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# Population growth in Mexico and its impact on mitigation components of nationally determined contributions

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RESUMEN

En 2050 la mayor parte de la población en México tendrá entre 44 y 50 años de edad. Se espera que para 2100 la población disminuya a 116 millones, 9% menos que en 2020. Recientemente, México ratificó su compromiso para enfrentar la crisis climática planetaria al actualizar su contribución nacional determinada, aumentando su meta de reducción de gases de efecto invernadero de 22 a 35% para 2030. El principal objetivo de este artículo es estimar las emisiones de carbono en 2018 (condiciones previas a la pandemia) de componentes de mitigación seleccionados y compararlos con los valores estimados para 2030, considerando la variación de la población en un escenario tendencial. Si el crecimiento se da a una tasa compuesta exponencialmente, este ejercicio de proyección indica que para el 2030 el sector transporte (público y privado) podría reducir sus emisiones de $CO_2$ en 21%, el sector residencial aumentaría sus emisiones de $CO_2$ en 4.1%, y el sector de residuos municipales aumentaría sus emisiones de metano en un 10%. Es recomendable cuantificar el impacto diferenciado del cambio climático en la vida de diversos grupos de población y posteriormente evaluar la efectividad de soluciones que reduzcan la exposición de estos grupos al cambio climático, potenciando su rol como agentes de acción climática en términos de descarbonización y/o resiliencia a sus efectos.

ABSTRACT

By 2050, most of the population in Mexico will be between 44 and 50 years old. By 2100, the population is expected to decrease to 116 million, 9% less than in 2020. Mexico recently ratified its commitment to face the planetary climate crisis by updating its nationally determined contribution, increasing its goal of reducing greenhouse gases from 22% to 35% by 2030. The main goal of this article is to estimate carbon emissions in 2018 (pre-pandemic conditions) of selected mitigation components and compare them with estimated values for 2030, considering the population variation under a business-as-usual scenario. If growth takes place at an exponentially compounded rate, this projection exercise shows that by 2030, the transport sector (private and public) could reduce its $CO_2$ emissions by 21%, the residential sector will increase its $CO_2$ emissions by 4.1%, and the municipal waste sector would increase its methane emissions by 10%. It is advisable to quantify the differentiated impact of climate change on the lives of diverse population groups, and after evaluating the effectiveness of solutions that reduce the exposure of these groups to climate change, to enhance their role as agents of climate action in terms of decarbonization and/or resilience to its effects.

**Keywords:** population growth, carbon emissions, mitigation component.

## 1. Introduction

Latin America and the Caribbean (LAC) countries are in the middle of the established period to achieve the sustainable development goals (SDGs) of the 2030 agenda for sustainable development. Progress towards these goals and targets was seriously hampered by the coronavirus disease (COVID-19) pandemic, which caused a strong impact in the world from 2020 and jeopardized progress towards the achievement of the 2030 agenda in large regions of the planet, including LAC, the most affected region by the pandemic (ECLAC, 2023).

Mexico has shown significant improvement opportunities to achieve the SDGs, as was proven by its recent overall score of 70.2/100 published at the Sustainable development report 2022, given its 2000 base score of 62.25, which implies an advance of only 13% in 22 years (Sachs et al., 2022).

Recently, Mexico ratified its commitment to face the planetary climate crisis by updating its nationally determined contribution (NDC). The Secretaría de Medio Ambiente y Recursos Naturales (Ministry of Environment and Natural Resources, SEMARNAT) (SEMARNAT, 2022) has set the following mitigation goals:

- Increasing the reduction of greenhouse gases from 22 to 35% by 2030 with respect to its baseline, with national economic resources that will contribute at least to 30 and 5% through cooperation and international financing destined for clean energy.
- Mexico can conditionally increase its goal up to 40% by 2030 with respect to its baseline if international financing, innovation, and technology transfer are scaled up and if other countries (the largest emitters) make proportionate efforts towards the more ambitious goals of the Paris Agreement.
- Mexico ratified the goal of unconditionally achieving a 51% reduction of black carbon emissions by 2030 and 70% conditionally.

The Mexican government quantified the trend scenario projected by 2030 without the intervention of a mitigation policy at 991 megatons of equivalent carbon dioxide (Mt $CO_2$e). The 35% reduction by 2030 implies a reduction of 347 Mt $CO_2$e in that year, while compliance with conditional commitments amounts to 397 Mt $CO_2$e (Fig. 1). The implementation period of the updated NDC is from 2020 to 2030, and the policies implemented as of 2013 are considered after the publication of the Ley General de Cambio Climático (General Law on Climate Change) (SEMARNAT, 2022). As mentioned by SEMARNAT, the mitigation measures derived from the NDCs update at the sectoral level focus on the following sectors: land use, land use change and forestry (LUCF), transport, electricity generation, industry, oil and gas, agriculture and livestock, residential and commercial, and waste.

Extensive research has proven the relationship between population change and variation in carbon emissions, concluding that decreasing population

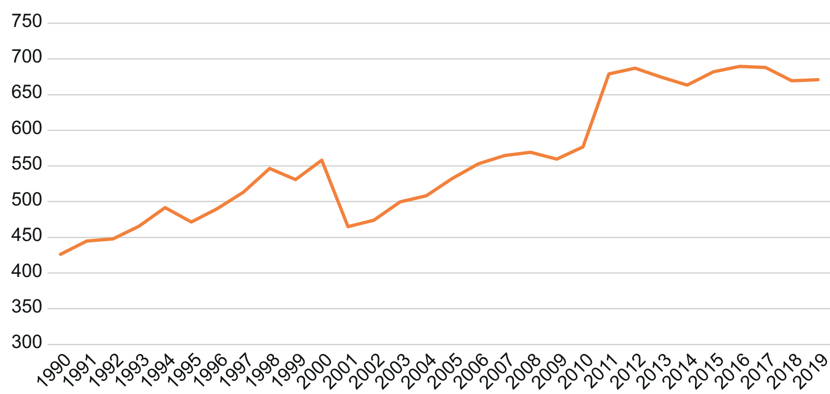


Fig. 1. Historical Green House Gases in Mexico, 1990-2019 (Mt $CO_{2e}$).
Source: own elaboration based on Climate Watch (2023).

growth could reduce emissions to desirable values to avoid dangerous climate change (O'Neill et al., 2020; Casey and Galor, 2017).

