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Trends in household energy-related GHG emissions during COVID-19 in four Chilean cities

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ABSTRACT

The coronavirus disease 2019 (COVID-19) pandemic has strongly affected economies and human lifestyles globally. The changes observed in domestic energy consumption patterns have had an impact on household greenhouse gas (GHG) emissions. Since GHG emissions inventories are only available at the country level and at annual intervals, most studies have calculated the local emission variations by extrapolating annual emissions with smaller time and territorial scale consumption data. This research presents a bottom-up method, based on the exploitation of a survey addressed to 1200 households, that provides the information to calculate directly the variation in their energy-related GHG emissions, without the need for extrapolations. This method has been applied to four medium-sized Chilean cities with serious air quality problems. Given the high correlation between atmospheric pollutants such as NO_x and CO₂ emissions, we estimate that before the appearance of COVID-19, *per capita* CO₂ emissions were already high. The results show that space heating-related GHG emissions have increased moderately (between 1 and 6%), while emissions from electricity and gas consumption for non-heating uses have increased significantly (between 8 and 23%). This has harmed the household economy, highlighting the importance of considering socioeconomic aspects when assessing the impact of COVID-19 in its entirety.

KEYWORDS



COVID-19; domestic energy use; greenhouse gas emissions; environment; air pollution; Chile

Introduction

Researchers from around the world are investigating the impact of the coronavirus disease 2019 (COVID-19) on the environment. One of the positive impacts of the COVID-19 on the environment, emphasized at the international level, has been the reduction of CO₂ emissions. While it is evident that confinement measures have negative effects on the economy of societies and countries [1–3], it is fair to suppose that they would generate benefits for the environment. Le Quéré et al. [4] determine that between April 2019 and April 2020, worldwide CO₂ emissions have been reduced by 26% (2.6 Gt CO₂) due to the measures to curb down COVID-19. In a similar study, Liu et al. [5] estimate a significantly lower reduction, 8.8% comparing emissions between January and June 2019 with those of the same period in 2020. The EIA [6] has evaluated that the fall during said

period was 5%. Forster et al. [7] calculate a global drop in emissions similar to that of Le Quéré et al. [4]. The case studies for specific countries also show similar dynamics. For example, a preliminary study indicated a 25% reduction of greenhouse gas (GHG) emissions in China [8]. Recently, a study from Italy declared a reduction of GHG emissions by 20% [9]. During 2021, new results have been published for China [10], China, India, US and EU [11,12], and European countries [13], all of them reporting a fall in GHG emissions. As the pandemic advances around the world, many studies have published results regarding the local environmental effects of COVID-19, mainly the reduction in air pollution [7–9,14–19].

Most studies normally calculate the variation in energy-related GHG emissions during the COVID-19 pandemic by extrapolating annual to monthly trends using aggregated data on energy consumption available on a monthly or daily basis [4,5,7].

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The national results have also been extrapolated for smaller territorial units such as provinces and cities based on their weight in terms of emissions compared to the national average during previous years [9]. While the use of extrapolation and proxy reduces the accuracy of the obtained data, these estimations work as a first approximation to the order of magnitude of emission variation. Unlike these studies, the method employed in the present study consists of directly surveying households through a questionnaire about their energy consumption before and during the lockdown restrictions. In this way, the need to extrapolate values expressed in larger time frames and territorial scales is avoided.

Whereas COVID-19 has involved and achieved an abrupt and positive change in the behavior of individuals in relation to CO₂ emissions like no environmental policy thus far, its long-term effects remain to be seen [20]. A reason to be skeptical regarding the long-term effects is the way in which the sanitary measures have impacted on everyday practices. The impacts of COVID-19 on behavioral changes have been analyzed primarily in terms of reduced mobility in cities [21,22], the reduction in the air transportation sector [23], and eating behaviors [24–26]. This study contributes on this regard by examining the trends in the household energy-related GHG emissions before and during the pandemic in Chilean cities. More specifically, it estimates the potential increase of GHG emissions from domestic energy use, which can be affected by the COVID-19 confinement measures in four medium-sized Chilean cities (Coronel, Temuco, Valdivia and Osorno).

Studying the case of medium-sized Chilean cities is relevant for two reasons. First, the selected cities are among the most polluted in Chile and the world. Given that there is a high correlation between GHG emissions and local pollutants associated with the burning of fuels in industries, motor vehicles, heating systems, and electricity generation plants [5,7], it is presumed that the energy-related GHG emissions of these cities must also be high. Second, there are few studies focused on medium-sized cities despite the fact that various reports maintain that urban growth in Latin America will occur mainly in small and medium-sized cities [27–29]. Lockdowns and coronavirus restrictions, when imposed in countries marked by inequality, can be beneficial to the environment in terms of CO₂ emissions, but at the same time, they provoke sudden and massive job

losses, or in the best cases, transform in-person office work into remote work from home, affecting households' economy and lifestyles. As a result of spending more time at home, and given that part of the energy used in industries, offices and shops has been transferred to households, lockdowns may have increased household energy bills and the residential energy-related GHG emissions [30], as well as aggravated the already existing situation of energy poverty (i.e. when the level of energy consumption is insufficient to meet certain basic necessities, such as space heating and domestic hot water) [31].

As the present study manifests, Chilean researchers are also interested in benefiting from the reduction in the GHG emissions in cities, particularly from well-known sources of contamination, such as the traditional wood-based heating systems. This concern is not only due to the latest international environmental agreements and as a contribution to global environmental issues, but also as a necessity to enhance the local wellbeing in terms of respiratory health and thermal comfort that also results in an improved environmental quality. Changes in behavior must be an essential component of policies to reduce GHG emissions and tackle climate change [32], and in this sense, COVID-19 represents an opportunity to analyze these changes and move towards more sustainable practices at the household level. Therefore, analyzing these data and their trends allows us to identify further research and development, and policy needs, in order to achieve environmental and economic sustainability.

