efficiency of the power conditioning unit, including the inverter; and N_{sh} is the number of effective sunshine hours. In the present study, this equation was used to calculate the hourly solar energy output for a typical day for the months of December, January, and February. E_{sol} and N_{sh} are defined by the results from the solar radiation calculation on ArcGIS; A is known through the digitization of the sample rooftops; and the value for η_{PCU} is taken from Singh and Banerjee (2015), who have calculated it to be 85% through simulations performed in PVSyst. The efficiency of the panel was considered to be 14.69%, which is the median efficiency found in the SRoeCo Solar database of commercially available solar panels (SRoeCo Solar, n.d.). As of March 15, 2018, the database contains 17,893 entries for solar panels. The median was selected to measure the typical case scenario. Equation 2 is then modified to Equation 3 to calculate the total annual solar output.

$$\boldsymbol{E_{PV,\text{annual}} = E_{sol,\text{annual}} \times A \times \eta_{PV} \times \eta_{PCU}} \quad \textbf{(3)}$$

where $E_{PV,\text{ annual}}$ is the total annual energy output of the solar photovoltaic panel (kWh); $E_{\text{sol, annual}}$ is the average incident solar energy in one year on a unit area (kWh/m^2); and the rest of the variables are the same as in Equation 2.

In addition to these factors, it is necessary to compute the effect of temperature on solar photovoltaics systems. The rated efficiency of solar panels is measured under Standard Test Conditions, where the panel receives 1000W/m^2 of solar radiation with a module temperature of 25°C (Phoenix Solar, n.d.). However, when temperatures rise, the efficiency of the panel decreases. This effect is measured by the Power Temperature Coefficient (PTC), which is the percentage that reflects the change in efficiency for every degree Celsius that the temperature varies from the standard 25°C. The PTC of a typical multi-crystalline solar panel is rated 0.05% per degree Celsius (Trina Solar, n.d.). Singh and Banerjee (2015) include this coefficient into their equation to create Equation 4.

$$\sum_{N_{sh}} \boldsymbol{E}_{\mathbf{PV}} = \sum_{N_{sh}} \left(\boldsymbol{E}_{\mathbf{sol}} \mathbf{\ x\ } \boldsymbol{A} \mathbf{\ x\ } \boldsymbol{\eta}_{\mathbf{PV}} \mathbf{\ x\ } \left(\mathbf{1 + PTC\ x\ (}\boldsymbol{T}_{\mathbf{panel,h}} \mathbf{- 25) / 100}\right) \mathbf{\ x\ } \boldsymbol{\eta}_{\mathbf{PCU}}\right) \tag{4}$$

where $T_{\text{panel,h}}$ is the monthly mean panel temperature during the *ht*h hour (°C), which is calculated by Equation 5.

$$\boldsymbol{T}_{\mathbf{panel,h}} = \boldsymbol{T}_{\mathbf{Air,h}} + \left(\mathbf{(NOCT\ -20)/800\ x\ }\boldsymbol{E}_{\mathbf{sol}}\right) \tag{5}$$

where $T_{\text{Air,h}}$ is the monthly mean ambient temperature during the *ht*h hour; E_{sol} is the incident solar energy in one hour on a unit area (Wh/m^2); and NOCT is the Nominal Operating Cell Temperature (°C), which the temperature reached on the surface of a solar panel when it is exposed to 800 W/m2 of solar radiation at an ambient temperature of 20°C with wind speeds of 1meter per second. The NOCT used for this study comes from Muller (2010), which reports an average NOCT under typical conditions of 48.7°C.

Using these equations, the total annual photovoltaics output potential was calculated for the study area, as well as the daily hourly output for an average January day and an average July day. These calculations were completed in Microsoft Excel by exporting the attribute table from the final rooftop layer in ArcGIS.

Results and Discussion

In the present section, the results of the analysis of solar potential carried out for the residential rooftops of the City of Buenos Aires are summarized and discussed. First, an overview of the results for the sample set is given, followed by the statistical analyses of the roof sizes and parcel sizes of the sample set; the extrapolation of roof size to the study area, based on the results of the regression models; and finally, the results of the calculation of solar potential for the extrapolated rooftop area, along with the peak shaving analysis.

Summary of Sample Set Attributes

The results of the digitization of the sample set of 285 residential rooftops were summarized into an Excel table. This was done by spatially joining the parcel layer to the sample rooftop layer in ArcGIS and exporting the resulting attribute table to Excel. Table 3 shows the summary of the statistics of the sample rooftops, calculated in Excel.

Table 3. Summary of sample set attributes

	Class 0	Class 1	Class 2	Class 3	Total
No. of Floors	1-3	4-10	11-17	18+	-
No. of Parcels	333	42	9	1	385
Minimum Parcel Size (m2)	48	119	298	-	48
Maximum Parcel Size (m2)	835	770	16217	-	16217
Average Parcel Size (m2)	**230**	**308**	**2237**	**520**	**287**
Minimum Roof Size (m2)	46	90	173	-	46
Maximum Roof Size (m2)	498	457	3494	-	3494
Average Roof Size (m2)	**153**	**204**	**676**	**375**	**171**
Average Roof/Parcel Ratio	**0.69**	**0.71**	**0.6**	**0.72**	**0.69**
Average Corrective Coefficient	**0.54**	**0.51**	**0.49**	**0.49**	**0.54**

In Table 3 both the average parcel size and average roof size seem to increase with each class, suggesting that taller buildings are located on larger parcels and have larger rooftops. However, Class 2 displays significantly larger numbers in both parcel size and roof size than the other classes. Upon inspection, the maximum parcel size of 16,217 m^2 and the maximum roof size of 3,494 m^2 in Class 2 correspond to sample number 84, which is a block-sized parcel with a large housing complex, comprising of five residential towers. Class 3 only has one sample, which is why the statistics shown for this class are simply the attributes of the single sample. The average parcel size and roof size for the entire sample set reside between Class 0 and Class 1 with an average roof/parcel ratio of 0.69.

An important figure in Table 3 is the average corrective coefficient of 0.54, which is later used for extrapolation to the entire study area. This coefficient reflects the actual available rooftop area for the installation of solar photovoltaic panels. While the corrective coefficient calculated in the sample set accounts for unavailable surfaces occupied by other uses such as water tanks, machines rooms, ventilation shafts, etc., it does not take into account shadowing from these objects, from trees, or from neighboring buildings. For this reason, a shadowing coefficient was adopted from literature and included into the corrective coefficient. Table 4 lists the values of shadow coefficients used in different studies around the world. For this study, an average was calculated from these coefficients found in the literature. The average obtained was then included into the corrective coefficient calculated from the sample set to form a final corrective coefficient of 0.26. Table 5 displays the final corrective coefficient adopted for this study in comparison to corrective coefficients found in the literature. As can be seen in Table 5, the resulting corrective coefficient for this study lies in the mid-range of the coefficients used in similar studies.

Table 4. Values of shadowing coefficient from literature

Study	Area Covered	Shadow Coefficient
Rodriguez et al. (2017)	Ludwigsburg, Germany	0.7
Bergamasco & Asinari (2011)	Piedmont, Italy	0.46
Wiginton et al. (2010)	Ontario	0.3
Izquierdo et al. (2008)	Spain	0.43
This study	**Buenos Aires**	**0.47**

Table 5. Values of roof utilization coefficient from literature

Study	Area Covered	Corrective Coefficient
Mainzer et al. (2017)	Freiburg, Germany	0.39
Rodriguez et al. (2017)	Ludwigsburg, Germany	0.25
Singh & Banerjee (2015)	Mumbai, India	0.28
Byrne et al. (2015)	Seoul, Korea	0.39
Mainzer et al. (2014)	Germany	0.27
Bergamasco &Ainari (2011)	Piedmont, Italy	0.145
Wiginton et al. (2010)	Ontario	0.19
Izquierdo et al.	Spain	0.194
This study	**Buenos Aires**	**0.26**

Roof Size and Parcel Size Correlation and Regression Analysis

The foundation of this study is an estimation of residential rooftop area in the entire city of Buenos Aires, based on the hypothesis that parcel size correlates to roof size. A quick scatter plot of the sample set data shows that there seems to be an upward trend, where roof area increases with parcel area (Figure 2). However, an outlier can be observed on the top right of the graph, which is the same inflated number that was identified in Table 3. While it seemed intuitive to remove sample number 84 from the study, given that it is not representative of the parcels in the city, for completeness it was decided that the study should proceed with the analyses considering two scenarios, one with sample 84 and one without in order to understand how the outlier influences the regression analysis. It is important to note that residential parcel sizes above 5,000 m^2, 10,000 m^2, and 15,000 m^2 only make up 0.065%, 0.02%, and 0.014% of the total residential parcels, respectively.

