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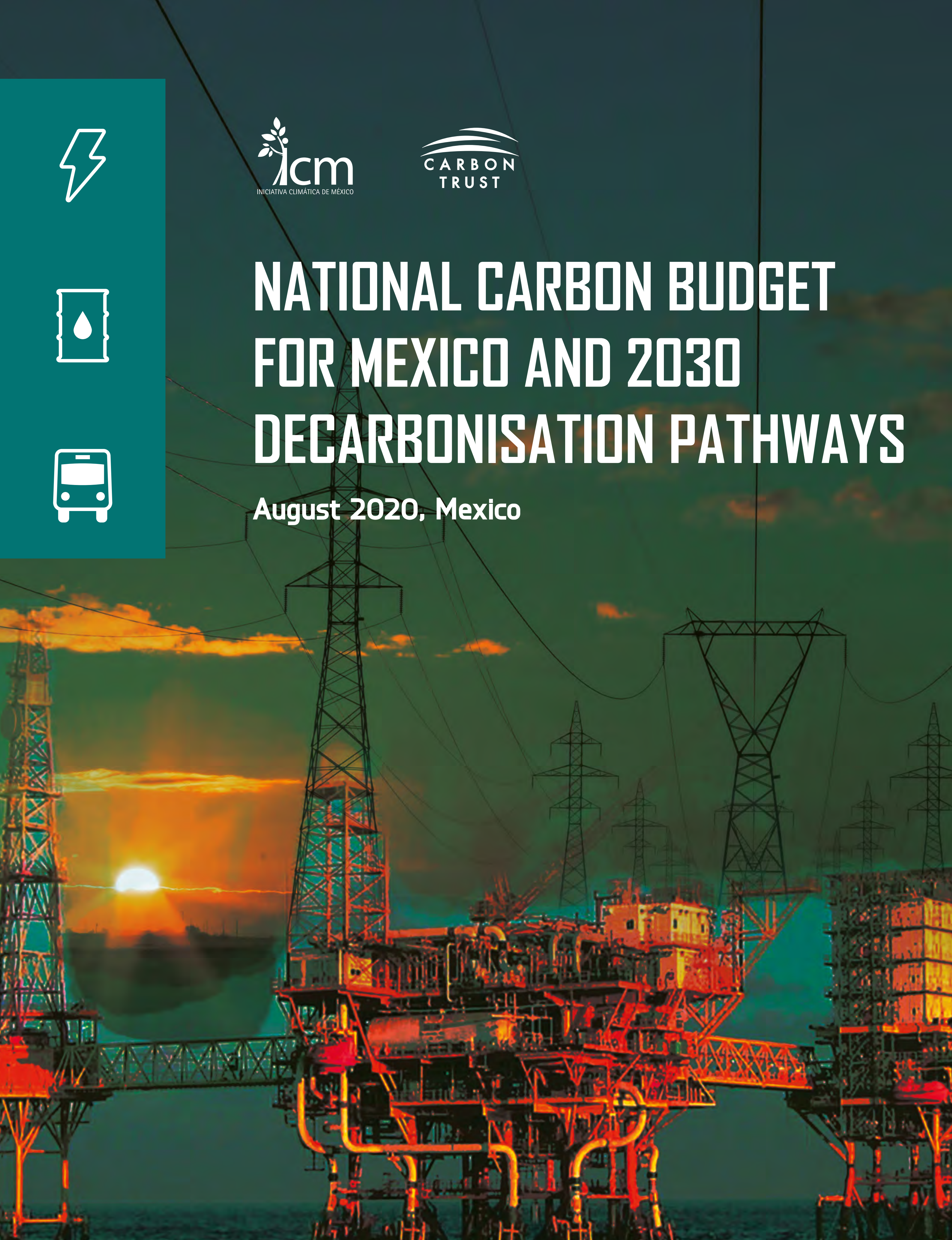
NATIONAL CARBON BUDGET FOR MEXICO AND 2030 DECARBONISATION PATHWAYS

August 2020, Mexico



NATIONAL CARBON BUDGET FOR MEXICO AND 2030 DECARBONISATION PATHWAYS

August 2020, First Edition. Mexico City, Mexico

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Cite as: Sierra Brozon, L., Jano Ito, M., Olea Tinoco, F., Ruiz Vilar, A., Islas Cortés, I. (2020) "National Carbon Budget for Mexico and 2030 Decarbonisation Pathways" Mexico City

UK PACT

Publication prepared as part of the 2030 Sectoral Decarbonisation Plans, a project implemented by Iniciativa Climática de México (ICM) in alliance with the Carbon Trust and the World Resources Institute (WRI) Mexico, supported by the United Kingdom Partnering for Accelerated Climate Transitions (UK PACT) Programme. The contents of this document are the responsibility of the authors and do not necessarily reflect the views of these organisations or the UK PACT Programme.

AUTHORING ORGANISATIONS

Iniciativa Climática de México (ICM)

As a non-profit, tax exempt organization devoted to reducing emissions of greenhouse gases and compounds, ICM focuses on climate mitigation policy, decarbonisation of the energy matrix, and sustainable and low carbon transportation. ICM works to enable the public policy, technical, financial and political conditions to increase Mexico's mitigation ambition and strengthen implementation capacities with the aim to achieve and surpass the mitigation goals stated in the General Law on Climate Change and the Mexican Nationally Determined Contribution (NDC), to support global efforts to hold the increase in the global average temperature to well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. ICM is part of international coalitions to improve accountability and transparency in the implementation of the Mexican NDC.

Carbon Trust

The Carbon Trust is a not-for-dividend company with the mission to accelerate the move to a sustainable, low carbon economy. We provide specialist support to business and the public sector to help cut carbon emissions, save energy, and commercialise low carbon technologies. By stimulating low carbon action, we contribute to key goals of lower carbon emissions, the development of low carbon businesses, increased energy security and job creation. Our approach and services are based on 18 years of experience in providing specialist support to business to help cut their environmental impacts, save energy, and commercialise low carbon technologies. The Carbon Trust has extensive experience developing and updating NDCs and creating decarbonisation strategies in Latin American countries, as well as experience in developing and evaluating energy policies, incentive mechanisms, financial instruments and developing emissions scenarios across the world. We have 215 experts working around the world from offices in the UK, Mexico, the Netherlands, USA, South Africa, China, Singapore, and Brazil.

World Resources Intitute (WRI) México

WRI is a global research organization that spans more than 60 countries, with offices in the United States, China, India, Brazil, Indonesia and more. Its more than 1,000 experts and staff work closely with leaders to turn big ideas into action to sustain our natural resources —the foundation of economic opportunity and human well-being. Its work focuses on seven critical issues at the intersection of environment and development: climate, energy, food, forests, water, cities and the ocean. WRI mission is to move human society to live in ways that protect Earth's environment and its capacity to provide for the needs and aspirations of current and future generations. It measures its success through real change on the ground. The approach involves three essential steps: Count It, Change It, and Scale It. Count It. We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Its rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. Change It. It uses our research to influence government policies, business strategies, and civil society action. WRI tests projects with communities, companies, and government agencies to build a strong evidence base. Scale It. Once tested, WRI works with partners to adopt and expand its efforts regionally and globally. WRI engages with decision-makers to carry out its ideas and elevate its impact.

ACKNOWLEDGEMENTS

This publication was produced by Iniciativa Climática de México (ICM) in alliance with the Carbon Trust and the World Resources Institute (WRI) Mexico, as part of the 2030 Sectoral Decarbonisation Plans, a project supported by the United Kingdom Partnering for Accelerated Climate Transitions (UK PACT) Programme. The objective of the project is to develop decarbonisation pathways (for electricity, oil and gas, and transport) under the framework of a preliminary deep decarbonised 1.5°C and 2°C-based 2050 National Carbon Budget, providing support for decision making on policy design and the definition of implementation pathways for Mexico to increase mitigation ambition, comply with the Paris Agreement commitments, foster low-carbon and resilient development, and alleviate poverty.

This publication would not have been possible without the support, guidance, and knowledge of the UK PACT and the Department for Business, Energy and Industrial Strategy (BEIS) team in Mexico and in the UK, specially to Gabriela Rodríguez, Maite Salinas, Adriana Ochoa and Yvonne Davidis at the UK Embassy in Mexico.

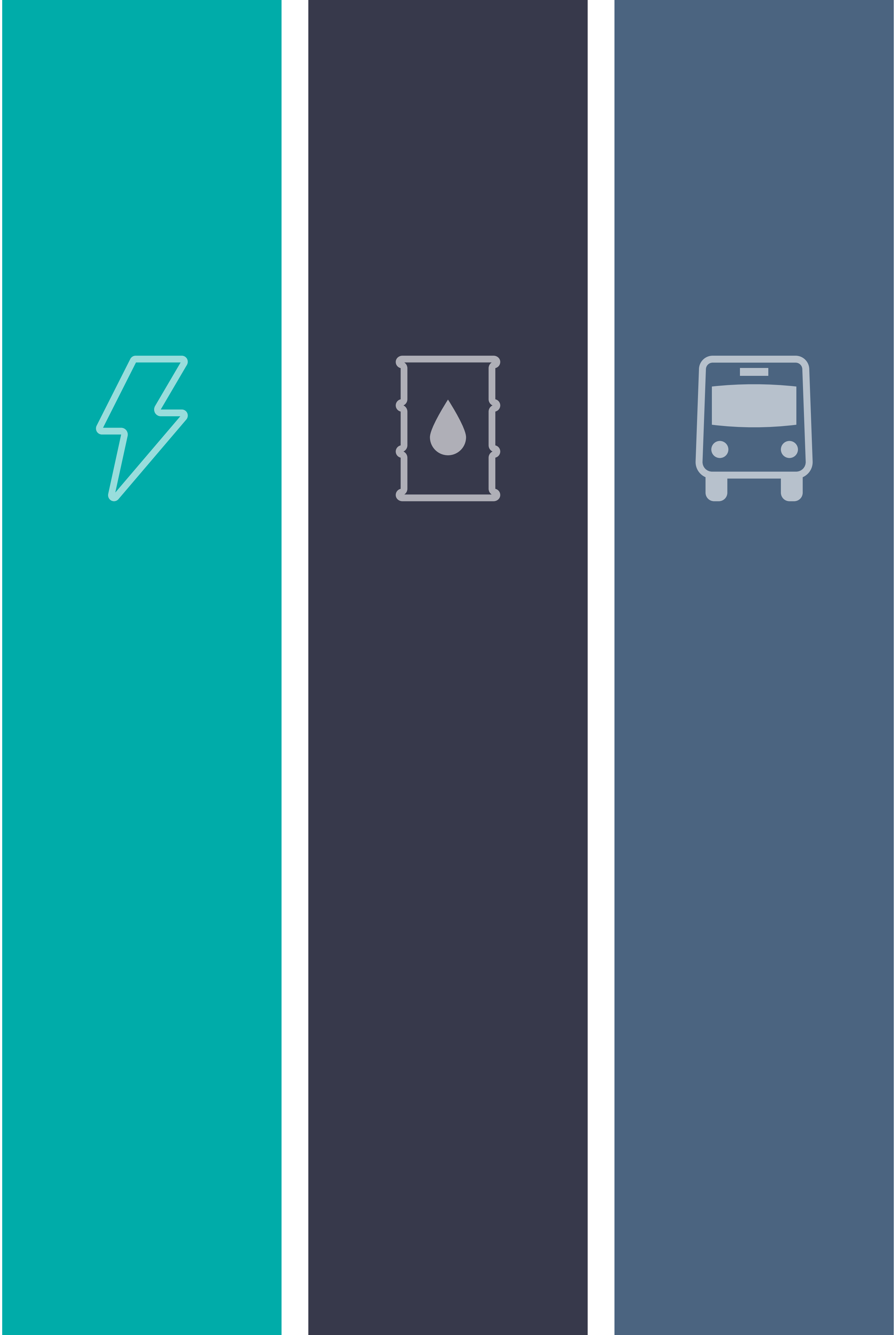
Special recognition goes to the Centro Mario Molina for their analysis of the oil and gas sector. This work would not have been possible without their expertise and contribution.

Our gratitude to the leaders of each of our organisations for their trust and institutional support: Adrián Fernández Bremauntz, ICM; Simon Retallack, Carbon Trust; and Adriana de Almeida Lobo, WRI Mexico. Special thanks to all our colleagues at ICM, WRI Mexico and Carbon Trust involved in the discussions and/or activities that resulted in this document. Special thanks to Horacio Limón Vidal and Fernando C. Vidal Ortega for their support in the development of this project.

TABLE OF CONTENTS

Figures

Tables



1.

EXECUTIVE SUMMARY

The Paris Agreement represented a significant step towards an international regime that can tackle climate change and its negative impacts. In this agreement, countries committed to limit the increase in the average surface temperature of the planet "well-below" 2°C, and to "pursue efforts" to keep warming to 1.5°C based on pre-industrial levels. As part of this commitment, countries presented nationally determined contributions (NDCs), which included actions to mitigate greenhouse gases (GHGs) emissions. However, the definition of the required mitigation contributions from every nation for achieving the Paris Agreement's long-term goals is a complex task that is being assessed and should be fully addressed.

As an initial breakthrough towards understanding the effects of cumulative carbon emissions on climate change (increase in average global temperature), climate scientists have found a linear relationship between these two physical phenomena. This breakthrough has significant implications for policymakers since it is possible to determine the emissions reductions required to avoid a dangerous temperature increase of the Planet. This information represents a critical benchmark to set national emissions pledges according to the long-term mitigation goals.

This report offers an alternative to existing modelling emissions scenarios and an initial effort to increase the clarity and ambition for the development of emission reduction scenarios for Mexico to achieve the Paris Agreement temperature targets. This report estimates a 1.5°C National Carbon Budget and analyses mitigation measures and technologies for three critical sectors of the Mexican economy: electricity, oil and gas, and transportation. This information aims at strengthening Mexico's planning and decision-making to enable an increase in its climate mitigation ambitions.

After this summary and introduction (sections 1 and 2, respectively), section 3 undertakes the carbon budget concept, its limitations, and the climate science that supports it. This section also provides an example of the United Kingdom (UK) policy approach, using a carbon budget as part of its climate policy.

Section 4 is devoted to the description of the **methodology** used to estimate the Mexican National Carbon Budget for the 2°C and 1.5°C targets. For both targets, the historical contribution of Mexico for the 1850 to 2014 period was 1.39% of cumulative global emissions. Based on this, Mexico's carbon budget to limit global mean temperature to 2°C and 1.5°C is 22.2 $GtCO_2e$ and 8.89 $GtCO_2e$, respectively, for the 2019 to 2100 period. Based on a top-down approach, an initial sectoral allocation is estimated: 19% for electricity generation, 10% for the oil and gas sector and 22% for the transport sector.

Section 5 presents an analysis of the **electricity sector**, examining first its current context, and then analysing a baseline and the decarbonisation scenarios. The baseline scenario (business as usual, BAU) served as a benchmark while the decarbonisation scenario portrays the necessary emissions reductions in the electricity sector to achieve the 1.5°C target. Next, the modelling was divided into two periods, from 2019 to 2030, considering existing mitigation measures; and 2030 to 2050, addressing technologies for deeper decarbonisation. This sector was analysed using an optimisation model for the electricity sector of Mexico (PLEXOS).

The baseline scenario shows that the electric power sector's GHG emissions increase from 149 million tonnes of CO_2e in 2019 to 160 million tonnes of CO_2e in 2030. The decarbonisation trajectory, presented in Figure i, requires the reduction of emissions to 68 million tonnes of CO_2e in 2030. On this path, the participation of natural gas (combined cycle utilities) should be reduced from 43% in 2019 to 37% in 2030. Additionally, the wind should generate 93.9 TWh (18% of total generation) in 2030, while solar PV 83.2 TWh (16% of total generation). The distributed generation should increase from 2 TWh (1% in total generation) in 2019 to 20.8 TWh in 2030 (4% of total generation).

In the decarbonisation pathway for the period 2030 to 2050, natural gas combined cycles must reduce their participation from 52% in 2023 to 14% in 2050. Meanwhile, the required electricity to cope with the increasing demand must be generated in part by wind and solar PV, which could account for 27% each by 2050. This electricity system can reduce greenhouse gas emissions to 44 MtCO2e by 2050, achieving the required carbon budget.

Finally, the estimation of the marginal abatement cost curve (MACC) was crucial in the development of the decarbonisation and baseline scenario (Figure ii). As observed, geothermal, wind and solar PV generation technologies have negative costs, indicating that the investment in these technologies can be recovered and are cost-effective. Additionally, while storage or distributed generation still have high costs, their mitigation potential could be higher as their technological development advances rapidly.

Section 6 is dedicated to the **oil and gas sector**, analysing its historical development, current situation and the main processes that take place along its value chain. The analysis of the sector's development path and its associated GHG emissions is based on three scenarios: government projections scenario (CNH); the oil and gas natural resources depletion; and the decarbonisation scenario grounded on GHG emission path for 1.5°C.

For the CNH scenario, after 2024, greenhouse gas emissions increase above the decarbonisation scenario levels because of the increment in oil and gas production from unconventional resources. The cumulative emissions for the CNH scenario correspond to 524 million tonnes of CO_2e (2019 to 2030 period) exceeding the required carbon budget by 24 million tonnes of CO_2e. In the case of the depletion scenario, the natural depletion trend and production of oil and natural gas has a significant contribution to mitigation GHG emission. For the decarbonisation scenario, the resulting cumulative emissions between 2019 and 2030 is 380 million tonnes of CO_2e. The mean trajectory between the CNH scenario and the depletion scenario has an estimated cumulative emission of 452 tonnes of CO_2e for 2019-2030 (Figure iii). The 2050

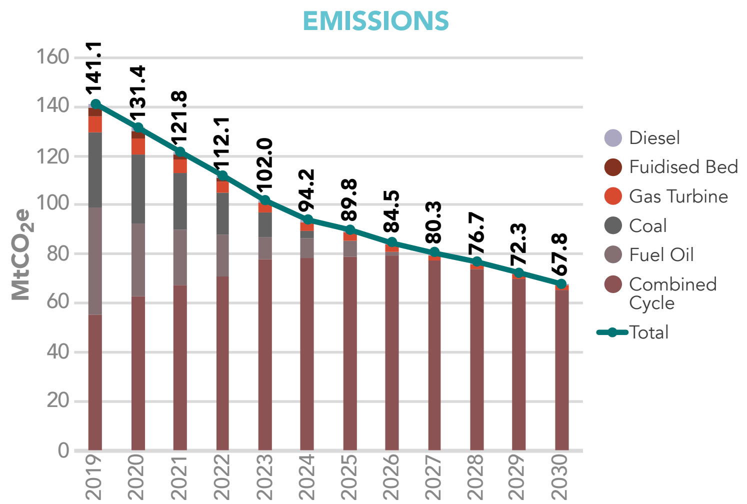


Figure i. Annual emissions of GHG for the electricity decarbonisation scenario (MtCO2e)