In order to study the relationship between population growth in Mexico and carbon emissions from mitigation components, keywords such as social impact, gender, and population perspective were found on the description of the different mitigation measures proposed by SEMARNAT (2022) and their components; therefore, this study considers that population variation directly affects the following mitigation components:

- Transport, through the consolidation of electric mobility, transformation of public transport and the transition to more efficient vehicles.
- Residential and commercial, by promoting energy efficiency, optimizing energy consumption, promoting mechanisms and regulations that promote the inclusion of best practices in new construction and renovations, and reducing the consumption of firewood.
- Waste, by improving the comprehensive management of municipal solid waste (MSW), as well as wastewater treatment, reuse, recycling, composting, and bio digestion, in addition to also considering advancing in the capture and use of biogas.

Once the mitigation components related to population growth have been established, the main goal of this study is to estimate carbon emissions in 2018 (pre-pandemic conditions) of the selected mitigation components and to compare them with estimated values for 2030, considering the population variation under a business-as-usual scenario. The results obtained will allow future work to quantify and compare the impact of the different mitigation measures proposed by the federal government.

### *1.1 Analysis of the population trend*

In general, current Mexicans would like to live in a country with less inequality and more social mobility. In this regard, there are different visions, depending on the person's socioeconomic status. One of the characteristics of income distribution in Mexico is the increasing gap between high-income individuals and the rest of the population: using current family income, the ratio of decile 10 to decile 1 is 18.3. With a Gini coefficient of around 0.5, only 3% of those born in the bottom quintile will rise to the top, and only 2% of the top quintile will end up at the bottom, with minor change over time in the last few years. This social rigidity leads to "opportunity hoarding": those who start from a disadvantaged position will have fewer opportunities to succeed, while those born into privilege will continue to accumulate more advantages throughout their lives, which they can later pass on to their children (Campos-Vázquez et al., 2022).

Population growth in Mexico, measured as a percentage change, was about +3% between 1950 and 1976 (Fig. 2). Between 1977 and 1995, change was +2%, and from 1996 to 2019, change has been reduced to just +1% (TEDb, 2019).

According to the most recent Population and Housing Census of 2020 (INEGI, 2021), 126 014 024 people live in Mexico, which ranks 11th among the most populated nations in the world. Between 1950 and 2020, the population in Mexico has grown more than four times. In 1950, there were 25.8 million people, while in 2020 there were just over 126 million. From 2010 to 2020 the population increased by 14 million inhabitants. The most populated entities are the State of Mexico (16 992 418), Mexico City (9 209 944), and Jalisco (8 348 151) (Fig. 3).

In 2020, the population pyramid showed that:

- For each 100 inhabitants, 51 are women and 49 nine men.
- However, there are more men in the age range of 0 to 19 years.
- From the age of 20-24 the number of women is greater than the number of men.
- The graph is widest in the center and narrows at the bottom, meaning that the ratio of girls and boys has decreased over time (Fig. 4).

Estimated data from the Consejo Nacional de Población (National Population Council, CONAPO) (CONAPO, 2023) show that in Mexico, the midyear population by 2030 will be about 138 070 271 inhabitants, 9.6% more than in 2020, of which 51.1% will be women and 48.9% men (Fig. 5).

By 2050, most of the population will be between 44 and 50 years old. By 2100, it is estimated that the

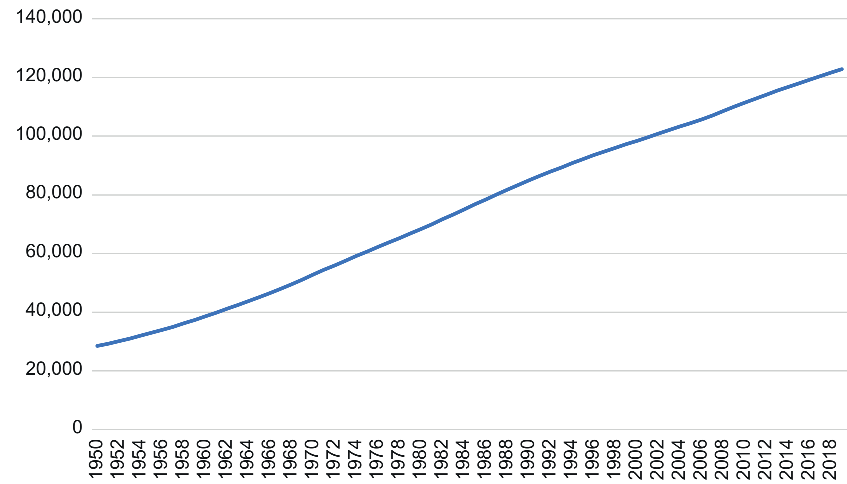


Fig. 2. Mid-year population for the period 1950-2019 ($\times 10^3$).
Source: own elaboration based on Total Economy Database (TEDb, 2019).


Fig. 3. Most populated entities in Mexico, 2020.
Source: INEGI (2021).

Mexican population will decrease from 127 million in 2022 to 116 million. This decrease is due to the fact that the fertility rate decreased from 6.7 to 1.8 percent between 1950 and 2022, whereas this indicator must exceed 2.1 to ensure the replacement of the population (World Bank, 2023).

