

The diverse impacts of COVID-19 on electricity demand: The case of Chile

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ABSTRACT

This paper analyzes the impacts of the first wave of COVID-19 (March 2020 - September 2020) on the electricity demand of different types of consumers in Chile, including residential, commercial, and industrial demand. We leverage data from 230 thousand smart meters of residential and commercial consumers in 32 communes of Santiago (the capital city of Chile), which allows us to investigate the evolution of their demands with an hourly temporal resolution. Additionally, we use demand data of large industrial consumers provided by the Chilean system operator to study the impact of the pandemic on different economic sectors. This paper demonstrates that the COVID-19 pandemic, and the associated containment measures, have featured a drastically different impact on the various types of consumers in Chile. In particular, we show that the demand of residential consumers has increased throughout the first wave, even when we isolate the effects of the pandemic from those related to weather. Furthermore, we study how these effects change in different communes of Santiago, contrasting our findings with the socio-economic levels of the population. In effect, we find different demand response patterns depending on the socio-economic background of consumers. We also show that commercial demand has significantly declined due to the containment measures implemented and that the hospitality and construction economic sectors have been the most affected in the country.

1. Introduction

1.1. Motivation

The pandemic of COVID-19 started in November 2019 in the Chinese province of Hubei. Since then, it has gained global attention due to the rapid growth in daily infections and the resulting collapse of health systems. In March 2020, COVID-19 was declared a pandemic by the World Health Organization (WHO) [1].

In order to contain the spread of the pandemic and thus alleviate the health systems, several states around the world adopted policies that restrict the mobility of people. In Chile, it was decreed a state of catastrophe on March 18, 2020, and quarantines were first established at the end of that month, being implemented by zones (usually communes¹). In the case of Santiago (the capital city of Chile), where the

largest population is concentrated, a total quarantine was declared on May 15, 2020 [2].

In the context of the pandemic, containment measures aimed at curbing the spread of the virus have impacted the electricity demand of several countries. In [3], the International Energy Agency reports the variation in electricity demand with respect to 2019 for some countries of Europe, China and India. The report determines that Italy experienced the sharpest drop in electricity demand, featuring a decrease of over 25% during April 2020. Similarly, [4] reports changes in electricity demand for seven Regional Transmission Operators (RTO) of the United States. The New York Independent System Operator (NYISO) and Midcontinent Independent System Operator (MISO) jurisdictions

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¹ The commune is the basic administrative division of the city. For example, the city of Santiago –formally called the province of Santiago– is divided into 32 communes.

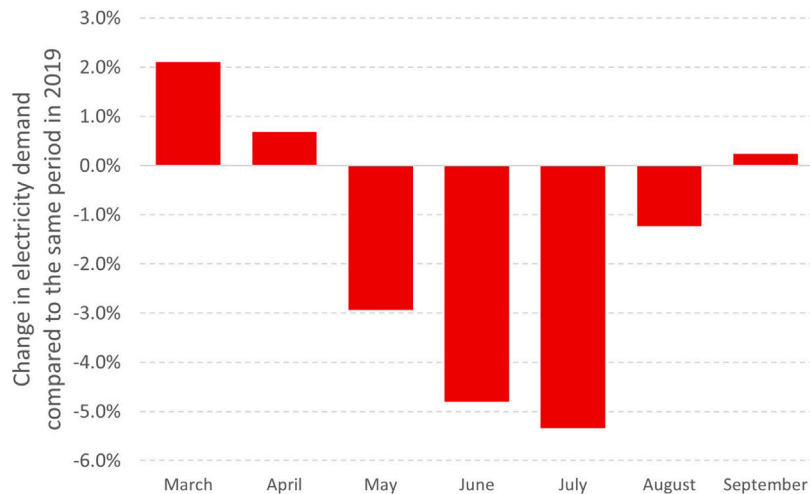


Fig. 1. Variation in electricity demand with respect to the same period in 2019 (The first case of COVID-19 in Chile was reported in March 2020) [6].

showed the largest decreases (around 10%) in demand compared to 2019.

In Chile, the reduction in mobility prompted by quarantines and other containment measures has also affected economic activity (that decreased by 14.1% in the second quarter of 2020 with respect to the same period in 2019 [5]) and, consequently, the national demand for electricity, as shown in Fig. 1. This demand declined in approximately 3.5% with respect to the previous year during the period that ranges from May to August 2020.

In this context, there is an interest by policymakers, regulators, planners, system operators, and electricity companies in understanding the consequences of the pandemic on electricity demand more profoundly. First, from a technical point of view, the changes in demand patterns have posed challenges to system operators related to frequency control and voltage control due to a higher share of renewable generation (as a consequence of lower overall demand) and higher uncertainty in the forecasted demand [7]. Second, there are discussions regarding whether scheduling and planning tools should consider the demand variations due to the pandemic in order to plan a more reliable and resilient power system in the medium- and long term. In several cases, the changes in the demand patterns have introduced deep uncertainties [8]. And third, from a regulatory viewpoint, several households have observed a dramatic decrease in their incomes as a consequence of the shut down of commercial and industrial activities, whereas their electric consumption has increased due to lock-down measures. Thus, different states have prepared public policies to support residential consumers during the crisis (e.g., Chile, Portugal, Belgium, and Italy [9]). All of the above, and other relevant topics related to system operation, planning, and the energy policy, require a better understanding of the impacts of the pandemic on electricity demand at all levels.

1.2. Objective and contributions

This paper aims to analyze the impact of the first wave of the COVID-19 pandemic (March 2020 - September 2020) on the electricity demand in Chile. The effects on residential and commercial consumers are studied leveraging data from 230 thousand smart metering devices in Santiago, capturing the evolution of these effects throughout the different containment measures established by the authorities. Additionally, the high resolution of the smart-metered data allows us to examine changes in hourly demand patterns and compare the impact on different parts of Santiago. In this way, we investigate the relation between this impact and the socio-economic level of the population, which is particularly important in Latin America. Finally, we study the impact of the pandemic on the different economic sectors of the

country, determining which ones have been more affected. To the best of our knowledge, a comprehensive analysis like this has not been carried out in the literature so far.

The contributions of this article are summarized as follows:

- Determine the impact of the COVID-19 pandemic on electricity demand in Chile, differentiating among residential, commercial, and industrial consumers.
- Use data from 230 thousand smart meters installed in the city of Santiago to study the evolution of hourly demand from residential consumers throughout the pandemic.
- Separate seasonal behavior of residential demands (typically driven by temperature) from those associated with the COVID-19 pandemic.
- Identify the impacts on residential consumers localized in various zones/communes of Santiago, discussing potential relations between the intensity of the impacts and the socio-economic background of the consumers.
- Determine the impact of the COVID-19 pandemic on the electricity demand from various industrial sectors, disaggregating the effects on different consumers categorized according to their economic activity (hotels, mining, agriculture, etc.).
- Provide a rich dataset of aggregated measurements of smart meters during the first wave of COVID-19, publicly available in [10]. Remarkably, this repository has been developed using an advanced data visualization tool, allowing users to interact with large datasets in a straightforward fashion. Developed in collaboration with Enel Distribución (a distribution company) and the Chilean Energy Ministry, this has been a valuable tool for the electricity sector in Chile and a key practical output of this work.

This article is structured as follows. The Literature Review section describes the main findings of studies related to the impact of COVID-19 in electricity markets. The Method of Analysis section describes the procedures, data sources, and case studies. The Results and Discussion section quantifies the impacts of the COVID-19 pandemic on electricity demand for regulated (residential and commercial) and industrial consumers. In addition, possible causes of the impacts are analyzed considering socio-economic and climatic variables. Finally, the Conclusions section summarizes the main results and lessons drawn from this study.

2. Literature review

Since the beginning of the pandemic, several research efforts have been focused on quantifying the impact of COVID-19 on the energy demand. The authors in [9,11] provide a comprehensive review of the

impacts of the pandemic on the energy demand in different regions, including the European Union, United States, Southeast Asia, Africa, Japan, Korea, China and India. The effects of containment measures on the overall electricity demand of six countries of Europe are studied in [12]. The authors investigate the relation between the intensity of such measures and the decline in demand, showing that countries with more restrictive measures, such as Spain and Italy, experienced larger demand reductions during weekdays. Similarly, [13] compares the evolution of electricity consumption of five European countries considering the severity of their measures. In fact, countries with severe lockdowns features significant changes in the electricity demand. Conversely, in the Swedish case, where no quarantines were adopted, the energy consumption remained in the pre-pandemic levels. The impact of the pandemic on the energy demand of other regions is also described in the existing literature, including South Korea [14], Turkey [15], Brazil [16,17], United Kingdom [18], Canada (Ontario) [19], United States [4,20] Italy [21], Israel [8], India [22], Serbia [23], China [24], Japan [25], Bangladesh and Nepal [26].