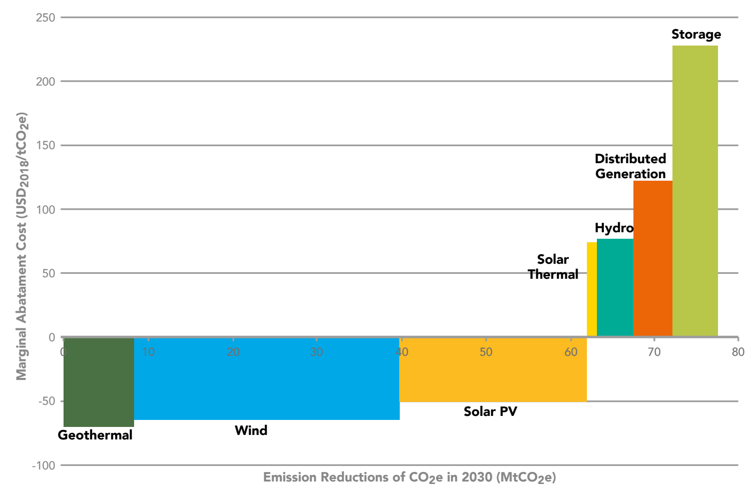


Figure ii. Marginal abatement cost curve for the electricity sector

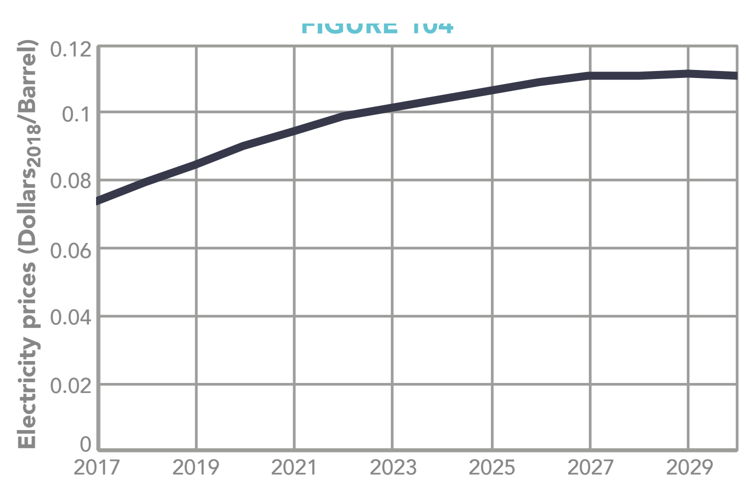


Figure iii. Decarbonisation scenarios for the oil and gas sector

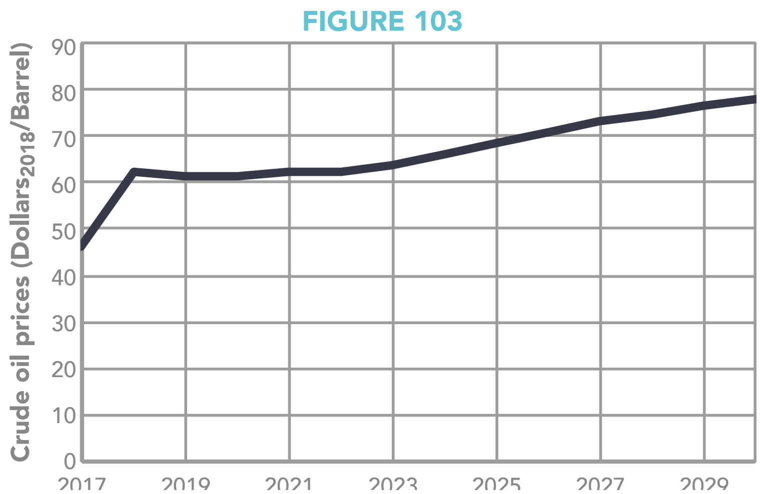


Figure iv. Marginal abatement cost curve for the oil and gas industry

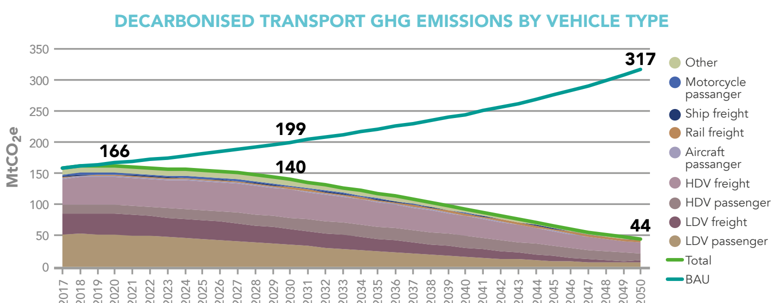


Figure v. GHG emissions by vehicle type for the transport sector

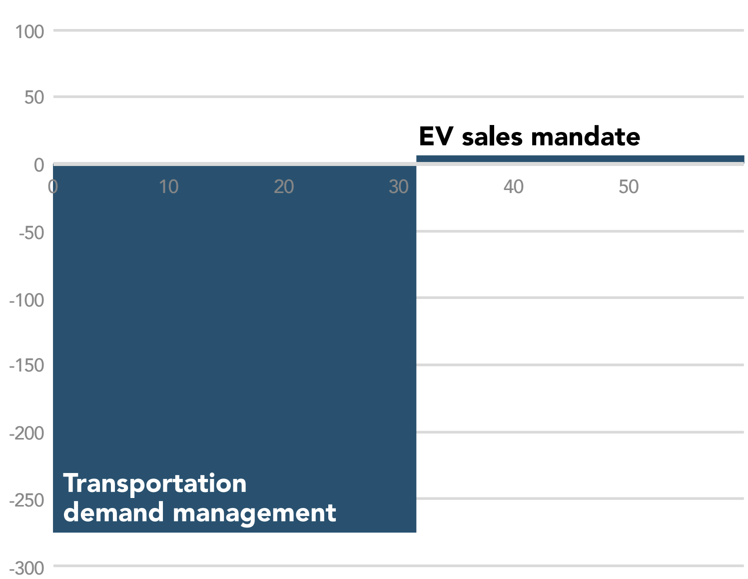


Figure vi. Marginal abatement cost curve by 2050 for the transport sector

decarbonisation pathway requires that unconventional resources remain unburned. Moreover, the current development trend of electric vehicles could increase their penetration, reducing the demand for oil refining.

The analysis of GHG emission reduction potentials included several economic assumptions, taking a comprehensive bottom-up engineering approach. The mitigation technologies and measures analysed were: natural gas recovery and compression in marine platforms, improvement in the efficiency of flaring, enhance oil recovery with and without carbon capture and storage (CCS) technology, replacement of wet seals with dry seals in centrifugal compressors, methane leak detection and repair, installation of vapour recovery units in storage tanks, energy efficiency in gas processing boilers and cogeneration. In the case of oil refining, different mitigation measures included thermal integration, economisers, fouling reduction, heat recovery from regenerators, air excess control, air preheating, and vacuum pumps. The estimated mitigation potential is 25.3 million tonnes of CO_2e per year in 2030 (Figure iv).

The opportunities for Mexico's oil and gas sector decarbonisation are significant, and several of the mitigation measures can also deliver substantial economic benefits. Methane fugitive emissions reductions are also fundamental for the mitigation efforts, and the existing regulations should be encouraged and enforced. In addition to this, the rational and efficient use of energy within PEMEX facilities is crucial to reduce greenhouse gas emissions, as cogeneration could provide a cost-effective solution.

Section 7 focuses on the **transport sector** decarbonisation, which has the highest emissions among sectors, as it represents 23% of Mexico's GHG emissions. Additionally, transportation emissions in Mexico grow faster than any other sector in absolute terms, climbing at an annual rate of 2.1% per year from 2005 to 2015 (SEMARNAT, 2017). The sector has emissions dependent on three main activity levers: demand for travel, modal distribution, and energy/emissions. Additional conditions and considerations that affect the sector are prices and availability of fuels and other resources; policy and regulatory framework; sociodemographic and cultural effects; financing options for infrastructure development and technological alternatives. For this sector, the proposed decarbonisation pathway results in sector GHG emissions of 140 $MtCO_2e$ by 2030 (30% below BAU), and 44 $MtCO_2e$ by 2050 (86% below BAU) (Figure v).

The decarbonisation pathway is approached through the Avoid-Shift-Improve framework. The strategies included avoiding emissions through the reduction in demand for motorised travel and control rampant road transport growth with transport demand management measures. Shift to low/zero-carbon modes of transport, increasing trips efficiency for transportation systems and non-motorised travel like cycling, and walking. These strategies require further development of urban public transportation nationally, shifting freight and long-range travel to railways, promoting active mobility (walking and cycling) and the research into new mobility services. Improve the energy efficiency of all transport modes through direct policies to strengthen fuel economy standards, eliminate ineffective and non-progressive fossil-fuel subsidies, develop electric mobility to ensure rapid penetration of zero-emission passenger vehicles. There are new technologies that require further development, like zero-carbon options for heavy-duty road transport and fully electrified rail services. Aviation and shipping require a 1.5°C-compatible long-term vision, along with the development of options and technology. In the meantime, demand management is critical for curbing growth.

A comprehensive Avoid-Shift-Improve approach to decarbonisation will result in more significant abatement than any focus on specific technologies. As a result, it could be possible to reduce the existing vehicle fleet by 8% and 40% in 2030 and 2050, respectively. For these years, the penetration of hybrid vehicles could reach 23% and 91%, respectively. Energy efficiency could be increased by 10% and 15%; with emission reductions of 66% and 80% in comparison to the baseline scenario. Mitigation measures can help to reach the 2°C scenario but would not be enough to reach the 1.5°C scenario. The following figure presents the marginal abatement cost curve for the transport sector (Figure vi).

Actions will be needed in all three areas, from long-term land-use planning (avoid), to inducing and implementing public transportation and cycling (shift), to fuelling vehicles cleanly and efficiently (improve), to decarbonise the sector. Although these opportunities are all within reach, they will require serious policy commitments and will need to overcome a legacy of dependence on and planning around carbon-intensive travel.

In conclusion, based on the decarbonisation pathways for the electricity, oil and gas and transport sectors, it is technically and economically feasible for Mexico's GHG emissions to be aligned with a trajectory limited to a 1.5°C temperature increase. ◆

2. INTRODUCTION

Mexico has achieved remarkable progress in its climate change legal and institutional framework, including the submission of a nationally determined contribution (NDC), the Mid-Century Strategy, and the recent Climate Change Law reform that incorporates the Paris Agreement's targets including the efforts to hold the increase of the global average temperature to well below 2°C and pursuing efforts to limit the temperature increase to 1.5°C. However, the latest IPCC Special Report on Global Warming of 1.5°C highlights the importance of increasing ambition on climate action at the national level, as this increase seriously threatens sustainable development and the efforts to eradicate poverty.

Despite the legal advances in Mexico, key challenges on climate action still need to be addressed to limit the country's emissions below the 1.5°C trajectory. The domestic NDC's conditional and non-conditional goals are not consistent with the 1.5°C temperature limit, and the compliance of the national and international mitigation goals has been insufficient. Moreover, the country has not developed the policy instruments required to set the emission reductions needed by 2050 and the subsequent sectoral decarbonisation plans. This study does not aim to address all these challenges, but it represents an essential effort towards the definition of science-based climate targets and proves that a 1.5°C-trajectory is technically and economically feasible.

This effort was possible due to the generous support of the UK Partnering for Accelerated Climate Transitions (UK PACT) Programme with the objective to introduce the concept of carbon budget together with its estimations at the national and sectoral levels. Grounded on the evidence of the impact of greenhouse gas (GHG) emissions on the global climate system, carbon budgets are an innovative concept and measurement that serve as a powerful and straightforward metric to establish emissions limits, connecting the climate science and climate policy. Some countries, such as the United Kingdom, have already adopted carbon budgets in their policy targets.

The following work focuses on the methodology used to estimate the Mexican national carbon budget for the 2°C and 1.5°C targets. These initial sections, led by ICM and Carbon Trust, conclude with an initial estimation of the sectorial allocation. That is the remaining GHG emissions allowed for a 2°C and 1.5°C temperature increase limit. Then, three sectors (electricity, oil and gas, transport) are analysed, decarbonisation routes developed, and marginal abatement costs estimated for the mitigation measures. The electricity sector (Section 5) was analysed by Iniciativa Climática de México (ICM), the Centro Mario Molina (CMM) contributed with the analysis of the oil and gas sector (Section 6), and the transport sector was analysed by the World Resources Institute (WRI) Mexico (Section 7).

The results provide critical insights to understand technical needs for compliance with both Mexico's NDC and the General Climate Change Law. Based on these outputs, the study analyses each sector's pathway and the main actions for achieving long term mitigation goals. The carbon budget provides a robust methodological approach to define national and sectoral mitigation targets and pathways. The results show the technical feasibility and cost-effectiveness of driving sectors' decarbonisation pathways aligned to 1.5°C scenario. Importantly, the outputs reveal that the required measures can deliver relevant co-benefits, such as improving air quality and human health. This analysis thus offers technical insights that can inform the decision-making in climate policy planning. This exercise is the first for Mexico based on the carbon budget; thereby, future efforts should undertake similar analysis for other sectors, such as agriculture, forestry and other land use (AFOLU), and industry. ◆

KEY POINTS

CLIMATE SCIENCE AND THE CONCEPT OF THE CARBON BUDGET

- Carbon budget: the finite total amount of CO_2 that can be emitted into the atmosphere by human activities while still holding global warming to a desired temperature limit.

- In context with the IPCC definition of the necessity of keeping the global temperature increase below 1.5°C or 2°C, the carbon budget could be seen as "a fixed amount of carbon that humanity can emit between now and 2050 to avoid disastrous climate-related events".

- Any global temperature target reduction implies a limited CO_2 "budget": a finite amount of CO_2 allowed to emit to stay below a given target, irrespective of the scenario that leads to those emissions.

- Carbon budgets depend on international negotiations and can have different approaches. This study focuses on the allocation of a carbon budget considering GHG emission shares (historical cumulative emissions by country divided by the historical cumulative global emissions).

- The UK is a successful example of how carbon budgets can contribute to achieve more ambitious climate targets. It has established five legally binding 5-year carbon budgets to reach the net zero emissions goal by 2050 and it has already complied with the first three.

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3. CLIMATE SCIENCE AND THE CONCEPT OF THE CARBON BUDGET

Section authored by
ICM and Carbon Trust

3.1. GEOPHYSICAL RELATION BETWEEN GLOBAL TEMPERATURE INCREASE AND ACCUMULATED CO2 EMISSIONS

Science has proved that the increase in maximum global mean temperature as a result of CO_2 emissions is nearly proportional to the total cumulative carbon emissions (MacDougall, Zickfeld, Knutti, & Matthews, 2015; Knutti & Rogelj, 2015). This relationship has derived in efforts to establish common and mutually agreed emission budgets that facilitate designing and planning climate policies and actions. These budgets, typically known as carbon budgets are compatible with limiting warming to below the 1.5 and 2°C temperature thresholds.

In the aim of understanding the global warming phenomena, scientists have concluded that CO_2 is the largest contributor to the total warming both in the past and future, and that most of the CO_2 emitted stays in the atmosphere for centuries (Huber & Knutti, 2012). From the radiative forcing point of view, further warming may be avoided if emissions were stopped today and could be reversed if CO_2 was removed actively from the atmosphere (Knutti & Rogelj, 2015). Additional future warming is therefore, largely determined by our future emissions (Davis, Caldeira, & Matthews, 2010; Matthews & Solomon, 2013).

Moreover, scientists have identified that even if emissions of a certain gas were eliminated entirely, the radiative forcing would decrease on a timescale determined by the respective lifetime of the gas in the atmosphere. For CO_2, the timescales on which it is removed from the atmosphere by the ocean and biosphere are similar to those for ocean heat uptake (Knutti & Rogelj, 2015). The decreasing radiative forcing compensates the consummation of the warming, which leads to keeping temperature nearly constant for centuries if CO_2 emissions are stopped (Friedlingstein, et al., 2011; Frölicher, Winton, & Sarmiento, 2014; Gillett, Arora, Matthews, & Allen, 2013; Matthews & Caldeira, 2008; Plattner, et al., 2008; Solomon, Plattner, Knutti, & Friedlingstein, 2009). However, sea level rises due to the ocean heat uptake and melting of large ice sheets will continue to happen for millennia even after surface temperatures are stabilized (IPCC, 2013, pp. 1102-1119; IPCC, 2013, pp. 1179-1189; Solomon, et al., 2010). In summary, Climate Change is irreversible in the sense that many of its effects will persist even if CO_2 emissions are stopped. Our emissions commit many future generations to changes and challenges we do not know how to deal with today, and potentially to impacts we may not even be aware of today (Knutti & Rogelj, 2015).

To better understand the relationship between GHG emission reductions and the warming of the Earth, it is necessary to define the concept of **climate sensitivity**, which measures the response that the climate system has to a constant radiative forcing. The above means the degree of increase in the global average temperature in response to a variation, among other variables, of the atmospheric concentration of carbon dioxide.

The definition of a carbon budget is based on the Transient Climate Response to Cumulative Emissions (TCRE) (Rogelj et al., 2019), which defines the relationship between climate sensitivity and the carbon budget, i.e.

the change in the average surface temperature per unit of total cumulative carbon dioxide in the atmosphere, the primary cause of climate change (cumulative CO_2 emissions) (MacDougall, 2016). TCRE is defined as the global average surface temperature change per unit of total cumulative anthropogenic CO_2 emissions, typically 1,000 Petagrams of Carbon (PgC). In the IPCC AR5 Working Group I (WGI) report, TCRE was assessed to be 'likely' (that is, with greater than 66% probability) to remain between 0.8 to 2.5 °C per 1,000 PgC, for cumulative CO_2 emissions less than about 2,000 PgC and until the time at which temperature peaks (Rogelj, et al., 2016).

The linearity argument and the range for TCRE are based on a range of models as well as observed GHG attributable warming due to historical emissions (IPCC 2013a, section 12.5.4). Even with large variations in the pathway of CO_2 emissions during the twenty-first century, the transient temperature paths as a function of cumulative CO_2 emissions are very similar. Once all pathways achieve the same end-of-century cumulative CO_2 emissions, the temperature projections are virtually identical (Rogelj, et al., 2016). Additionally, according to the IPCC (2014) it considers physical and carbon cycle feedbacks and uncertainties, but not additional feedbacks associated for example with the release of methane hydrates or large amount of carbon from permafrost. Mathematically, Matthews et al. (2009) expressed this metric as a product of two quantities:

$$\mathrm{CCR}^{1} = \frac{\Delta T}{E_T} = \left(\frac{\Delta T}{\Delta C_A}\right) * \left(\frac{\Delta C_A}{E_t}\right)$$

Where t is time, ΔT is the change in the global mean surface air temperature, ΔC_a is the change in the atmospheric carbon level, and E is the cumulative carbon emissions. With the former expression in mind, it is possible to comprehend the value of the TCRE and its direct relevance to current climate policy as the approximate linearity between warming and cumulative emissions that leads to a remaining carbon budget with any given warming threshold, including the 1.5°C and 2°C thresholds of the Paris Agreement long-term temperature goal (Millar, R.J. and Friedlingstein, P., 2018).

From the linearity argument we can determine that every ton of CO_2 adds about the same amount of warming, no matter when and where it is emitted. Therefore, any global temperature target reduction implies a limited CO_2 "budget": a finite amount of CO_2 allowed to emit to stay below a given target, irrespective of the scenario that leads to those emissions.

3.2. MODELLING OF CLIMATE AND SOCIETAL ACTIVITIES (INTEGRATED ASSESSMENT MODELS, IAMS)

When it comes to measure and analyse the feasibility of climate change mitigation strategies, the most applied tools are integrated assessment models (IAMs). IAMs, according to van Vuuren et al. (2011), try to explain the complex relations between environmental, social and economic factors that affect future climate change. IAMs also give insight into the possibility to achieve medium and long-term targets based on mitigation actions planned in different regions (L. Clarke et al., 2009).

The IPCC mentions that these models are also characterized by a dynamic representation of coupled systems, including energy, land, agricultural, economic and climate systems (Weyant, 2017). They are global and through their use it is possible to identify the consistency of different pathways with long-term goals of limiting warming to specific levels (IPCC, 2018).

Geels et al. (2016) supports the previous idea mentioning, that the analytical strengths of IAMs are the capacity to mix scientific, engineering, economic information and future paths (such as: demographic dynamics, economic performance and interactions within industrial sectors). Other strengths are the ability to create projections at an aggregate global level and include different policy scenarios (Geels et al., 2016). One example in the electricity sector is made by Foley et al. (2016), who used a new carbon cycle model emulator, GENIEem, in an IAM setting, finding that in a scenario where 90% of the electricity sector is decarbonised, there is a possibility to maintain by 2100 an increase of temperature of 2°C.

For the 1.5°C trajectory, the reference models used to estimate these pathways are presented in *Section 2 Supplementary Material of the Special Report Global Warming 1.5°C*. Specifically, these models are: the Asia-Pacific Integrated Model, the Global Change Assessment Model Version 4.0, Model for Energy Supply Strategy Alternatives and their General Environmental Impact-Global Biosphere Management, Regional Model of Investments and Development –Model of Agricultural Production and its impacts on the Environment and the World Induced Technical Change Hybrid-Global Biosphere Management.

1 Carbon Climate Response later known as TCRE

3.3. THE CARBON BUDGET, ITS DEFINITION, CHARACTERISTICS AND LIMITATIONS

The improvement of the tools for the analysis of the impact of human activities on the climate allows to establish the concept of the carbon budget. According to Rogelj et al. (2019), carbon budgets are defined "as the finite total amount of CO_2 that can be emitted into the atmosphere by human activities while still holding global warming to a desired temperature limit". Based on the established definition, the carbon budget is helpful to summarise the climate challenge and to explain the importance of net zero emissions (Glen P. Peters, 2018).