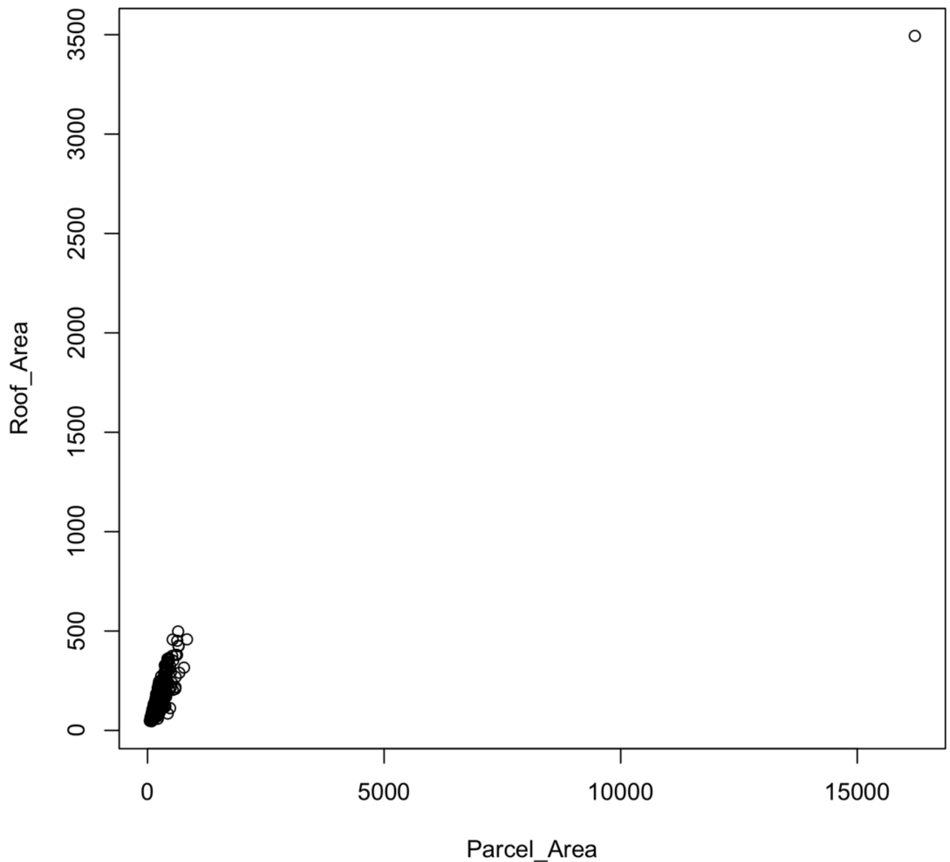

Figure 2. Scatterplot of Sample Set by Parcel Area and Rooftop Area

To have a better sense of the relationship between roof size and parcel size, a bivariate correlation analysis was done to identify the measure of linear correlation between roof size and parcel size in the total sample set and in each individual class. The correlation analysis was performed using Pearson's Method in the statistical software R. Table 6 shows the results of the analysis.

Table 6. Standard Correlation Between Roof Size and Parcel Size by Class and by Total Sample Set for Scenarios with the Outlier and Without the Outlier

	Class 0	Class 1	Class 2	Class 3	TOTAL
With Outlier	0.805	0.7485	0.9975	-	0.9505
p-value	< 2.2e-16	1.202E-08	2.47E-09	-	< 2.2e-16
Without Outlier	0.805	0.7485	0.9778	-	0.828
p-value	< 2.2e-16	1.202E-08	2.68E-05	-	< 2.2e-16

All classes show statistically significant positive relationships between roof size and parcel size. The strongest correlation can be seen in Class 2 with a 0.9975 coefficient with the outlier and 0.9778 without the outlier. Class 3 only has one data point. Therefore, a correlation analysis was not performed on this class. In the analysis of the total sample set, the scenario with the outlier also has a higher correlation coefficient than the scenario without the outlier. Therefore, an assumption can be made that the outlier is influential in the correlation. In either case, the results point to a strong and statistically significant correlation between roof size and parcel size, which is of great interest in this study as the total rooftop area is to be estimated based on the parcel size.

In order to extrapolate from the sample set results, it is necessary to run a bivariate linear regression model to analyze the relationship between rooftop area and parcel size. The previous correlation analysis showed that there is a significant relationship between the two variables. A bivariate regression model provides the means through which the rooftop area from the sample set can be extrapolated to the entire study area by identifying the intercept and the coefficient for the linear fit of rooftop to parcel size. Table 7 displays the results from the regression model. Both scenarios show significantly high adjusted R^2 values, although the scenario with the outlier outperforms the second scenario by far with an adjusted R^2 value of 0.90, compared to 0.68. It is clear from this analysis that the outlier is greatly influential in the regression model. It can be seen in Class 2 that the inclusion of the outlier increases the significance level of the regression as well as the adjusted R^2 value.

Table 7. Bivariate Regression Model of Roof Size and Parcel Size by Class and by Total Sample Set for Scenarios with the Outlier and Without the Outlier

	Class 0	Class 1	Class 2	Class 3	TOTAL
With outlier					
Adj R2	0.647	0.5493	0.9944	-	0.9031
Intercept	**32.95*** **	**93.33*** **	**223.8*** **	-	**109.2*** **
Coefficient	**0.519*** **	**0.3597*** **	**0.202*** **	-	**0.2157*** **
P-value	2.20E-16	4.92E-11	2.47E-09	-	2.20E-16
Without outlier					
Adj R2	0.647	0.5493	0.9489	-	0.6848
Intercept	**32.95*** **	**93.33*** **	-27.30994	-	**34.46978*** **
Coefficient	**0.519*** **	**0.3597*** **	**0.71641*** **	-	**0.52166*** **
P-value	2.20E-16	4.92E-11	2.68E-05	-	2.20E-16

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Class 3 only has one entry. Thus, regression analysis was not done for this class.

Considering the presence and the influence of the outlier in the sample set, it was decided that a weighted least squares regression be done on both scenarios to see if the models perform better when the weights of the influence of the outliers are reduced. In this method, each point is assigned a weight based on the variance of its fitted value. The aim is to assign smaller weights to points with higher variances to reduce their influence on the regression line. In this case, the weight was determined to be $1/\sigma_i^2$, where σ is the result of the regression of the absolute values of the residuals against the predictor, which is the parcel area (PennState, n.d.-b). The results are displayed in Table 8 below.

The weighted least squares regression did not improve the overall model for the scenario with the outlier, despite the fact that there were improvements in the individual classes. The adjusted R^2 value dropped from 0.9031 to 0.6314. This analysis further supports the assumption that the outlier plays an important part in the determination of the correlation between roof size and parcel size. With the reduction of the influence of the outlier on the model, the correlation is weakened. On the other hand, the regression model of the second scenario was strengthened by the application of the weights, increasing its adjusted R^2 value from 0.6848 to 0.7373. This seems to suggest that even without outlier number 84, there is high variability in the residuals. By lowering the influence of the higher variances, the model was improved.