Materials and methods

Case study

This study aims to assess the GHG emissions from domestic energy use in four cities in central-south Chile: Coronel, Temuco, Valdivia and Osorno (Figure 1). These cities all experience severe air pollution episodes that occur primarily in the winter, due to the use of wood biomass as the main source of energy for heating and cooking purposes. Indeed, the four cities present annual average concentrations of coarse and fine particulate matter (PM₁₀ and PM_{2.5} respectively) regularly exceeding the World Health Organization guidelines [33,34]. In 2020, according to data from Bloomberg Green and the NGO OpenAQ [35], Temuco was declared the most air polluted city in the world.



Figure 1. Study areas. Source: Own elaboration.

Table 1. Annual and winter average temperatures in the four cities in 2020 and 2019 [36].

Average temperature in 2020 (variation compared to 2019)	Coronel	Temuco	Valdivia	Osorno
Annual (Jan. 1 st – Dec. 31 st)	12.8 °C (–0.08 °C)	11.4 °C (–0.08 °C)	10.9 °C (+0.07 °C)	11.2 °C (–0.22 °C)
Winter (Jun. 21 st – Sept. 20 th)	9.6 °C (–0.03 °C)	7.5 °C (–0.27 °C)	7.1 °C (+0.05 °C)	7.2 °C (+0.08 °C)

It should be noted that Chile, due to its location in the southern hemisphere, is in winter between mid-June and mid-September. Table 1 presents the annual and winter average temperatures in the four cities in 2020, along with their variation compared to the same period in 2019 [36]. In the four studied cities, the cold climate implies the massive use of space heating.

The cities studied are located in the central-south zone of Chile (Figure 1). Coronel, located in the Biobío Region, is the least populated city in the study (116,262 inhabitants). It is functionally integrated within the metropolitan area of

Concepción, along with the neighboring cities of San Pedro de la Paz and Lota [37]. The city of Temuco, which is the most populated of the four (342,488 inhabitants), comprises the municipalities of Temuco and Padre las Casas and serves as the main work and study hub for the Araucanía Region [38]. The cities of Osorno and Valdivia present similar demographic statistics (around 160,000 inhabitants), and are articulators of other smaller urban settlements in the regions of Los Lagos and Los Ríos, respectively.

The effects of the COVID-19 pandemic have been significant in terms of population infections

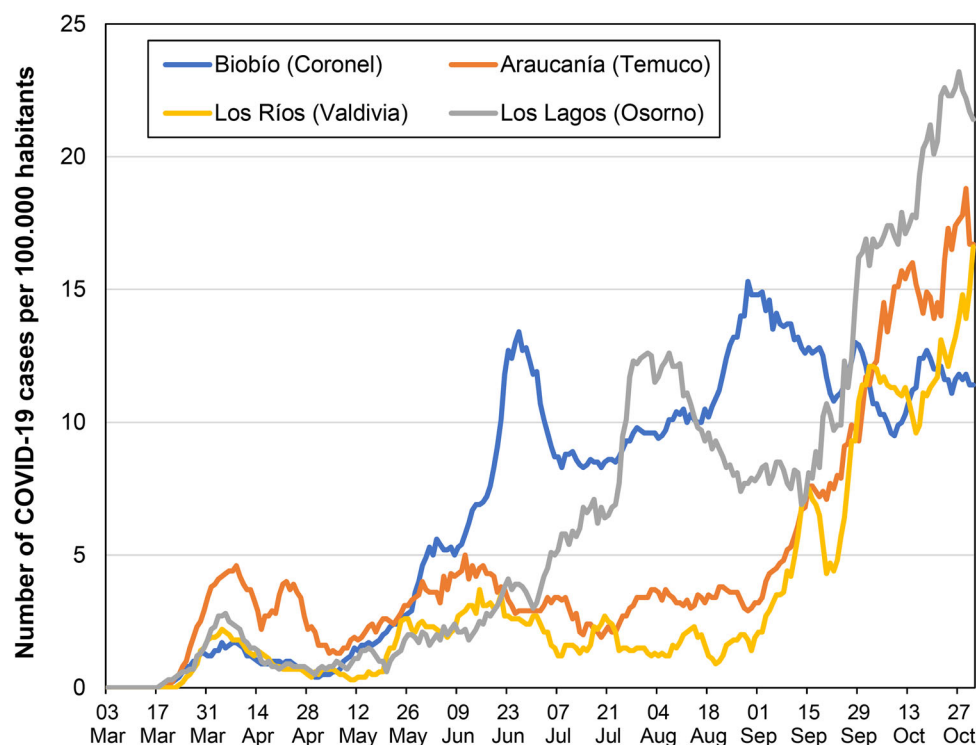


Figure 2. Evolution of COVID-19 cases *per* 100,000 inhabitants for the Regions of the four cities under study for 2020 [39].

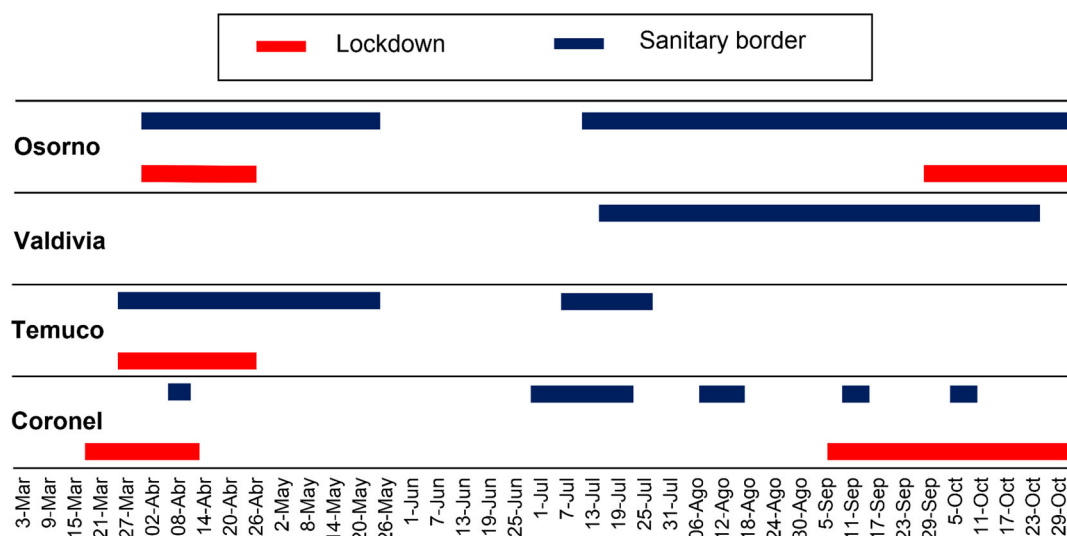


Figure 3. Health control measures for the cities studied. Source: Own elaboration based on press reviews.