Other works have studied the impact of containment measures on different segments of consumers. For example, [27] studies the changes in the overall residential demand of several countries between March and May of 2020, showing that it increased in up to 32%. Ref. [28] determines potential changes in residential demand in Cordoba (Spain), by examining a referential consumer that represents a household of four people. It also studies the changes in health centers' demand patterns caused by the pandemic. Ref. [29] estimates the increases in residential demand by analyzing the electricity demand patterns of 17 households in Queensland (Australia). Ref. [23] simulates the electricity consumption of a household according to the different containment measures taken by the Serbian Government. Additionally, [14] quantifies the correlation between the energy demand of several buildings and pandemic indicators, highlighting that commercial and industrial buildings show a downward trend in demand, whereas residential buildings increase their demand.

In the case of industrial consumers, containment measures may have had different impacts depending on the economic activity. This is examined in [30] for the Brazilian market, quantifying the impact of the pandemic on electricity demand across different economic sectors. The authors show that the most affected sectors have been the automotive, services, and textile industries, with demand reductions of around 25%. Ref. [31] analyzes the impact of containment measures on industrial demand, disaggregating by economic sector in different provinces of Canada. The authors highlight the impact on the electricity demand of the oil industry. In the same line, in [24], the electricity demand variation is used to estimate the impact on other macroeconomic variables in China. In [22], the authors study the economic impacts across India, finding that those vary significantly among different states. Interestingly, the electricity demand variations have allowed policymakers to estimate the impacts of the pandemic on the economy.

The utilization of data gathered by smart meters devices has the potential to provide important insights on the effects of the pandemic on electricity demand. In this context, [32] uses data from 350 thousand smart meters in Melbourne (Australia), showing that residential demand increased by 14%, whereas commercial and industrial demand decreased by 7% and 1%, respectively. Similarly, [33] studies the data from 2 thousand consumers in the United Kingdom, determining that households increased their demand by an average of 17% when containment measures were in place during March, 2020. Ref. [34] examines demand data during the quarantines of the first two weeks of the pandemic, concluding that household's demand increased by 11% in Ireland. In turn, [35] studies the demand of multiple households in Austin, Texas, analyzing the impact of containment measures on their demand patterns. Finally, [27] reviews several articles related to changes in demand patterns, highlighting that, due to the containment measures, people wake up later and use more electricity at home throughout the day.

An important challenge that arises when quantifying the impact of containment measures on the demand for energy is isolating their effects from those related to temperatures, which also affect demand patterns. This is addressed in [20], where the authors use regression models to separate the effect of climatic variables, and thus study the effects of the pandemic on electricity demand in the United States. Similarly, [14] adjusts electricity demand time series to exclude the climatic effects. In the same vein, [4] examines the impacts of the pandemic in the United States. To do so, the authors use a database that contains information of electricity demand, health indicators, climate variables, and mobility indexes, among others. Through a backcasting methodology, they estimate the changes in electricity demand caused by the pandemic.

Finally, Table 1 summarizes the main findings of the reviewed publications related to a country. Remarkably, the vast majority of the papers includes analyses of the impact on the overall, national-wide electricity demand. The impact of the pandemic on the residential sector has been quantified in [14,23,26,27,29,32–34]. The Latin America experience has been presented in [16,17,27]. None of the publications (particularly those related to Latin America) has undertaken a detailed analysis of the pandemic on the different types of consumers, including data from smart meters, the socio-economic level of residential consumers, and the different economic sectors of industrial and commercial demand, such as the one developed in our paper.

3. Method of analysis

3.1. Overview

This section describes the methods used to analyze the impacts of COVID-19 on the electricity demand of different types of consumers. Due to the data sources available, the analysis is composed of two main parts: the study of regulated consumers, i.e., residential and small commercial consumers, and the study of industrial consumers.

In the case of regulated consumers, we use hourly demand data from a comprehensive set of smart meters installed uniformly across the city of Santiago (interestingly, circa 10% of the regulated consumers have a smart meter installed). The time series of demand per smart meter is then characterized according to the communes where the consumers are located and differentiated between residential and commercial. Thus, by simply inspecting the evolutions of demand data during the first wave of the pandemic, we can straightforwardly identify trends in various time scales (hourly, daily, weekly), and compare the demand evolutions across different types of consumers and communes. This analysis presents both average consumptions and their deviations in each commune and type of consumer. To better understand the impacts of the pandemic, we analyze the changes in demand using two benchmarks: (i) the energy consumption right before the pandemic (March 2020), and (ii) the energy consumption during the same period of the previous year (2019). To further isolate the impacts of the pandemic, separating it from seasonal effects, we propose a simple but workable method based on identifying consumers who are weather-insensitive. Thus, the behavior of these weather-insensitive consumers can more confidently demonstrate the effect of the pandemic, isolating it from the impacts of the temperatures on demand levels. Finally, as some of the communes of the city of Santiago can be straightforwardly classified in a particular socio-economic level, we examine whether the demand changes during the pandemic present some common features in communes with similar incomes.

In the case of industrial consumers, we use monthly demand data provided by the system operator for each large consumer, and classify each of them according to its economic activity. Thus, by comparing the demands of 2020 with those of 2019 (during the same period of the year), we are able to identify the impacts of the pandemic on the consumption of each economic sector in Chile.

Next, we present the details of the analyses mentioned above along with the different case studies.

Table 1
Summary of publications about country-related COVID-19 impacts on electricity demand.

Source	Country	Economy	Findings
[32]	Australia	Developed	Reduction of 7% of national-wide electricity demand during March 2020 compared to 2019. Residential demand grew by 14% during March 2020
[19]	Canada (Ontario)		Reduction of 14% of overall electricity demand during April 2020 compared to 2019
[11]	France		Reduction of 20% of national-wide electricity demand during the third week of lockdown period compared the same period of 2019
[27]	Germany		Reduction of 6% of national-wide electricity demand during May 2020 compared to 2019
[34]	Ireland		Increment of 11% in residential demand comparing two weeks before and after lockdown
[21]	Italy		Reduction of 20% of national-wide electricity demand during May 2020 compared to 2019
[25]	Japan		Reduction of 8% of overall electricity demand (in Kansai) during April and May 2020 compared to 2019
[12]	Sweden		Increment of 2% of overall electricity demand in 2020 compared to 2019
[18,33]	UK		Reduction of 16% in overall electricity demand during the first lockdown period compared with the average of the last three years. Residential demand shows a growth of 17%
[27,35]	US		Reduction of 19% of overall electricity demand during April 2020 compared to 2019. In Austin, residential demand increased 32% during the first three weeks of lockdown
[23]	Serbia	In transition	Simulation shows that the residential demand sector could increase up to 58% of their electricity demand due to containment measures
[26]	Bangladesh	Developing	Reduction of 14% of national-wide electricity demand during 2020 compared to 2019. Residential demand increased 15% during 2020 compared to 2019
[17]	Brazil		Reduction of 19% of overall electricity demand (south subsystem) comparing periods before and after implementation of containment measures
[24,27]	China		Reduction of 11% of national-wide electricity demand during March 2020 compared to 2019
[27]	India		Reduction of 4% of national-wide electricity demand during 2020 compared to 2019
[26]	Nepal		Reduction with a range between 21%–28% in nation-wide electricity demand during 2020 compared to 2019
[14]	South Korea		Reduction 10% of national-wide electricity demand during April 2020 compared to 2019. An increment of 5.5% in residential demand during March 2020 compared to 2019

3.2. Analysis of regulated demand: residential and commercial

Below, we present the method to study the impact of containment measures aimed to limit the expansion of COVID-19 on the demand of regulated consumers. These correspond to small consumers, formally known as residential and commercial.

In order to study these residential and commercial segments, information from 230,000 smart metering devices of Enel Distribución installed in the capital city of Santiago (32 communes) was used. These data are protected by a Non-Disclosure Agreement (NDA) and have been sufficiently aggregated in this article to protect consumers' privacy.