Table 8. Weighted Least Squares Regression Model of Roof Size and Parcel Size by Class and by Total Sample Set

	Class 0	Class 1	Class 2	Class 3	TOTAL
With Outlier					
Adj R2	0.725	0.6478	0.9993	-	0.6314
Intercept	**21.92*****	**59.02*****	**225.2*****	-	**92.794*****
Coefficient	**0.57268*****	**0.48039*****	**0.2016*****	-	**0.27799*****
P-value	2.20E-16	8.07E-11	1.35E-12	-	2.20E-16
Without outlier					
Adj R2	0.725	0.6478	0.9483	-	0.7373
Intercept	**21.92*****	**59.02*****	-25.39989	-	**22.3126*****
Coefficient	**0.57268*****	**0.48039*****	**0.71253*****	-	**0.5774*****
P-value	2.20E-16	8.07E-11	2.77E-05	-	2.20E-16

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Class 3 only has one entry. Thus, regression analysis was not done for this class.

Extrapolation of Sample Rooftop Area to Study Area

To estimate the total rooftop area in the study area, equations were built from the resulting coefficients of the regression models to apply them to the parcel data for the city. Equations from the better performing models were used for both scenarios. In the case of the scenario with the outlier, the equations by class were constructed from the results of the weighted model found in Table 8, while the equation for the total sample set was obtained from the unweighted model in Table 7. For the scenario without the outlier, all equations were constructed from the results from the weighted regression model found in Table 8. Given that no linear regression analysis was done for Class 3, the equations for the total sample set are applied for Class 3 in both scenarios.

The rooftop area was calculated directly in ArcGIS, given the large size of the dataset. In addition to using the equations to calculate the rooftop area from each parcel size, the corresponding corrective coefficients were applied to each class and on the total population to obtain the available rooftop area for solar photovoltaic systems. The results can be observed in Table 9, where both total rooftop area and the available rooftop area for solar are displayed for each scenario by class and by total. It is interesting to see that the total available rooftop area by sum of classes is similar between the two scenarios, but the total obtained through the regression analysis differs greatly. For the scenario with the outlier, the estimated total available rooftop area is 11,288,624 m^2 while the other scenario has an estimate of 12,155,877 m^2. Evidently, the inclusion of the outlier affects the slope of the regression equation by lowering it compared to the equation of the regression without the outlier, thus, yielding a smaller estimate of the available rooftop area. Observing the results in Table 9, it seems that, compared to the total by sum of classes, the total available rooftop area calculated through the regression equation is underestimated in the scenario with the outlier and overestimated in the scenario without the outlier. For this reason, the study proceeded with the result from the total by sum of classes. To be on the conservative side, the estimate of 11,813,458 m^2 from the scenario with the outlier was adopted, as it is a slightly smaller estimate of available rooftop area.

Table 9. Rooftop Area Estimation Based on Regression Analysis for Scenarios with and Without the Outlier

	Class 0	Class 1	Class 2	Class 3	TOTAL (Sum of classes)	TOTAL (Regression Analysis)
With outlier						
Total Area (m2)	37,654,381	6,241,577	2,032,813	251,273	46,180,044	43,417,784
Available Area (m2)	9,790,140	1,497,978	467,547	57,793	**11,813,458**	**11,288,624**
Without outlier						
Total Area (m2)	37,654,382	6,241,577	2,280,678	511,703	46,688,339	46,753,370
Available Area (m2)	9,790,140	1,497,978	524,556	117,692	**11,930,366**	**12,155,877**

Calculation of Total Rooftop Solar Potentials in Study Area

After estimating the total available rooftop area, Equations 2, 3, 4, and 5 from the methods section above were used to calculate the solar potentials based on this estimation and the incoming solar radiation levels, obtained from the city government's database. The calculation for total annual rooftop solar potential yielded an annual potential solar electricity generation of 2,061 GWh for the residential rooftops in the City of Buenos Aires. Figure 3 displays the annual solar potential per residential parcel, based on the estimated available rooftop area.To put this result into perspective, according to the latest annual report from Cammesa, the Greater Buenos Aires Area consumed 51,683 GWh in 2016 (Cammesa, 2016a). The City of Buenos Aires is responsible for 23% of that total, which makes its annual electricity consumption about 11,887 GWh (Buenos Aires Ciudad, 2014). In other words, the potential annual generation from solar systems on residential rooftops in Buenos Aires is equal to approximately 17% of the total electricity consumption of the city in 2016.

This is a promising result. However, of greater interest to this study is the peak-shaving potential of rooftop solar systems in order to address the electricity crisis that the city faces annually. Peak-shaving consists of lowering the electricity consumption from the grid during the periods of maximum demand. This study proposes the use of solar-generated electricity to offset the demand on the grid and lower the daily peak demand in order to avoid power outages.

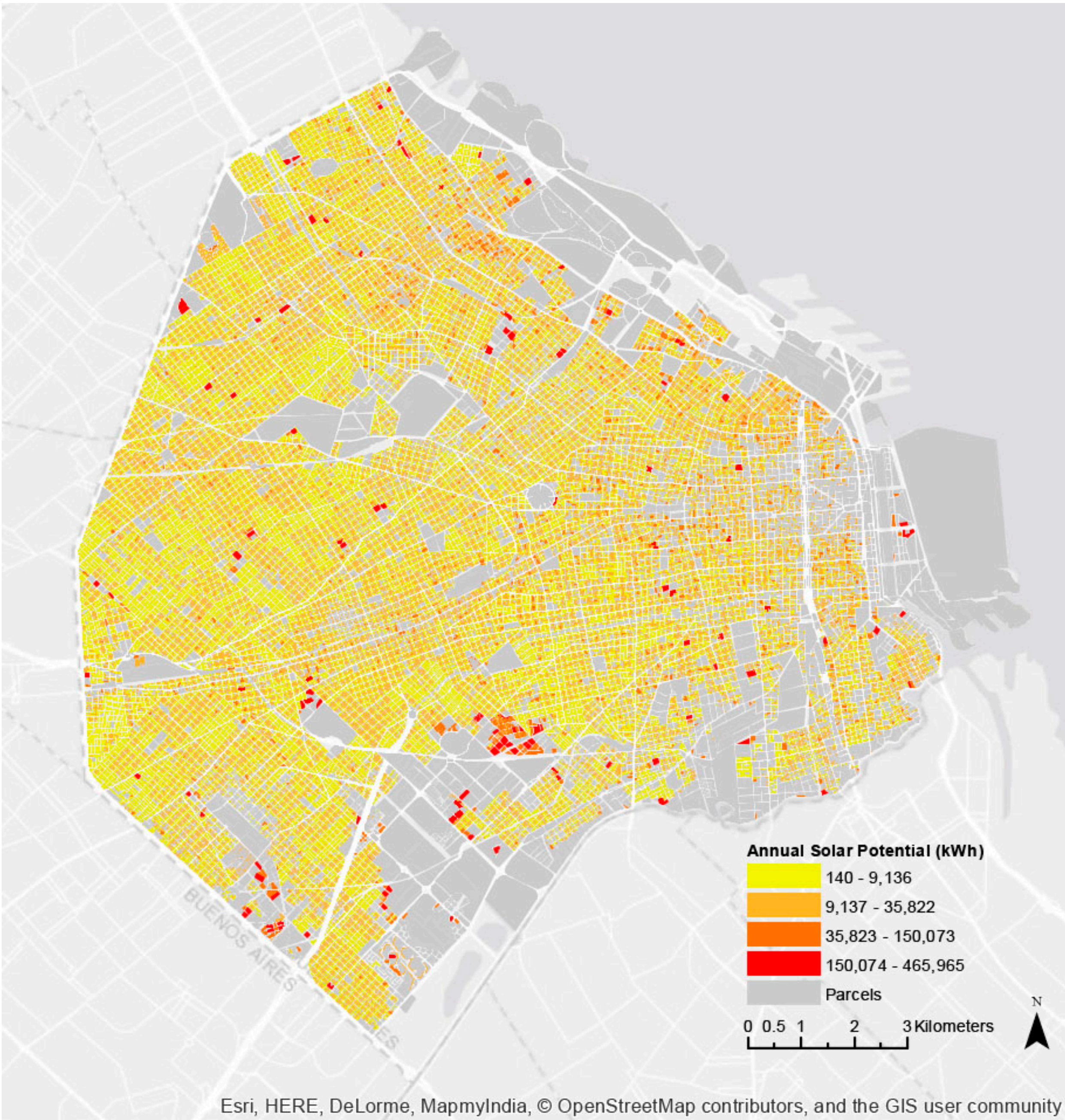

Figure 3. Annual Solar Potential on Buenos Aires Residential Parcels Based on Estimated Available Rooftop Area