and health control measures (Figure 2 and Figure 3). The four regions where these cities are located showed an increasing trend in confirmed cases during 2020, but with differentiated boom and bust moments. The Araucanía had a boom before all other regions, which resulted in the first lockdown at the end of March 2020 in that region. Although the curve in the Los Lagos Region was less pronounced around that time, the case of Osorno was particularly critical in terms of positivity testing, and a lockdown was also decreed during that time in Los Lagos. The subsequent rise in new infections in Los Lagos since July was mainly due to the detection of a significant number of

new cases in the city of Puerto Montt, gradually complemented by other cities, including Osorno. This is why Osorno went into lockdown again in early October. The Biobío Region maintained a growth curve with two critical periods in June and September. During that second wave of new cases, the Health Ministry declared lockdown restrictions for the Biobío Region. The Araucanía Region shows a sharp rise in new cases since September 2020, with particularly critical levels of positivity testing in the city of Temuco, for which lockdown restrictions were declared again in October. Los Ríos was one of the least affected regions in the country, before it eventually experienced a sustained

Table 2. Fuels used for space heating (share by type).

	Firewood				Kerosene	Electric Power	Gas	Oil	Coal	Other
	Dry	Wet	Pellet	Other						
Coronel	75.0%	2.7%	2.3%	0%	7.3%	9.0%	3.7%	0.0%	0.0%	0.0%
Temuco	54.0%	1.3%	10.0%	0.6%	10.7%	8.0%	7.0%	0.7%	0.0%	7.7%
Valdivia	67.3%	1.0%	10.7%	0.7%	5.3%	3.7%	3.0%	1.3%	0.3%	6.7%
Osorno	67.3%	4.0%	10.0%	0.7%	5.3%	6.0%	1.4%	1.0%	0.0%	4.3%
Total	65.9%	2.2%	8.2%	0.4%	7.2%	6.7%	3.8%	0.8%	0.1%	4.7%

exponential boom of new cases starting in September, and lockdown restrictions went into force on November 7, 2020.

Survey data

The assessment of the GHG emissions from household energy consumption was carried out by processing surveys of consumer energy expenditure, multiplying monetary units of consumption by the corresponding fuel emission factors. The energy-related GHG Emissions Survey conducted during the winter of 2020 is a longitudinal survey that seeks to monitor the same cohort and to compare consumption patterns in the context of the COVID-19 pandemic between the winter of 2020 and the summer of 2021, as well as to inquire into prior situations related to the winter of 2019. The survey is an original questionnaire, which was inspired by the work done in the city of Concepción [40]. The survey was applied to 1,200 households during September 2020 (winter), and was conducted randomly among heads of households using a Computer-Assisted Telephone Interviewing (CATI) system. The 1,200 surveys were distributed equally among the four cities studied, with samples of 300 households per city.

The survey data show an average home floor area of 90.4 square meters, and an average household occupancy of 3.3 inhabitants. Only 31% of households declared that their homes count with thermal insulation (Annex Tables 1 and 2). Across the four cities studied, wood is the main fuel used for space heating (Table 2). While space heating is produced from the combustion of wood in 66% of the homes surveyed in Temuco, the share of wood for space heating reaches a value of 80% in Coronel and Valdivia, and up to 82% in Osorno. In Temuco, fuels such as kerosene (10.7%), electricity (8%) and gas (7%) have a more important share than in the other three cities. Regarding the type of wood used for space heating, the shares of dry and wet firewood (i.e. bricks, branches, stumps, roots, etc.) range between 67% and 75% for the cities of Temuco, Valdivia and Osorno, where the share of pellet is close to 10%. Wet firewood

seems to have a low presence in the survey responses in all cities, with the highest share of 4% in Osorno. It is worth noting that the use of wet wood (i.e. wood with a weight moisture content superior to 25%) is punishable by law, which may have biased survey responses. The reported share of 'other' fuels cannot be neglected, particularly for the cities of Temuco (7.7%) and Valdivia (6.7%). Burning fuels, such as almond and hazelnut shells and olive stones would generally fall into the latter category, as well as other non-authorized combustibles like charcoal and wet firewood.

Energy-related GHG emissions calculation

The inventory of GHG emissions from domestic energy use is the environmental impact indicator used in this research study. The reason for this is to allocate the emissions associated with burning fuel and electricity consumption as we deem appropriate. The criteria for assigning this indicator is to count (i) the direct GHG emissions from fuel use in the homes, in the place where fuel is burnt and GHG are emitted, as well as (ii) the indirect GHG emissions from electricity use, since electricity is generally generated in power plants located away from the place where it is consumed. The GHG emissions indicator used in the study provides insights into domestic energy use practices and their environmental impact. Numerous studies indicate the convenience of using environmental impact measures aimed at consumption rather than production [41–43].

We use a bottom-up approach to analyze exclusively the activity of consuming energy in homes. In order to calculate GHG emissions, it is necessary to know the fuel consumption of the households. The most effective way to obtain this data from the survey was by identifying each household's monetary expenditure on energy fuels. The fuel expenditure was then converted to unitary quantities according to standard market prices for each of the different fuels, differentiated by city and referenced at the time of the study in Annex Table 3.

In Chile, and especially in the central-south and south of the country, where the four studied cities

Table 3. CO₂ equivalent emission factors [44,45].

Fuel type	Emission factor (kgCO ₂ -eq/kg _{fuel})
Kerosene	3.359
Natural gas	2.472
Liquefied petroleum gas (LPG)	3.202
Dry wood	1.767
Wet wood	1.263
Oil	3.399

are located, space heating is essential for all households during wintertime [54] and the main contributor to the GHG emissions of the residential sector [40]. Table 3 shows the fuel emission factors by type used to calculate the GHG emissions. These emission factors are obtained from the IPCC database [44] and converted to kilograms of CO₂ equivalent emitted per kilogram of fuel (annotated kg_{CO₂-eq}/kg_{fuel}). The estimate for the emissions factor takes into account the amount of CO₂, in addition to the CO₂ equivalent of the amounts of methane (CH₄) and nitrous oxide (N₂O) emitted during the combustion of 1 kg of each fuel [45].