A carbon budget represents numerically, the maximum number of CO_2 emissions that could be released in a given period to stabilise the global temperature within a defined range. The methodology to define a carbon budget is aligned to the latest IPCC report which outlines the necessary conditions to keep the increase in global temperatures below 1.5°C or 2°C.

A carbon budget is based on the argument that every ton of CO_2 adds about the same amount of warming, no matter when and where it is emitted. Thus, a carbon budget aims to set a finite amount of CO_2 allowed to emit to stay below a given target, irrespective of the scenario that leads to those emissions. The term "carbon budget" emerged because of the similarity to a financial budget. Based on the above, we can define a carbon budget as a fixed amount of carbon that humanity can emit between now and 2050 to avoid disastrous climate related events —this facilitates the design and implementation of decarbonisation pathways.

The establishment of national carbon budgets primarily depends on the state of international negotiations and the allocation agreed within them. The issue of allocation is not simple and there is a debate on taking a 'tragedy of the commons' or a 'collective action dilemma' approach. The governance of shared natural resources has also been viewed from a bottom-up perspective so that individual nations can propose their shares of the global carbon budget (Raupach et al, 2014).

Several methods have been proposed and used to allocate carbon budgets among countries relying on quantifiable metrics (Raupach et al, 2014). As mentioned by Gignac and Matthews (2015), the allocation of carbon budgets follows two extremes. On the one side, carbon budget allocations can be based on current emissions shares of GHG emissions, while on the other, a per capita emissions objective could be defined. Within the latter mentioned frameworks, there have been several allocation proposals that consider several factors such as equity, the specific financial and mitigation capacities of countries, the political and social feasibility, and environmental balance and effectiveness (Gignac and Matthews, 2015).

The allocation of a carbon budget considering GHG emission shares (historical cumulative emissions by country divided by the historical cumulative global emissions) is simple and could use historical data estimated by the Potsdam Institute for Climate Impact Research (PIK). The consideration of per capita emissions has been traditionally used through the contraction and convergence method developed by the Global Commons Institute (Meyer, 2000). This method consists of a two-stage process that sets a per capita emissions objective for a given year to be achieved by all countries or regions. The rationale behind this method relies on an initial increase or decrease in emissions (depending on the per capita emissions of the specific country) and their convergence to the established per capita goal.

In this work, a historical perspective was taken because of its simplicity and the availability of information to estimate historical cumulative emissions. Moreover, this is an approach that considers equity in the historical contribution of countries to a common problem. While the contraction convergence approach takes into consideration inequities that gradually adjust, it does not take into consideration the historical responsibility of different countries. The issue of inequity and a just allocation of a carbon budget is complex and still requires a higher degree of analysis but given the scope of this work it was considered as adequate.

3.3.1. THE UK CARBON BUDGET APPROACH

The UK has achieved outstanding reductions in GHG emissions in the last decade. Between 2012 and 2016 the use of coal to generate electricity was reduced from 40% to 9%. In 2017, the UK achieved a 42% reduction in emissions compared to 1990 and provisional 2018 figures show reductions reached 44% relative to 1990 (CCC, 2019). The Climate Change Act (CCA), enacted in 2008 has been a significant milestone for the UK's climate policy. Under the CCA, the UK has set legally binding five-yearly carbon budgets, which mark staging posts on the way towards the net-zero goal by 2050. So far, the first five carbon budgets have been set down in legislation, covering the period 2008-2032. The political success and the reduction of emissions respond to the design of the CCA, that sets short and long-term goals, yet remains flexible to adjust to new evidence and progress accomplished. It is also important to mention the empowerment this law granted to the Committee on Climate Change (CCC), which acts as an independent body in charge of evaluating the country's progress and making recommendations to the government.

Strengths

- Carbon budgets are a useful guide for defining and characterizing the emissions pathways that limit warming to certain levels, such as 1.5/2 °C relative to pre-industrial levels.

- In the UK the carbon budgets are a legally binding instrument with long term goals. The Climate Change Council —an independent British body— is in charge of evaluating progress towards climate goals and thus has contributed to promoting transparency and credibility in the UK's climate policies. Having 5-year carbon budgets has facilitated progressing towards the 2050 goal, by having periodical reviews whilst having an opportunity to adjust policies and programmes to ensure the completion of the net zero goal.

- Furthermore, a carbon budget can improve consistency among different climate goals and policies, for instance by using the same baseline to create the emissions scenarios for 2050.

- To ensure that there is a steady progress towards the 2050 goal, the CCA created the Committee on Climate Change (CCC). The committee was set as an independent body assigned to recommend the maximum levels of emissions for each carbon budget to the government. In turn, the government must place a proposed budget to Parliament. The committee's advice must be based on wide-ranging evidence on costs and benefits of reducing emissions, including the implications of uncertainties emerging from future technology developments.

- Overall, between 1990 and 2017 the UK has reduced its emissions by 42%, has so far met the first and second carbon budget goals, and are well on their way to meet the third's (see figure 1) (CCC, 2019). This positions the UK as the leader of any other G7 nation in terms of emission reductions and growth in national income over this period (BEIS, 2018).

Limitations

- As any model, carbon budgets have a certain level of uncertainty. For example, the UK's carbon budgets account for the existing potential emissions reductions across sectors and the potential deployment of new technologies (i.e. electric vehicles, CCS); as well as other drivers such as barriers for implementation, economic and political changes, and consumer behaviours.

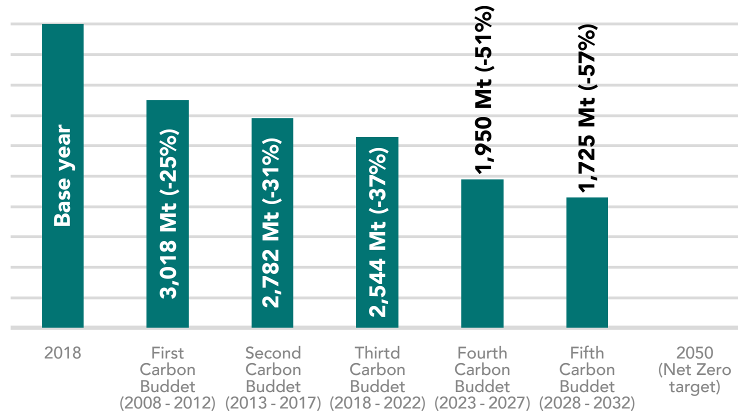

Figure 1. UK's Carbon Budgets targets.

Additionally, there is an important challenge on how to communicate these uncertainties as they are linked to the approach used to define the budget.

- Additionally, Rogelj et al. (2019) explain that, "decomposing the remaining carbon budget into its contributing factors allows one to identify a set of promising avenues for future research. An area of research that could advance this field is a closer look at TCRE. Future research is anticipated to narrow the range of best estimates of TCRE as well as to clarify the shape of the uncertainty distributions surrounding this value".

Drawing from publicly available information and academic literature, as well as interviews with experts, a series of recommendations excerpt from the UK climate policy experience aimed at helping decision makers shape the coming national climate change agenda in Mexico. Among the key findings and recommendations from this study are: 1) the CCA is characterized by having a long-term focus, which inhibits interest groups from promoting short-term measures or an approach that is not aligned with the act; 2) the CCA is highly focused on achieving goals through the usage of five-year carbon budgets, in which both the market and government intervention play a fundamental and complementary role; 3) the CCC is an independent body responsible for making recommendations to parliament. Due to its independence and its own budget provision, it has an influence on the long-term mitigation and adaptation plans in the UK; 4) Once a year, the CCC publishes a monitoring report that assesses whether policies have been enough to meet carbon budgets. The government is obliged to respond, which guarantees transparency and accountability. ◆

4. ESTIMATION OF A CARBON BUDGET FOR MEXICO[2]

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4.1. CONDITIONS TO ESTIMATE THE NATIONAL CARBON BUDGET

To estimate the carbon budget, the first step was to obtain a database consistent with the expected trajectory that would maintain the increase of the global mean temperature within the 2°C Paris Agreement threshold. The Working Group III[3] of the Intergovernmental Panel on Climate Change (IPCC) reviewed projection scenarios that resulted from several Integrated Assessment Models (IAMs) and compiled an official database from the International Institute for Applied System Analysis (IIASA) for the Fifth Assessment Report (AR5). The IIASA database comprises 31 models (sometimes in different versions) and 1,184 scenarios in total (IIASA, 2014). For this project, the RCP2.6[4] trajectory from the AR5 was used as reference.

This trajectory is characterised by the consideration of a peak in the radiative forcing[5] of ~3 Wm^{-2} (~490 ppm CO_2e) in 2050 and a decline to 2.6 Wm^{-2} by the end of 2100. Furthermore, the selected scenarios presented carbon dioxide and the equivalent carbon dioxide emissions projections from the models that are defined in the P1[6] scenarios[7] from the document *Technical Annex – Synthesis report on the aggregate effect of the intended nationally determined contributions* of the United Nations Framework Convention on Climate Change.

The P1 scenario was selected because of its assumption of immediate (e.g. as of 2010) global mitigation action, enough to achieve a least-cost emissions trajectory during the 21st century (UNFCC,

2 The methodology in this section was first developed from an analysis sponsored by GIZ CONECC with a document titled, ***Presupuestos de Carbono: Una oportunidad para ampliar la ambición climática del sector eléctrico***. It is important to acknowledge that this work only considered one sector, and with several iterations the ICM model was developed for the purpose of this study.

3 The IPCC Working Group III focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere.

4 RCP stands for Representative Concentration Pathways. Specifically, the RCP2.6 was developed by the IMAGE modeling team of the PBL Netherlands Environmental Assessment Agency (Van Vuuren et al., 2011).

5 According to the IPCC (2014), radiative forcing is the net change in the energy balance of the Earth system due to some imposed perturbation. It is usually expressed in watts per square meter averaged over a particular period of time and quantifies the energy imbalance that occurs when the imposed change takes place.

6 Is important to remark that there are also other scenarios such as the P2 and the P3, but for the purpose of the exercise, those won't be considered.

7 With a probability equal or above 66%.

2015). Additionally, the selected scenarios included a 66% or higher probability of maintaining the global mean temperature below 2°C by the end of 2100. The previously mentioned models and their associated trajectories for the P1 scenario consist of a list of 14 different simulation results which are presented in Table 1.

The data from emission pathways of the previously presented models and scenarios was used, and a statistical analysis was performed. The median for carbon dioxide and the equivalent carbon dioxide yearly emissions were calculated. The emission trajectories obtained were consistent with the trajectory of the RCP2.6 pathway. The following table presents the values obtained from the 14 different models and for carbon dioxide and equivalent carbon dioxide emissions.

The results presented in Table 2 are the global emission trajectories within the required temperature increase limit. The estimation of the global carbon budget from the results presented in Table 2 was used to validate the methodology of this project. The RCP 2.6 trajectory for carbon dioxide global emissions were taken from this table, and a polynomial regression of the data was estimated. The following regression was obtained for the global emissions trajectory (T_{Global}).

$$T_{Global} = 1.6399 * 10^{-4}\, t^3 - 1.0102t^2 + 2{,}073.7225t - 1{,}418{,}272.022 \quad \textbf{(1)}$$

From equation (1) the R2 value was 0.994. The global carbon budget (B_{Global}) was estimated by integrating equation (1) since the carbon budget represents the area under the emissions trajectory. The integral is defined as:

$$B_{Global} = \int_{2011}^{2100} (1.6399 * 10^{-4}\, t^3 - 1.0102t^2 + 2{,}073.7225t - 1{,}418{,}272.022)\,dt \quad \textbf{(2)}$$

In equation (2), B_{Global} is valued in Gigatonnes of carbon dioxide and evaluating equation (2) for the 2011–2100 period resulted in a carbon budget of 1,007.5 $GtCO_2$, which is similar to what was estimated in the AR5 of the IPCC and other authors (see Table 3). This validation was useful in order to have an accurate estimation for the carbon budget of Mexico. Once the methodology was validated, the carbon budget for Mexico and its respective economic sectors (transport, oil and gas, and electricity) were calculated.

Table 1. **Description of the IAM models included in the P1 scenario.**

MODEL	ASSOCIATED EVALUATION
Global Change Assessment Model Version 3.0 (GCAM 3.0)	EMF27-450-FullTech
Global Change Assessment Model Version 3.1 (GCAM 3.1)	LIMITS-500
Integrated Model to Assess the Global Environment Version 2.4 (IMAGE 2.4)	AME 2.6 W/m2 OS
	AMPERE2-450-FullTech-OPT
	AMPERE3-CF450
	EMF27-450-FullTech
	LIMITS-450
Model for Evaluating Regional and Global Effects of GHG reductions policies (MERGE-ETL_2011)	AMPERE2-450-FullTech-OPT
	AMPERE2-450-LimSW-OPT
	AMPERE2-450-LowEI-OPT
	AMPERE2-450-NucOff-OPT
	AMPERE3-CF450
Regional Model of Investments and Development Version 1.5 (REMIND 1.5)	EMF27-450-FullTech
	LIMITS-450

Source: UNFCCC (2015). Technical Annex-Synthesis report on the aggregate effect of the intended nationally determined contributions.

Table 2. **Median from the projections of the scenario P1 used at the AR5-IPCC.**

YEAR	MEDIAN ($MTCO_2$)	MEDIAN ($MTCO_2E$)
2005	32,826.09	44,052.66
2010	35,401.68	46,710.98
2015	35,823.09	47,722.02
2020	35,743.74	47,097.87
2025	34,342.64	45,346.19
2030	31,333.30	42,334.19
2035	26,890.75	38,234.09
2040	20,046.02	32,036.74
2045	17,893.72	29,105.44
2050	15,374.09	26,674.21
2055	ND	ND
2060	6,939.03	18,824.37
2065	ND	ND
2070	-326.65	10,898.20
2075	ND	ND
2080	-5,137.22	5,866.98
2085	ND	ND
2090	-9,597.65	716.37
2095	ND	ND
2100	-10,886.73	-1,775.73

Source: IIASA. AR5 Scenario Database.

Table 3. Comparison of ICM global carbon Budget estimate with respect of the IPCC and other authors estimations

AUTHOR (S)	PERIOD	CARBON BUDGET ($GTCO_2$)
ICM	2011 – 2100	1,007.48 $GtCO_2$
AR5-IPCC Working Group III	2011 – 2100	990 $GtCO_2$
Rogelj et al. (2015)	2011 – 2100	790 $GtCO_2$
Knutti and Rogelj (2015)	2013 – 2100	969 $GtCO_2$
Millar and Friedlingstein (2018)	2016 – 2100	823 $GtCO_2$
Gignac and Matthews (2015)	2014 – 2100	930 $GtCO_2$

4.2. THE 2ºC NATIONAL CARBON BUDGET

In the case of Mexico and using the database of the Potsdam Institute for Climate Impact Research (PIK) for greenhouse gas emissions, the historical contribution of the country for the 1850–2014 period was 1.39% of global cumulative emissions. This percentage was used to adjust the global emissions trajectory outlined in Table 2, assign 1.39% of those emissions to Mexico and estimate the RCP2.6 trajectories for the Mexican case. Additionally, an emissions-trajectory curve was estimated through a polynomial regression so that the obtained equation could be used to estimate the carbon budget. The obtained equation is presented below.

$$T_{Mexico} = (2.2467 * 10^{-3})t^3 - 13.8406t^2 + 28{,}409.6464t - 19{,}430{,}085.48 \quad (3)$$

In equation (3), the dependent variable corresponds to the annual carbon dioxide emissions (T_{Mexico}) in Megatonnes of carbon dioxide. Meanwhile, the independent variable is time (t) represented in years. For equation (3), the coefficient of determination (R^2) was 0.9937. The carbon budget represents the area under the emissions trajectory curve and for that reason equation (3) was integrated for the limits of 2011 and 2100. The following equation presents the integral:

$$B_{Mexico} = \int_{t_0=2011}^{t_T=2100} (2.2467 * 10^{-3}t^3 - 13.8406t^2 + 28{,}409.6464t - 19{,}430{,}085.48)\, dt \quad (4)$$

In equation (4), $B_{México}$ corresponds to the carbon budget for Mexico and the carbon budget was estimated in 13.945 $GtCO_2$ considering the period from 2011 to 2100. It is important to highlight that the emissions pathway for Mexico might differ from the actual values of greenhouse gas emissions estimated in the National Inventory *(Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero 1990–2015*). For this reason, the obtained results were adjusted to have a carbon budget according to national values in terms of greenhouse gas emissions that could be useful for climate policy in Mexico. The new emissions trajectory follows the RCP2.6 trajectory but is indexed to equivalent carbon dioxide emissions of the National Inventory. A new polynomial regression was performed and summarised in equation (5).

$$T_{Mexico} = (2.1086 * 10^{-3})t^3 - 12.9982t^2 + 26{,}696.34393t - 18{,}268{,}514.77 \quad (5)$$

In equation (5) the R^2 coefficient for this estimation was 0.9944. The dependent variable (T_{Mexico}) is in million tonnes of equivalent carbon dioxide and the independent variable (t) in years. Once the regression was estimated, the next step was to obtain the integral (B_{Mexico}) evaluated from 2019 to 2100, which is represented in the following equation.

$$B_{Mexico} = \int_{t_0=2019}^{t_T=2100} (2.1086 * 10^{-3}t^3 - 12.9982t^2 + 26{,}696.34393t - 18{,}268{,}514.77)\, dt \quad (6)$$

Resulting from equation (6), the estimated national carbon budget for the 2019–2100 period is 22,722.21 $MtCO_2e$ or 22.7 $GtCO_2e$. In order to enhance the carbon budget estimation, it was necessary to take into account the surplus of emissions generated between the historical emissions of CO_2e and the estimated carbon budget from regression (6) for 2010 to 2018 period. Whit this estimation it was possible to readjust Mexico's RCP2.6 trajectory and the available carbon budget. The historical emissions from this period were obtained from the National Inventory and the emission surplus was 293.47 $MtCO_2e$.

The calculation of the emissions surplus served to repeat the carbon budget procedure presented above. The emissions trajectory is expressed in the following equation.

$$T_{Mexico} = (1.8545 * 10^{-3})t^3 - 11.4221t^2 + 23{,}439.2980t - 16{,}025{,}182.84 \quad (7)$$

The statistical estimation in equation (7) had a R^2 coefficient of 0.999. Consequently, the carbon budget was estimated with equation (8).

$$B_{Mexico} = \int_{t_0=2019}^{t_T=2100} (1.8545 * 10^{-3} t^3 - 11.4221 t^2 + 23{,}439.2980 t - 16{,}025{,}182.84)\, dt \quad (8)$$

With equation (8), the national carbon budget for the 2019–2100 was 22,194.19 $MtCO_2e$ or 22.2 $GtCO_2e$.

4.3. THE 1.5ºC NATIONAL CARBON BUDGET

The calculations in the previous section illustrate the estimation of a carbon budget aimed at limiting the average temperature increase of the planet in 2°C. A carbon budget for a 1.5°C increase in the average temperature of the planet was calculated as well. The methodology used for this purpose follows the same procedure as for the 2°C national carbon budget, with the main exception that for this case, the data input was derived from Section 2[8] Supplementary Material of the Special Report: Global Warming of 1.5°C. The reason behind the change was the necessity to explore the results and projections of the models using the SSPs[9] scenarios, particularly those that are aimed at achieving a radiative forcing of 1.9 Wm^{-2} by the end of the 21st century (SSPx-1.9) and limit the increase of the global mean temperature of the planet in 1.5°C. Table 4 presents the models and the evaluated scenarios used to measure the viability to achieve with a 66% or greater probability an increase of the global mean temperature of 1.5°C by the end of the century.

Supplementary Material of the Special Report Global Warming of 1.5°C using Table 4 as reference, the database from the *SSP Public Database Version 2.0* was taken as input for the calculations (IIASA, 2018). The review of the models and scenarios from the IIASA database made it possible to calculate the median of the SSPx-1.9 trajectory of equivalent carbon dioxide. The selected projections where those closer to the net zero emissions target by 2050. The selected representative models were: AIM/CGE-SP2-1.9, REMIND-MagPIE-SSP2-1.9 and REMIND-MagPIE-SSP2-1.9. Figure 2 presents the emission pathways and their medians.