## 2. Methods

Supported on different databases such as the Base de Indicadores de Eficiencia Energética (Energy Efficiency Indicators Database, BIEE), basic statistics from de Secretaría de Infraestructura, Comunicaciones y Transportes (Ministry of Infrastructure, Communications and Transportation, SCT), prospective studies of the energy sector published by the Secretaría de Energía (Ministry of Energy, SENER), as well as various specialized publications, this study performs a quantitative analysis and trend projection of data about energy consumption and carbon emissions from the road transport, residential and waste sectors, considering the impact of expected population growth between 2018 and 2030.

The main tool for projecting current values is the compound annual growth rate (CAGR), which is the annualized average rate of revenue growth between two given years, assuming growth takes place at an exponentially compounded rate.

The equation to calculate CAGR is:

$$CAGR = \left(\frac{final\ value}{initial\ value}\right)^{\frac{1}{n}} - 1 \tag{1}$$

where $n$ is the difference between final year and initial year.

The present and future analysis of the information recovered from different databases aims to generate carbon emissions indicators by type of mitigation component (transport, residential, and MSW) for the years 2018 and 2030. These indicators will allow us to define whether the mitigation components considered will meet their emissions reduction goal under a business-as-usual scenario and, if necessary, make the necessary adjustments to achieve it.

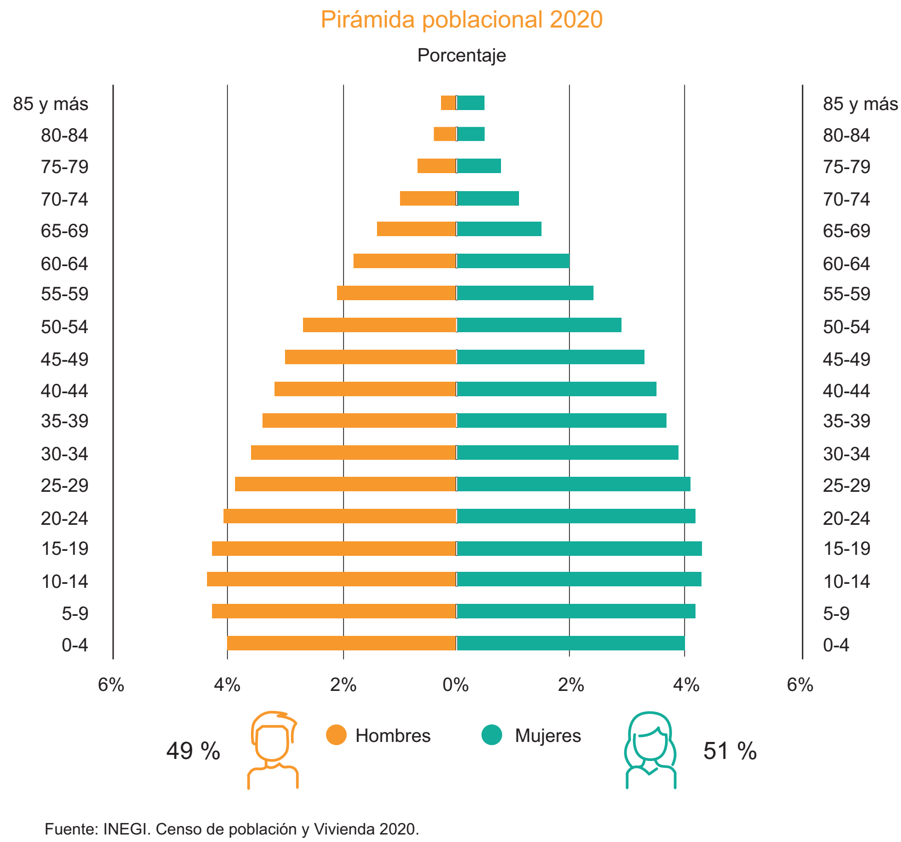


Fig. 4. Population pyramid in Mexico, 2020. Source: INEGI (2021).

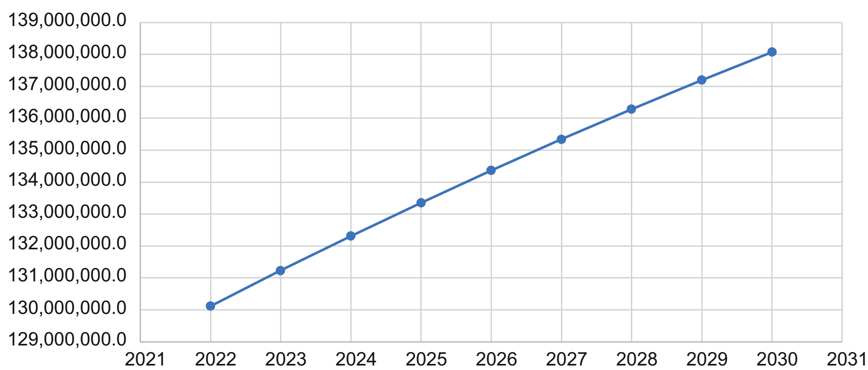


Fig. 5. Mid-year population for the period 2022-2030. Source: own elaboration with data from CONAPO (2023).

## 3. Results

As a summary of different calculations made in this section (medium-term projection and energy and mass balance), Table I shows carbon emissions by mitigation component in 2018 and 2030. It also shows the percentage variation caused by population growth, displaying that under a business-as-usual scenario, just the transport sector could contribute to reducing carbon emissions. In the case of transportation, the reduction in emissions results from the reduction in fuel consumption per kilometer traveled. In the residential and waste sectors, there is a direct relationship between population growth and carbon emissions generated.