Although the exact installed capacity cannot be calculated from the results of this study, a rough estimate can be made based on the available rooftop area. 11,813,458 m^2 of rooftop area could potentially hold about 1,872 MW in installed PV capacity, when considering the Solartec SOL-6P-60-265-4BB PV panel, which is about 1.64 m^2 and has a peak rating of 260 W (Solartec, n.d.). The most recent peak record that occurred on February 8, 2018, at 3:35 pm reached 26,320 MW on a national level (Cammesa, n.d.). Locally, Edesur, which services the southern parts of the city and Greater Buenos Aires, peaked at 4,146 MW at 3:45 pm, and Edenor, which services the northern parts of the city and Greater Buenos Aires, peaked at 5,177 MW at 4:10 pm. While these numbers represent the electricity consumption of the Greater Buenos Aires area, the impact that the installed rooftop PV systems would have on lowering peak demand is clear. Table 10 summarizes the general findings of this study.

Table 10. Summary of Study Findings

Summary of study findings	
2016 City electricity use (GWh)	11,887
Available rooftop area for solar photovoltaic installation (m2)	11,813,458
Potential installed capacity (MW)	1,872
Solar potential electricity supply (GWh)	2,061
Potential of rooftop solar supply as a % of city total electricity use	17%
Solar potential load shaving during 9 am to 6 pm in January	61%
Solar potential load shaving during 9 am to 6 pm in July	19%

To estimate peak-shaving potential in more detail, the hourly production of electricity from rooftop solar was compared to the daily load profile of the city for the months of January and July, which are the hottest and coldest months of the year, respectively. While peak-shaving in the summer is the main interest, given the frequency of blackouts due to extreme heat and electricity demand, July was also analyzed as the month with the worst case scenario for solar electricity generation as well as high electricity demand due to the need from building heating systems.

Unfortunately, daily consumption profile data from Cammesa are only available for the Greater Buenos Aires Area, which includes the City of Buenos Aires, but is not limited to the city. While the exact data of the consumption profile for the city is not available, it can be calculated from the Greater Buenos Aires profile, based on the estimate that the City of Buenos Aires' share of electricity consumption makes up 23% of the total electricity consumption of the Greater Buenos Aires Area (Buenos Aires Ciudad, 2014). Some differences may exist between the estimated consumption profile and the true consumption profile given that the City of Buenos Aires does have a more active nightlife than the surrounding areas. Nonetheless, in the interest of potential peak shaving during daylight hours, it was deemed an acceptable approximation.

Figures 4 and 5 below display the estimated consumption profiles of the city for January 2017 and July 2016 along with the peak-shaving potential from residential rooftop solar systems and the winter and summer season maximum consumption profiles. These were estimated from the national season maximums found in Cammesa's 2016 Annual Report (Cammesa, 2016a). This metric measures the winter and summer days of 2016 with the highest consumption profiles, which correspond to extreme low-temperature days in the winter and high-temperature days in the summer.