The demand data from each smart metering equipment contains the following information of a consumer:

- Location data: This item includes the geographical coordinates, address, and commune of the consumers.
- Commercial data: This includes the type of billing (used to differentiate between residential and small business consumers) and the type of tariff or plan of the consumer.
- Electricity demand: The energy consumed (in kWh) from January 2019 to September 2020 with hourly resolution.

Additionally, we conduct more in-depth case studies focused on five communes that represent different socio-economic realities of the city.

These communes are: Las Condes, Santiago,² La Florida, La Cisterna and Renca. The numbers of smart meters per commune and type of consumer considered in the numerical studies are presented in the Appendix.

In this way, the impacts of COVID-19 on regulated consumers are analyzed through the following four case studies:

3.2.1. Case i: Trends in weekly demand of residential and commercial consumers during the pandemic

The weekly electricity demand variation is studied, having as a reference the first week of March 2020 (week 10). During this week, the Chilean Government had not decreed the state of catastrophe yet, so it is not affected by the pandemic. The demand obtained from each smart meter is aggregated (summed) for each week and then the weekly demand is averaged within every commune. In this way, we obtain the average weekly demand for residential and commercial consumers of each commune. Apart from the average weekly demands, we present the respective 10–90th percentile ranges to illustrate the associated deviations. These data are used to study the evolution of the average

² Note that in this case, we are referring to the commune of Santiago, which is located in the city of Santiago.

demand on the five selected communes between March 2, 2020 and September 21, 2020.

3.2.2. Case ii: Isolating pandemic effects from seasonal weather effects on residential demand trends

This case study aims to examine the changes in the electricity demand of residential consumers whose demand is not sensitive to temperatures. In this particular segment of non-temperature-sensitive consumers, the increase in demand in 2020 compared to 2019 can be mainly attributed to the effects of the COVID-19 pandemic and the associated containment measures implemented by the authorities.

To identify these consumers, their average demand during cold (week of April 22 and May 6, 2019) and warm weeks of 2019 (week of March 4 2019) are compared. In this work, a consumer is considered to be insensitive to temperature if its average demand during cold weeks is similar to that during warm weeks (setting a tolerance for variations that can be considered negligible).

For this set of consumers that are not very sensitive to temperatures, the variation of the average monthly demand in 2020 is compared to their average monthly demand in the same months of 2019. The variations are attributed to the effects of containment measures aimed at curbing the spread of COVID-19.

3.2.3. Case iii: Behavioral changes (at an hourly level) of residential demand

Unlike the previous cases, in this case study we analyze hourly variations in demand within representative weeks, including the pre-pandemic period (represented by the week of March 2, 2020), the initial period of intensive quarantines (represented by the week of April 20, 2020), the period of total quarantines (represented by the week of June 22, 2020), and the period of gradual reopening (represented by the week of September 21, 2020). In this way, we study changes in demand patterns throughout the day, which strongly correlate with consumers' daily habits (wake-up time, workday, meals, breaks, etc.). In this line, we also analyze the temporal shifts of intraday peak demand. This analysis is carried out for two of the five selected communes (Las Condes and Renca, representing two extremes of the socio-economic spectrum). In this analysis, we obtain the average hourly demand and the respective 10–90th percentile ranges.

3.2.4. Case iv: Overview of the impact of the pandemic on the 32 communes of the metropolitan region

The overall impact of the pandemic in the region is studied in this case. We do so by quantifying the variation in average communal demand during the representative weeks with respect to the week of March 2, 2020 (week 10). The representative weeks used in this analysis are the same as those described in case iii.

Finally, the differences in the impacts of COVID-19 on the different communes according to their socio-economic level are discussed.

3.3. Analysis of industrial demand by economic sector

We use the data from 2500 large consumers who have publicly reported their demands for several years (this database is managed by the Chilean system operator, i.e., National Electrical Coordinator) to quantify the impacts of the pandemic on the electricity demand of industrial consumers. We group the large consumers, and their associated data, according to their economic activity. The economic activity of each large consumer can be obtained from the public database of the Internal Revenue Service of Chile (this service defines 17 categories for all economic activities in Chile). After grouping large consumers, we can compare the average monthly electricity demand of each economic sector during 2020 (between the months of January and September) with respect to the same months of 2019. In this way, we can identify which industries have been more affected by the COVID-19 pandemic in terms of electricity demand. Fig. 2 illustrates this method.

4. Results and discussion

This section presents and analyzes the results in terms of the impact of the containment measures implemented to curb the spread of COVID-19 on the evolution of electricity demand of regulated consumers (i.e., residential and small commercial consumers) in the metropolitan region/area (Región Metropolitana), and the impact on the industrial demand of different economic sectors at a national level. The period under study ranges from the week of March 2 (week 10) to the week of September 21 (week 39), 2020.

4.1. Trends in regulated demand - residential and commercial

This sub-section describes the results of the four case studies (presented in Section 3.2) for regulated consumers.

4.1.1. Case i: Trends in weekly demand of residential and commercial consumers during the pandemic

Fig. 3 shows the evolution of the demand of regulated consumers throughout the period under study. Colored areas highlight different containment measures undertaken by the Chilean government authorities, which are described in Table 2. Notice that residential demand increased with respect to week 10 (March 2, 2020), opposed to the systemic trend (Fig. 1) of decreasing electricity demand from May to July.

Fig. 3 shows that since the implementation of school closures in week 12 (March 16, 2020), small commercial consumers experience a gradual reduction in their demands compared to week 10 (March 2, 2020). This reduction reached its lowest point during week 15 (April 6, 2020). Particularly, the communes of Santiago and Las Condes, underwent demand reductions of 47% and 42%, respectively, compared to week 10. The other communes experienced demand reductions of around 15% during week 15.

The electricity demand from small businesses experiences a recovery during the period of gradual quarantine, specifically between weeks 15 and 20 (May 11, 2020). For example, Las Condes consumed 58% during week 15 (compared to week 10), figure that rises to 72% during week 20. This recovery is, however, greatly impacted by the total quarantine policy implemented during week 21 (May 18, 2020). During that week, the demand of Las Condes decreased to a 66% of the demand of week 10. Small businesses in the Santiago commune were the most affected in terms of electricity demand during week 21 (May 18, 2020), consuming around 57% of the electrical energy consumed in week 10.

Interestingly, the electricity demands of small commercial consumers on the five communes under analysis reach their peak around week 26. This week coincides with the coldest period of the winter (see Fig. 4).

Finally, during July and August, electricity demand maintained a relatively stable trend. Consumers in Santiago reduced their demand the most during this period, consuming on average around 63% of the electrical energy they consumed during week 10.

Fig. 3 also shows trends in residential demand. During the first weeks of the pandemic, when school closures were mandated (weeks 12–14), demand in Las Condes and Santiago increased by approximately 10% compared to week 10. On the other hand, residential demand in Renca and La Cisterna increased at a lower rate of around 5%. From the end of April (week 18), residential electricity demand significantly increased as a consequence of the pandemic and lower temperatures in Santiago.

Peak demand occurred in week 26 (June 22, 2020). During this week, consumers in Las Condes increased their demand 2.7 times (on average) compared to week 10, while in Renca, consumers increased their demand 1.6 times.

After the peak-demand week, the gradual reopening policy and rising temperatures cause a reduction of residential demand. After the arrival of spring in week 39, the demand of consumers in Las Condes

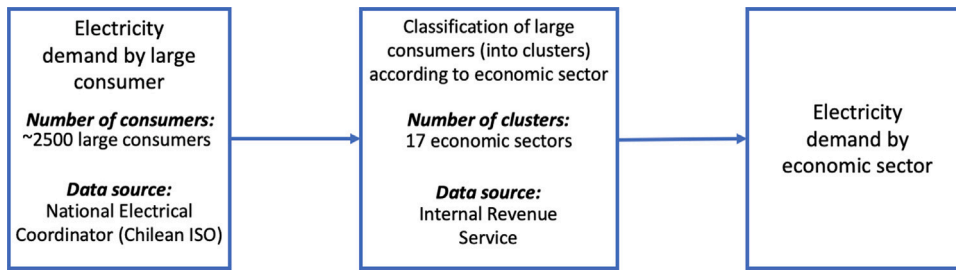


Fig. 2. The scheme describes the data and the method to quantify the electricity demand by economic sector.