Table I. Carbon emissions by mitigation component, 2018 and 2030.

| Mitigation component | 2018 | 2030 | Percentual variation |
|---|---|---|---|
| Transport (Mt $CO_2$) | 82.32 | 64.96 | –21.1 |
| Residential (Mt $CO_2$) | 75.43 | 78.56 | +4.15 |
| Municipal solid waste (Mt $CH_4$)* | 0.28-0.68 | 0.31-0.75 | +10 |

*Methane production from sewage sludge is not considered.

These results indicate that the population in general should be involved, firstly, in understanding that they are part of the problem and also of the solution through adequate public policies at the different levels of government. These policies promote the convergence of government, academia, industry, and society to define road maps that allow the achievement of the objectives and goals proposed for reducing carbon emissions.

### *3.1 On-road vehicles (automobiles, commercial buses, and motorcycles)*

Travel behavior in cities will not reach a "new normal" post-coronavirus pandemic. Travel habits are still uncertain, and several other crises coincide with recovery from the pandemic. Many cities have addressed the connectivity challenge by promoting active modes of transport and micro-mobility. The freedom to work from home promoted several positive effects. However, fewer trips to the office can lead to more non-work commuting. It can also lead city dwellers to move to the suburbs, prolonging occasional trips and potentially increasing car dependency (ITF, 2023).

In Mexico, the pandemic caused a reduction in the energy consumption of road transport but not in the number of automobiles, buses, and motorcycles (Fig. 6). After an 8.4% increase in energy consumption between 2009 and 2018, in the period 2018-2020 the consumption of the transport sector fell by 29%, going from 2205.1 to 1576.11 PJ. In contrast, the growth in the number of automobiles, buses, and motorcycles showed a CAGR of 4.8%, 2.9%, and 14.4%, respectively (BIEE, 2023).

With an overall population of 125.3 million people, at the end of 2018, the transportation sector

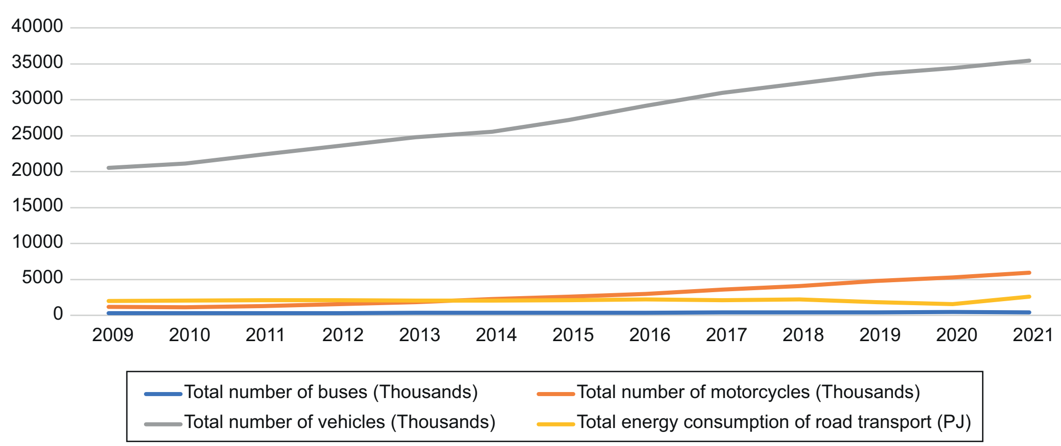


Fig. 6. Variation in the number of automobiles, trucks, and motorcycles vs. energy consumption (PJ), 2009-2021. Source: own elaboration based on BIEE (2023). Automobiles are defined as motor vehicles intended for the transport of people, which have up to seven seats (including the driver), comprising cars and SUV-type trucks. Buses include urban and suburban vehicles, microbuses, school buses, pick-up trucks (used for the transfer of workers), buses, and, in general, vehicles with eight seats or more intended for public or private transportation of people.

continued as the largest end consumer of energy in Mexico, with a share of more than 40% of total demand (SCT, 2019). Energy consumption of the transport sector was 2454.7 PJ by 2018, of which 89.8% was consumed by road transport (BIEE, 2023). In the same year, automobiles consumed 49.5% of the energy demanded by road transport, showing a CAGR of 18.4 % from its energy consumption growth during the period 2009-2018 (Table II).

By type of fuel, in 2018, gasoline-powered automobiles had the highest participation, with 99.2% of the 32.29 million total vehicles, showing a $CAGR_{2009-2018}$ of 5.1%.

By 2020, the number of automobiles was 33 987 million, with a share of more than 99% of gasoline vehicles. During the 2009-2020 period, hybrid and electric cars and cars converted to compressed natural gas (CNG) had the highest CAGR, with 65.9 and 43.8%, respectively, although with a share below 0.15% each. The number of cars per capita in 2020 was 0.27.

Regarding buses, 444 000 vehicles circulated in 2018, of which 54.6% used diesel, 25.4% LP gas and CNG, and 20% used gasoline as fuel.

One of the internal combustion vehicles that has significantly increased its presence in Mexico is motorcycles, going from 1.2 million in 2009 to 4.08 million in 2018, almost a four-fold increase in nine years. By 2020, the number of motorcycles increased to 5.26 million, which stands for a $CAGR_{2009-2020}$ of 14.4%, with a per capita value of 0.042 motorcycles per inhabitant.

To obtain the $CO_2$ emissions generated by cars in 2018, the proposed method starts with the number of cars, by type of fuel, multiplying it by the average number of kilometers traveled, then multiplying the result by the average fuel efficiency (L $km^{-1}$), with which the liters of each fuel consumed are obtained. This value is multiplied by the emission factor of each type of fuel in units of $kgCO_2$ $L^{-1}$ published by the Instituto Nacional de Ecología y Cambio Climático (National Institute of Ecology and Climate Change, INECC) (INECC, 2014), with which the $CO_2$ generated by each type of automobile is obtained (in Mt $CO_2$) (Table III).