As mentioned above, the most common fuel used in the selected cities for space heating is wood. Although the use of firewood certified by the National Firewood Certification System (SNCL) is mandatory, according to data from the same entity, only 23% of the firewood used is certified. Therefore, an emission factor is added corresponding to wet wood (with more than 25% humidity). As for the GHG emissions associated with biomass combustion, there is no clear consensus among scientists [55]. There are sources that recognize biomass as carbon neutral, since it is considered that the combustion process emits the same amount of CO₂ as the biomass absorbed during its growth [56]. And while this seems to be true in global calculations [57], if we consider the scope of study at the national level, we see that emissions of GHG and products of incomplete combustion derived from wood burning are significant, particularly when firewood or charcoal is burnt in open-fireplaces or wood stoves with low thermal efficiency [58]. Also, the emission factor of firewood varies according to the plant species used in its combustion [58]. The study uses the IPCC standardized factor [44,45], which considers the use of certified eucalyptus and pine firewood. In the case of charcoal, there are more than 15 varieties used for heating. Although it has a different origin, its conditions of concentration and emission of CO₂, CH₄, and N₂O are equivalent, such that the emission factor calculated corresponds to the average of the individual factors.

For the calculation of the GHG emissions related to the consumption of electricity, we converted the surveyed monthly monetary consumption (CLP) into kilogram of CO₂ equivalent using the average electricity price in March 2020, that includes market price, standing charge and taxes (159 CLP/kWh) [52,53], and the electricity emission factor provided by the Chilean National Energy Commission (CNE) for March 2020 (0.4398 kg CO₂-eq/kWh) [59]. The electricity GHG emission factor depends on the primary energy sources used for its generation, and the same emission factor is used for the four cities studied as it corresponds to a national indicator.

Results

As mentioned above, the inventory of GHG emissions is a global environmental indicator that allows for calculations at different levels: by country, by city and, with some adjustments, the inventory of entities such as public and private institutions. On this occasion, the decision was made to calculate the GHG emissions as a measure of CO₂ equivalent emissions, corresponding to the use of energy at the household level.

Domestic energy consumption

Of the total energy used for space heating, wood biomass holds a share of 84% on average across the four cities in 2020 (between 78% in Temuco and 89% in Coronel), only two points less than in 2019. Wood biomass is followed distantly by kerosene, a petroleum derivative used in specifically conditioned stoves, representing 7% of the total energy for space heating, and then by electricity, gas, oil and others with a share of 2% each. It is important to note that the share of wood biomass for space heating in the four studied cities is more than twice the national average [54]. This is due to the abundant presence of local wood biomass in the central-south regions [60], explaining why this resource is strongly integrated into Chilean cultural practices for space heating. Most consumption for space heating increased in 2020 compared to 2019, with the exception of oil (Table 4). The largest increases are observed in the consumption of electricity and kerosene, while the increase in wood biomass consumption is the least significant.

Regarding the consumption of electricity and gas for uses other than space heating, there is a significant increase in all studied cities between March 2020 (before the pandemic) and July 2020

Table 4. Fuel consumption difference for space heating between 2019 and 2020.

	Firewood	Kerosene	Electricity	LPG	Natural Gas	Charcoal	Oil	Others
Coronel	+5%	+7%	+25%	+16%	N/A	+4%	N/A	-10%
Temuco	+1%	+26%	+24%	-11%	+12%	N/A	0%	+19%
Valdivia	-3%	+56%	+36%	+22%	-14%	+100%	+6%	+38%
Osorno	+1%	+18%	+33%	+7%	+6%	N/A	-12%	+6%
Average	+1%	+27%	29%	+8%	+1%	+52%	-2%	+13%

Table 5. Fuel consumption difference for uses other than space heating between March and July 2020.

	Electricity	Gas
Coronel	+15%	+23%
Temuco	+18%	+18%
Valdivia	+14%	+8%
Osorno	+16%	+15%
Average	+16%	+16%

(during the pandemic) (Table 5). This is clearly due to spending more time at home in July 2020, using more electricity to run computers and other devices for studying and working at home, as well as using more gas to cook and to produce domestic hot water.

GHG emissions from utilities other than space heating

One of the sources of CO₂ equivalent emissions in the residential sector is the consumption of electricity and gas (i.e. LPG + natural gas) to meet the household's energy demand for equipment such as kitchen counter appliances, oven, hot water production, lighting, as well as other small domestic appliances that consume electricity or gas. The results are summarized in Figure 4 and Annex Table 4.

The GHG emissions from electricity use for utilities other than space heating increase on average across the four studied cities from 100 to 115 kg CO₂-eq *per* household. With respect to the use of gas for cooking and/or hot water production, there is also an increase from 57 kg CO₂-eq *per* household in March 2020 to 67 kg CO₂-eq *per* household in July 2020. As can be seen in Figure 4, between March and July 2020 (late summer and early winter), the period in which the most restrictive lockdown policies occurred during the first wave of infections, the household gas and electricity consumption grew significantly, and as a consequence, so did its related GHG emissions. This result was expected given that household members spend more time at home, so more energy is spent on lighting, on operating computers, and other devices necessary for remote working (printers, etc.), as well as for domestic hot water and cooking. Coronel was the city where the GHG emissions from gas and electricity consumption

grew the most between March and July 2020, and Valdivia where the GHG emissions grew the least.

GHG emissions from space heating

Space heating is the activity that represents the largest share of energy use in Chilean dwellings [54]. For that reason, we calculate the CO₂-eq emissions related to the combustion of different fuels used during winter. The values found in Figure 5 and Annex Table 5 correspond to kg of CO₂-eq *per* household surveyed in each of the four cities studied.