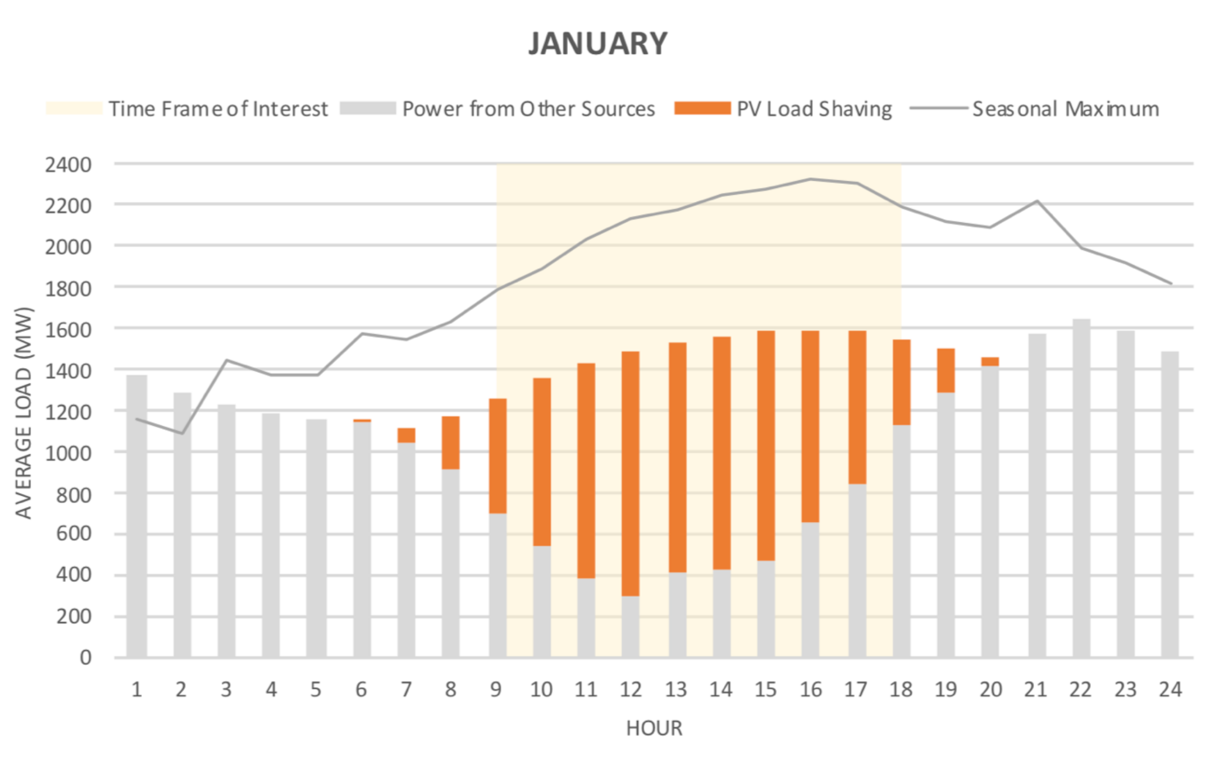

Figure 4. Peak Shaving Analysis for Daylight Hours in January

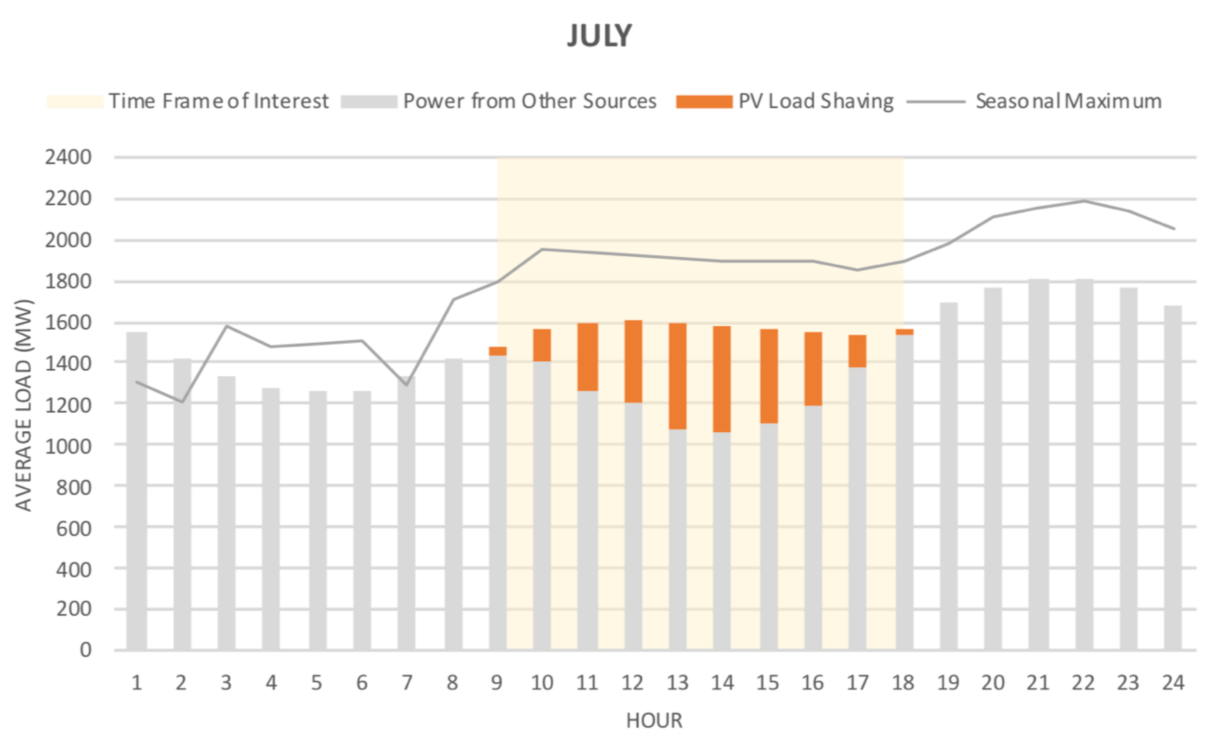

Figure 5. Peak Shaving Analysis for Daylight Hours in July

Looking at the two figures, there are several observations to highlight. The first is that despite the fact that there is a greater frequency of power outages in the summer compared to the winter, the typical daily load for July is higher than the load for January. While this is counter-intuitive considering the situation of the electricity grid in Buenos Aires, this can be explained by a greater use of heating systems in the winter than air-conditioning units in the summer. The second observation is that the daily seasonal maximum profile is actually much higher in January than in July. As opposed to January, July's season peak occurs at night when the temperatures are coldest and building heating systems are fully functioning. However, it is not nearly as high or as enduring as January's peak. This is made evident when comparing the number of hours that demand is maintained above 2,000 MW. July's peak above this threshold lasts approximately 6 hours between 7 pm and midnight, while January's peak lasts around 12 hours between 11 am and 10 pm. In addition, high-degree days are more common in the summer months than low-degree days are in the winter. In 2016, there were 33 days between May and September where the average daily temperature was below 10°C, but there were 48 days between December and March where the average daily temperature was above 26°C. This is a steep increase from 25 days in 2014 and 37 days in 2015 (Cammesa, 2016a). Taking these observations into account, Figures 3 and 4 show that rather than the average daily profiles, what is impacting the electricity grid are the extraordinary days where consumption peaks are maintained over a long period of time, which is the case for days like the January seasonal maximum profile.

The third observation pertains to the peak-shaving that could be obtained from the contribution of electricity generated from rooftop solar systems. It is evident that the solar resource can significantly lower the day-time peak in the summer. For the time frame of 9 am to 6 pm, electricity generated from rooftop solar could potentially cover 61% of the city's typical electricity needs. This would be particularly useful for the seasonal maximum profile days, in which 43% of the electricity needs could be serviced by rooftop solar systems. On the other hand, the benefit is less apparent for the winter, where the peak occurs at night both in the average daily profile and the seasonal maximum profile. In the case of a typical July day, only 19% of electricity needs during the 9 am to 6 pm time frame could be covered by rooftop solar.

In both January and July scenarios, the incorporation of electricity storage systems would greatly increase the impact of rooftop solar on peak-shaving. Given that load demand does not align with the solar electricity generation, but rather, is higher during evening hours, using additional storage could shift some of the production towards night-time load reduction. This would greatly benefit peak-shaving in the winter. Electricity storage systems are further elaborated in the following section.

Discussion

This study sought to answer the questions: *What is the solar photovoltaic potential of residential rooftops in the City of Buenos Aires, Argentina, and to what extent can residential rooftop photovoltaic systems contribute to peak-shaving?*

This study found that at 2,061 GWh, the annual solar potential of PV systems on Buenos Aires' rooftops is vast. This number equates to powering over 343,000 homes annually, with the assumption that an average household consumes about 500 kWh per month. At the current electricity rate of $0.14 USD per kWh (ARS $2.65), the total solar PV production could yield a total annual savings of $288,482,554 USD for the consumers (Edenor, 2018).[3] In addition, at the cost of $71 USD to produce 1 MWh of electricity in Argentina, the generated solar electricity

[3] The electricity rate corresponds to the Edenor tariff for small residential consumers with a monthly consumption of 500 kWh. The cost in USD is calculated at an exchange rate of $20.45, as of April 10, 2018.

could save the electricity generating sector about $146 million USD (Ministerio de Energía y Minería, 2016).The estimated solar potential is also significant when contemplating the Renewable Energy Plan launched in 2015. The national government established this plan to promote the use of renewable sources for electricity, setting a goal to achieve a contribution of 20% from renewable sources to the energy mix by 2025 (Ley N° 27191, 2015). As of 2016, electricity from renewable sources only makes up 3% of the grid mix (Cammesa, 2016a). However, if all the available rooftop area estimated in this study were utilized for solar panels, its sole contribution to the grid mix would be 20%.

In terms of peak-shaving potential, it was found that the potential is greater for January than for July, which was to be expected given the higher radiation values in the summer. However, when observing the results outside of the 9 am to 6 pm time frame, it is clear that the rooftop solar systems fall short for peak-shaving, given that the peaks usually occur at night. A more appropriate term for the rooftop solar contribution would be load-shaving, considering that, while it does not reduce the peak, it does reduce the daytime load. The only exception is when the summer maximum profile is taken into account. This profile falls into line with the historical peaks recorded by Cammesa, which were reached between 2:20 pm and 3:35 pm. For these extraordinary days, which are actually becoming more common as seen from the Cammesa statistics, the solar contribution can be considered peak-shaving (Cammesa, 2016a).

Considering the shift between peak solar production and peak demand, the results of this analysis suggest that the use of energy storage is necessary to successfully address peak-shaving. Energy storage would allow part of the electricity generated during the day to be stored and used at times when the solar panels no longer generate electricity. Figures 6 and 7 display how the use of energy storage might address the city's nighttime peaks in January and July. These figures are simply illustrative. The peak-shaving curve of energy storage and discharge would most likely look different, as each home's storage system would be programmed according to its particular situation.