Table 4. Models and their SSPs considering a radiative forcing of 1.9 Wm-2

MODEL	SCENARIO
Asia-Pacific Integrated Model (AIM)	SSP1, SSP2
Global Change Assessment Model Version 4.0 (GCAM4)	SSP1, SSP2, SSP5
Model for Energy Supply Strategy Alternatives and their General Environmental Impact- Global Biosphere Management (MESSAGE-GLOBIOM)	SSP1, SSP2
Regional Model of Investments and Development – Model of Agricultural Production and its Impact on the Environment (REMIND-MagPIE)	SSP1, SSP2, SSP5
World Induced Technical Change Hybrid-Global Biosphere Management (WITCH-GLOBIOM)	SSP1, SSP2, SSP4

Source: Own elaboration with information from the IPCC Section 2

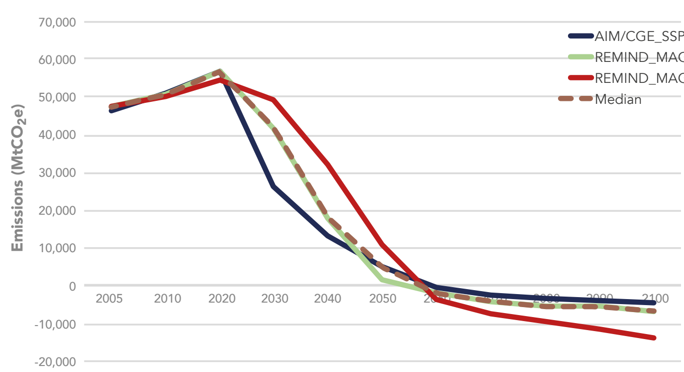


Figure 2. Projected emissions from 2005 to 2100 of equivalent carbon dioxide that maintain the global mean temperature at 1.5°C with a probability of 66% or greater

With the calculated median, the next step was to multiply the vector by 1.39% in order to obtain Mexico's SSPx-1.9 trajectory. Figure 3 presents the resulted trajectory.

Taking into account the necessary adjustments of the trajectory as in the previous sections for the 2°C temperature increase limit[10], the next step was to estimate the emissions trajectory equation through the polynomial regression. Equation (9) presents the emissions trajectory.

8 Mitigation pathways compatible with 1.5ºC in the context of sustainable development.

9 Shared Socioeconomic Pathways, Rogelj et al. (2018) establishes that: “This framework provides a basis of internally consistent socio-economic assumptions that represent development along five distinct storylines: development under a green growth paradigm (SSP1); a middle of the road development along historical patterns (SSP2); a regionally heterogeneous development (SSP3); a development that results in both geographical and social inequalities (SSP4); and a development path that is dominated by high energy demand supplied by extensive fossil-fuel use (SSP5).”

10 Meaning that it considers the emission surplus emitted from 2010 to 2018.

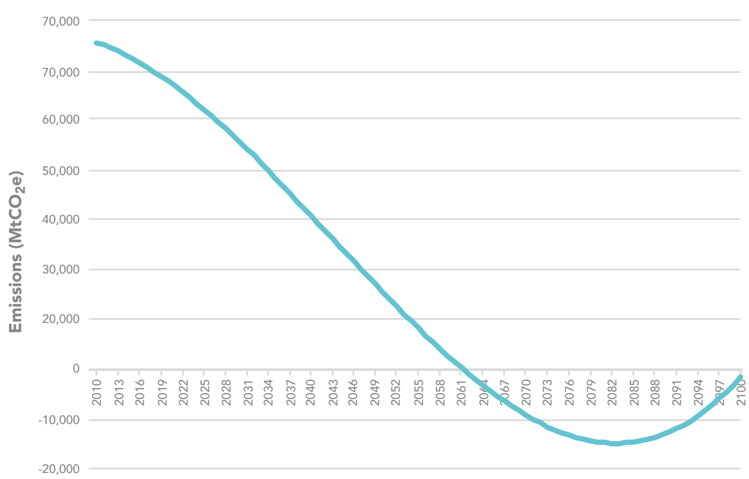


Figure 3. Mexico's SSPx-1.9 Trajectory

$$T_{Mexico} = (3.2873 * 10^{-3})t^3 - 20.1480t^2 + 41{,}147.1961t - 27{,}999{,}957.83 \quad (9)$$

From the statistical analysis, the estimated R^2 coefficient was 0.999. Equation (10) presents the estimation of the carbon budget for the 2019 to 2100 period.

$$B_{Mexico} = \int_{t_0=2019}^{t_T=2100} (3.2873 * 10^{-3}t^3 - 20.1480t^2 + 41{,}147.1961t - 27{,}999{,}957.83)\, dt \quad (10)$$

The result from the evaluation of equation (10), resulted in the 1.5°C national carbon budget of **8.89 $GtCO_2e$** for the 2019–2100 period.

4.4. CARBON BUDGET SECTORIAL ALLOCATION

To elaborate the decarbonisation pathways for the selected sectors[11] of this study, it is important to estimate the sectorial allocation of the national carbon budget[12]. Initially, the historic and projected emissions models that were developed and analysed were considered and compared, with the objective of identifying coincidences and differences in sector allocation projections.

The models used for the allocation were: GHG emissions baseline 2012; MACC curves 2013; POLES Mexico 2015; Mexico's 2050 Calculator 2015; and, the Energy Policy Simulator Mexico (EPS Mexico). The first model was developed by SEMARNAT for the 5th National Communication with INECC's dataset from the 2010 GHG emissions inventory. The MACC curves 2013 model was developed by McKinsey alongside INECC. The third model was created by Enerdata alongside INECC. The Calculator was elaborated by Centro Mario Molina with collaboration of the Mexican Energy Ministry (SENER) and UK's DECC. Finally, the EPS Mexico was developed by Energy Innovation with the collaboration of WRI Mexico and the Centro Mario Molina in 2015, and recently updated by WRI Mexico.

With the results obtained in the emissions models, two scenarios were projected: The *Business as Usual Trend* and the *Conditional NDC Scenario*. The allocation was based on simulation scenarios from the EPS Mexico considering the Conditional NDC Scenario for year 2020. This selection resulted in the following participation for each sector: 19% for the electricity generation sector; 22% for the transport sector; 17% for the industry sector; 10% for the oil & gas sector; 8% for the buildings sector; 6% for the waste sector; 16% for the agriculture sector; and, 2% for the LULUCF[13] sector. Taking into consideration a constant allocation for each sector, in the next table (Table 5) and figures (Figures 4 and 5) it is possible to observe the proportion of each sector and its 2°C and 1.5°C carbon budget.

For the purpose of this study, only the electricity generation (19%), oil and gas (10%) and transport (22%) sectors are considered. Is important to highlight that this approach is an initial analysis and recognises the limitations of using only three sectors for the decarbonisation pathways. To create a more robust analysis, it is important to consider the remaining sectors. Additionally, based on several discussions in different workshops, another area of opportunity of the present study is to acknowledge the dynamics within the emissions allocation for each sector, (that is, that allocation can be dynamic) one example is to take into account in the analysis the progressive nature of technology and the constant variations of socioeconomic factors and how different these allocations might be for each year considering these dynamics. These dynamics are expected to be addressed in future studies.

11 Electricity Generation Sector, Oil & Gas sector and Transport Sector.

12 See sub-section 4.3.

13 Land Use, Land Use Change and Forestry.

Table 5. Sector allocation and its 2°C and 1.5°C Carbon Budget from 2019 to 2100

SECTOR	CONSTANT ALLOCATION (%)	2°C CARBON BUDGET (GTCO2E)(+)	1.5°C CARBON BUDGET (GTCO2E)(+)
Electricity Generation	19	4.0	1.6
Transport	22	4.8	1.9
Industry	17	3.7	1.5
Oil & Gas	10	2.2	0.9
Buildings	8	1.8	0.7
Waste	6	1.3	0.5
Agriculture	16	3.5	1.4
LULUCF	2	0.4	0.2
TOTAL	**100**	**22.2**	**8.9**

Note: (+) Rounded figures may not sum the total.

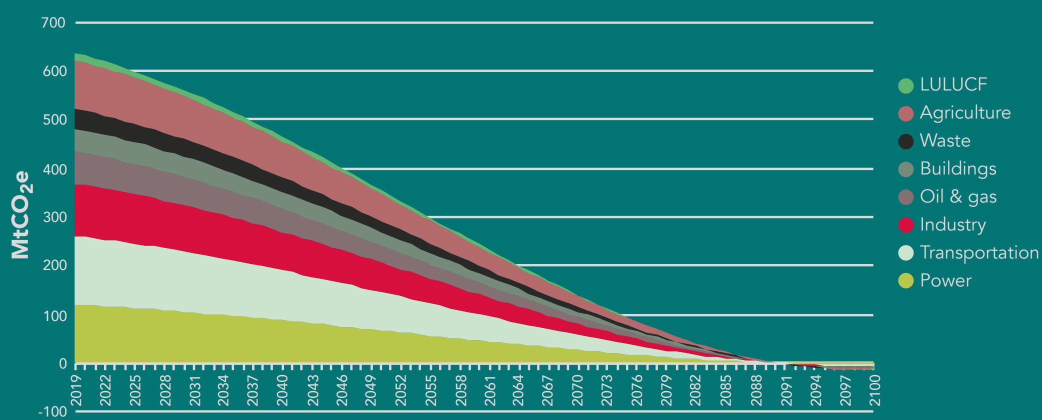


Figure 4. 2°C Carbon Budget for Mexico with Constant Sector Allocation

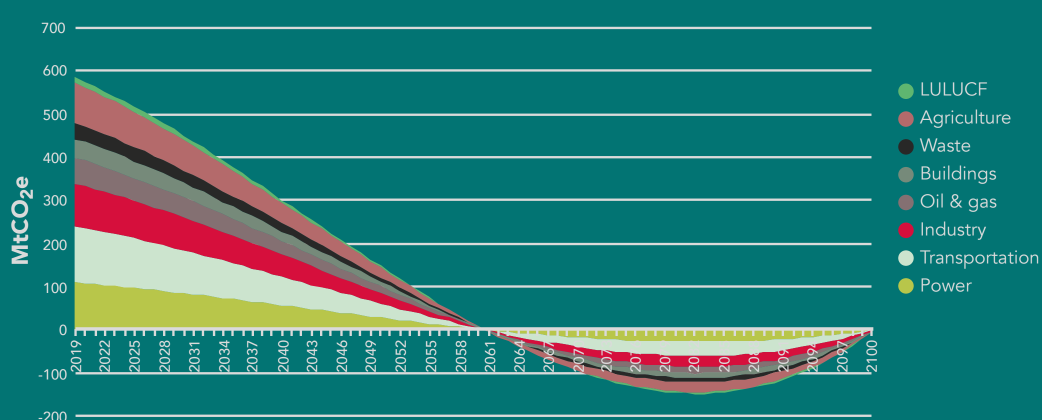
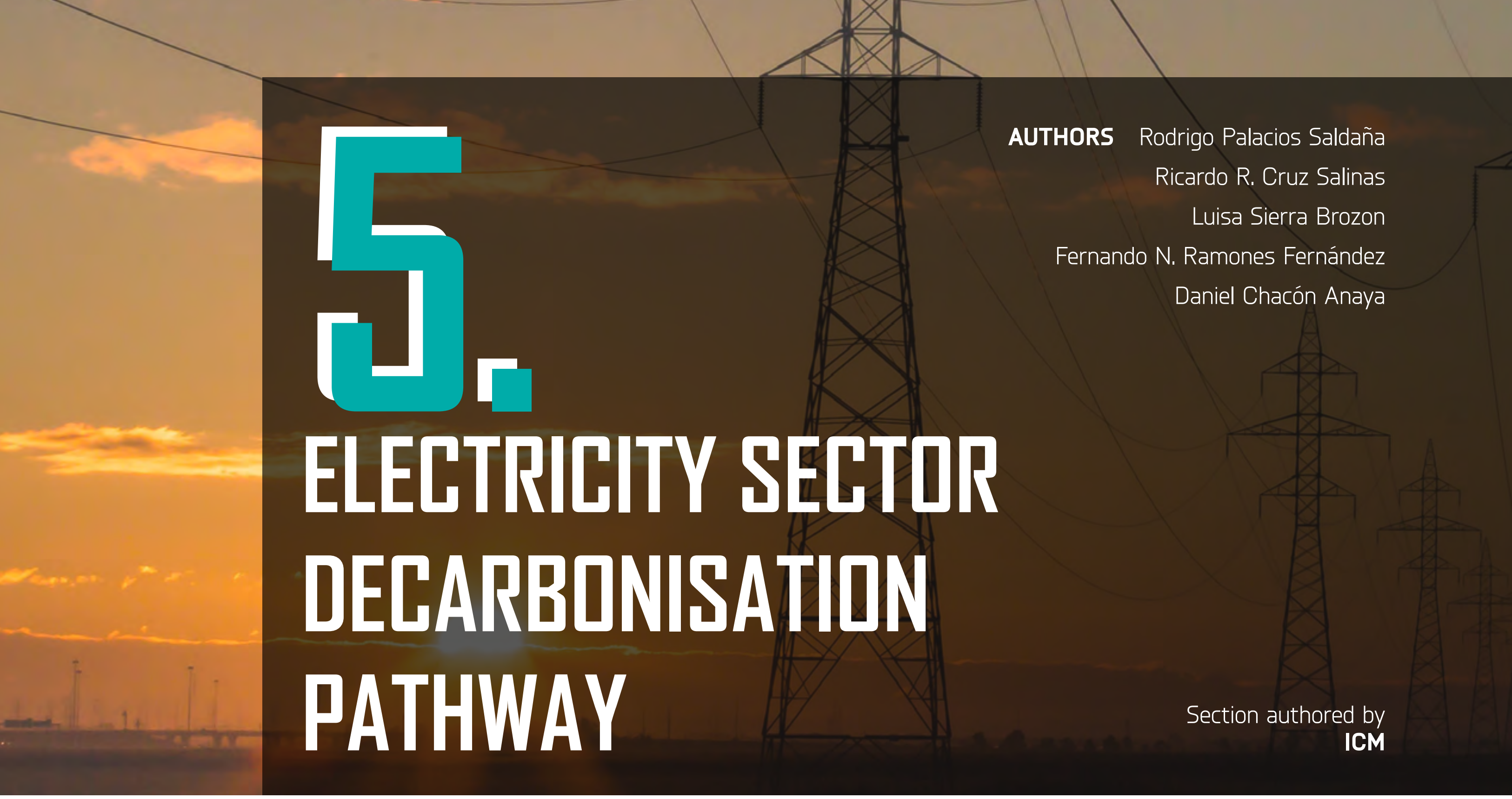


Figure 5. 1.5°C Carbon Budget for Mexico with Constant Sector Allocation

The following Sections of this work focus on the three previously mentioned sectors and expand on the possible mitigation alternatives for these sectors for achieving the 1.5°C carbon budget by taking a bottom-up approach which differs from the top-down initial estimate presented in this section. The definition of a final carbon budget must be based on an iterative process (both top-down and bottom-up perspectives) but this work represents an initial effort. ◆



5. ELECTRICITY SECTOR DECARBONISATION PATHWAY

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KEY POINTS

ELECTRICITY SECTOR

- Reaching the carbon budget is feasible with a high penetration of solar PV and wind power.
- Solar PV and wind power are cost effective technologies, bringing economic, social and environmental benefits.
- The electricity matrix should stop using coal and fuel oil for thermal power plants. Natural gas in open and combined cycles can serve as load following technologies complementing intermittent renewable resources.
- Energy storage opportunities should be further studied so that the required regulatory framework can promote their participation in the future for reducing intermittency issues.
- Transmission and distribution investments can be reduced if distributed generation is promoted. Distributed generation could provide larger flexibility to the network.
- Energy efficiency must be better understood and considered because of its benefits in reducing energy demand.
- A higher penetration of electric vehicles can reduce emissions in the transport sector. However, charging patterns should be studied and both regulatory and non-regulatory schemes should be implemented to modulate these patterns.

5.1. REGULATORY FRAMEWORK OF THE ELECTRICITY SECTOR

In 2014, the Mexican Congress passed the Electric Industry Law (LIE for its Spanish acronym) as part of the broader reform to the energy sector. The LIE completely changed the electric industry by liberalising the sector through enabling further private investments and projects. This Section describes how the electric industry is structured into three main activities: a) Generation, b) Transmission and Distribution, and c) Retailing. Furthermore, the Section explains the role of the energy authorities within the current legal framework.

5.1.1. THE ENERGY AUTHORITIES

The LIE defined the energy entities and their role in the new electricity sector structure. The Energy Secretariat (SENER) is the ministry for energy affairs and defines the energy policy and planning the energy sector. The Energy Regulatory Commission (CRE) regulates different markets and energy-related activities. In the case of the electricity sector, CRE is the institution that receives and approves permits and looks after an adequate performance of the wholesale electricity market and other economic instruments. It also establishes tariffs for transmission, distribution, and the operation of the system and retailing.

The National Energy Control Centre (CENACE) is an independent institution that operates both the power system and the wholesale market. As the Independent System Operator (ISO) it manages all power system devices within the system, from the generation units to the transmission grid. As the Independent Market Operator (IMO), CENACE manages the market supply and determines the LMP.

The Federal Electricity Commission (CFE) is the state-owned company, and it is regulated by the same rules of the LIE that apply for every other company. However, its subsidiaries CFE-Transmission and CFE-Distribution have by law the monopoly for electricity transmission and distribution activities.

5.1.2. GENERATION

Generation corresponds to the production of electricity using different technologies. Even though private participation was allowed before the energy reform, private generators could only sell electricity to CFE. With the reform, a wholesale market was created, and generators are allowed to directly sell electricity to wholesale consumers. Power plants with a generation capacity of 0.5 MW or higher, or power plants owned by a generator who is participant of the wholesale market, require a permit from the energy regulator (the *Comisión Reguladora de Energía*, CRE) to operate. The same case applies for electricity imports, while in the case of power plants used for emergency self-supply, permits are not required. The generators who do not require a permit are able to sell electricity to suppliers (DOF, 2014; Jano-Ito, 2016).

5.1.3. OPERATION OF THE WHOLESALE MARKET

The *Centro Nacional de Control de Energía* (CENACE, by its acronym in Spanish) controls the operation of the wholesale market and CRE determines the rules. In this market, generators, qualified consumers and suppliers (both basic and qualified) participate CENACE acts as the independent system operator and determines the economic dispatch of generation plants, demand reductions (controllable demand) and imports and exports of electricity to maintain the security of the system. CENACE calculates prices known as Local Marginal Prices (LMP) through every node of the system. The generators offer the totality of their available capacity while consumers. Market bids by generators and controllable demand users, are based on costs. The information on costs and capacities is acquired by CENACE, and CRE observes that the information is consistent and determines payments or charges for deviations (DOF, 2014; Jano-Ito, 2016).

Although the energy sold in the wholesale market is valuated in LMPs, all the energy of the system is managed by CENACE. For instance, a generator may have a Power Purchase Agreement (PPA) with a qualified user on 80% of the generation capacity and its remaining 20% generation capacity is sold in the wholesale market —assuming that all of it is sold. CENACE pays the generator the equivalent to the 20% of the generation capacity at the LMP, even though CENACE handled 100% of the generated electricity, since all of the electricity was delivered to the power grid. Nevertheless, CENACE charges the generator for the costs of transmission, distribution and the corresponding fees for the 100% of the electricity. With regards to the qualified user, they will receive their corresponding energy (80% generation capacity from the generator in this example) as a result of CENACE's operation of the power system. However, the qualified user will not pay for that energy to CENACE, except for the corresponding transmission, distribution and other fees; but will pay for that energy directly to the generator as arranged in the PPA.

The other form in which wholesale occurs is in bilateral contracts. Bilateral contracts are part of the electricity sector structure and correspond to agreements between a generator and a qualified user, a generator and a supplier, and a supplier and a qualified user for energy or an associated product. The terms of the contract are not regulated by any of the energy authorities (DOF, 2014).

5.1.4. TRANSMISSION AND DISTRIBUTION

The transmission and distribution of electricity from the generation units to the consumption centres is exclusive to the State. Transmission takes electricity from the generation units to the distribution centres; and distribution, delivers electricity from the distribution centres to the consumption centres. The companies in charge of these activities are CFE-Transmission and CFE-Distribution. Every generator or user of the electricity grid has to sign a connection contract with these companies, depending on the type of the service needed (DOF, 2014).