The use of wood biomass for space heating corresponds to an annual average of almost 2 tons of CO₂-eq *per* household. In general, an increase in emissions can be observed in all cities during the year 2020. In any case, the increase in emissions is not very pronounced, between 1 and 6%, with Coronel being the city where emissions from space heating increased the most. This is mainly explained by the predominant use of LPG, kerosene, and firewood. Thus, it can be stated that the various COVID-19 containment measures increased the use of fuels for the purpose of space heating in all the four cities under study.

The average of nearly 2 tons of CO₂-eq *per* household for heating purposes is high in part due to the use of fairly inefficient energy systems, but also, and to even higher proportions, to the low thermal energy efficiency of the houses [61]. In the surveyed households' sample, more than two thirds (69%) of the respondents declared the absence of thermal insulation. It is worth mentioning that the annual energy-related GHG emissions from space heating in the four cities under study is higher than the national average (1.56 tons of CO₂-eq *per* year) calculated by applying the same emission factors to the national average consumption by fuel shown by In-Data CDT [54], but this is also due to the colder climate of the study areas analyzed.

Discussion

The lockdowns in force during the winter of 2020 in the Chilean cities of Coronel, Temuco, Valdivia,

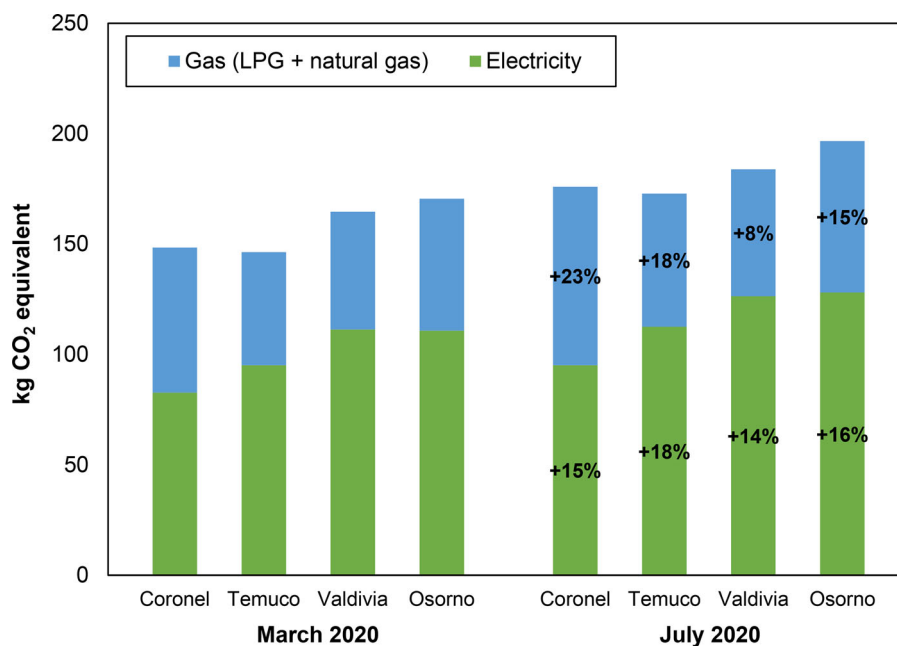


Figure 4. Monthly CO₂-eq emissions from electricity and gas used for utilities other than space heating (home average).

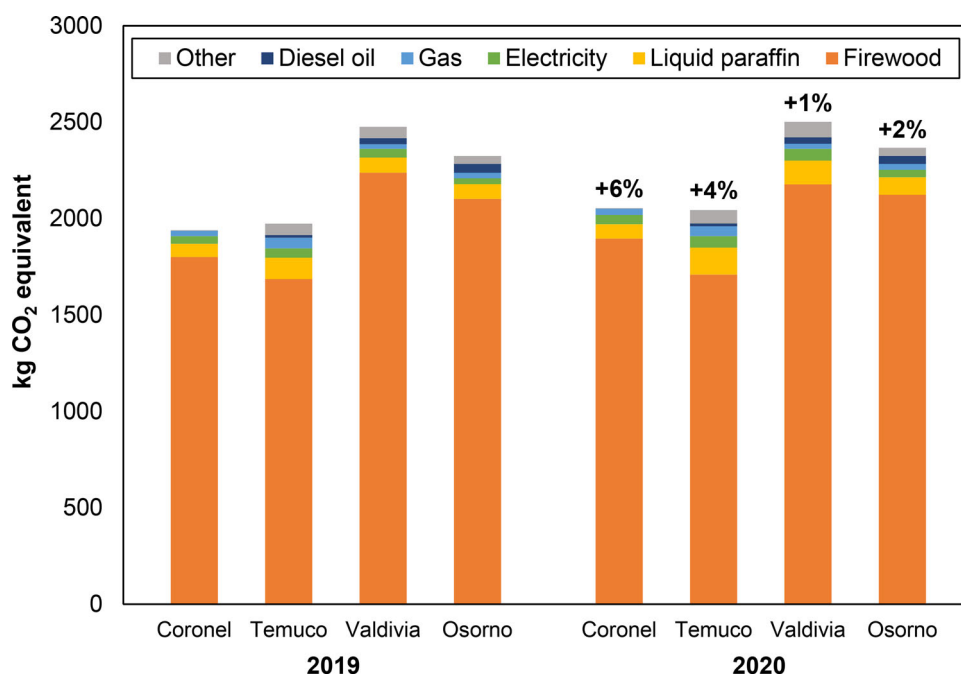


Figure 5. Annual CO₂-eq emissions by energy used for space heating (home average).

and Osorno have changed the energy consumption patterns of the households, in comparison to the winter of 2019 and March 2020, in some respects. Evidently, the COVID-19 virus, which has claimed more than 38,000 lives in the country up to date, increases the mortality rate, affects the health of the population, generates isolation, reduces family income, and hinders the ability to balance personal and professional life, among others. One benefit, according to international evidence, is the foreseeable reduction in GHG emissions causing global warming, thus contributing to a slowdown in the increase of the Earth's temperatures.