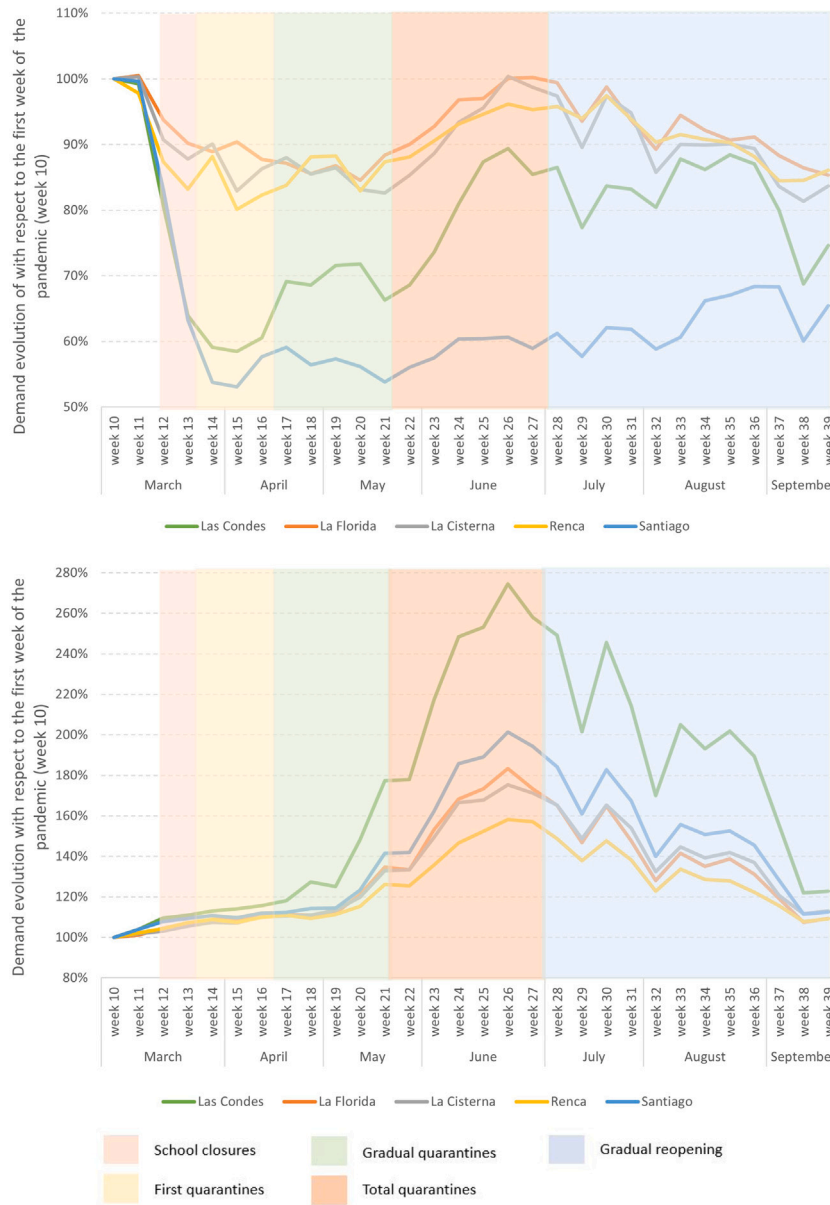


Fig. 3. Variation in regulated commercial (upper graph) and residential (lower graph) electricity demand during the weeks of the pandemic in 5 communes of Santiago.

reached a 23% increase (compared to week 10), while in the other communes, it reached increases of around 10%.

It is important to notice that the above studies the evolution of the average demand per commune on a weekly basis. However, there is a significant variety of demand evolutions across consumers within a commune. In this regard, Fig. 5 presents a box and whisker plot of

demands in every commune. In all the cases, the box and whisker have their maximum width during the winter months.

Fig. 3 also shows an important relation between the demand of the different communes and the containment measures. This can be observed more clearly in the first weeks of the pandemic (weeks 12–16), where all the communes under study showed an important change in demand (between 7% in La Cisterna and 16% in Las Condes

Table 2
Containment measures applied by the Chilean government during the pandemic (all dates correspond to 2020).

Milestone	Period	Comments
School closures	Since week 12 (03/16)	This policy is in effect from March 16 until the end of the study horizon.
First quarantines	From week 14 to week 16 (03/30 – 04/13)	This period begins with the quarantine of four communes in the eastern part of Santiago, and ends with the reopening of these communes. At the end of this period, only two communes remain in partial quarantine (Santiago and Ñuñoa).
Gradual quarantines	From week 16 to week 21 (04/13 – 05/18)	During this period the authorities gradually increase the number of communes in quarantine. At the end of this period, all the 32 communes under study are in quarantine.
Total quarantine	From week 21 to week 27 (05/18 – 06/29)	During these weeks the authorities establish a quarantine for the whole metropolitan area (Región Metropolitana), allowing only the so-called essential activities. ^a
Gradual reopening	From week 27 (06/29)	Since the week of June 29, and as a result of improvements in the epidemiological indicators, the authorities begin to reopen communes.

^aA set of activities deemed by the authority as critical for the society, e.g., healthcare workers, food supply chains.

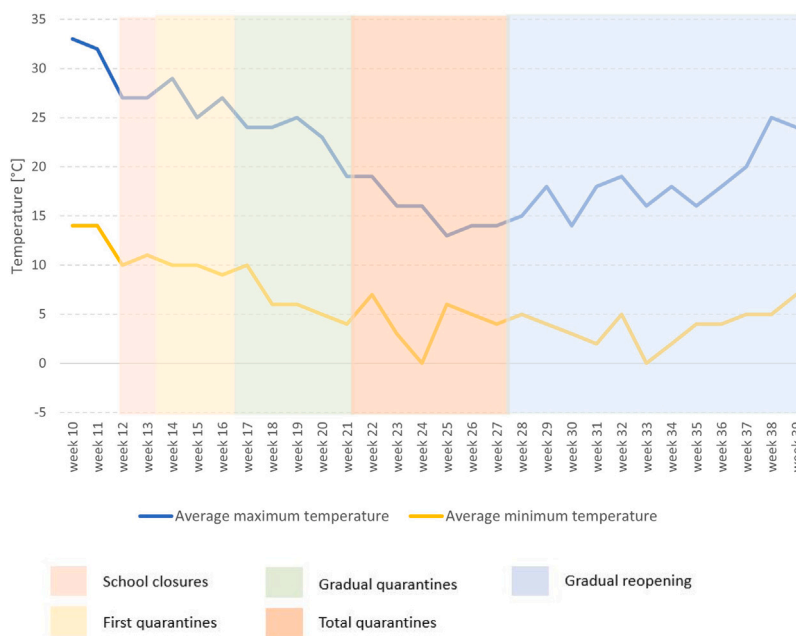


Fig. 4. Evolution of weekly maximum and minimum temperatures (seven-day averages). The different containment measures throughout the period are described by the colored areas.

with respect to week 10 for residential consumers) prompted by the first containment measures imposed by the Chilean government. Note that these weeks are prior to the increase in demand due to lower temperatures.

Finally, it is worth noting that the largest demand increases are observed in the socio-economic sectors with the highest income. Fig. 6 shows the distribution of monthly gross salaries in 32 communes of the metropolitan area (Región Metropolitana), based on data from the National Statistics Institute [36]. Communes in the eastern part of the region, like Las Condes, present the highest salaries (around 2,300 USD per month on average). Other communes, such as Santiago and La Florida, present average salaries for the region (around USD 1,000 per month on average). Finally, communes like La Cisterna and Renca are at the lower-end of the income distribution for the region (around USD 650 per month on average).

The largest increases in demand were observed in the commune of Las Condes (higher-income commune), while the smallest changes were observed in Renca and La Cisterna (lower-income communes).