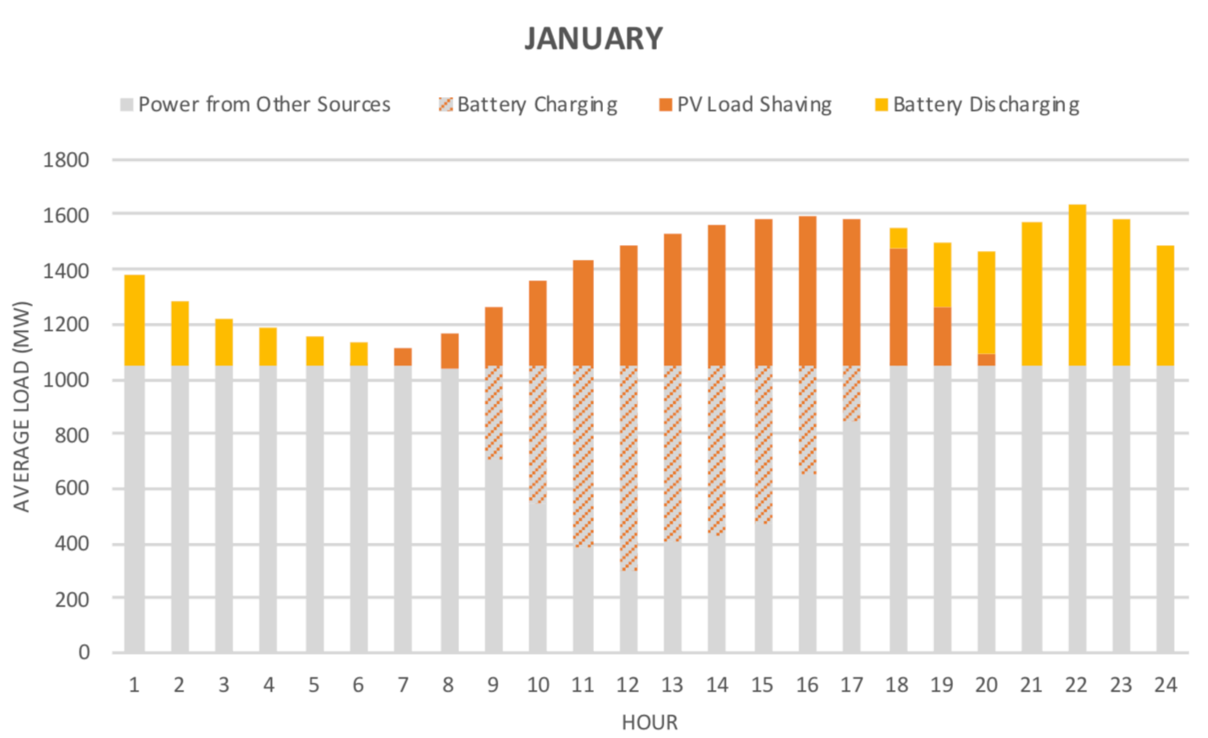

Figure 6. Peak Shaving Analysis with Battery Storage for January

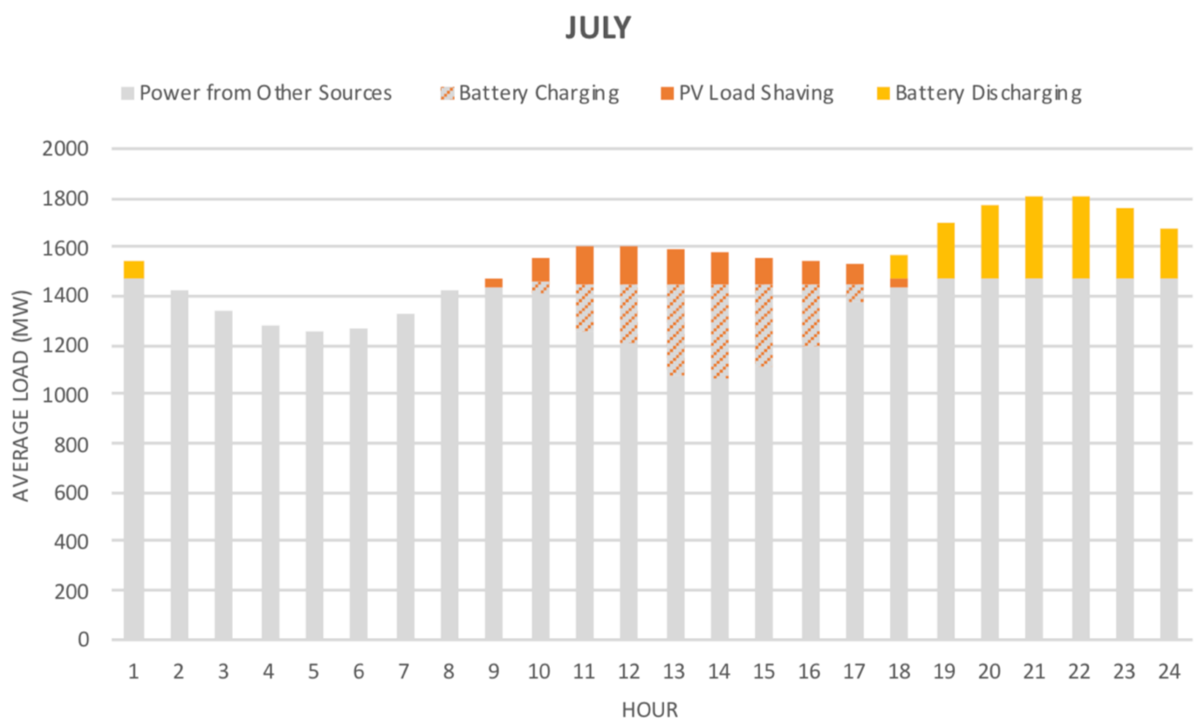

Figure 7. Peak Shaving Analysis with Battery Storage for July

There is a large range of technologies in existence that can serve as energy storage on different scales, particularly for intermittent renewable energy sources such as solar energy. To name a few, there is battery storage, pumped hydro, compressed air, and flywheel. However, many of these technologies are either not mature enough or are prohibitively expensive. In addition, they are usually most suited for large-scale applications, given that they can be capital-, and infrastructure-intensive (Carver, 2015). Thus, the most familiar and popular storage technology for small-scale applications is battery storage.

The most common batteries are lead-acid and lithium-ion batteries. Lead-acid batteries are the cheaper of the two and are simpler to manufacture. Unfortunately, they have a low recharge rate and a low cycle-life (Carver, 2015). On the other hand, lithium-ion battery technology has gained popularity and its performance has been improving steadily over the years. The batteries are light-weight with high capacity and high life-cycle (Blomgren, 2016). The main disadvantage of this technology is the cost. However, the market pull for this technology is strong, as demand increases with its growing applications in the electronics, automobile, and energy industries. This is driving research and development while bringing the costs down. From 2013 to 2016, the cost of lithium-ion batteries in residential applications went from around $3,000 USD per kWh of installed capacity to $1,700 USD per kWh of installed capacity. It is projected to continue falling, potentially reaching the range of $290 USD per kWh to $520 USD per kWh by 2030 (Schmidt, Hawkes, Gambhir, & Staffell, 2017).

In Argentina, there is currently no market for solar home batteries. Some companies, such as Hissuma-Solar, sell solar kits with small batteries that can help power a few of the household loads or can be used as backup power in the case of a power outage (Hissuma-Solar, 2017). These kits have become increasingly popular as an option to deal with the power outages. They peaked interest in particular as electricity prices began to climb in 2016 as a result of the partial removal of government subsidies on utilities (Jurado, 2016). However, they still require a huge upfront investment that many households cannot afford. Fortunately, the outlook for solar energy and battery storage is optimistic. In addition to the dropping international prices, the first plans for national lithium-ion battery production are underway. Despite the current lack of a market, two companies, Jujuy Litio SA and Litarsa are looking to pave the way for battery technology in Argentina, choosing to focus on hybrid automobile batteries, home batteries, and batteries for public lighting (Manzoni, 2018). With this, as new markets for solar energy emerge, as prices become competitive, and as solar policy is made, the vast solar potential of Buenos Aires' rooftops can finally be tapped into to deal with the electricity crisis that the city faces.

Recommendations and Conclusions

Electricity consumption will continue to rise in the City of Buenos Aires as its population increases. Increasing consumption will put further stress on the grid, leading to continued large-scale power outages in the city. Furthermore, as the effects of climate change become more severe and the frequency of heat waves increases, demand for electricity will grow even further. Without appropriate intervention, the energy crisis will only deepen. Fortunately, as observed in the previous chapter, there is a vast solar resource on the residential rooftops of Buenos Aires with significant load-shaving potential. In addition, if battery storage is included in the rooftop solar systems, there is great peak-shaving potential available.

Despite the positive outlook of rooftop solar potential in Buenos Aires, there are still hurdles to overcome. The main one is the cost associated with solar PV systems. A small 3-panel system with 240W polycrystalline panels and a 4 kWh battery system costs around $3,470 USD (ARS $71,000), without considering the cost of battery replacement over the lifetime of the system (Hissuma-Solar, 2017).[4] These systems are useful for powering basic loads such as a refrigerator, a television, a computer, and lamps, and can provide electricity for about 4 hours in the case of a power outage. Considering that the average monthly income of a typical household in Buenos Aires is around $1,270 USD (ARS $26,000),[5] without financing options and incentives, it is difficult for households to afford the upfront cost of installation of a rooftop solar system, let alone a small solar generator like the one mentioned above (Buenos Aires Ciudad, 2017).