Given a correlation value of 0.985, 0.88, and 0.944 between the number of automobiles, buses, and motorcycles (respectively), and the population variation

Table II. Energy consumption by type of vehicle, 2018.

| Type of vehicle | Energy consumption (PJ) | Share of energy consumption (%) | $CAGR_{2009-2018}$ (%) |
|---|---|---|---|
| Automobiles | 1090.7 | 49.5 | 18.4 |
| Bus | 116.3 | 5.3 | 17.7 |
| Motorcycles | 24.8 | 1.1 | 377.3 |

CAGR: compound annual growth rate.

Table III. Calculation of automobile carbon emissions by fuel type, 2018.

| Fuel type | Automobiles | Average (km $year^{-1}$) | Average (L × 100 $km^{-1}$) | Amount of fuel (L × $10^6$) | Emission factors ($kgCO_2$ $L^{-1}$) | Emission (Mt $CO_2$) |
|---|---|---|---|---|---|---|
| Diesel | 57.2 | 12 374.9 | 8.002 | 56.64 | 2.6 | 0.147 |
| CNG* | 1.8 | | | 1.78 | 2.69** | 0.0009 |
| Gasoline | 32 029.9 | | | 31 717.05 | 2.322 | 73.6 |
| LP gas | 159.5 | | | 157.96 | 1.58 | 0.25 |
| Total | | | | 31 933.4 | | 74.0 |

CNG: compressed natural gas.
*CNG density = 190 kg $m^{-3}$; **units in $kgCO_2$ $kg^{-1}$.

during the period 2009-2020, the carbon emissions projection exercise is carried out for 2030. First, the number of motor vehicles in 2018 was multiplied by a factor of 1.1017, which is the population variation from 2018 to 2030. Annually driven mileage (km year$^{-1}$) and fuel economy (L 100 km$^{-1}$) are adjusted according to their respective estimated CAGR over the same period.

In the case of automobiles, the short-term participation of hybrid and electric vehicles is still considered low. However, according to the sales forecasts made by the automotive consultancy JD Power (Alavez, 2022), it is expected to increase by 3% by 2030.

The calculations carried out show that automobile carbon emissions could be reduced from 74 to 56.1 Mt $CO_2$ between 2018 and 2030 because of less distance traveled and an 8% decrease in fuel economy.

Regarding passenger buses, following the calculation procedure applied for automobiles and considering the number of buses using natural gas as LP gas due to a lack of information, a value of 9 Mt CO2 by 2030 is estimated (Table IV).

Although there is an increase in the number of buses, they will travel 17% fewer kilometers, and their fuel economy will decrease by 1%, which could mean a reduction of 11 percentage points in reduction of carbon emissions between 2018 and 2030.

Concerning motorcycles, according to the data projection values obtained for 2030, resulting from a 10% increase in the number of motorcycles, a 66% increase in the distance traveled (as it is a low-cost mobility model), and a 5% decrease in fuel economy, the carbon emissions of this type of vehicle would increase 72% compared to 2018, with an estimated value of 2.96 Mt $CO_2$ in 2030 (Table V).

*3.2 Residential*

Data from the 2020 population and housing census show that in Mexico there were 35 219 141 inhabited private homes (3.6 inhabitants per home), of which 29% were between 11 and 20 years old. Of the inhabited private homes, 99% had electricity, 96% had drainage connected to the public network, and 78% had piped water inside the home (INEGI, 2023).

Regarding the type of internal services and amenities available in each dwelling, Table VI shows the percentage of inhabited private homes that had a refrigerator, washing machine, computer, TV service, air conditioning, and internet.

In 2020, the energy source most used for cooking was LP gas, which was used in 75.9% of homes. This was followed by biomass and natural gas, which were available in 13.8% and 8.7% of homes, respectively (Fig. 7).

Table IV. Calculation of carbon emissions from buses by type of fuel, 2018.

| Fuel type | Automobiles | Average (km year$^{-1}$) | Average (L × 100 km$^{-1}$) | Amount of fuel (L × $10^6$) | Emissions factor (kg$CO_2$ L$^{-1}$) | Emission (Mt $CO_2$) |
|---|---|---|---|---|---|---|
| Diesel | 242.3 | 40 619.18 | 16.04 | 1578.7 | 2.596 | 4.1 |
| Gasoline | 88.5 | | | 576.4 | 2.322 | 1.34 |
| LP gas and CNG | 112.7 | | | 734.3 | 1.58 | 1.16 |
| Total | | | | | | 6.6 |

Table V. Motorcycles' carbon emissions, 2018.

| Fuel type | No. of motorcycles (× $10^3$) | Average (km year$^{-1}$) | Average (L × 100 km$^{-1}$) | Amount of fuel (L × $10^6$) | Emission factors (kg$CO_2$ L$^{-1}$) | Emission (Mt $CO_2$) |
|---|---|---|---|---|---|---|
| Gasoline | 4080.15 | 4,515.7 | 4.009 | 738.6 | 2.322 | 1.72 |

Table VI. Percentage of inhabited homes in 2020 that owned internal services and amenities.

| Internal service and amenities | Refrigerator | Washing machine | Computer | TV service | Air conditioning | Internet |
|---|---|---|---|---|---|---|
| Inhabited homes (%) | 87 | 73 | 37 | 43 | 17 | 52 |

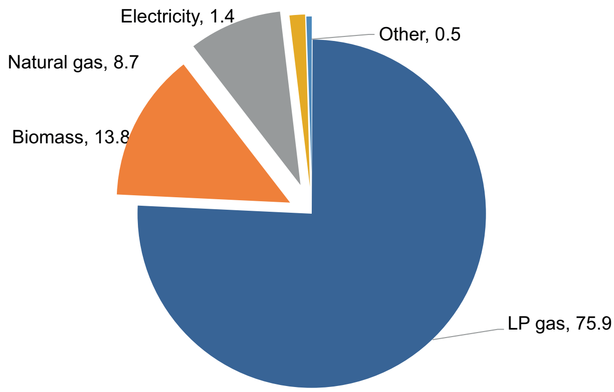


Fig. 7. Percentage of households in Mexico using a specific energy source for cooking.