CRE determines the general conditions for the operation of the transmission and distribution networks. In case of emergencies, transmission and distribution companies are not responsible for cost changes in the wholesale market. The transmission and distribution companies are required to connect generation in a non-discriminatory manner, when technically feasible. When not included in the expansion and modernisation plans, generators or final users are able to construct the required facilities under the supervision of CENACE (DOF, 2014; Jano-Ito, 2016).

CRE defines every year a tariff that CENACE takes into account while operating the power system and assigns the cost of transmission and distribution to the market participants. CENACE transfers these payments to CFE-Transmission and CFE-Distribution (DOF, 2014).

5.1.5. RETAILING

Energy and the associated products' trade are divided into two activities: wholesale and retail. Wholesale may occur in two forms: one, is the wholesale electricity market, the market operated by CENACE in which the generators offer generation of energy and associated products; and on the other hand, the Market Participant Qualified Users where the suppliers offer energy and associated products (DOF, 2014; Jano-Ito, 2016).

Supply services are provided to final users and representing generators (those who do not require a permit from CRE). Basic service suppliers provide electricity to any basic consumer located in their operation zones. Last resort and qualified suppliers provide services to qualified consumers. Qualified consumers are defined as those who have a demand greater than 1 MW. If the qualified user has a demand higher than 5 MW and 20 GWh per year, it may register as a market participant qualified user (DOF, 2014; Jano-Ito, 2016).

Basic users are those users who have an electricity demand under 1 MW. Basic suppliers and basic users need to sign a contract under CRE terms. The tariff of the electricity delivered as basic service is also regulated by CRE, so neither the supplier nor the basic user may change the corresponding payment (DOF, 2014; Jano-Ito, 2016).

Small-scale power systems are those that are not connected to the grid but supply electricity to consumers and are authorised by SENER. In the case of distributed generation, these systems have access to the distribution network and CRE establishes the mechanisms to regulate them (DOF, 2014; Jano-Ito, 2016).

5.1.6. DISTRIBUTED GENERATION

Distributed Generation is defined and regulated by the LIE as generation units under 500 kW connected to the distribution grid. Given the maximum capacity of the distributed generation systems, its owner —who often is a basic user— is recognised as an exempt generator. Hence, he cannot offer the energy produced directly in the wholesale market.

CRE has defined two contract models that an exempt generator has to sign: one with CFE-Distribution, to have the generator's system connected to the grid; and the other with the supplier, whether basic or qualified. The latter can be established through one of the following mechanisms:

- Net metering. During a billing period, the energy that the distributed generation system sends to the grid is subtracted from the energy the supplier sells to the user. At the end of the period, if the energy from the supplier is higher than the energy generated by the user, the user pays for the electricity at the tariff set in the supply contract. On the other hand, if the distributed system delivered more energy to the grid than the supplier, this energy is subtracted from the user bill. If the credit has not been used by the user, the supplier pays that energy at the LMP.

- Net billing. The user pays the supplier for all the consumed energy at the tariff of the contract, while the supplier will pay the user for all the energy given to the grid by the distributed system at the LMP.

- Total sale. All the energy generated by the distributed system is sold to the supplier at the LMP.

5.1.7. CLEAN ENERGY CERTIFICATES

One of the most important associated products for the decarbonisation of the electricity sector is the Clean Energy Certificate (CEL) that is given by every MWh generated by a clean energy generation unit. The recognised clean technologies in the LIE are all the renewable sources, nuclear, biomass and efficient cogeneration. CRE grants CELs to the clean energy generators who may sell their electricity to suppliers or qualified users. Clean energy generators are rewarded for this electricity because electricity market participants are forced to comply with clean energy generation obligations established by the government (DOF, 2014). The current administration requested a change in the assignment of certificates so that CFE's geothermal and hydro power plants could receive certificates. These power plants were not part of the scheme since most of them were built before 2014.

5.2. ELECTRIC INFRASTRUCTURE 2018

In this section, the situation of the electricity sector in 2018 (base year of the study) is presented. It is important to mention that although most of the data presented here used to be published in the Development Programme of the National Electricity System (PRODESEN), the last PRODESEN, for the 2019-2033 period, has missing data. For this reason, this study is based on the PRODESEN for the 2018-2033 period which has data available until December 2017.

The data previously mentioned was adjusted to 2018 using information from different official sources which include the generation permits emitted by CRE, the Environmental Impact Statements (EIS) submitted to SEMARNAT, and the registered infrastructure projects by the Federal Government. Press-releases and experts involved in the sector were also consulted. The following sections present the estimated data for 2018.

5.2.1. INSTALLED CAPACITY

In 2018, Mexico had a total installed capacity of 70.4 GW (Figure 6). From this figure, 6.4 GW of installed capacity corresponded to combined cycle (38%). This generation technology was followed by hydro with 12.6 GW (18%), fuel oil with 10.6 GW (15%), wind with 4.2 GW (6%) and solar PV with 1.6 GW (2%). Renewable energy sources represent around 28% of total installed capacity and 32% if the other clean technologies are considered (SENER, 2018b).

5.2.2. TRANSMISSION AND DISTRIBUTION

Mexico's National Electricity System (*Sistema Eléctrico Nacional*, SEN) is divided into 9 regions and a small transmission system (Mulegé). These regions are coordinated by the National Centre of Energy Control (CENACE). The electricity system of Baja California is connected to the Western Electricity Coordinating Council (WECC) in the United States (US), whereas the seven continental areas form the National Interconnected System (*Sistema Interconectado Nacional*, SIN) (Jano-Ito, 2016). The country is further divided into 53 transmission zones, as shown in Table 6 and Figure 7. The total installed capacity of the transmission assets is 76.3 GW extending through more than 107 thousand kilometres (SENER, 2019b).

The lines between the transmission regions in Figure 7 have a specific transmission capacity listed in Table 7.

In the case of electricity distribution, CFE-Distribution has 16 business units in the country, as shown in Figure 8. The grid distributes electricity to more than 42 million users and comprises around 838,831 kilometres. It must be mentioned that in this study, given the magnitude of the sector, and the fact that there is no available data of the grid, distribution is not modelled.

Figure 6. Power generation installed capacity

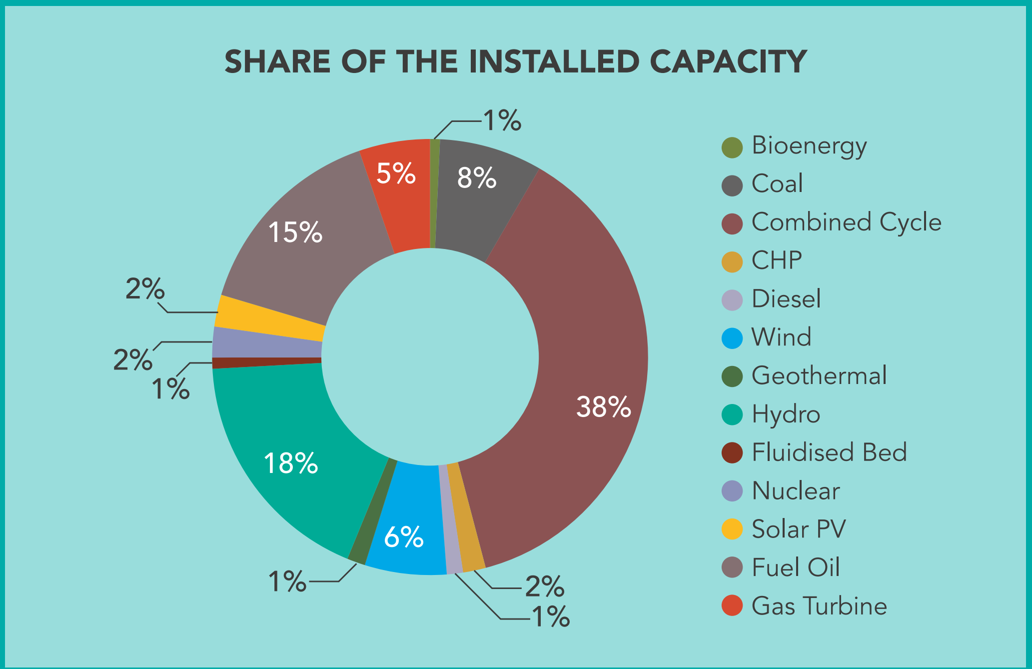


Table 6. Transmission zones and control regions

TRANSMISSION REGION	CONTROL REGION
01-Hermosillo	04-Noroeste
02-Cananea	04-Noroeste
03-Obregon	04-Noroeste
04-Los Mochis	04-Noroeste
05-Culiacan	04-Noroeste
06-Mazatlan	04-Noroeste
07-Juarez	05-Norte
08-Moctezuma	05-Norte
09-Chihuahua	05-Norte
10-Durango	05-Norte
11-Laguna	05-Norte
12-Rio Escondido	06-Noreste
13-Nuevo Laredo	06-Noreste
14-Reynosa	06-Noreste
15-Matamoros	06-Noreste
16-Monterrey	06-Noreste
17-Saltillo	06-Noreste
18-Valles	06-Noreste
19-Huasteca	06-Noreste
20-Tamazunchale	06-Noreste
21-Guemez	06-Noreste
22-Tepic	03-Occidental
23-Guadalajara	03-Occidental
24-Aguascalientes	03-Occidental
25-San Luis Potosi	03-Occidental
26-Salamanca	03-Occidental
27-Manzanillo	03-Occidental
28-Carapan	03-Occidental
29-Lazaro Cardenas	01-Central
30-Queretaro	03-Occidental
31-Central	01-Central
32-Poza Rica	02-Oriental
33-Veracruz	02-Oriental
34-Puebla	02-Oriental
35-Acapulco	02-Oriental
36-Temascal	02-Oriental
37-Coatzacoalcos	02-Oriental
38-Tabasco	02-Oriental
39-Grijalva	02-Oriental
40-Ixtepec	02-Oriental
41-Lerma	07-Peninsular
42-Merida	07-Peninsular
43-Cancun	07-Peninsular
44-Chetumal	07-Peninsular
45-Cozumel	07-Peninsular
46-Tijuana	08-Baja California
47-Ensenada	08-Baja California
48-Mexicali	08-Baja California
49-San Luis Rio Colorado	08-Baja California
50-Villa Constitución	09-Baja California Sur
51-La Paz	09-Baja California Sur
52-Los Cabos	09-Baja California Sur
53-Mulege	10-Mulege

Figure 7. Control regions and transmission zones map

Table 7. Transmission capacity between lines

TRANSMISSION REGION	CONTROL REGION
Hermosillo->Obregon	980
Cananea->Hermosillo	975
Cananea->Moctezuma	400
Obregón->Los Mochis	680
Culiacán->Los Mochis	890
Mazatlán->Culiacán	1450
Mazatlán->Tepic	1380
Juárez->Moctezuma	640
Moctezuma->Chihuahua	640
Chihuahua->Laguna	330
Durango->Mazatlán	640
Durango->Aguascalientes	300
Laguna->Durango	550
Laguna->Saltillo	550
Rio Escondido->Chihuahua	450
Rio Escondido->Nuevo Laredo	400
Rio Escondido->Monterrey	2100
Reynosa->Nuevo Laredo	140
Reynosa->Monterrey	2060
Matamoros->Reynosa	1400
Monterrey->Saltillo	1500
Saltillo->Aguascalientes	1290
Valles->San Luis Potosí	1500
Huasteca ->Valles	1050

TRANSMISSION REGION	CONTROL REGION
Huasteca ->Tamazunchale	1200
Huasteca ->Güémez	1700
Huasteca->Poza Rica	1875
Tamazunchale->Querétaro	1780
Güémez->Monterrey	1500
Tepic->Guadalajara	1178
Guadalajara->Aguascalientes	1000
Guadalajara->Salamanca	700
Guadalajara->Carapan	700
Guadalajara->Lázaro Cárdenas	580
Aguascalientes->Salamanca	880
San Luis Potosí->Aguascalientes	1300
Salamanca->Querétaro	1600
Manzanillo->Guadalajara	3000
Carapan->Salamanca	700
Lázaro Cárdenas->Carapan	720
Lázaro Cárdenas->Central	2900
Lázaro Cárdenas->Acapulco	350
Querétaro->San Luis Potosí	425
Querétaro-Central	1800
Poza Rica->Central	4100
Poza Rica->Puebla	310

TRANSMISSION REGION	CONTROL REGION
Veracruz->Poza Rica	750
Veracruz->Puebla	1100
Veracruz->Temascal	350
Puebla->Central	3000
Acapulco->Puebla	300
Temascal->Puebla	3000
Coatzacoalcos->Temascal	1750
Tabasco->Lerma	1200
Grijalva->Temascal	2800
Grijalva->Coatzacoalcos	2100
Grijalva->Tabasco	1450
Ixtepec->Temascal	2500
Lerma->Mérida	850
Lerma->Chetumal	140
Mérida->Cancún	825
Mérida->Chetumal	135
Cancún->Cozumel	48
Tijuana->Ensenada	255
Tijuana->Mexicali	520
Mexicali->San Luis Rio Colorado	390
Villa Constitución->La Paz	80
La Paz->Los Cabos	200

Figure 8.
Distribution units
of CFE

5.3. ELECTRICITY MATRIX AND GREENHOUSE GAS EMISSIONS

The estimation of greenhouse gas emissions is based on the existing infrastructure for electricity generation. PRODESEN 2018-2032 is used for this purpose. According to this source, in 2018 total electricity emissions accounted for 124 million tonnes of CO_2e.

5.4. CARBON BUDGET FOR THE ELECTRICITY SECTOR

The carbon budget was estimated through the methodology developed by ICM. The remaining carbon budget of the electricity generation sector for the trajectory that maintains the global mean temperature at 2°C is 4.0 $GtCO_2e$ for the 2019-2100 period. Replicating the same exercise, considering the 1.5°C trajectory, the carbon budget for the electricity sector was estimated in 1.6 $GtCO_2e$ for the period 2019-2100.

5.5. FUTURE OF THE ELECTRICITY SECTOR

5.5.1. SCENARIOS

In this section, the rationale behind each modelled scenario of the electricity sector is described. Further information regarding the construction of the scenarios and their characteristics are presented in the following sections. Based on the previous sections and the available information, 2018 was selected as the base year. The simulation was performed using PLEXOS, which is a linear programming model for electricity systems.

5.5.1.1. BASELINE SCENARIO (S1)

This scenario serves as a benchmark to understand the implications of the decarbonisation measures. In other words, the baseline scenario is the Business-As-Usual or Current-Policies scenario. Therefore, in order to have the most realistic scenario, data from PRODESEN 2018-2032 was used and revised with PRODESEN 2019-2033 expansion plan. With the use of PLEXOS and this information, this scenario was run and the economically efficient dispatch of generating units was obtained following the expected demand growth. PRODESEN 2019-2033 has its own demand forecast, but this data was not used in this study. The demand forecast was kept constant for all scenarios and is presented in section 5.5.2.6. Additionally, in terms of new generation capacity, after 2033, the model adds capacity according to the catalogue described in section 5.5.2.2.

5.5.1.2. DECARBONISATION SCENARIO (S2)

The main characteristic of this scenario is that it is designed to achieve the decarbonisation of the electric sector. For this, the carbon budget was its main driver and restriction. The modelling was divided in two periods: The first, runs from 2019 to 2030 and considers that in the search for the decarbonisation there are certain limits and barriers for the technologies. It is worth mentioning that such barriers were identified by experts in a workshop held by the consortium where the scenario assumptions were discussed. The second period focuses on the longer term, running from 2030 to 2050. In this case, the barriers are eventually overcome, and the decarbonisation is deeper.

5.5.2. SCENARIO INPUTS AND ASSUMPTIONS

This section presents relevant information regarding the scenario assumptions and the description of the inputs. In each section, the information sources are mentioned with a description of the scenario-creation process.

5.5.2.1. SEN PERFORMANCE IN THE SHORT TERM

The model used for the electric system is capable of representing the operation of any power system in the long-term and in the short-term. As the goal of this study is to determine the least-cost carbon-free power system expansion plan by 2050, the long-term is the main time frame. Nevertheless, the features of the model under a short-term time frame are relevant since there are operational variables that determine the technical feasibility of the system´s performance. The latter becomes of significant importance in the specific case of the intermittent nature of renewable resources.

Additionally, modelling the short-term features of the electricity market can be used to analyse its impact on investment decisions, since a greater penetration of low-marginal-cost power plants such as wind and solar, could affect investment cost recovery and the whole expansion plan of the power system.

One of the necessary parameters for the short-term is the hourly demand profiles for each of the modelled regions. This information is presented in section 5.5.2.6. The other parameters that represent the operation of the power system include the following elements:

- Up and down ramps. This information refers to the ability of a generator to adjust their operation level[14] in a certain time period.

- Minimum stable level. It is the minimum operation level of a power plant. Below that level, the power plant cannot operate correctly and must be shut down.

- Start-up cost. It is the cost incurred by a power plant to start its operation before it can deliver electricity to the grid.

Data for these parameters was available for some power plants in PRODESEN. For the missing information, estimates were confirmed through interviews with experts.

5.5.2.2. Power plant expansion plans

The expansion of the installed capacity is the result of two kinds of additions: The first, known as the endogenous additions, are the power plants that the model incorporates considering their economic and technical characteristics. The technical characteristics (costs and engineering data) of these power plants are exogenously defined and introduced as a catalogue of expansion alternatives in the future which the model endogenously determines. The second type of additions, known as exogenous, do not result from the model simulations. These power plants are also introduced to the model as a list. In this study, for the Baseline Scenario and the 2019-2033 period, power plants correspond to exogenously added plants, which are already in construction.

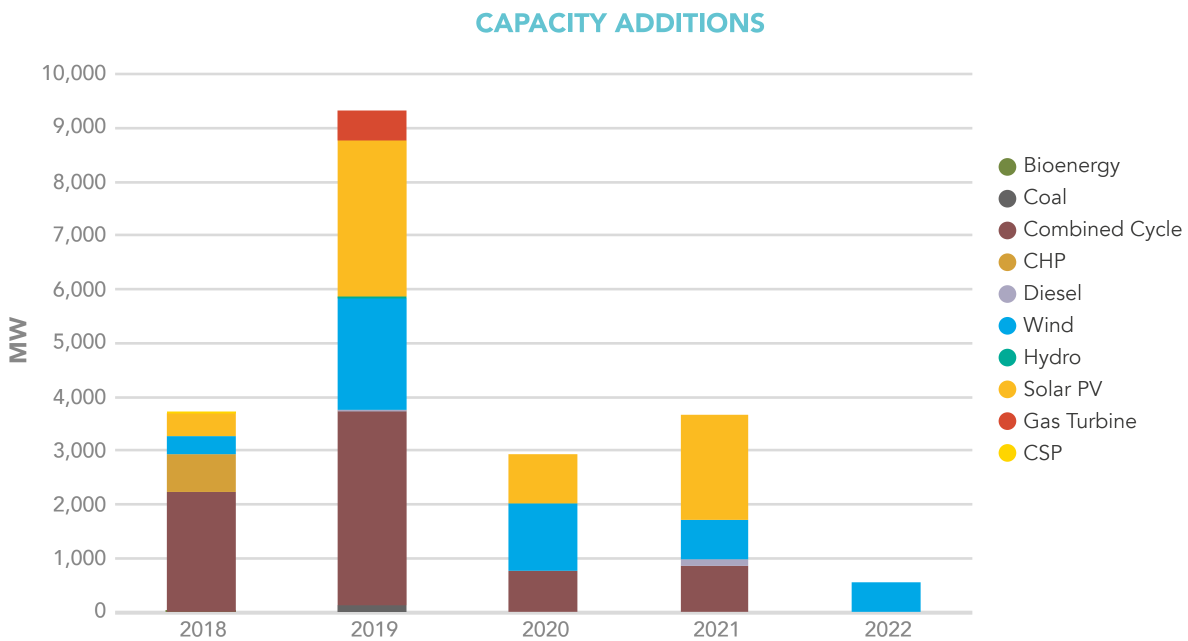
The catalogue of the exogenous additions was built using the PRODESEN 2018-2032 addition plans but only considering those projects to be installed before 2023. Additionally, official information sources such as, the generation permits issued by CRE, the Environmental Impact Statements (EIS) delivered to the Ministry of Environment and Natural Resources (SEMARNAT, by its acronym in Spanish), and Federal Government information sources were reviewed to determine the latest status of the projects reported under construction in PRODESEN 2018-2032. The latter allowed the inclusion of the projects from the three long-term auctions and those that are planned but have not yet been built. Figure 9 shows the total exogenous addition by technology.