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[4] The cost in USD is calculated based on the exchange rate of $20.45, as of April 14, 2018.
[5] Income in USD is calculated based on the exchange rate of $20.45, as of April 14, 2018.

However, the end of the tariff freeze has offered some changes to the roadmap of rooftop solar photovoltaic systems. While upfront costs are still high, the payback period has dropped considerably making, what was impossible a few years ago, now more viable. For instance, in 2015, an article in the local newspaper La Nación, calculated that the payback period for a 4-240W-panel system without backup batteries was 98 years, considering the subsidized cost of electricity (Vegas, 2015). Today, the Hissuma-Solar generator kit can be paid back in only seven years for a household that consumes 500 kWh monthly (Jurado, 2016). As payback times for these systems become shorter with the end of subsidized electricity bills and with the falling prices of solar technologies, access to these systems will increase, but financial aid will be needed in order for solar technologies to reach the average consumer.

Thus, an important piece of this system is solar policies and regulations. Apart from the effect of the frozen tariff policy on the viability of solar systems, the lack of incentives and regulations are also an important barrier. First of all, there were no regulations in place for the injection of electricity produced from distributed solar systems into the grid (Fenés, 2014). Even if a person could afford a PV system, the excess electricity produced during the day would be lost because it would not feed into the grid. However, in September 2017, the government sanctioned a project to allow residents to produce their own energy based on renewable sources (Ley N° 27424, 2017). With changing legislation and the restructuring of the utility tariffs, the distributing companies started updating the grid and rolled out a plan to install meters that will allow clients to sell electricity back to the grid, should they decide to invest in PV systems (Pablo Fernández Blanco, 2017).

This is the beginning of incentivizing the installation of distributed PV systems. To further promote the incorporation of rooftop solar PV systems into the electricity grid, some recommendations are made below.

- The government should establish subsidies for rooftop solar PV installations and battery installations. Subsidies formerly used for utilities could be redirected towards rooftop solar subsidies. Incentives should be prioritized for solar installations that include a battery backup in order to address the shift in peak load demand in relation to solar electricity production. The installed battery should be able to handle at least 4 hours of the house load in order to cover the evening peak demand.
- Low-interest loans and financing options should be offered by local banks. The province of Santa Fe already has a program that offers credit through Banco Santa Fe for solar thermal installations in the form of low-interest loans with up to 60 monthly installments or 18 installments with no interest through their credit card (Santa Fe, n.d.). The City of Buenos Aires could likewise offer such loans and financing options through a city bank for solar PV systems.
- The government should offer deductions on annual taxes, such as the property tax and the income tax for those who install solar PV systems in their homes.
- Net metering should be regulated. Both Edenor and Edesur should offer the installation of bi-directional meters and full-retail net metering, which would encourage consumers to invest in solar PV systems in order to reduce their bills or even generate a small income.
- Solar campaigns should be made to raise awareness of the possibilities of solar energy on rooftops in Buenos Aires. More studies, such as the present one, should be done and their results distributed on local media in order to educate people regarding solar energy. A

platform should be created where all the relevant information regarding solar energy for residential rooftops can be easily found.

- Solar access rights should be discussed and possibly legislated. This is particularly important in urban settings where new construction or neighboring trees could potentially cast shadows on existing rooftop solar systems or prevent a home from the future use of rooftop area for solar PV systems.
- The Buenos Aires building code and urban planning code should be updated to account for rooftop solar PV installations. Given height restrictions in many zones in the city, the codes should be modified to account for the additional height that rooftop systems might add to buildings.

Future Research

There are several recommendations for future research. In the first place, a building rooftop footprint dataset should be created for future studies, where each rooftop is manually digitized using satellite imagery. In this study, the total available rooftop estimation was based on statistical analysis rather than on actual data from rooftops in the city. This was due to the lack of available data on building footprints. A building rooftop footprint dataset would allow a more accurate estimation of the total rooftop area. However, even with this limitation, the methodology used in this study may be helpful for future studies of other cities in Argentina that face the same data limitations.

It must also be mentioned that this study only included the solar potential of the City of Buenos Aires. In reality, the impacts of power outages stretch further to include the Greater Buenos Aires area. Future studies may include the calculation of the Greater Buenos Aires area for a more comprehensive idea of how rooftop solar systems can be used to reduce peak demand and deal with the power shortages in the summer.

Finally, financial feasibility was only briefly considered in this research. Further studies should include an in-depth analysis of the cost of solar installations given that the economic component is an important part of the decision to adopt solar or not. In addition, it is one of the greatest barriers that people face when considering solar PV.

Conclusion

Even with the limitations mentioned before, this study presents valuable information regarding the solar resource that is available on the rooftops of Buenos Aires. It is the first study of its kind to estimate the solar potential for the city and to analyze its peak-shaving potential. Through sample analysis, statistical analysis, and extrapolation, it was estimated that the available rooftop area for solar is 11,813,458 m^2. A rooftop area of this size was estimated to produce 2,061 GWh annually, which is about 17% of the city's total annual electricity consumption. More importantly, Buenos Aires rooftops have the solar potential to reduce the daytime load by 61% in January and 19% in July. Considering the difficulties that the city faces each summer with the recurring power outages, this result points to rooftop solar systems being a possible solution to the electricity crisis. However, it was also found that in order to completely address peak-shaving, it is necessary for the rooftop solar systems to have a form of electricity storage given that the peaks usually occur in the evenings. Even small battery systems that may provide power for 4 or 5 hours can significantly reduce peak demand.

In light of these findings, the study has presented several recommendations in support of the implementation of solar technologies on Buenos Aires rooftops, including offering financial incentives through financing options, tax deductions, and subsidies; regulating net metering in both Edenor and Edsur, the electricity distributing companies servicing the city; raising awareness of the benefits and feasibility of installing rooftop solar systems; and updating building and zoning codes to account for and facilitate the installation of these systems.

The significance of this study also lies in its replicability to other parts of Argentina. When data are scarce, the sampling methods and extrapolation through statistical analysis used in this study can be replicated to estimate a city's rooftop area. Solar potential assessments for cities are important to pave a way for solar energy to be considered a viable alternative source of electricity for cities. As Byrne et al. say, "It is the only indigenous supply resource which all cities possess" (2014).

All in all, incorporating solar PV on Buenos Aires rooftops would be beneficial to address the electricity crisis. It is clear from this study that with the abundance of solar resources available on the city rooftops the potential is great. Furthermore, adding the extra solar installed capacity would bring Argentina closer to its goal to have 20% of its electricity proceed from renewable energy sources by 2025.

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Appendix A

National Electricity Consumption Peaks Compared to Maximum Temperature and Power Outage Reports