Various studies have captured how policies to curb down COVID-19 have affected CO₂ emissions [4–7], but the data that show the impact on energy consumption in homes are based on simple and debatable assumptions. Le Quéré et al. [4] only contemplate an increase in emissions when the widest range of restrictions possible is reached. Liu et al. [5] do not separate emissions in homes from those in offices and businesses. They estimate a net drop in emissions for the sum of homes, businesses, and offices. Therefore, their study does not allow for the examination of the transfer of emissions from offices and businesses to households. They only assign a variation in CO₂

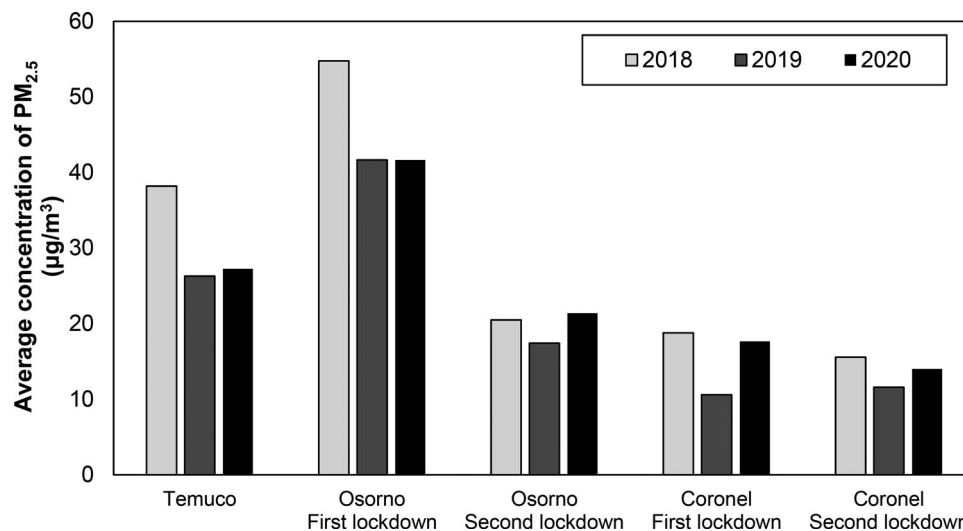


Figure 6. Average daily PM_{2.5} concentrations for lockdown days in the studied cities and comparison to the same days in previous years [62].

emissions from heating due to the difference in temperatures between 2019 and 2020. This hypothesis is based on a case study applied to Paris, where a zero case increase in emissions is detected in the residential sector. Forster et al. [7] present the most elaborate estimates. Using data from the UK smart meter analysis carried out by Octopus Energy, they estimate that, in homes that were unoccupied in 2019, residential emissions have increased by 20%. However, homes where there were already family members during working hours only saw emissions increasing by 4%, so they estimate that the overall increase is very small compared to the changes occurring in other sectors. Our study aims to capture the change experienced in the volume of residential energy use using a bottom-up method. That is, collecting information on the real behavior of a population sample through a detailed questionnaire on the patterns of energy consumption in their homes before and after the application of anti-pandemic policies.

Although national GHG emissions may have decreased during the COVID-19 pandemic, due to lockdown restrictions, the present study shows that GHG emissions from domestic energy use have actually increased: between 14 and 18% for electricity and gas (non-heating purpose), and between 1 and 6% for space heating energy in the case of the four cities under study. Such an increase is explained mainly by the rise in domestic energy demand during the pandemic due to more time spent at home. We observe that our results largely coincide with global variations of residential CO₂ equivalent emissions estimated for 69 and 123 countries (covering 97% and >99% of

global CO₂ emissions) in Le Quéré et al. [4] and Forster et al. [7], respectively. In both studies, emission growth rates are estimated to vary between 3 and 20%. Our results fall within this wide range. The significant increase in household electricity consumption (Table 5) is also detected in the five communes of Santiago representatives of the different socio-economic levels, where an increase of up to 17% in June 2020 compared to the same period in 2019 is observed [30].

Effect on air pollution

It is worth mentioning that the four cities under study present air pollution as a key environmental issue, which in normal years tends to show higher levels in the winter season due to the use of firewood in the residential sector. A relevant question was the incidence of COVID-19 confinement measures on pollution levels, as less industrial and motorized vehicle activities, but also a greater use of heating fuels, was observed. Figure 6 shows a comparison of the average daily PM_{2.5} concentrations between lockdown days and the same days in previous years [62]. The first lockdowns in Temuco and Osorno were in early autumn, and a similar behavior in PM_{2.5} concentration levels can be observed with respect to the previous year, while 2018 was the most contaminated year. On the other hand, the second lockdowns of Osorno and Coronel started at the end of the winter and continued during the spring, which was colder than usual that year. Although the two cities present different levels of air pollution in 2020, these values are similar to 2018 levels and higher than 2019. Finally, it cannot be stated that COVID-19 lockdowns led to an improvement in air quality in

Chile, as was the case in Italy [63,64] and in China [16], showing the need to incorporate more detailed analyses of weather scenarios in order to define ventilation conditions in Chilean cities.

This study opens up new avenues of analysis on the impacts of COVID-19 on GHG emissions at the household level, which represent a significant share of the global GHG emissions. The diminution of wet wood use, the emerging use of pellet-based heaters and the electrification of heating systems observed during the 2020 pandemic in the studied cities may be linked to the current Governmental plans and incentives, such as the Prevention and/or Atmospheric Decontamination Plans (i.e. *Planes de Prevención y/o Descontaminación Atmosférica, PPDA*) started in 2015, and the Program 'Change your heat' (i.e. *'Recambia tu calor'*) implemented in the winter 2020 in the 10 most air polluted communes of Chile, including Temuco and Osorno. These plans are aiming at reducing the air pollution by reducing the use of firewood for residential space heating, but their effectiveness in the long term and in times of pandemic remains to be demonstrated.

Future investigation

A statistical analysis about the factors influencing the energy-related GHG emissions is beyond the scope of the present study. However, our preliminary results revealed that independent variables such as household occupancy, floor area and room number (i.e. [Annex Table 1](#)) have no statistical significance in explaining the energy-related GHG emissions. This may be due to the behaviors and practices of the energy-consumers in the area of study. For instance, larger families living in larger homes do not necessarily use larger amounts of energy, as they might only heat selected rooms within the house. Other factors, such as the home thermal performance, or the climate conditions (i.e. outdoor temperature, relative humidity, wind and solar radiation) may explain more significantly the energy-related GHG emissions of households. In this sense, the slightly colder winter in Coronel and Temuco in 2020 compared to 2019 (i.e. [Table 1](#)) may be responsible for part of the increase of energy consumption for space heating observed in 2020 (i.e. [Table 4](#)). On the contrary, the slightly warmer winter in Valdivia and Osorno in 2020 may have reduced energy consumption by a small amount.