The potential projects for the non-renewable technologies catalogue was built in a similar way as the exogenous additions and the expansion plans from PRODESEN 2018-2032 were taken into consideration. Following, a revision of the availability of fuels, such as natural gas, in each region was made to determine the feasibility of new power plants. For the renewable technologies, the potential projects were determined as explained in the previous section. The total capacity of non-renewable potential projects is shown in Table 8.

5.5.2.3. Power plants decommissioning

Decommissioning a power plant is a decision that considers several factors including the lifespan of the plant, its economic performance and sometimes

Figure 9. Exogenous additions by technology



14 The capacity delivered to the grid.

Table 8. Non-renewable potential capacity

MODEL	ASSOCIATED EVALUATION
Combined Cycle	28,105
CHP	2,383
Diesel	176
Nuclear	4,081
Gas Turbine	2,124

the status of the power system or other non-technical factors. In the Baseline scenario (S1), it is considered that until 2030 there will no decommissioning of power plants. This assumption corresponds to the PRODESEN 2019-2033, and the modernisation plans for some of the power plants presented by the current administration. For the Decarbonisation scenario (S2), the decommissioning plans from PRODESEN 2018-2032 are considered[15]. These retirements are known as exogenous retirements (ASF, 2019). Additionally, if the model results show that a certain power plant is not necessary anymore, i.e. it does not generate energy in a year, it is retired. These types of retirements are known as economic retirements. It is worth saying that, as the model is representing the electricity sector only as a wholesale market[16], there is a chance that certain economic retirements turn out to be impossible due to the existence of contracts or other legal dispositions. Figure 10 presents the capacity for retirement from each technology. Figure 11 shows the evolution of the remaining capacity after the retirements, assuming no additions. For both scenarios, after 2030, the decommissioning of the power plants is only driven by its economic lifetime

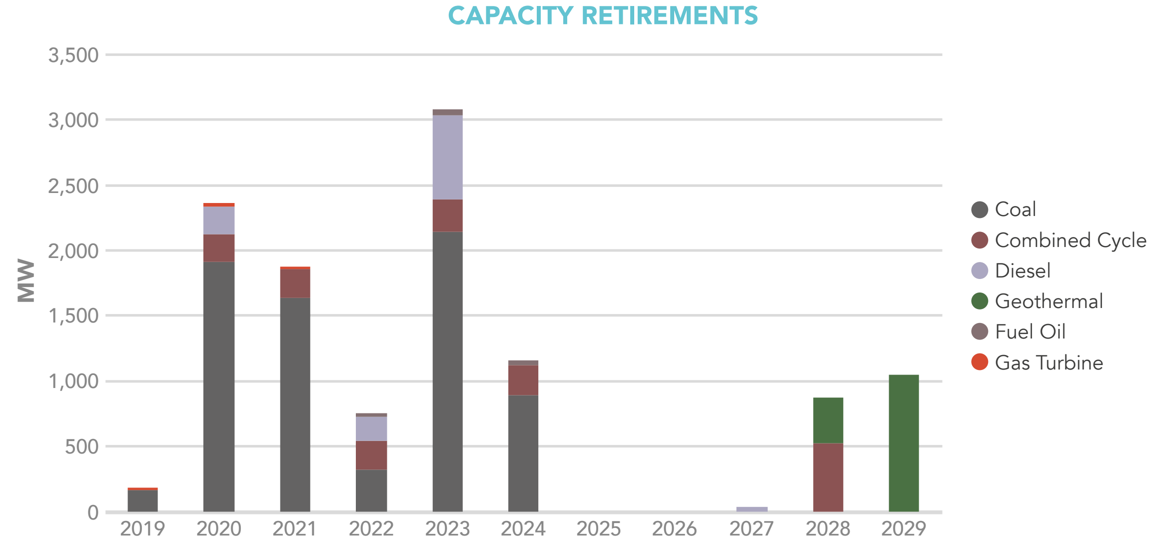


Figure 10. Retirement capacity for each technology

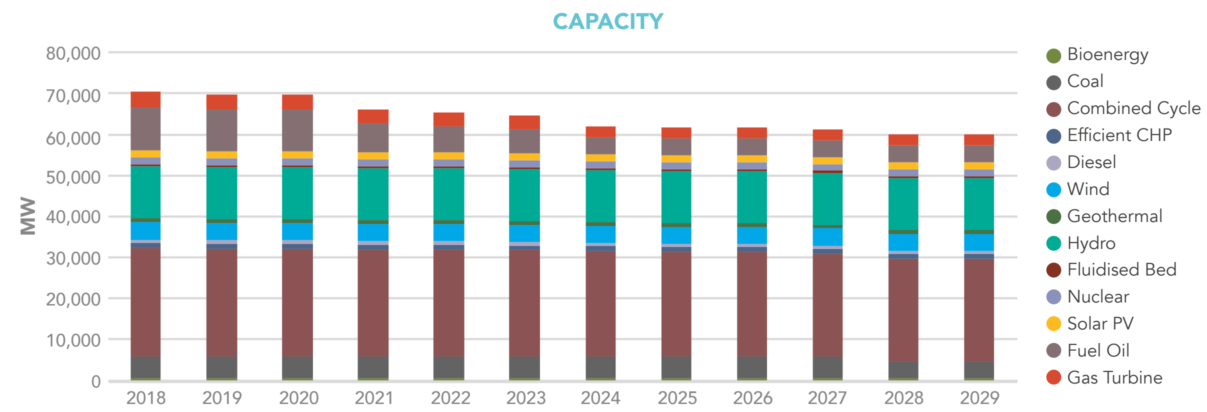


Figure 11. Evolution of the remaining capacity after the retirements

15 There are power plants that were programmed to be decommissioned by 2018 or 2019 but are still in operation.

16 This work did not the legal status of the power plants. This means that if in reality a power plant is not participating in the wholesale market but only generating and selling energy in terms of a contract signed before the LIE or through a power purchase agreement (PPA), the model considers it as any other power plant scheduled by CENACE.

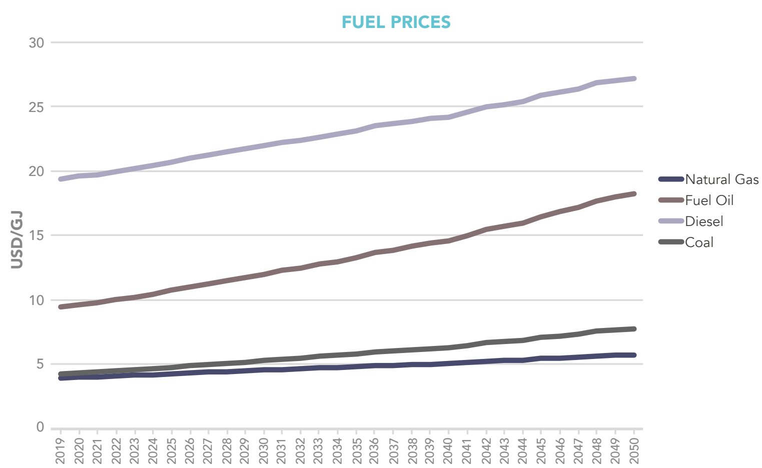
5.5.2.4. Economic assumptions

In this section, two economic assumptions are described: the fuel costs and the technology costs. It is worth mentioning that these parameters do not vary through the scenarios.

5.5.2.4.1. FUEL COSTS

The electric and the oil and gas sectors are closely linked since the fuels from the oil and gas sector are important inputs to the electricity sector. In the same way, fuel consumption is an important driver for the oil and gas sector. Fuel prices for natural gas, diesel, fuel oil, and coal are inputs that come directly from the study explained in Section 6. Figure 12 presents the evolution of fossil fuel prices

Figure 12. Evolution of fuel prices



5.5.2.4.2. TECHNOLOGY COSTS

Technology costs are one of the most important inputs to the model. These costs can be separated into three categories: construction costs, also known as capital costs (CAPEX); variable operation and maintenance (O&M) costs; and fixed O&M costs. Construction costs not only include the construction of the facilities, but also the engineering and development costs and the financing costs. The variable O&M costs are those incurred for all the required inputs of the power plant and they depend on the level of usage of the facility, or in other words, on the amount of generated energy. The fixed O&M costs do not depend on the generated energy as they must be paid even when the power plant is not operating such as wages. Usually, there's a correlation between these costs and the size of the plants. As this study is focused on the long-term planning, technological learning was identified as a relevant parameter to be considered. Hence, it was introduced as a progressive reduction of the construction costs (Figure 13). The technology cost data sources[17] were analysed and compared with the PRODESEN 2018-2032 to obtain the costs that best reflect the Mexican environment. Table 9 shows the technological costs for the electric generation technologies. It is worth mentioning that the O&M are for both the potential projects and the exogenous additions, while the construction costs are only for the potential projects.

Figure 13. Evolution of construction costs given by the technological learning

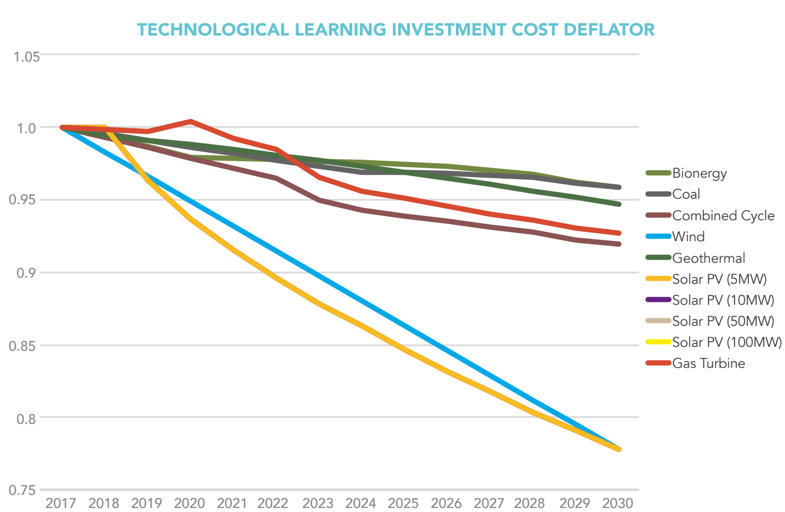


Table 9. Economic information of power plants

	CAPEX [USD/KW]	FO&M [USD/KW]	VO&M [USD/MWH]
Bioenergy	3989.8	111.7	5.6
Coal	2119.1	33.8	2.4
Combined Cycle	1159.7	19.0	3.3
Diesel	3342.8	46.4	5.2
Wind	1562.6	38.1	0.0
Geothermal	2114.8	105.1	0.1
Hydro	2316.1	24.4	0.0
Nuclear	6289.5	101.1	2.4
Solar PV (5 MW)	1515.4	10.7	0.0
Solar PV (10 MW)	1383.6	10.7	0.0
Solar PV (50 MW)	1229.9	10.7	0.0
S (100 MW)	1131.0	10.7	0.0
Fuel Oil	2391.5	35.8	3.0
CSP	7255.0	48.6	0.0
Gas Turbine	858.5	5.1	4.8

5.5.2.5. RENEWABLE ENERGY POTENTIAL

Renewable energy potential stands for both the projects that may be installed in each region and the short-term availability profiles for intermittent technologies. For the potential renewable energy projects, three information sources were consulted: The first one was

17 The LAZARD LCOE (LAZARD 2019), IRENA (IRENA 2018), and NREL (NREL 2019) publications.

the PRODESEN 2018-2032 in which the additional projects of the plan were considered. The generation permits issued by CRE and Federal Government information were also considered to identify renewable energy projects that are already in operation.

The second information source was the INEL (National Clean Energy Inventory), published by SENER that establishes a catalogue of projects that may be installed in the country. Each renewable energy potential is classified as proven (project in any stage of the construction work) or probable (identified potential without engineering or economic studies). Projects under the probable category were not considered for this study.

The third information source was the AZEL (the Clean Energy High Potential Zones Atlas), also published by SENER. Although, this also has a catalogue of potential projects that may be installed in the country, these projects are classified as probable. It is also important to mention that as a recommendation of the US National Renewable Energy Laboratory (NREL), the potential from AZEL taken to the model was reduced by 3.5% for solar and 25% for wind as that reduction corresponds to the exploitable potential.

The three information sources were analysed, refined and compiled to integrate a unique potential for renewable projects' catalogue for the model. Figure 14 shows the total capacity per technology that the model has the possibility to install as endogenous additions. This catalogue is the same for the two scenarios in this study.

As the short-term performance of the system is also important to define an expansion plan that could be operationally feasible, the short-term availability profiles of both intermittent renewable energy sources (wind and solar) were included in the model. Each hourly profile was estimated based on the profiles published in PRODESEN 2018-2032, and profiles from different sources including Imperial College London/ETH Zürich (2019), PVWatts (2019) or NREL Data Viewer (2019) and the information gathered from experts. The result is a forecasted wind and solar hourly profile for each region from 2019 to 2050 as shown in Figure 15 where the solar profile for 2019 in the Hermosillo region is shown. To see the hourly variation there's another example in Figure 16 where the wind profile for the first week of 2019 in Hermosillo is shown.

5.5.2.6. DEMAND FORECAST

Demand is the main driver of the model as it is the restriction that must be fulfilled. This parameter must not only be satisfied by the year but hour by hour. This study started by taking the historical load withdrawals of each load region as published by CENACE. This data corresponds to the hourly demand CENACE manages. As shown in Figure 17, every load zone has a particular behaviour, driven by factors such as the local temperature, the population, and the activity level.

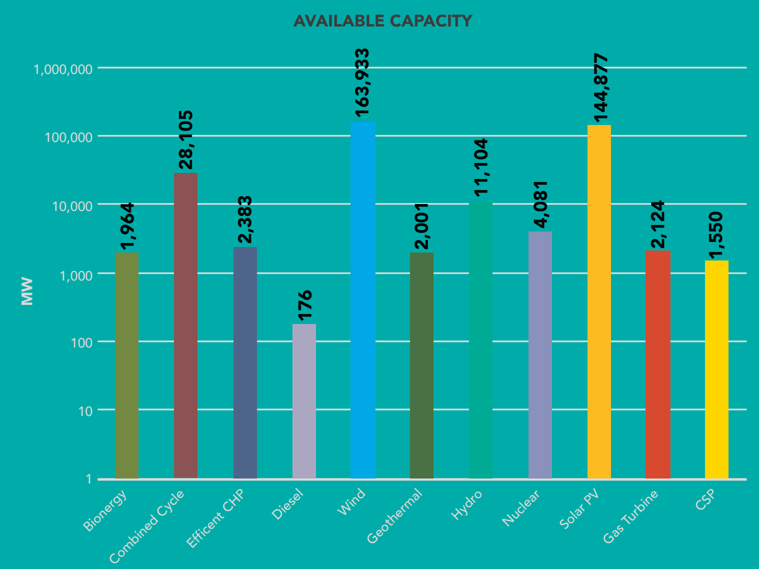


Figure 14. Renewable energy potential

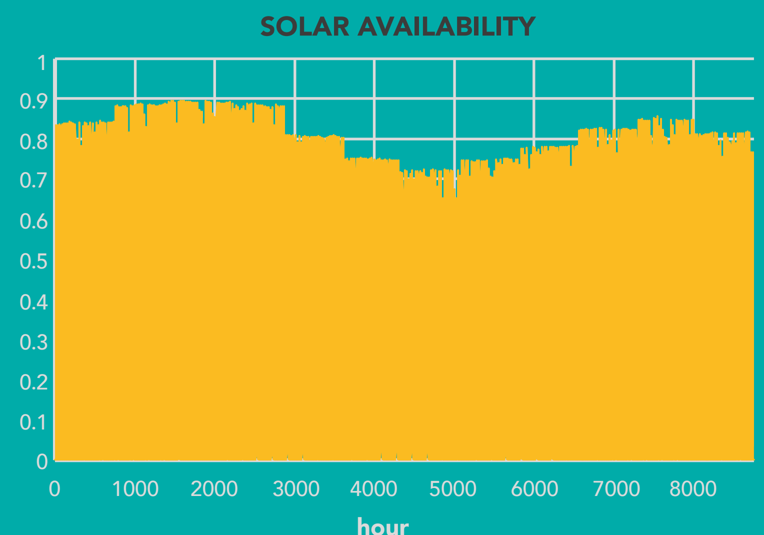


Figure 15. Short-term solar profiles for a whole year

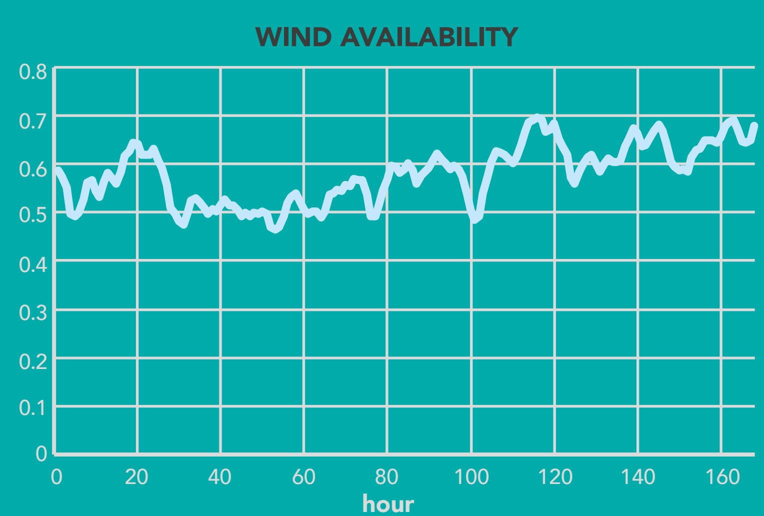


Figure 16. Short-term wind profiles for a single week

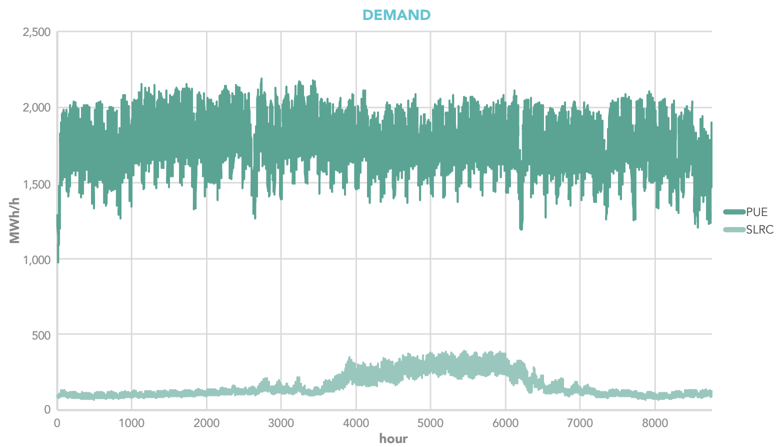


Figure 17. Comparison of load profiles

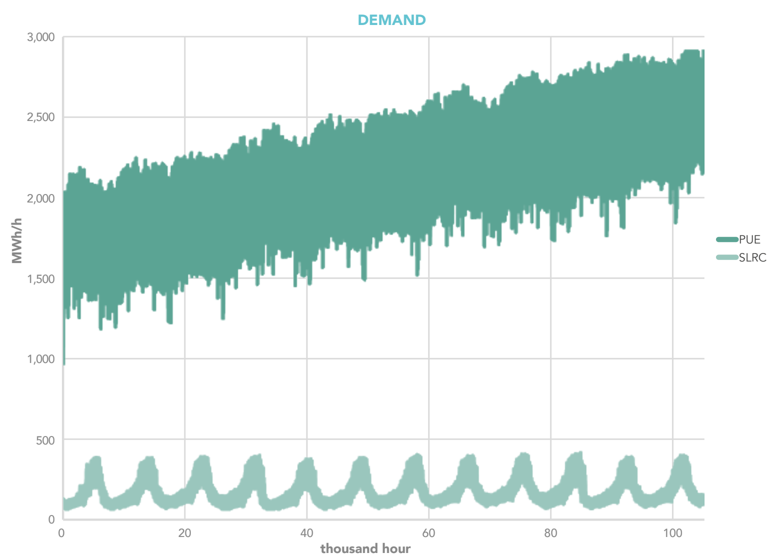


Figure 18. Hourly demand forecastprofiles

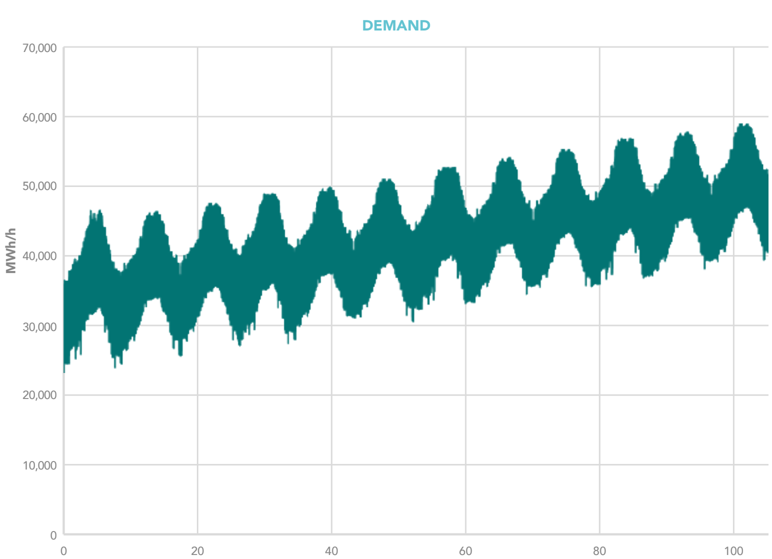


Figure 19. Demand forecast of the entire sector

It shows a comparison between two load zones with very different behaviours: PUE (Puebla) that corresponds to a city that has more than 1.5 million inhabitants, where the warm temperatures are very stable through the year; and SLRC (San Luis Rio Colorado) that is a smaller city with only 192 thousand inhabitants with a highest temperature summers in the country.