These differences observed across the analyzed communes may be explained by a potential lower response to confinement [37] and low temperatures (due to reduced levels of electrification of heating solutions) in lower-income communes. Interestingly, using metrics of mobility calculated with data from mobile/cell phones, the authors in [38] demonstrate dependencies between people’s income and mobility levels under quarantine. In fact, [38] demonstrates that people with higher incomes are more likely to work from home, reducing their mobility levels. Conversely, people with lower incomes tend to feature higher mobility levels as they likely need to commute to undertake their work. Hence, reference [38] found that communes with higher incomes (e.g., Las Condes) present, on average, higher reduction levels in their mobility under quarantine. This is in opposition to the case in lower-income communes such as Renca, where mobility levels are, on average, higher. This relation between the mobility levels of the population and their incomes may help explain a key observation presented in our study, where higher-income communes feature, on average, a higher rise in their electricity consumption during lockdown

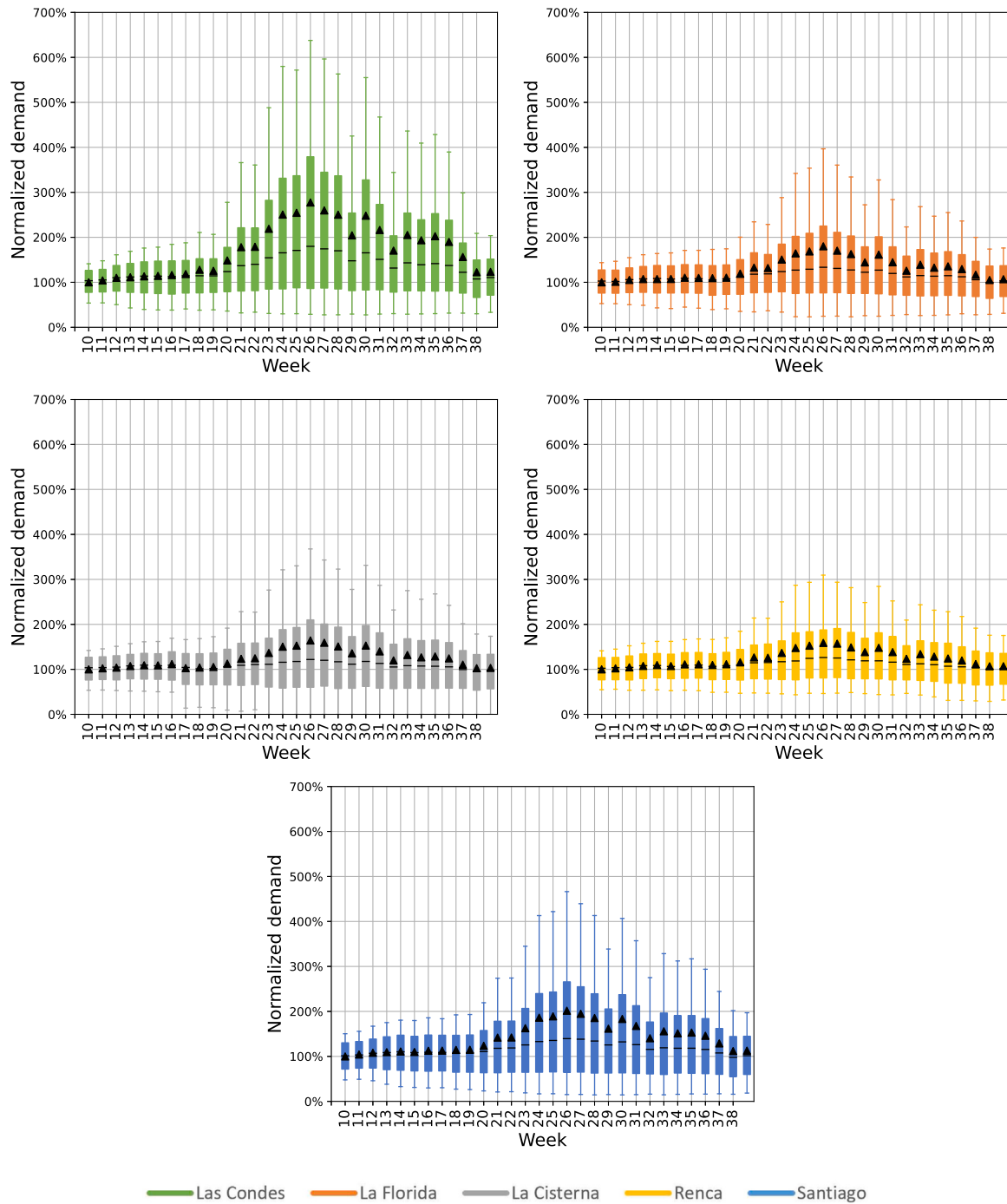


Fig. 5. Box and whisker plot showing the residential demand normalized (divided) by the average demand of week 10. For every commune, the horizontal line and the black triangle indicate the median and average value. The lower (and upper) edges of the box are the 25th (75th) percentile. Whiskers represent the range between 10th and 90th percentile.

measures. Importantly, the relation between income and mobility during lockdown was observed in several countries, and it is not particular to Chile [39,40].

Previous studies [41–44] demonstrate that only income does not explain the energy-use behavior of the householders, but that it may be one of the factors related to household energy demand. Furthermore, studies show a variety of results, demonstrating different levels of dependencies between income and electricity demand. For instance, [43] shows a small dependency between these factors, while [44] illustrates that their dependencies may be more important. However, none of these studies were undertaken under a pandemic; thus, previous

conclusions must be taken with care under the current situation. Under the current COVID-19 pandemic, lockdown measures significantly affected the population’s mobility and, thus, the time people stay at home. In several cases, like in Santiago, these mobility changes feature dependencies with the socio-economic background of the population. This has been studied and demonstrated for the specific case of Chile in [38], but this is not particular to one country [39,40]. Importantly, the reader must bear in mind that, in our study, no other demographic and socio-economic factors have been analyzed (besides income).

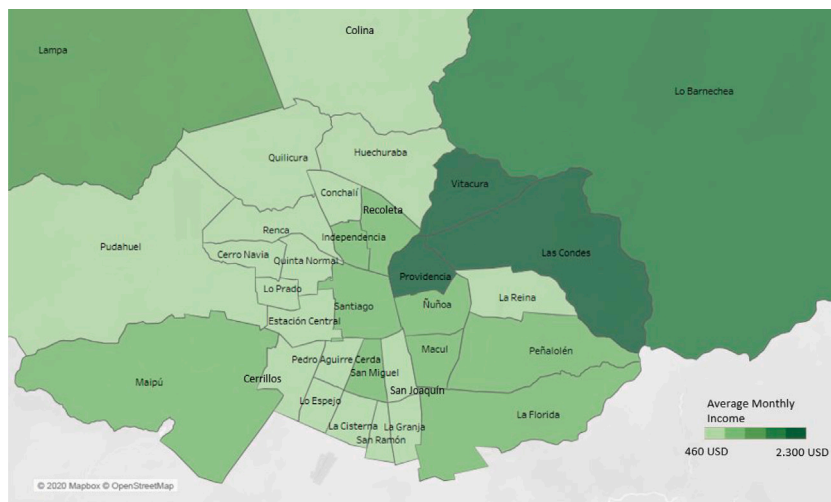


Fig. 6. Distribution of average monthly incomes according to the National Institute of Statistics [36].

Table 3
Variation between 2019 and 2020 of the electricity demand of consumers who are not sensitive to changes in temperature.

Month	Increase in demand [%]
March	9
April	8
May	12
June	17
July	13
August	10
September	7

4.1.2. Case ii: Isolating pandemic effects from seasonal weather effects on residential demand trends

The rise in residential electricity demand shown in Fig. 3 can be explained mainly by two factors: quarantines and lower temperatures as winter approaches. These factors can act in combination (i.e., households may consume more electricity during cold days in a pandemic situation because people spend more time inside the house). This section seeks to separate them to isolate the impact of the pandemic. In this way, the increases in electricity demand in 2020 are analyzed with respect to demand during the same period in 2019 for a subset of consumers whose demand is not very sensitive to temperature changes.

The average increases in demands from consumers who are not very sensitive to temperatures are calculated for each representative commune, and the results are summarized in Table 3. During April, the demand of these consumers experienced an increase of 8% compared to the same period in 2019. This increase rises to 12% during May, when the gradual quarantine policy was implemented. The greatest changes are observed from June to August, when there is an increase of up to 17% compared to the same period in 2019. During these months, the containment measures implemented were total quarantine and gradual reopening (from July 29, 2020). Finally, during September, a large part of the metropolitan area (Región Metropolitana) had partially reopened its activities, so the increase in demand for this month reached 7% compared to the same month in 2019, the lowest values throughout the period. This result is consistent with the situations in the United States and Australia, which feature a growth of 20% and 14%, respectively, in their residential demand compared to 2019 [9].