Table VII. Effect of the pandemic on energy consumption, variation between 2018 and 2020 (in PJ).

| Energy source | 2018 | 2020 | Variation (%) |
|---|---|---|---|
| Electricity | 227.79 | 260.09 | 14.2 |
| Natural gas | 30.15 | 25.95 | –14.0 |
| LP gas | 246.44 | 289.53 | 17.5 |
| Biomass* | 249.07 | 330.26 | 32.6 |
| Total | 753.46 | 905.83 | 50.3 |

*Firewood, agricultural and livestock waste.

As for the use of renewable energy sources, only 10% of inhabited homes used solar heating, and less than 1% had solar panels in 2020 (Data México, 2023).

In 2018, the residential sector energy consumption was 760.5 PJ, of which 32.7% came from biomass combustion, 32.4% from LP gas combustion, 30% from electricity, and 4% from natural gas combustion (BIEE, 2023).

The increase in energy consumption in the residential sector was notorious by more than 50% during 2020 compared to 2018, caused by the reduction in mobility due to the coronavirus pandemic, where biomass consumption showed the greatest increase with 32.6 % (Table VII).

In 2020, 13.8% of inhabited homes consumed biomass for cooking, that is about 4.86 million homes, where approximately 17.5 million people lived. This means that 14% of the Mexican population consumed 36% of the total residential sector energy requirement. By 2020, only 3.4% of homes had efficient stoves (BIEE, 2023).

From the information obtained previously, the per capita energy consumption for the residential sector can be estimated as being 6.01 and 7.19 GJ person$^{-1}$ in 2018 and 2020, respectively.

To estimate the carbon emissions emitted by each source of energy consumed by the residential sector, a quantitative analysis of the available information and the use of unit conversion factors were carried out.

For example, in the case of electricity, based on an annual publication of the Comisión Reguladora de Energía (Energy Regulatory Commission, CRE) (CRE, 2019), it was obtained that the emission factor of the national electric sector for 2018 was 0.527 $tCO_2e$ $MWh^{-1}$, therefore, the 227.78 PJ were multiplied by the conversion factor of 277 800 MWh $PJ^{-1}$ and the resulting value was multiplied by the aforementioned emissions factor and divided by $1 \times 10^9$ to convert from kilograms to megatons, obtaining 33.35 Mt $CO_2e$ as a final result. In this case, due to lack of information, $CO_2e$ emissions will be considered as $CO_2$ emissions.

Since the conversion efficiency of natural and LP gas to energy or heat through combustion is less than 100%, the volumetric consumption values reported on the prospective studies published by SENER (2018a, b) for the period 2018-2032 were consulted. Table VIII shows the main data used to estimate the value of carbon emissions by type of energy source during 2018.

To estimate carbon emissions by 2030, the $CAGR_{2009\text{-}2018}$ from consumption by type of energy source was first estimated, and then the value of en-

Table VIII. Estimation of $CO_2$ emissions by energy source, 2018.

| Energy resource/year | 2018 | Emissions factor | Emissions ($Mt\ CO_2$) |
|---|---|---|---|
| Electricity | 227.79 PJ | 0.527 $tCO_2e\ MWh^{-1}$ | 33.35 |
| Natural gas* | $958 \times 10^6$ $m^3$ | 2.69 $kgCO_2\ kg^{-1}$ | 1.9 |
| LP gas | $9157 \times 10^6$ L | 1.58 $kgCO_2\ L^{-1}$ | 14.47 |
| Biomass** | 249.07 PJ | 2.314 $kgCO_2\ kg^{-1}$ | 25.71 |
| Total | | | 75.43 |

*Density = 0.737 kg/$m^3$; **firewood with 63.14% carbon content and non-volatiel compound (NCV) = 22.41 MJ $kg^{-1}$.

ergy consumption was projected for the year 2030 (Table IX).

To corroborate the trend values obtained by 2030, they were compared with information available from projections of volumetric consumption made by SENER in its prospective studies 2018-2032, which consider population variation and technological change.

Thus, in the case of LP Gas, SENER (2018b) projected that its consumption would decrease eight percentage points between 2018 and 2030, going from 157.8 to 145.5 thousand barrels per day (TBD). This decrease is derived from various effects that affect demand, such as an improvement in equipment performance for heating water and cooking food, a greater introduction of solar heaters, and the substitution of LP gas for natural gas.

The volumetric demand for natural gas during the same period would increase by 35%, associated with fuel distribution extension from different regions of the country and the expansion of gas pipeline infrastructure. The consumption of firewood will be reduced by 15% due to the estimated urbanization in rural localities, which will allow household access to other types of fuels (SENER, 2018b).

Therefore, the negative trend of the estimated energy consumption from LP gas and firewood could be corroborated, but not that of natural gas. Indeed, the natural gas volumetric demand for residential consumption estimated by SENER (2018a) would increase from $2.77 \times 10^6$ to $3.7 \times 10^6$ $m^3$ $day^{-1}$ between 2018 and 2030.

In the case of electricity, the prospective study carried out by SENER (2018c) for the consumption of the national electricity sector projected an average annual growth rate of 3.1% during the period 2018-2032.