Another factor influencing the energy-related GHG emissions is the fluctuation of energy prices.

Indeed, energy prices can have a crucial impact on consumptions, as well as on the choice for adopting one energy or another. The price of firewood and electricity, the two main energy resources here (i.e. [Table 2](#), [Table 4](#), [Table 5](#)), remained steady between July 2019 and July 2020. As for firewood, the significant role it plays within the local economies continues to make it the most economic and accessible energy in the studied cities. That is why its demand and supply have not been affected during the COVID-19 crisis. In the case of electricity for residential consumers, the auction-based market scheme implemented in 2005 under the Law Number 20,018 (Short Law II) entails energy investors to compete for long-term contracts, and therefore this ensures price stability. While the price of firewood and electricity were stable during the COVID-19 pandemic, those of other fuels, such as pellet, LPG and natural gas have increased by 6%, 12% and 5% respectively, on average in the studied cities between July 2019 and July 2020, and the price of kerosene decreased by 16%, according to historical data by region from the National Commission of Energy (CNE) for hydrocarbon fuels and electricity [47,65] and from the National Service of Customers (SERNAC) for woody biomass [46]. While the increase in price of pellet, LPG and natural gas may have limited a further increase of residential energy-related GHG emissions, the price reduction of kerosene over the studied period may explain its increase in consumption (i.e. [Table 3](#)). Else, despite steady prices, the consumption of firewood did not increase as much as the one of electricity for heating purposes (i.e. [Table 3](#)). This is a clear indication of the preference households had for electrical heaters, used mostly as extra heating, to match the increased demand. This could be due to the incentives encouraging the adoption of electrical heaters, a possible increased awareness about the health issues arising from wood burning-related air pollution, the lower total heating efficiency of traditional wood stoves compared to electrical heaters, or a combination of these factors. Overall, the weight of the various local factors involved, including energy price changes influencing household energy-related behaviors and consumptions, should be investigated statistically in future analyses.

Beyond the impact on emissions, the COVID-19 pandemic has also affected the household economy. Indeed, 59% of the surveyed households declared to have suffered an income reduction

since the beginning of the pandemic. Such data are relevant for analyzing solutions to compensate for the economic weight of the health crisis on households, correlated with the drop in consumption of businesses, institutions, and educational establishments, which were fully or partially closed during the pandemic. Regarding the socio-economic level of families, according to a 2016 study in central-south Chilean cities [31], the household expenditures on firewood were similar between the different socio-economic groups -with the exception of the wealthiest but minority group-, confirming different impacts of the energy price on the household economy and the importance of addressing energy poverty. This phenomenon should be further investigated considering the wide range of socio-economic factors and the ways the pandemic has affected everyday practices, in order to reveal the broader picture and to design better and updated policy frameworks.

Final considerations

The COVID-19 pandemic has environmental implications, but equally important are the opportunities that arise to implement measures for changing practices and behaviors in order to improve the sustainability of cities. Megahed & Ghoneim [66] emphasize the importance of designing a healthy and sustainable built environment by reassessing fundamental assumptions in urban and architecture approaches. Given that the majority of Chilean residential buildings lack adequate thermal insulation and airtightness [33], improving their thermal performance could substantially reduce residential energy use and the related GHG emissions [67], while at the same time diminishing air pollution levels in such cities where wood is the main source of energy for space heating and cooking. Increasing the energy efficiency and thermal performance of buildings also implies the implementation of mechanical ventilation systems, which can help to prevent COVID-19 transmission [68]. Improving the thermal performance of residential buildings could be done firstly by implementing stricter regulatory standards and certification for new constructions and the refurbishment of existing buildings, aiming to improve the buildings' energy efficiency. At the same time, efforts should be made to fill the technical and engineering skills gaps existing in the national construction sector, by promoting the formation and training of specialized professionals, as well as the development of Chilean industries able to offer

energy efficient materials, equipment and technologies to the national market. Secondly, there is a clear need to transition from fossil fuel burning systems to efficient electrical equipment for space and water heating, such as ground- and air-source heat pumps. This includes the provision of financial incentives to promote the installation of such systems and, especially, the replacement of open fireplaces and old wood stoves with highly efficient heating systems. Then, when high levels of energy efficiency and electrification are reached, the next step, in order to radically reduce the GHG emissions from electricity used in buildings, is to decarbonize the electric grid, replacing fossil fuel power plants with carbon-neutral ones, such as solar, wind, wave or high enthalpy geothermal, as the country possesses an immense potential for all of these. It is worth mentioning that the implementation of these measures could create numerous new jobs, as demonstrated in Scott et al. [69], Wei et al. [70], Garrett-Peltier [71], and Nasirov et al. [72]. In the short-term, the proposed policies would help to stimulate the country's economy, particularly suited for those adversely affected by the COVID-19 recession.

Conclusions

This article evaluates the trends in the household energy-related GHG emissions before and during the coronavirus pandemic in Coronel, Temuco, Valdivia, and Osorno, four medium-sized cities in Chile. For this purpose, we analyze the energy consumption of homes using a bottom-up method based on surveying households before and during the COVID-19 confinement. Instead of extrapolating yearly national GHG emissions into smaller time frames and territorial scales, our method allows a more robust estimation of the changes of domestic energy-consuming behaviors that have occurred during lockdowns.

Results indicate that the energy-related CO₂ equivalent emissions from households have increased in our sample of medium-sized Chilean cities. Direct and indirect emissions (i.e. from burning fuels and electricity consumption respectively) associated with heating, though modest, have increased (between 1 and 6%). A significant increase is observed in the volume of emissions due to a greater energy use for utilities other than heating. Working remotely from home and the respective closure of workplaces, schools and universities explain this increase.