Date	Peak Demand (MW)*	Time of Peak	Max. Temp. in Bs. As. (Celsius)	Power Outage (Y/N)	Affected Neighborhoods	Source
2/7/12	**21,907**	15:35	31	Y	Almagro, Boedo, Caballito, Recoleta, Villa Pueyrredón	(De Santis, 2013)
2/16/12	**21,949**	15:10	31	Y	Abasto, Almagro, Balvanera, Flores	(De Santis, 2013)
1/30/13	**21,982**	14:30	32	Y	Caballito, Almagro, Mataderos, Barracas, Villa del Parque, Parque Chacabuco, Parque Patricios, Paternal	(De Santis, 2013)
2/1/13	**22,169**	15:35	35	Y	Almagro, La Paternal, Caballito, Flores, Mataderos, Villa Lugano, Villa del Parque, Villa Devoto, Barracas, Villa Mitre, Villa Santa Rita, Parque Patricios	(De Santis, 2013)
7/22/13**	**22,552**	20:26	8	Y	Balvanera	(De Santis, 2013)
12/16/13	**23334**	15:00	31		Palermo, Villa Urquiza, Belgrano, Saavedra, Balvanera, Almagro, Caballito, Mataderos, Liniers, Flores	(De Santis, 2013)
12/17/13	**23,433**	14:20	33	Y	Almagro, Palermo, Villa Urquiza, Caballito, Recoleta, Belgrano, Mataderos, Balvanera, Flores, Parque Chacabuco	(De Santis, 2013)
12/23/13	**23,794**	14:20	33	Y	Palermo, Belgrano, Caballito, Villa del Parque, San Cristóbal, Almagro, Flores, Boedo	("Los cortes ahora son intermitentes y afectan a casi todos los barrios," 2013)
1/17/14	**23,978**	14:20	34	Y	Flores, Barracas, Boedo, Monte Castro, Parque Chas, Villa del Parque, San Telmo	("La térmica rozó los 40° y hubo cortes de luz en algunos barrios," 2014)
1/20/14	**24,034**	15:05	32	Y	Caballito, La Paternal, Barracas, Belgrano, Villa del Parque, Villa Santa Rita, Palermo	("El Gobierno admitió que los cortes de luz aún afectan a 7 mil usuarios," 2014)
10/27/14	22,147	14:26	33	N		
11/18/14	22,055	20:48	31	N		
12/9/14	23,104	15:15	28	N		
1/27/15	23,949	14:13	33	Y	Almagro, Recoleta, Flores, Floresta, Parque Chacabuco, Villa Devoto, Saavedra, Urquiza, Mataderos, La Boca, Caballito, Villa Crespo	("Otra vez hubo apagones y la gente estalló en las redes sociales," 2015)
2/6/15	23,573	14:19	29	N		
3/17/15	23,409	20:40	30	N		
4/13/15	20,116	19:50	28	N		
5/26/15	20,450	19:45	16	N		
6/23/15	23,529	19:50	10	N		
7/21/15	22,997	20:40	12	N		

Date	Peak Demand (MW)*	Time of Peak	Max. Temp. in Bs. As. (Celsius)	Power Outage (Y/N)	Affected Neighborhoods	Source
8/12/15	22,363	20:55	13	N		
9/9/15	21,398	20:14	19	N		
10/2/15	20,628	20:24	16	N		
11/2/15	20,411	20:52	18	N		
12/28/15	23,727	14:50	32	Y	Flores, Villa Lugano, Caballito, Villa Santa Rita	("Cortes de luz: más de 90 mil usuarios se encuentran sin servicio," 2015)
1/22/16	**24,885**	14:28	34	Y	Mataderos, Saavedra, Flores	("Más de 750 mil usuarios sufrieron cortes de luz en la Ciudad y el Conurbano," 2016)
2/12/16	**25,380**	14:35	34	Y	Balvanera, Caballito, La Boca, San Nicolás, Villa Lugano	("Récord de consumo eléctrico y cortes de luz por el intenso calor," 2016)
3/17/16	23,139	20:54	30	N		
4/27/16	21,340	20:48	12	N		
5/18/16	21,679	20:25	13	N		
6/10/16	22,638	20:15	11	N		
7/28/16	22,230	20:58	-	N		
8/2/16	21,455	20:50	-	N		
9/6/16	22,265	20:25	-	N		
10/19/16	19,051	20:25	17	N		
11/25/16	20,425	20:57	28	N		
12/21/16	23,266	15:22	32	N		
1/30/17	24,717	14:47	33	N		
2/24/17	**25,628**	14:25	31	Y	La Boca, Liniers, Mataderos, Monserrat, Nueva Pompeya, Chacabuco, Parque Patricios, Flores, Floresta, Barracas, Caballito, Villa Crespo, Almagro, Constitución, Palermo, Colegiales, Paternal, Chacarita, Villa Ortúzar, Nuñez, Saavedra	("Record de consumo y miles de cortes de luz," 2017)
3/2/17	24,906	15:05	32	Y	San Cristóbal, Caballito	("Agobiados por el calor y sin luz: 120.000 usuarios están sin servicio en Buenos Aires," 2017)
4/26/17	20,056	20:27	17	N		
5/31/17	22,058	20:40	13	N		
6/8/17	22,987	21:05	14	N		
7/17/17	23,529	20:45	15	N		
8/1/17	21,931	20:41	14	N		
9/26/17	20,369	20:15	19	N		
10/12/17	19,953	21:00	16	N		
11/15/17	21,585	14:40	28	N		

Date	Peak Demand (MW)*	Time of Peak	Max. Temp. in Bs. As. (Celsius)	Power Outage (Y/N)	Affected Neighborhoods	Source
12/29/17	24,696	14:40	32	Y	Mataderos, Villa Constitución, Villa Santa Rita, Boedo, Caballito, Balvanera, La Boca, San Nicolás, Villa Soldati	(“Más de 20 mil hogares están sin luz en Capital y Gran Buenos Aires,” 2017)
2/8/18	**25,994**	14:25	34	Y	Montserrat, Mataderos, Caballito, Villa Urquiza, Agronomía	(“Otro récord de consumo eléctrico, aunque con numerosos cortes,” 2018)
2/9/18	**26,320**	15:35	31	Y	Montserrat, Mataderos, Caballito, Villa Urquiza, Agronomía	(“Aunque bajó la temperatura, todavía quedan unos 80.000 usuarios sin luz en Capital y GBA,” 2018)

*Peak records are in bold.

**Peak record reached in July due to unsually cold winter

(Sources: Cammesa, www.tiempo.com)

Appendix B

Buenos Aires Parcel Data

The dataset named mo_parcelasdata is a polygon shapefile of Buenos Aires parcels. It is obtained from the Registry of Construction and Cadastre, under the Secretary of Planning of the Ministry of Urban Development. The native coordinate system is GCS_Campo_Inchauspe and the projected coordinate system is Argentina_GKBsAs. The parcel dataset includes important attributes such as the parcel identification number, total constructed area, and total parcel area. It does not include building footprint data nor building height data. It was last updated on February 25, 2018. It was retrieved from https://data.buenosaires.gob.ar/dataset/parcelas.

Buenos Aires Land Use Data

The dataset rus_ciudad_2010_2011 is a point shapefile of land uses per parcel in Buenos Aires. The dataset was produced by the Directorate-General of Territorial Diagnostics and Urban Projection, under the Sub-secretariat of Planning, under the Ministry of Urban Development and Transportation. Important attribute fields in the dataset include the parcel identification number, the street name and number, land uses, number of floors, and building type. The native coordinate system is GCS_Campo_Inchauspe and the projected coordinate system is Argentina_GKBsAs. The dataset was retrieved from https://data.buenosaires.gob.ar/dataset/relevamiento-usos-del-suelo.

Buenos Aires Meteorological Data

The datasets informacion-meteorologica-2011 and informacion-meteorologica-2012 are .csv files that contain meteorological information of Buenos Aires. The datasets are for the years of 2011 and 2011, containing the following fields: date, time, station number, wind speed, wind direction, temperature, relative humidity, atmospheric pressure, precipitation, solar radiation, and UV index. They were produced by the Environmental Protection Agency under the Ministry of Environment and Public Space. These data were retrieved from https://data.buenosaires.gob.ar/dataset/informacion-meteorologica.

ESRI World Imagery Data

The World_Imagery is a web map of high-resolution satellite imagery of the world. It was obtained from the ESRI online catalog on ArcGIS. The dataset is credited to ESRI, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, aerogrid, IGN, IPG, swisstopo, and the GIS User community. It was created on June 23, 2003, and las updated August 29, 2017. The layer is on the GCS_WGS_1984 coordinate system. It has one meter or better resolution in many parts of the world.

Argentina Consumption Data

The dataset dem-hor_2014_a_2017 is an excel table that contains the electricity consumption data for the different regions of Argentina, including Greater Buenos Aires, by the hour from 2014 to 2017. It was obtained from personal communications with Emiliano Marinozzi from the Global Control area of Cammesa. Older data from 2006 to 2013 are publically available on the Cammesa website, retrievable at http://portalweb.cammesa.com/Pages/Informes/Estadisticas1.aspx.