Importantly, Table 3 presents average variations, but the dispersion associated with these average values should not be overlooked. In order to analyze the dispersion, Table 4 shows the proportion of consumers that more than doubled their demand in different communes and months. This reveals, for example, that 8% and 10% of the consumers

Table 4
Proportion of consumers who at least doubled their demand in 2020 with respect to the same period in 2019.

Commune	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sept.
Las Condes	4%	7%	10%	17%	16%	17%	11%
La Florida	4%	5%	7%	17%	16%	15%	12%
La Cisterna	2%	4%	6%	10%	15%	14%	17%
Renca	2%	4%	6%	15%	14%	13%	10%
Santiago	4%	7%	8%	14%	14%	14%	10%

in Santiago and Las Condes, respectively, more than doubled their demand as a result of lockdowns during May (compared to the same month in 2019). In other communes, such as Renca and La Cisterna, these consumers represent approximately a 6% of the sample examined. The most critical period ranges from June to August, where the consumers who doubled their demand represent between 10% and 17% of the whole sample.

4.1.3. Case iii: Behavioral changes (at an hourly level) of residential demand

Behavioral changes of residential demand is analyzed through the hourly demand profiles presented in Figs. 7 and 8 for consumers of Las Condes and Renca. There is a pronounced peak at 10 pm every day for these two communes prior to the pandemic (week 10, corresponding to the week of March 2, 2020, and indicated in blue in Fig. 7). Likewise, a lower peak is observed between 8 am and 9 am during weekdays.

Once the pandemic started, during week 17 (from April 20, 2020, indicated in gray in Fig. 7), the daily peak demand increases and is shifted 2 h before, around 8 pm. Additionally, a second daily peak appears at 2 pm (sharper during weekend, as shown in the blue demand profile corresponding to week 10), considerably increasing energy demand during the afternoon. Finally, the peak observed in previous weeks during the morning (around 9 am) on weekdays disappears. Instead of this morning peak, demand gradually increases until the 2-pm peak.

In the week of maximum demand, week 26 (from June 22, 2020, indicated in yellow in Fig. 8), a combined effect of the pandemic and lower temperatures is observed. This explains the considerable increase in demand levels. Peak demand during these weeks occurs at 9 pm.

Finally, week 39 (from September 21, 2020, indicated in green in Fig. 8) is characterized by a reduction in demand levels, in line with the rise in temperatures and gradual opening policies. In addition, the morning peak (at 10 am) that existed during the pre-pandemic period reappears in Las Condes during September.

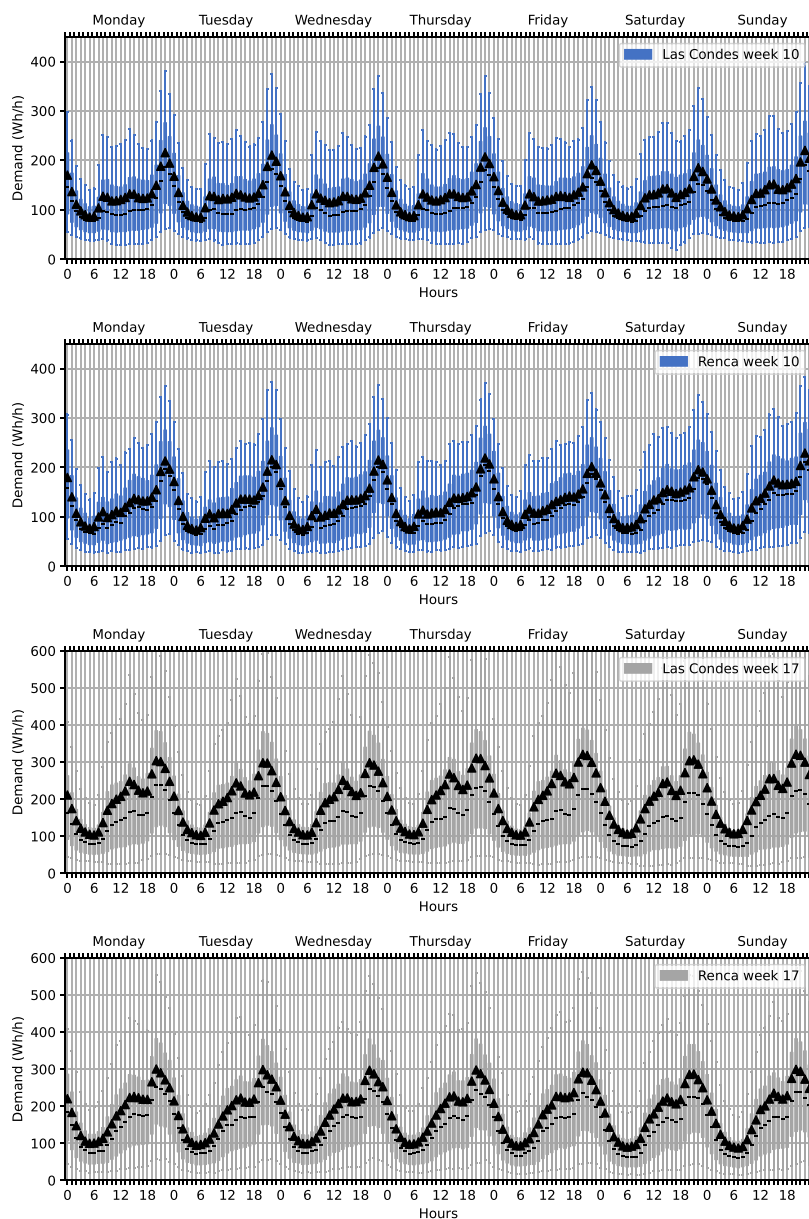


Fig. 7. Box and whisker plot showing the hourly residential demand in two weeks (weeks 10 and 17) and two communes (Las Condes and Renca). For every plot, the horizontal line and the black triangle indicate the median and average value. The lower (and upper) edges of the box are the 25th (75th) percentile. Whiskers represent the range between 10th and 90th percentile.

It is important to highlight the difference in the intensity with which the aforementioned changes occur in both communes. While in Las Condes (a higher-income commune) these changes are more pronounced, in Renca (a lower-income commune), the changes are milder. This could be explained by a potential lower response to lockdowns (information consistent with mobility reports [37]) and by a lower response to low temperatures (reduced electrification in heating solutions). This is consistent with the socio-economic levels of the communes shown in Fig. 6, as communes with higher incomes have more access to heating solutions using electrical equipment and a higher percentage of their population is able to work from home.

4.1.4. Case iv: Overview of the impact of the pandemic in the 32 communes of the metropolitan area

Figs. 9 and 10 present a general overview of how residential demand increased in all the communes of the metropolitan area (the city of Santiago) during the period under study. This increase was substantial, reaching 91% (on average for the 32 communes) during week 26

(June 22, 2020) with respect to the pre-pandemic period (March 2, 2020). These results emphasize that the greatest increase in demand has occurred in the eastern (higher-income) part of the region, in communes such as Vitacura, La Reina, Providencia and Las Condes. In Vitacura, for example, the increase in residential demand in week 26 reached 236% with respect to the demand in week 10 (March 2, 2020). On the other hand, during the same week, Cerro Navia was the commune with the lowest variation, reaching an increase of only 46% compared to week 10. These differences are in line with the socio-economic levels of the communes, as previously observed and discussed.