Some positive aspects can be seen regarding space heating: a) the lower use of wet wood, b) the higher use of electricity, c) the emerging use of more efficient pellet-based heaters, and d) some improvements in the home thermal insulation. However, considerable efforts still need to be made to reduce the GHG emissions from space heating, which has not dropped as much during the COVID-19 pandemic as would have been desirable.

On the other hand, the GHG emissions from domestic energy for other uses than heating have increased significantly (between 8 and 23%). This is an expected result, given that workers and students occupy their homes for longer periods of time, carrying out activities that would normally occur in schools, institutes, and offices. This transfer of emissions has had important socio-economic consequences, since spending on heating and other domestic energy has fallen upon families' shoulders at the time, while the household income has dropped due to a fall in economic activities.

From our perspective, changes in energy use patterns have harmed families, so it is important to try to balance a positive outlook in environmental terms with a more critical one regarding how households are affected economically by COVID-19. It is important to continue monitoring those trends in the future, as the issue of energy poverty is crucial in countries of the Global South like Chile, where the cold and humid climate is conditioning the demand for space heating. Income loss combined with poor thermal performance of buildings result in the adoption of the cheapest energy option (i.e. principally the air contaminating wood biomass) and this represents a challenge for the energy transition (electrification) and the achievement of the national decarbonization commitments. This is why it is fundamental to better understand the adaptation of energy-consumer behaviors in times of sanitary and economic crisis.

Finally, the present study provides valuable insights into domestic energy use practices in the four cities studied. Results can be used to examine in greater depth how household heating strategies in times of pandemic can contribute to the local and national objectives established by authorities, as well as for the design of new sustainability and climate change policies or the improvement of those already in force. In particular, the study draws attention towards the need to improve the overall thermal performance of residential buildings and to promote cleaner energy systems, in order to reduce GHG emissions and to provide the appropriate

conditions of thermal comfort and air quality for a healthier life in more sustainable cities.

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Disclosure statement

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In doing so we confirm that we have followed the regulations of our institutions concerning intellectual property.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due their containing information that could compromise the privacy of research participants.

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Annex Table 1. Descriptive statistics on occupancy, floor area, and room number characteristics of surveyed households.

		Household occupancy (persons)	Household floor area (m ²)	Household room number
Coronel	Mean	3.59	75.41	4.23
	Std. Dev	1.4	40	1.83
Temuco	Mean	3.36	94.94	4.53
	Std. Dev	1.33	67.55	1.94
Valdivia	Mean	3.31	98.83	5.08
	Std. Dev	1.39	56.44	2.23
Osorno	Mean	3.27	88.86	4.65
	Std. Dev	1.32	52.84	2.17
Total	Mean	3.38	90.41	4.54
	Std. Dev	1.36	56.52	2.03

Annex Table 2. Main construction material and presence of thermal insulation in surveyed homes.

	Concrete	Wood	Brickwork	Mixed	DK/NO	Thermal Insulation
Coronel	18.3%	12.0%	5.3%	64.0%	0.3%	31%
Temuco	15.7%	26.7%	5.7%	50.3%	1.7%	33%
Valdivia	9.0%	42.7%	3.0%	44.3%	1.0%	28%
Osorno	9.3%	46.0%	1.3%	41.0%	2.3%	31%
Total	13.1%	31.8%	3.8%	49.9%	1.3%	31%

Annex Table 3. Fuel prices.

Fuel	Location	Unitary price	Reference
Dry wood	Coronel, Temuco	140 [CLP/kg]	[46]
	Valdivia, Osorno	156 [CLP/kg]	[46]
Humid wood	Coronel, Temuco	84 [CLP/kg]	Assumed 40% cheaper than dry wood
	Valdivia, Osorno	94 [CLP/kg]	
Pellets	All	214 [CLP/kg]	[46]
Kerosene	Coronel	523 [CLP/kg]	[47]
	Temuco	520 [CLP/kg]	
	Valdivia	548 [CLP/kg]	
	Osorno	545 [CLP/kg]	
Liquefied petroleum gas (LPG)	All	1333 [CLP/kg]	[47]
Natural gas	Coronel	1990 [CLP/m ³]	[48]
	Temuco	1965 [CLP/m ³]	[49]
	Valdivia, Osorno	1309 [CLP/m ³]	[50]
Oil	Coronel	529 [CLP/L]	[47]
	Temuco	534 [CLP/L]	
	Valdivia	537 [CLP/L]	
	Osorno	538 [CLP/L]	
Coal	Coronel, Temuco, Valdivia, Osorno	1116 [CLP/kg]	[51]
Other	Coronel, Temuco, Valdivia, Osorno	628 [CLP/kg]	Assumed average value between dry wood and charcoal
Electric Power	Coronel, Temuco, Valdivia, Osorno	0.159 [CLP/kWh]	Average value in March 2020 (includes market price, standing charge and taxes) [52,53]

Annex Table 4. Monthly CO₂-eq emissions from electricity and gas used for utilities other than space heating (home average).

		GHG emissions from electricity and gas used for utilities other than space heating (kg CO ₂ -eq/month)	
City	Period	Electric Power	Gas
Coronel	March 2020	82.7	65.6
	July 2020	95.1	80.8
Temuco	March 2020	95.2	51.1
	July 2020	112.4	60.4
Valdivia	March 2020	111.2	53.4
	July 2020	126.3	57.6
Osorno	March 2020	110.7	59.8
	July 2020	128.0	68.6

Annex Table 5. Annual CO₂-eq emissions by fuel type used for space heating (home average).

		GHG emissions by fuel type used for space heating (kgCO ₂ -eq/year)							
City	Period	Firewood	Kerosene	Electric Power	LPG	Natural Gas	Coal	Oil	Others
Coronel	2019	1800	69	39	28	0	2	0	1
	2020	1896	74	49	32	0	2	0	1
Temuco	2019	1686	111	48	46	10	0	14	59
	2020	1709	140	60	41	11	0	14	70
Valdivia	2019	2238	79	45	15	9	0	32	58
	2020	2177	123	61	19	7	1	34	79
Osorno	2019	2102	77	29	25	3	0	46	42
	2020	2123	91	39	27	3	0	41	43