The demand forecast consisted of a statistical analysis using the available hourly data that goes from 2016/01/23 at 00:00 to 2019/12/19 at 23:00. After cleaning the data, the analysis decomposed the curve formed by those data into the trend, the median of the observations for the same day of the week of the same month for every year, and random noise. These three components are added in order to obtain a projection of the hourly demand. Figure 18 shows the demand forecast for the same two regions of Figure 17 from 2019/01/01 at 00:00 to 2034/12/31 at 23:00. It can be observed that as each region has its own performance, its projection of growth and performance is different as well.

After the determination of the demand forecast of each of the 108 load zones, they were grouped into the 53 modelled transmission regions. The annual energy demand for the whole country from 2019/01/01 00:00 to 2034/12/31 23:00 is shown in Figure 19.

It is important to mention that, although the demand forecast is the same for both scenarios, the impacts of distributed generation, storage, and electric vehicles are different from the Base scenario (S1) to the Decarbonisation scenario (S2). These impacts are further discussed in sections 5.5.2.7, 5.6.6 and 5.6.7.

5.5.2.7. ELECTRIC VEHICLES

As it may be seen in Section 7 of this work, electric vehicles (EVs) are one of the most important technologies in the decarbonisation of the transport sector. For the electricity sector, the energy demand has to be considered as it will increase as the EV fleet increases. Hence, this study takes the annual electricity demand given by the transport sector modelling in Section 7 and that is shown in Figure 20.

This annual electric demand, which is nationally aggregated, was split into the 53 transmission regions weighted by the vehicle-fleet[18] share by state and the number of transmission nodes within these regions. The share of vehicles per node was aggregated depending on the transmission region where each node belongs. Given the short-term characteristics for the modelling of the power sector, EV's charging behaviour is as important as the annual demand. Despite the fact that an EV is more likely to be charged after the returning-home trip —see (Nima, 2015)—, in this study, the EV profile was made by considering the findings

18 Light vehicles.

of Quiros-Tortos (Quiros-Tortos, 2019) where a) there are no significant variations across the seasons, only between weekdays and weekends, b) 70% of the EV charging occurs only once a day, and c) the probability of EVs charging in the same day is the one showed in Figure 21.

As a result of the previously mentioned considerations, the percentage of the maximum power demand if all the EVs were charged at the same time is showed in Figure 22.

Finally, this profile was combined with the distance travelled by vehicles, according to (ICM, 2019), and the share of vehicles in each transmission region to create the EV hourly profile so that it was added to the demand forecast described in section 5.5.2.6.

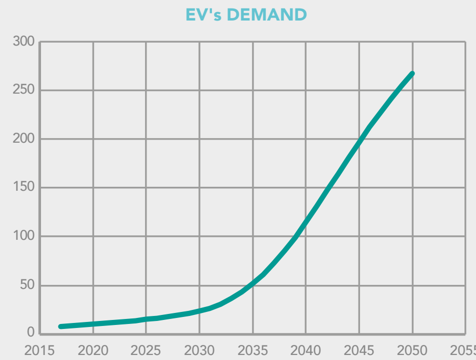


Figure 20. Electric vehicle demand of electricity

5.6. MITIGATION MEASURES

This section presents the different options that have the potential to reduce the GHG emissions if implemented. Here, the characteristics are described as well as what may be expected from them for the decarbonisation of the electricity sector.

5.6.1. SOLAR

This technology does not require any fuel consumption to produce power. It is expected to be one of the technologies with the greatest role in a carbon-free power system and, due to its lower costs, as a mitigation measure, it may be a cost-effective measure. Nevertheless, as it is an intermittent resource and its impacts on the power system short-term performance need to be addressed.

5.6.2. WIND

Similarly, to the solar, wind energy is carbon-free and it has the highest potential identified in this study. Therefore, it is also expected to be one of the most important generation technologies in the decarbonised electricity sector.

5.6.3. HYDRO

Although hydro is also renewable energy it has a minor potential, so, its role is expected to be lower than wind and solar. However, as it is a non-intermittent technology its contribution to the flexibility of the grid is an important feature to be considered.

5.6.4. GEOTHERMAL

Geothermal is a non-intermittent renewable resource. Nonetheless, as it depends on adequate geothermal sites, it has a very low potential when compared with wind or solar. This technology is expected to benefit the power system, although it doesn´t have particularly low

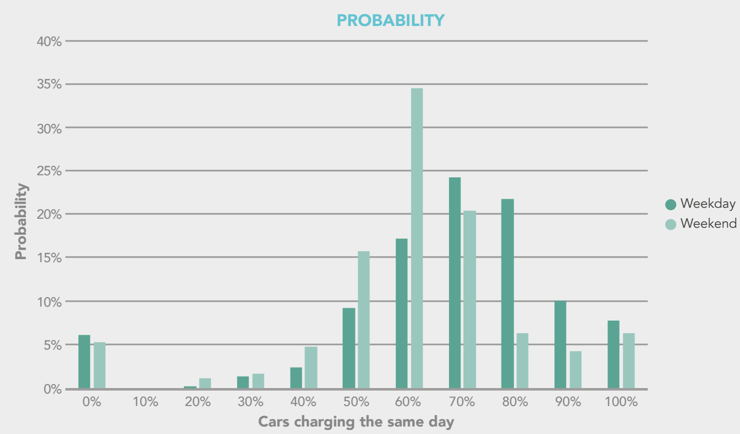


Figure 21. Probability of charging in the same day

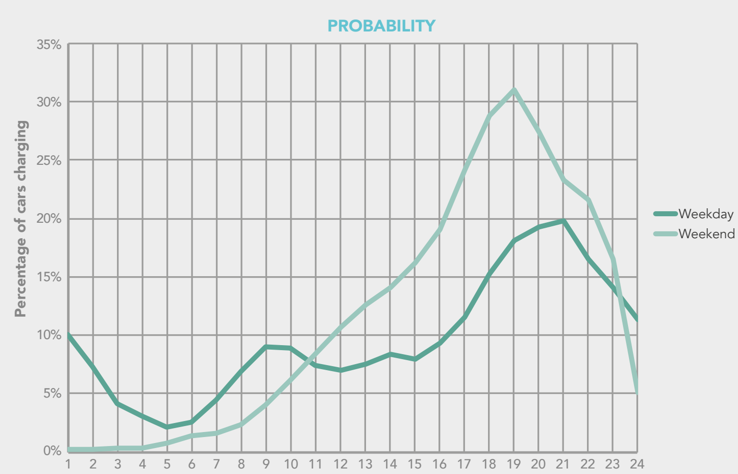


Figure 22. Electric vehicle charging

costs, but it has a capacity factor of nearly 90% which means it is available almost all year.

5.6.5. CONCENTRATED SOLAR POWER (CSP)

This technology is new for the Mexican system. As the management of intermittent solar energy is expected to be an important issue in the future, CSP could be a vital technology, despite its higher costs.

5.6.6. DISTRIBUTED GENERATION

Distributed generation (DG) is considered as a solar PV system under 500 kW of installed capacity that is connected to the distribution circuits[19]. For the purpose of this study, and due to the scope of the model that does not represent the distribution system, the effects of distributed generation are considered as a reduction of demand.

To determine the impact of distributed generation on demand profiles, the historical data of installed capacity for each state was taken as a base of the possible growth that was fitted to an S curve that considers the national potential of 16 GW for this technology.

In each scenario, although the potential is the same, the rate of adoption changes, being higher for the Decarbonisation scenario. Using the hourly solar profiles for each region, the energy delivered by the distribution generation systems was subtracted to the demand. Figure 23 shows the annual generation of DG in the country.

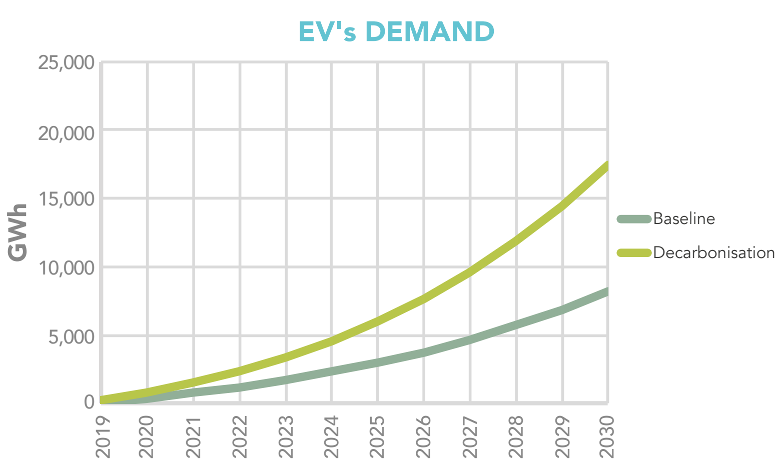


Figure 23. Annual generation of distributed generation sources

5.6.7. STORAGE

Energy storage systems will be treated according to current regulations, where they are not recognised in the Electricity Industry Law (LIE by its acronym in Spanish), as an activity of the electricity sector. In other words, currently an energy storage system has to be in the installation of the user or generator prior to the measuring equipment and cannot independently provide services related to the network or be operated by CENACE. Therefore, in scenarios S1 and S2 (first period) only storage facilities are considered according to the current regulation, while in the second period of S2, it is considered that the LIE is modified so that the storage systems are integrated as an activity of the National Electric System and can contribute to the system related services.

5.7. DECARBONISATION OF THE ELECTRICITY SECTOR

In this section, the decarbonisation measures and their integration in a single scenario are presented. Years 2030 and 2050 are the milestone in which the required level of each measure are analysed. Nonetheless, the pathway to be followed in order to decarbonise the electricity sector is also introduced. In the first part, as a matter of reference, the Baseline scenario results are given, in the second part, the baseline scenario will be compared with the results of the Decarbonisation scenario and also the implementation needed and its implications. Finally, the Marginal Abatement Costs (MAC) and the mitigation potential of the measures in the Decarbonisation scenario are presented.

5.7.1. BASELINE SCENARIO.

In order to measure what it is needed to decarbonise the electricity sector; the baseline scenario is required. In this scenario, the PRODESEN 2019-2033 capacity-addition-plan is replicated, as it was presented in section 5.5.1.1. This implies that for the 2019-2030 period, 59,242 MW should be installed with 21.6% of this capacity installed in 2019 and 18.3% in 2020. It is important to remark that a higher capacity is installed in the first two years, because it includes official plans of the Energy Secretariat (SENER), while installed capacity for the following years correspond to modelled additions. Figure 24 presents capacity additions for this scenario for each generation technology.

For the whole period, 55.5% of the additions correspond to renewable, 41.6% are fossil fuel technologies, and 2.9% correspond to other non-fossil energy technologies also known as clean. The generating capacity matrix changes from a 70% share of combined cycles, hydro and fuel oil in 2018 to a 74% share of combined cycles, utility-scale solar photovoltaic (PV), hydro and wind in 2030. These changes are shown in Figure 25 where it is clear that combined cycle will remain as the most important

19 According to the LIE.

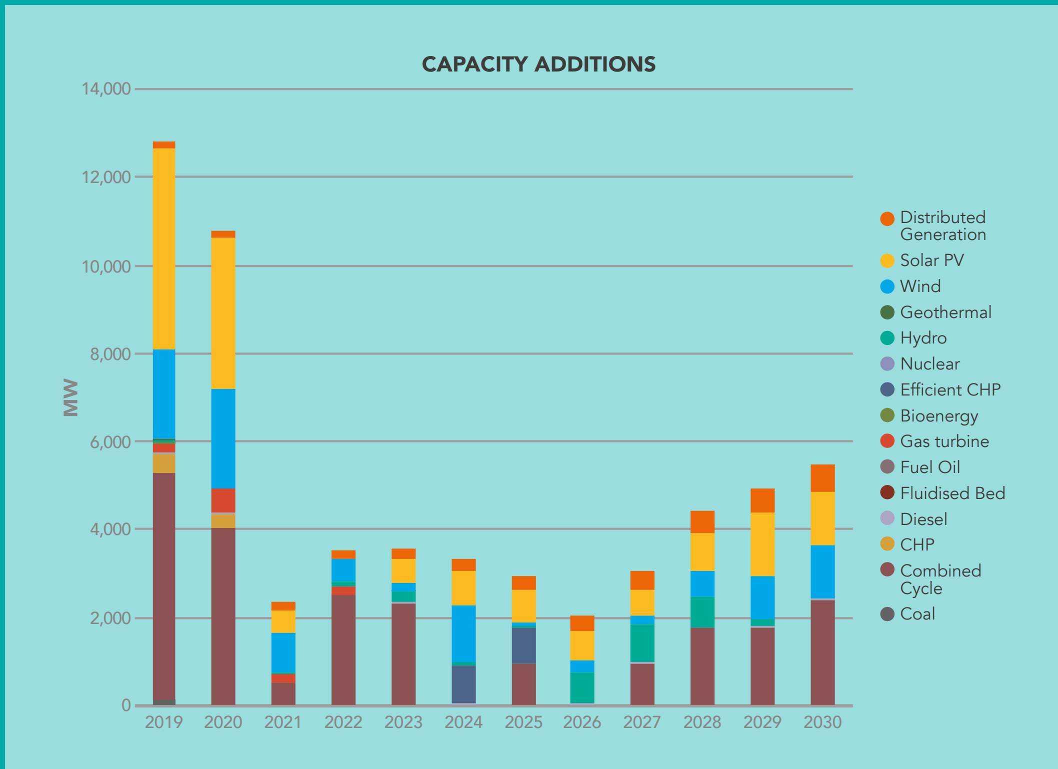


Figure 24.
Capacity additions
for the baseline

generating technology, increasing its installed capacity from 26,408 MW to 49,140 MW in 2030. Furthermore, it keeps its share in the generating matrix as it goes from 37% to 38% in the same period. Solar PV has the greatest increase, going from a 2% share of the installed capacity to 13% by increasing its capacity over ten times, from 1,664 MW to 17,109 MW. Wind also increases considerably from 6% in 2018 corresponding to 4,271 MW to 11% in 2030 with 14,764 MW. Hydro has a lower increase, going from 12,630 MW in 2018 to 15,555 MW in 2030. However, its share is still important decreasing from 18% to 12% in the same period. Fuel oil losses its share sinking from 15% in 2018 to 8% in 2030. However, its capacity installed (10,639 MW) remains the same. Coal increases due to a revamping in 2019 that adds 129 MW to the existing 5,378 MW. However, its share of 7% in 2018 falls to 4% in 2030. In the same way, gas turbines increase their installed capacity but lose their share. They pass from 3,713 MW (5%) to 4,852 MW (4%). Finally, it is important to mention that there are no retirements programmed in PRODESEN 2019-2032 plan.

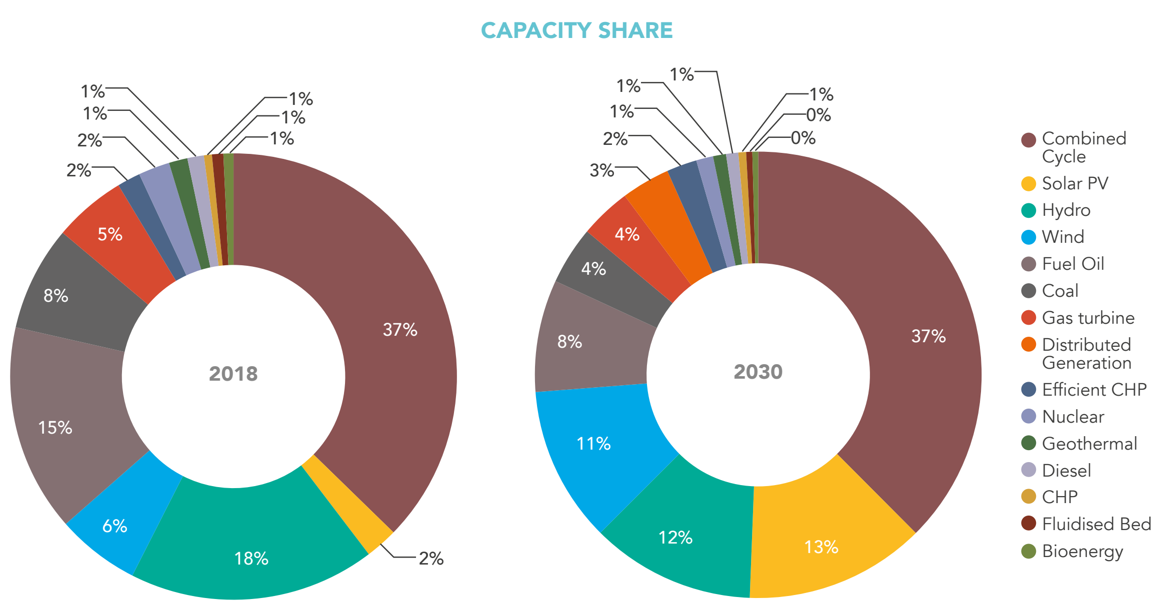
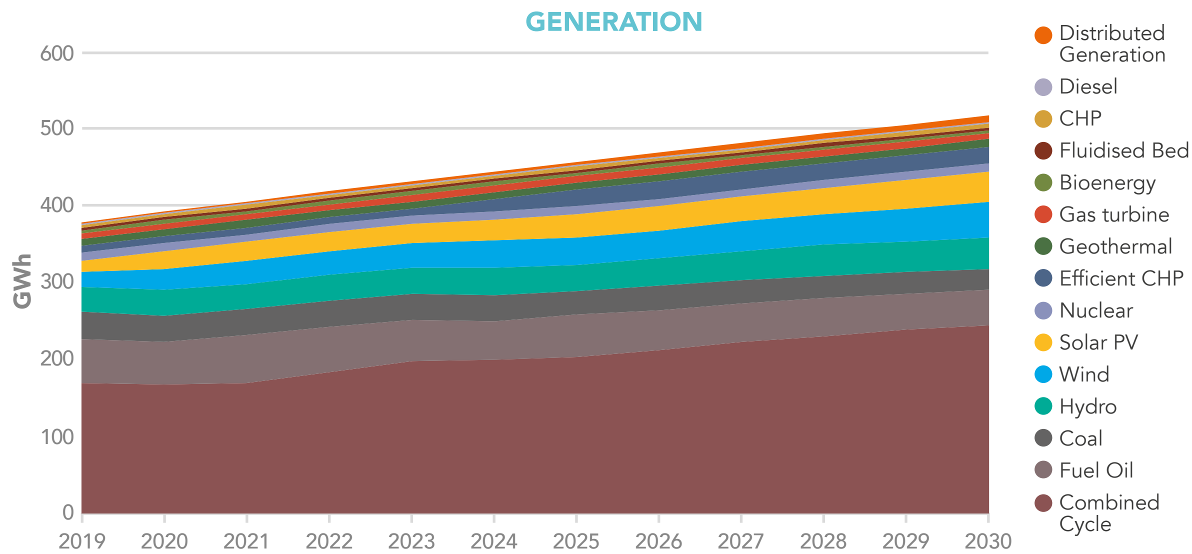


Figure 25.
Changes in
installed capacity
between 2018
and 2030

Figure 26.
Evolution of the electricity matrix



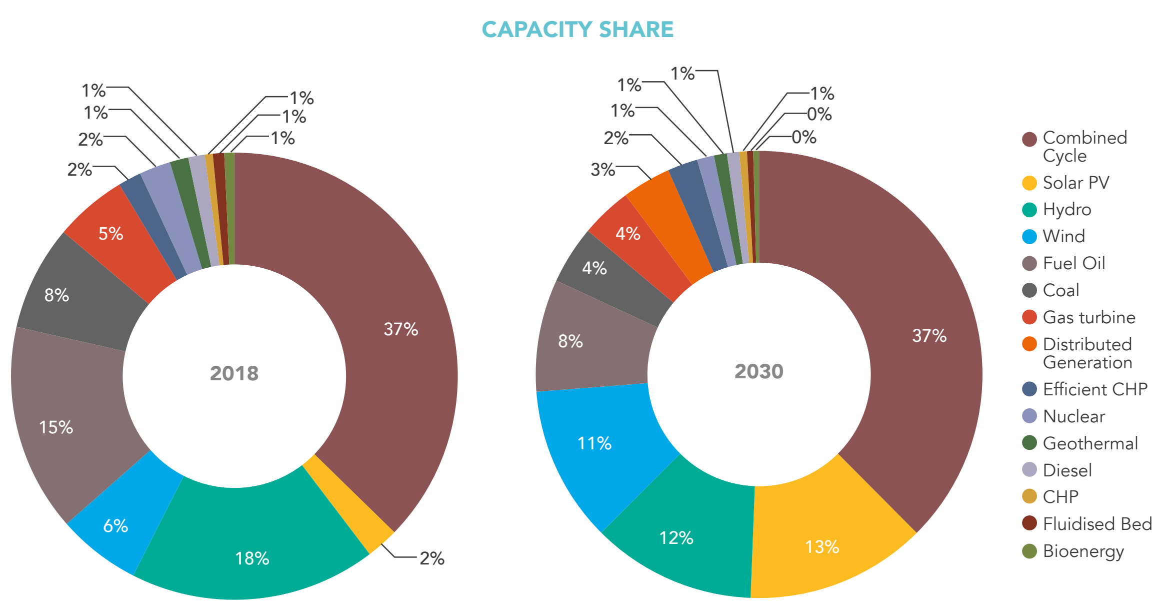
The generation of this scenario is the result of what the model considers the optimal way to use the power plants —and the transmission system— to satisfy the demand projection described in section 5.5.2.6. As it can be seen in Figure 26, combined cycle is the main generation technology and, alongside wind and solar PV, the one that most increases its generation. Fuel oil and coal reduce their energy production.