4.2. Trends in industrial demand by economic sector

Fig. 11 shows the variations in the total electrical energy consumed by Chile with a monthly resolution for the last three years. Although the first quarter of 2020 shows an increase of around 2.8% relative to 2019 (in line with the authority's projections), the electricity demand

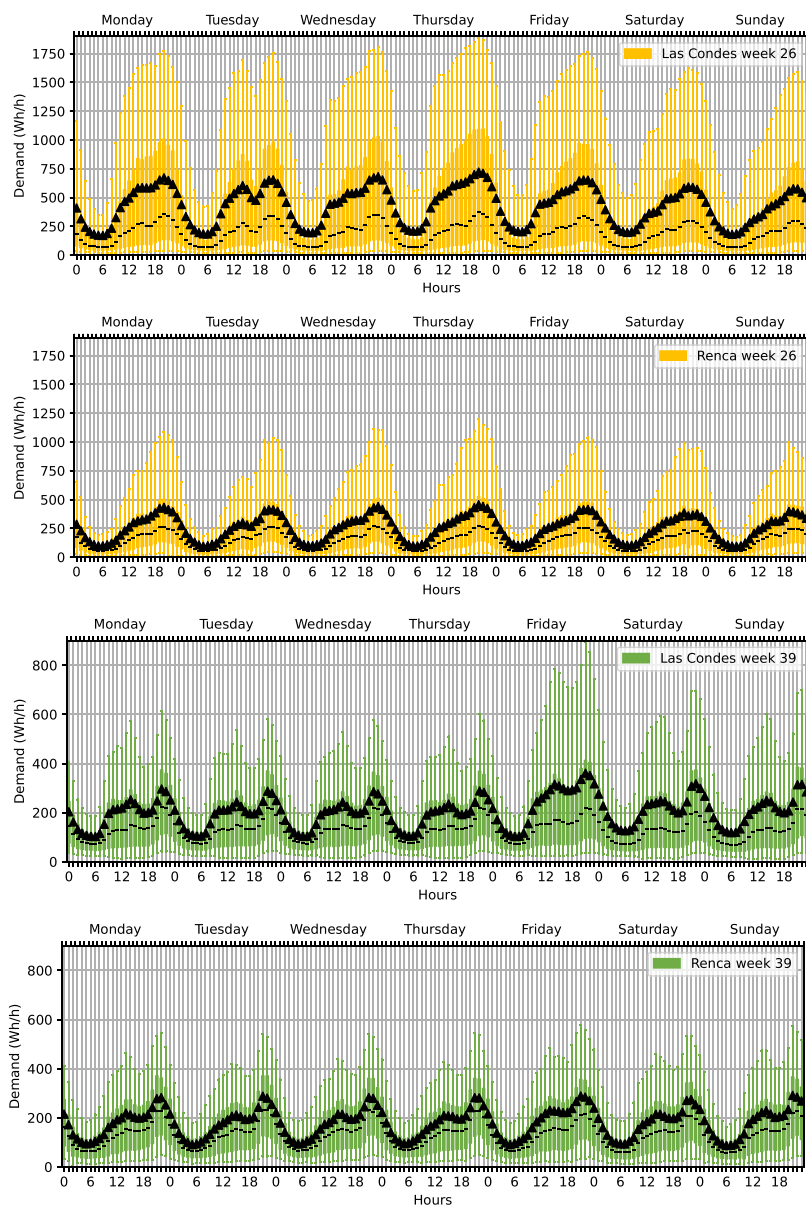


Fig. 8. Box and whisker plot showing the hourly residential demand in two weeks (weeks 26 and 39) and two communes (Las Condes and Renca). For every plot, the horizontal line and the black triangle indicate the median and average value. The lower (and upper) edges of the box are the 25th (75th) percentile. Whiskers represent the range between 10th and 90th percentile.

shows a significant drop since April, declining up to 5.3% during July 2020. Containment measures at a national level have directly impacted economic activity, which, according to official figures, fell by an average of 13% in April–August 2020. [5].

The pandemic has affected differently the electricity demand of the main sectors in the economy, as shown in Table 5. Hotels and Restaurants, along with Construction, stand out among the sectors that have been more affected by reducing electricity demand. This is explained by the forced closure of a large number of economic activities, the lower mobility of the population due to lockdowns, and the prohibition of national and international travels.

The restrictions on the mobility of the population under quarantines have also significantly affected the electricity demand of other sectors such as Financial Intermediation (Banks, Insurance Companies, Investment Companies, among others), Manufacturing Industries, Commerce in general, and Education (schools and universities).

One of the main economic activities of the country, Mining and Quarrying, showed significant growth in demand during the first half

of the year, despite the general restrictions imposed by the authorities. This is because Mining is considered an essential activity. In the same line, sectors that have shown a growth in electricity demand with respect to 2019 are Social and Health Services, Public Administration and Defence, Community Service Activities, and Fishing, as shown in Table 5.

5. Conclusions and future work

This paper analyzes the impact of lockdowns/quarantines associated with COVID-19 on the electricity demand disaggregated by consumer type (residential, commercial and industrial) in Chile. The impact of COVID-19 on electricity demand at different socio-economic levels in Santiago, Chile, is analyzed too.

These analyses show that the impact of COVID-19 on electricity demand varies widely by type of consumer. Regarding regulated consumers, for example, the demand of small businesses significantly dropped, decreasing more than 40% with respect to the pre-pandemic

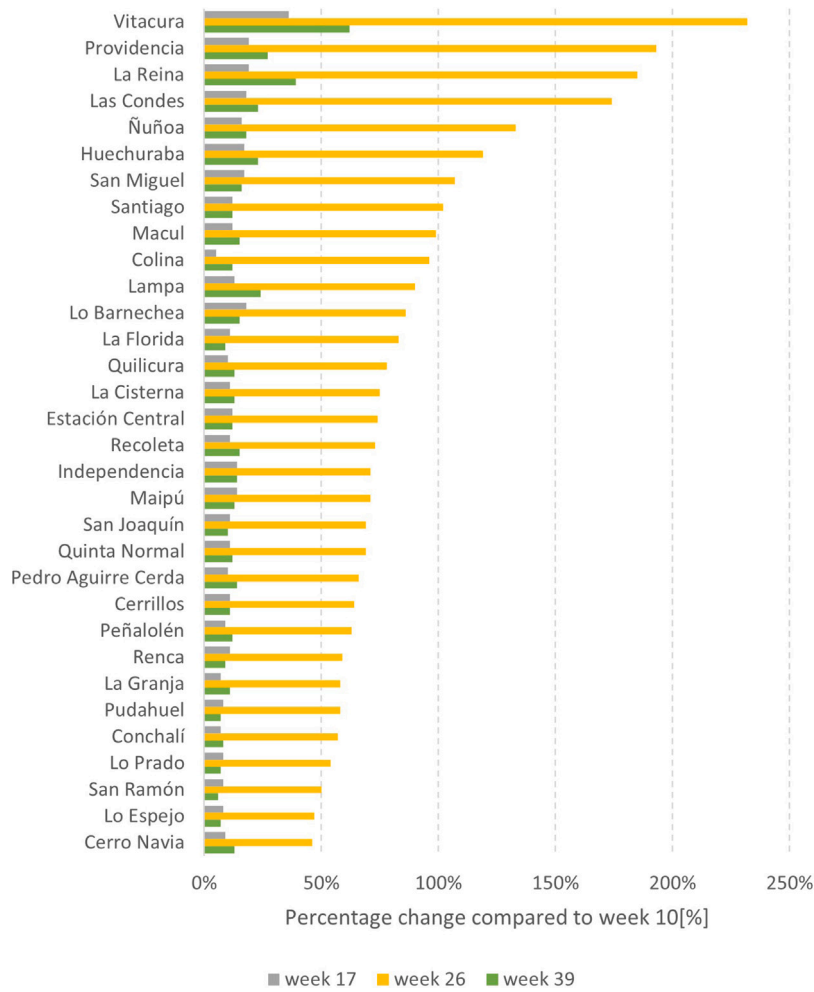


Fig. 9. Variation in residential demands in weeks 17 (week of April 20), 26 (week of June 22) and 39 (week of September 21). All with respect to week 10 (week of March 2).

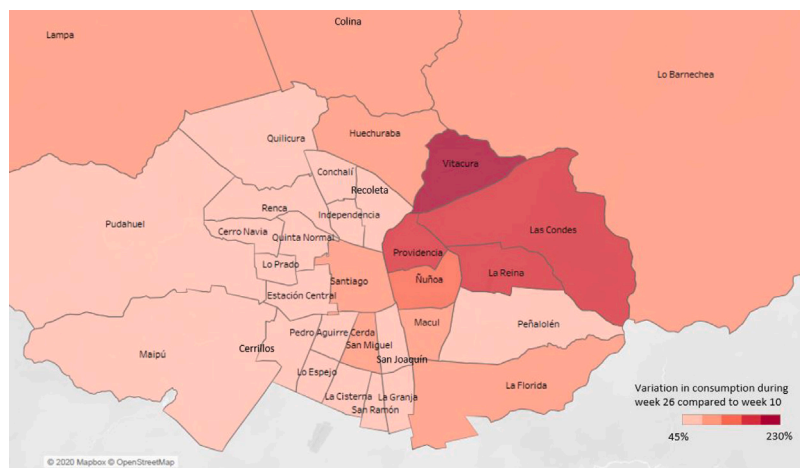


Fig. 10. Geographical distribution of demand increases during week 26 (week of June 22) compared to week 10 (week of March 2) due to the combined effect of seasonality and the pandemic.

situation in the communes of Santiago and Las Condes. This is consistent with the slowdown of the Chilean economy observed during the same period.