Given the above, for the calculation of carbon emissions to 2030 the following assumptions were considered:

a. Electricity consumption, estimated at 316.8 PJ by 2030, is contemplated. The most recent emission factor of the National Electric System of 2022 is used, which is 0.435 $tCO_2e$ MW $h^{-1}$ (CRE, 2023), 17.5 percentage points lower than in 2018.
b. To obtain the volumetric consumption of natural gas by 2030, the 2018 value ($958 \times 10^6$ $m^3$) was

Table IX. Projection of energy consumption from 2018 to 2030 (in PJ).

| Energy source | 2018 | $CAGR_{2009\text{-}2018}$ (%) | 2030 | Percentage change (2018-2030) |
|---|---|---|---|---|
| Electricity | 227.79 | 2.8 | 316.8 | +39 |
| Natural gas | 30.15 | –0.5 | 28.38 | –6 |
| LP gas | 246.44 | –1.9 | 196.09 | –20 |
| Biomass | 249.07 | –0.4 | 236.06 | –5 |

CAGR: compound annual growth rate.

Table X. Carbon emissions from residential sector energy consumption by 2030.

| Energy resource | Consumption | Emission factor | Carbon emissions ($Mt CO_2$) |
|---|---|---|---|
| Electricity | 316.8 PJ | 0.527 $tCO_2e\ MWh^{-1}$ | 38.29 |
| Natural gas | $1293.7 \times 10^6\ m^3$ | 2.69 $kgCO_2\ kg^{-1}$ | 2.56 |
| LP gas | $8,443 \times 10^6$ L | 1.58 $kgCO_2\ L^{-1}$ | 13.34 |
| Biomass | 236.06 PJ | 2.314 $kgCO_2\ kg^{-1}$ | 24.37 |
| Total | | | 78.56 |

multiplied by 1.35, according to the demand projection calculated by SENER (2018b).

c. For LP gas, the projected value by SENER of 145.5 TBD to 2030 is considered.
d. The estimated value of 236.06 PJ will be used for firewood consumption, which is five percentage points lower than in 2018.

Applying the same procedure to obtain carbon emissions in 2018, the 2030 emissions resulting from the different residential sector energy sources are 78.56 Mt $CO_2$ (Table X), an increase of 4.15% compared to 2018.

Based on the results obtained in this section, Table XI shows the variation in the carbon emissions from the residential sector (Mt CO2) in 2018 and 2030.

Given the results obtained, as stated by the Inter-American Development Bank (IDB, 2023), it is advisable to quantify the differentiated impact of climate change on the lives of women and diverse population groups, and subsequently evaluate the effectiveness of solutions that reduce the exposure of these groups to risk and vulnerability to climate change, enhancing their role as agents of climate action in terms of decarbonization and/or resilience of its effects, in addition to being participants on the job opportunities derived from the transition to an economy with zero net emissions.

Table XI. Variation of carbon emissions from the residential sector between 2018 and 2030 (in Mt $CO_2$).

| Energy resource/year | 2018 | 2030 | Variation |
|---|---|---|---|
| Electricity | 33.35 | 38.29 | +4.94 |
| Natural gas | 1.9 | 2.56 | +0.66 |
| LP gas | 14.47 | 13.34 | –1.13 |
| Biomass | 25.71 | 24.37 | –1.34 |
| Total | 75.43 | 78.56 | +3.13 |

*3.3 Urban waste*

The most recent National Census of Municipal Governments and Territorial Demarcations of Mexico City carried out in 2021, specifies that in Mexico, solid waste collection amounts to 106 523 t $day^{-1}$. This is 850 g of waste generated per person, and only 7% is recycled (Fig. 8). In the country, there are 2338 final garbage disposal sites, of which 89.8% do not have a biogas control system (which is generated from biodegradation), and 84.26% lack a collection and concentration of leachate (residual liquids) (La Jornada, 2023).

Biogas production involves the decomposition of organic matter through the anaerobic digestion process. It is composed of 55 to 70% methane ($CH_4$), 30 to 45% $CO_2$, and traces of other gases (WBA, 2017). $CH_4$ is the main contributor to the formation of ozone at ground level, a dangerous air pollutant. It is also a powerful greenhouse gas. Over a period of 20 years, its heating capacity is 80 times more powerful than that of $CO_2$. It is also responsible for about 30% of global warming since pre-industrial times and is spreading faster than ever since records began in the 1980s. According to data from the US National Oceanic and Atmospheric Management Office, even as $CO_2$ emissions slowed during the 2020 pandemic-related lockdowns, atmospheric $CH_4$increased. Therefore, it is essential to achieve its reduction to counteract climate change (UNEP, 2021).

At the country level, the produced municipal solid waste (MSW) typically consists of 51.6% organic waste, 28% potentially recyclable waste, and 19% non-usable waste (SEMARNAT, 2017). Currently, 47% of the solid waste produced is concentrated

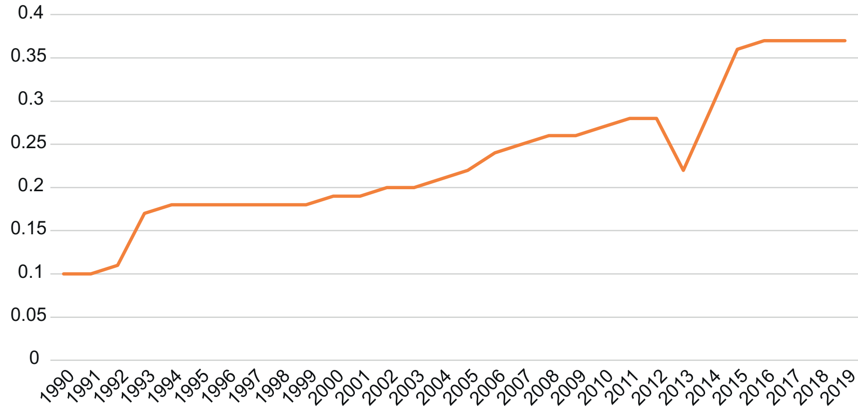


Fig. 8. Historical waste greenhouse gases emissions,1990-2019 (in t $CO_{2e}$ per capita).

in six entities: Mexico City (14.05%), the State of Mexico (11.22%), Jalisco (7.21%), Veracruz (5.50%), Nuevo León (4.84%), and Guanajuato (4.28%) (La Jornada, 2023).

Data published in The biogas handbook (Wellinger et al., 2013) show that organic waste consists of 10% solid matter (SM) and 80% volatile solids (VS) as a percentage of SM (Table XII).

Bong et al. (2018) determined that the biogas yield through the mono-digestion process of food residues is 0.27-0.642 $m^3$ $CH_4$ $kg^{-1}$ VS and for the co-digestion of food waste with other substrates it is 0.272-0.859 $m^3$ $CH_4$ $kg^{-1}$ VS, concluding that the variation in the characteristics of food waste, in terms of physical and biochemical properties, can affect the efficiency of the applied treatment.

In Mexico, during 2018, an average of 107 056 tons of garbage was collected daily, that is, 854 g per person, and it was produced in (INEGI, 2019):

- Households.
- Buildings.
- Streets and avenues.
- Parks and gardens.

Therefore, by effectively managing the 39.08 Mt of solid waste produced in 2018, 20.16 Mt of organic waste could be obtained. Considering the mono-digestion processes, 10% SM content, and VS = SM × 0.8, this could generate between 435.52 × $10^6$ $m^3$ and 1035.57 × $10^6$ $m^3$ of biomethane annually.

According to data projected by SENER (2018c), the residential sector's natural gas requirement in 2018 would be 958 × $10^6$ $m^3$, so the biomethane generation potential in the same year could supply between 45 and 108% of the demand.

Assuming the daily 2021 per capita waste production is constant until 2030 (0.85 kg per person), by 2030, approximately 42.84 Mt of total solid waste

Table XII. Generation of biomethane from diverse types of organic material.

| Raw material type | Mass solids (%) | Sludge volume of mass solids (%) | Sludge volume (%) | Biomethane yield ($m^3$ $CH_4$ kg $SV^{-1}$) | Biomethane production ($m^3$ $CH_4$ $m^{-3}$) |
|---|---|---|---|---|---|
| Fruit and vegetable waste | 15-20 | 75 | | 0.25-0.5 | |
| Sewage sludge | 5 | 75 | 3.75 | 0.4 | 15 |
| Concentrated sewage sludge | 10 | 75 | 7.5 | 0.4 | 30 |
| Food waste | 10 | 80 | | 0.5-0.6 | |

will be produced, of which 22.146 Mt would be organic waste. This amount of organic waste would have an annual biomethane generation potential of $478.36 \times 10^6$ to $1137.44 \times 10^6$ m$^3$.

In section 3.2, it was estimated that the residential sector would consume $1293.7 \times 10^6$ m$^3$ of natural gas by 2030. Therefore, the potential for generating biomethane from organic waste could supply between 37 and 88% of the natural gas consumption in the medium term.

Regarding wastewater sludge, target 6.3 of the Sustainable Development Goals (SDG) of the 2030 Agenda aims to halve the proportion of untreated wastewater discharged into bodies of water. In Mexico, 4357.56 ´ $10^6$ m$^3$ of household wastewater was produced in 2020, of which only 2543.65 ´ $10^6$ m$^3$ (58.4%) were safely treated (UN-Habitat/WHO, 2021).

During 2016, there were 3516 wastewater treatment plants, but only 72% were active, of which 18.32% reused some volume of water. Even though just one in four treatment plants is inactive, they represent 10% of the treatment capacity. This means that most inactive plants have low treatment capacity and they usually belong to small municipalities (Cáñez-Cota, 2022).

Considering a conversion factor of 0.000096 t of sludge for each cubic meter of municipal wastewater (Rojas and Mendoza, 2012), in 2020, the treated water in Mexico would have the potential to generate 242 975.5 t of sludge. The numerical value of sludge obtained is multiplied by one thousand to convert it to kilograms, then multiplied by 3.75% to obtain the sludge volume (SV) in kilograms, and, finally, the result is multiplied by 0.4 to obtain cubic meters of biomethane, obtaining a value of $3.64 \times 10^6$ m$^3$ of $CH_4$.

To obtain the potential of biomethane production by 2030, the value obtained from 2020 is multiplied by 1.095673851 (the population increase factor between 2020 and 2030), and the result is multiplied by 1.36 to consider the goal of the 2030 Agenda to halve the proportion of wastewater without treatment, obtaining a value of $5.43 \times 10^6$ m$^3$ of biomethane, which could contribute to cover 0.42% of the near future demand of natural gas for residential use.

Mexico requires investments, both centralized and decentralized, in wastewater transportation and treatment systems to minimize direct discharges into the environment and to guarantee that the collected flows are adequately treated before being dumped or reused. Thus, a shift towards a circular economy in which wastewater is considered a valuable resource will be promoted (UN Habitat/WHO, 2021).

## 4. Conclusions

This study's proposal has allowed us to explore how the behavior of the population and its growth would affect the generation of carbon emissions derived from daily activities. The resulting data show that in a business-as-usual scenario, there is a direct relationship between population growth in Mexico and carbon emissions, as other studies have shown for different regions of the world (Casey and Galor, 2017; O'Neill et al., 2020). Also, this study recognizes particularly important issues such as a high dependence on biomass as an energy source for heat and food preparation, and fuel whose high energy content is not used efficiently, causing high production of carbon emissions, as well as the growing trend of mobility by motorcycles, low-cost vehicles with poor environmental regulation will continue to affect the current lack of reliable mass transportation systems in many of the country's cities. This will make it possible for future work to explore different action scenarios where the general population will be involved as part of the solution and to find possible entrepreneurial opportunities. These circumstances would have to be motivated by more efficient public policies giving priority to new sustainable infrastructure projects.

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