On the other hand, residential consumers increased their demand since the implementation of the first lockdowns at the beginning of the

pandemic. The steepest increase occurred between June and August 2020, the months of lowest temperatures and the most restrictive mobility measures. Notably, the maximum increase occurred in the week of June 22, 2020, when demand was on average 91% higher than in the first week of March. This was the result of the combined

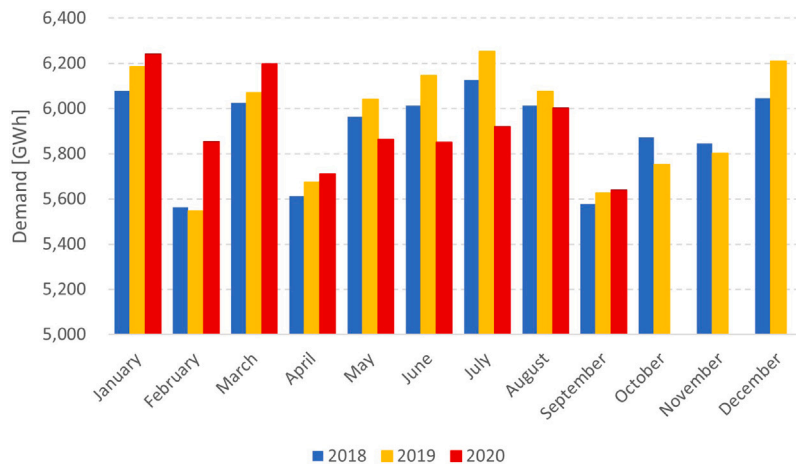


Fig. 11. Monthly electricity demand of the National Electricity System [6].

Table 5
Variations in 2020 demand by sector with respect to 2019. Sorted by impact in September.

Sector	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.
Hotels and Restaurants	3%	5%	-13%	-13%	-76%	-75%	-75%	-74%	-74%
Construction	-15%	-13%	-17%	-9%	-42%	-56%	-68%	-68%	-73%
Real estate activities, Business and Rental	-3%	-4%	14%	-21%	-15%	-11%	-31%	-21%	-39%
Manufacturing Industries non-Metallic (i)	-6%	-4%	-16%	-27%	-54%	-57%	-53%	-41%	-39%
Buildings and Condominiums (offices)	-9%	-4%	-14%	-9%	-46%	-54%	-53%	-48%	-30%
Manufacturing Industries Metallic	-5%	0%	5%	12%	-23%	-23%	-31%	-29%	-24%
Wholesale and Retail	-18%	-9%	-5%	19%	-47%	-28%	-21%	-18%	-16%
Teaching	-1%	-8%	-16%	-17%	-27%	-36%	-28%	-26%	-11%
Manufacturing Industries non-Metallic (ii)	-2%	3%	3%	9%	-9%	-20%	-15%	-16%	-6%
Financial Intermediation	-5%	10%	4%	4%	-8%	-14%	-15%	-13%	-5%
Mining and Quarrying	9%	14%	7%	10%	1%	2%	-2%	2%	-3%
Electricity Supply and Water Supply	7%	15%	10%	12%	-4%	-7%	-21%	-11%	-3%
Agriculture, Livestock, Hunting and Forestry	1%	1%	4%	10%	-2%	-7%	-11%	-7%	-2%
Social and Health Services	6%	8%	3%	9%	-7%	-5%	-5%	-3%	1%
Public Administration and Defence	3%	-5%	-2%	6%	-6%	-4%	-21%	1%	3%
Other Community, Social and Personal Service Activities	28%	35%	9%	16%	7%	19%	-6%	-3%	7%
Fishing	20%	20%	-1%	11%	11%	8%	2%	8%	8%

effect of the pandemic and lower temperatures. We estimate that the pandemic has accounted for a demand increase of up to a 17% in June, with respect to the same month of 2019. It is worth mentioning that the effect varies importantly across the different communes. In fact, it has been shown that the communes with higher demand increases correspond to those featuring higher incomes. Likewise, the results also show a wide dispersion in the demand variation within each commune.

Regarding the impact on industrial electricity demand, the sector with the most significant decrease was the Hotel and Restaurant sector, with reductions of up to 75% in the months of May–September 2020 with respect to the same period in 2019. Other sectors with significant decreases in electricity demand were Construction, Real Estate Activities, Non-Metallic Manufacturing Industries, and Buildings and Condominium (dedicated to working offices). Other sectors such as Fishing or Mining showed increases in their demand during most of the period under study, thus being less affected by COVID-19 lockdown measures.

An important conclusion of this work with potential impacts on public policymaking is that confinements can significantly increase residential electricity demand, which can impose additional costs on families. This could entail particular problems for vulnerable families who, in addition to the increased costs of basic services, may find themselves in complex financial situations as a result of the economic crisis associated with the pandemic. This is a problem that the authorities must analyze and address with special care.

The following possible applications and extensions of this study have been identified:

- Forecasting better demand responses to complex containment measures (that can vary per commune).
- Estimating more accurately the financial support needed to assist economically vulnerable families during the pandemic, of particular importance to policymakers
- Improving operational practices (including demand forecasting and network operation, e.g., reactive compensation due to voltage problems) in order to operate pieces of the network with significantly different load profiles.
- Identifying areas of the network with higher or lower stress levels due to the pandemic, which could justify bringing forward or delaying investment plans of electrical utilities.
- Identifying dependencies between different sectors (e.g., energy, transport, economy) in order to understand (a) the interrelationships among them better and thus (b) the overall effects of the pandemic.

Finally, it is important to emphasize that such detailed studies of electricity demand are not only relevant in the context of the pandemic. In general, in-depth monitoring and analysis of energy demand data has the potential to inform and improve decisions and processes in both the public and private sectors, for example, improving public policy decisions, regulatory design, grid tariff studies, system investment and operation, among others.

Table A.1
Number of smart metering devices by type of consumer and commune.

Commune	Residential	Small business
Cerro Navia	6581	195
Lo Espejo	1713	20
San Ramón	3080	129
Lo Prado	7128	180
Conchalí	11917	530
Pudahuel	5097	74
La Granja	2301	70
Renca	3510	130
Peñalolén	5050	221
Cerrillos	6334	197
Pedro Aguirre Cerda	2709	56
Quinta Normal	9833	520
San Joaquín	5649	167
Maipú	9468	193
Independencia	6622	480
Recoleta	11769	806
Estación Central	12144	508
La Cisterna	6960	891
Quilicura	3645	83
La Florida	9936	260
Lo Barnechea	484	26
Lampa	1385	96
Colina	1008	95
Macul	5641	264
Santiago	26686	3033
San Miguel	8262	351
Huechuraba	1070	88
Nuñoa	10633	682
Las Condes	12510	380
La Reina	5768	135
Providencia	9860	1112
Vitacura	3522	107
Total	218275	12079

CRedit authorship contribution statement

Miguel Sánchez-López: Writing – original draft, Software, Visualization, Investigation. **Rodrigo Moreno:** Conceptualization, Supervision, Methodology, Writing – original draft, Resources. **Diego Alvarado:** Writing – original draft, Formal Analysis, Visualization, Software. **Carlos Suazo-Martínez:** Writing – review & editing, Conceptualization, Resources, Supervision. **Matías Negrete-Pincetic:** Writing – review & editing, Conceptualization. **Daniel Olivares:** Writing – review & editing, Conceptualization. **Carlos Sepúlveda:** Writing – review & editing, Software, Visualization. **Héctor Otárola:** Writing – review & editing, Software, Visualization. **Leonardo J. Basso:** Writing – review & editing, Conceptualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Number of smart metering devices by type and commune

Table A.1 shows the amount of smart metering equipment distributed in the Metropolitan Region. Initially, 326 thousand devices

were counted, however, for data reliability reasons, 230 thousand were finally considered.

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