In fact, combined cycle produces 74.7 TWh more in 2030 than in 2019, reaching 244.3 TWh in 2030. Wind goes from 19.8 TWh in 2019 to 40.2 TWh in 2030, solar PV from 14.9 TWh to 40.6 TWh, and hydro from 32.3 TWh to 40 TWh in the same years. Other technologies that considerably increase their generation are distributed generation, from 1.7 TWh to 9.9 TWh, and efficient cogeneration from 9 TWh to 21.8 TWh. Coal and fuel oil reduce their electricity generation from 35.2 TWh to 27.5 TWh and from 56.7 to 46.5 TWh, respectively.

As Figure 27 shows, the contribution of combined cycle maintains around the same values, passing from 45% to 47%. Fuel oil is still the second largest technology in the matrix but losses 6% of the share while wind and solar PV pass from fifth and sixth place respectively to third and fourth, adding 4% each. Hydro goes down one place with 1% less and coal sinks to the sixth place from 9% of the share in 2019 to 5% in 2030

The diversification of the matrix, measured by the Shannon-Wiener Index is practically the same, with a small improvement as it goes from 1.889 in 2019 to 1.895 in 2030. GHG emissions do not reduce, as it can be seen in Figure 28. They are 7.5% higher in 2030 compared to 2019. This level of emissions does not comply with Mexico's NDC's for the Paris agreement in which the goal for 2030 was set in 139 $MtCO_2e$ which is 15% lower than the estimated baseline emissions.

Figure 27.
Changes in installed capacity between 2018 and 2030



The costs in this scenario are estimated in 182.9 billion USD for the whole period. From these costs, 30% correspond to investment costs, while fuel costs represent another 36%, and the remaining 25% are operation costs, as it is shown in Figure 29. The highest amount is spent in 2019 and 2020 when most of the investment is made with 15.7 and 13 billion USD, respectively. After that, the highest investment (5.3 billion USD) occurs until 2030. Fuel costs start in 5 billion, then they reach a maximum of 5.8 billion USD in 2028, and by 2030 they sum up to 2.6 billion USD. Operation costs start at 3.2 billion USD in 2019 and they end in 4.4 billion USD in 2030. Detailed tables of the corresponding investment, operation and fuel costs for each technology in every year may be found in the Annex.

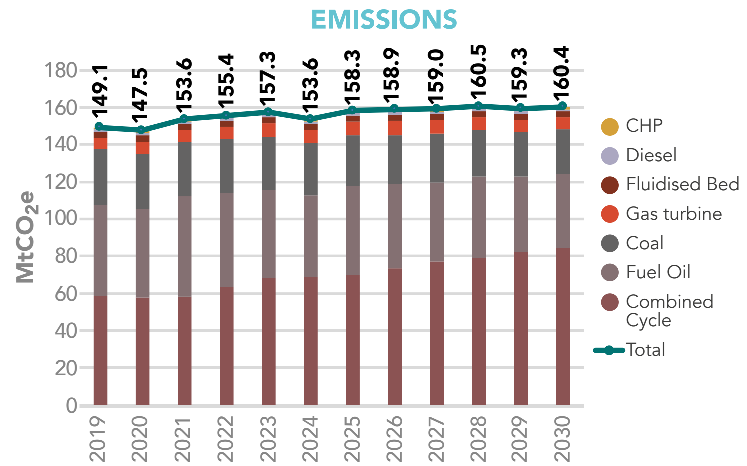


Figure 28. Greenhouse gas emissions for the baseline scenario

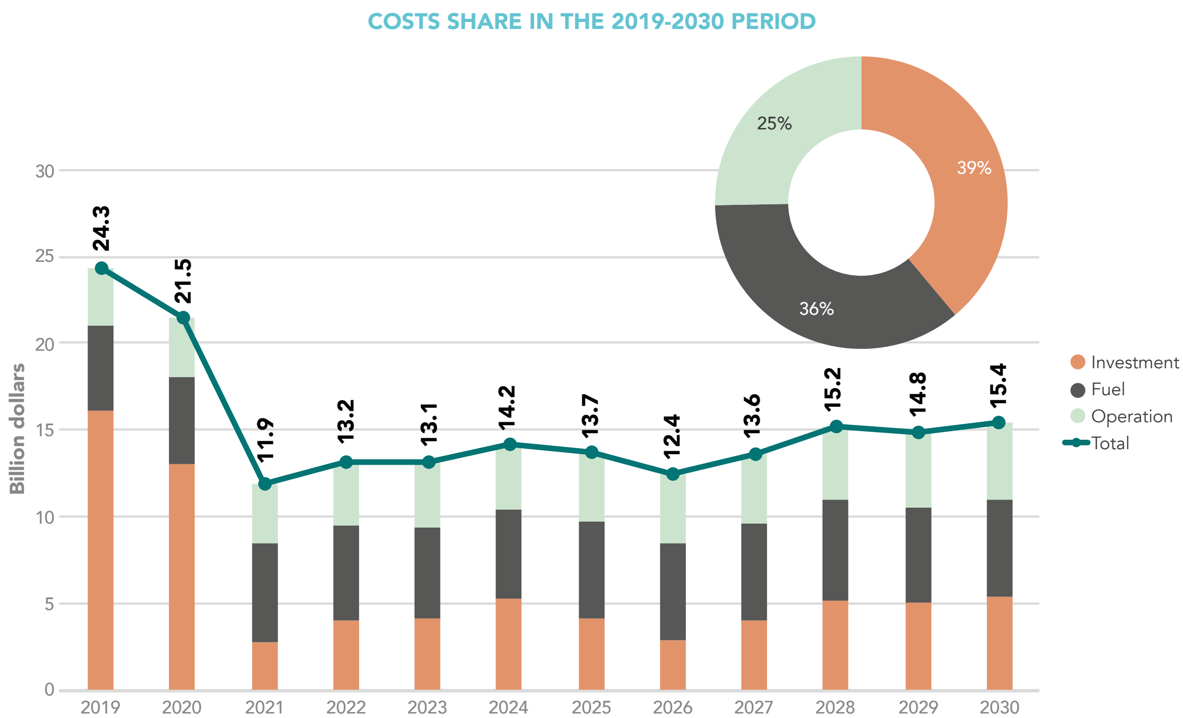


Figure 29. Costs of the baseline scenario

5.7.2. DECARBONISATION SCENARIO

5.7.2.1. DECARBONISATION TOWARDS 2030

The expansion plans of the Decarbonisation scenario are similar to the Baseline scenario for the first years of the simulation period because of the initial high increase imposed by the exogenous additions presented in section 5.5.2.3. In this scenario, capacity additions increase compared to the Baseline scenario because of the higher capacity required for renewable technologies. The total added capacity corresponds to 93,480 MW for the entire simulation period. As observed in Figure 30, during the first simulation years, capacity additions mainly correspond to solar PV, wind and natural gas combined cycles. The latter technology reduces its participation after 2027, with no new additions, the increase is replaced by solar PV and wind. The penetration of distributed generation gradually occurs from 103 MW in 2019 to 1,394 MW in 2030. The addition of fossil fuel-based technologies such as natural gas open cycles and diesel-powered engines are marginal.

In this scenario, for the 2019-2030 period, renewable energy corresponded to 80.4% of new additions while fossil-based technologies represented 16.2% and other non-fossil technologies 3.4%. In 2030, the energy matrix changes (Figure 31) and mainly includes 39 GW of natural gas combined cycles (27% of total installed capacity), 35 GW of solar PV (24%), 30 GW of wind (21%). The energy matrix also includes 17 GW of hydro, 9 GW of distributed generation while fuel oil and coal are no longer part of the matrix.

Figure 30. Capacity additions for the Decarbonisation scenario

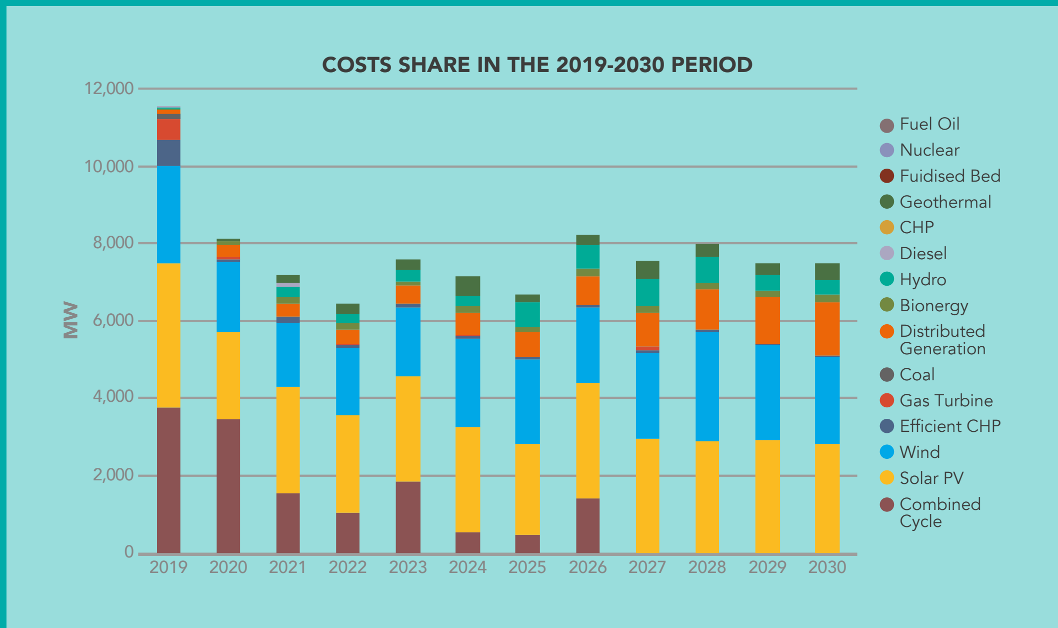
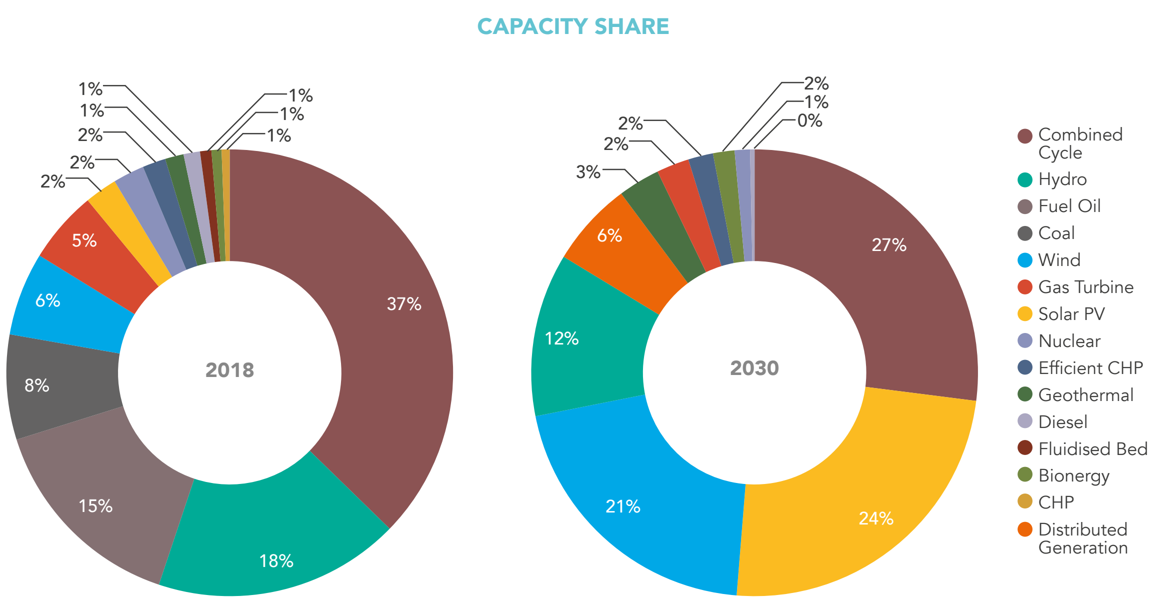


Figure 31. Changes in installed capacity between 2018 and 2030 for the Decarbonisation scenario



In comparison to the Baseline scenario, the Decarbonisation scenario takes into account the retirement of units with a high carbon intensity and with already expired economic lifetimes. As observed in Figure 32, the retirement of fuel oil and coal power plants were 10.6 GW and 5.5 GW, respectively for the 2019–2030 period. In the case of fluidised bed combustion, one unit of 280 MW is retired in 2021 while the other unit in 2023. The retirement of natural gas combined cycles corresponds to 1.6 GW, while 1 GW of open cycles and 105 MW of diesel combustion units are decommissioned. Foe geothermal, three units of a total of 60 MW are decommissioned between 2019 and 2021.

Figure 33 presents the evolution of electricity generation, and it can be observed that there is a transition from fossil-based technologies to renewable energy technologies. Natural gas combined cycles reach a generation peak in 2026 which declines and reaches 2020 and 2021 generation levels by 2030.

Figure 34 presents the comparison between the generation matrix of 2019 and 2030. Natural gas combined cycle technology generates 188.8 TWh increasing 28 TWh compared to 2019 levels. The participation of this technology reduces from 43% in 2019 to 37% in 2030. In this scenario wind generates 93.9 TWh (18% of total generation) in 2030 while solar PV generates 83.2 TWh (16% of total generation). Their

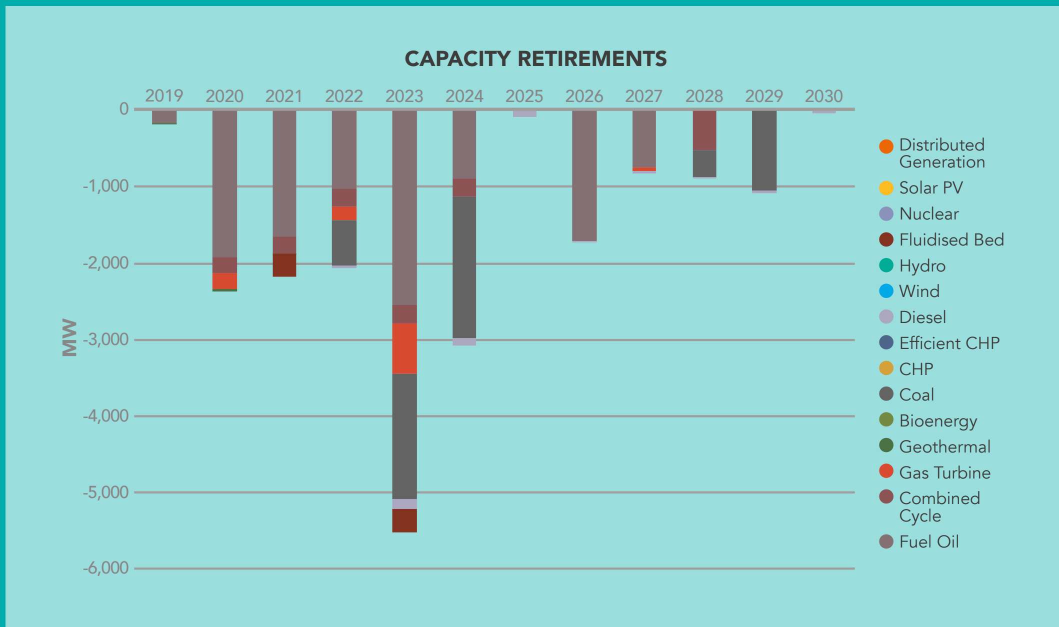


Figure 32. Capacity retirements for the Decarbonisation scenario

generation levels increased from 21 TWh and 12.8 TWh, respectively, in 2019. Hydro maintains its participation (9% of total generation) and its generation increases from 35.0 TWh in 2019 to 47.5 TWh in 2030. Geothermal energy increases its generation by four times, from 8 TWh to 32 TWh. Distributed generation presents the highest growth from 2 TWh in 2019 (1% of total generation) to 20.8 TWh in 2030 (4% of total generation). The case of bioenergy is similar, which increases from 4 TWh (1% of total generation) to 16.4 TWh (3% of total generation). CHP also increases its generation, from 11 TWh in 2019 to 15.8 TWh in 2030. Nuclear energy maintains its production of 10.2 TWh while open cycle gas turbines and diesel combustion systems reduce their electricity production.

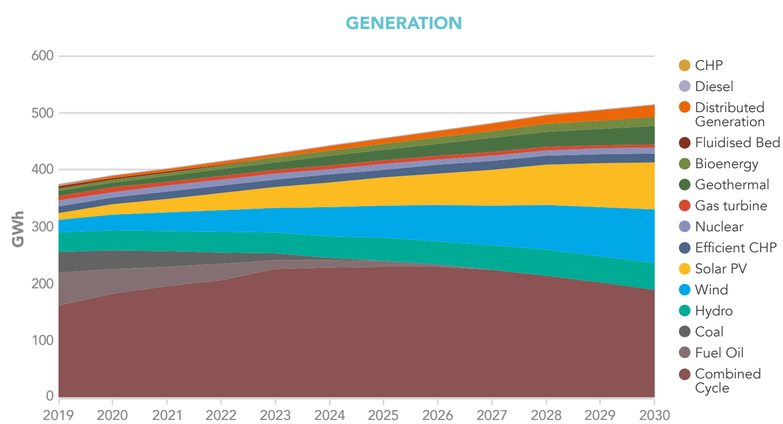


Figure 33. Evolution of the electricity matrix for the Decarbonisation

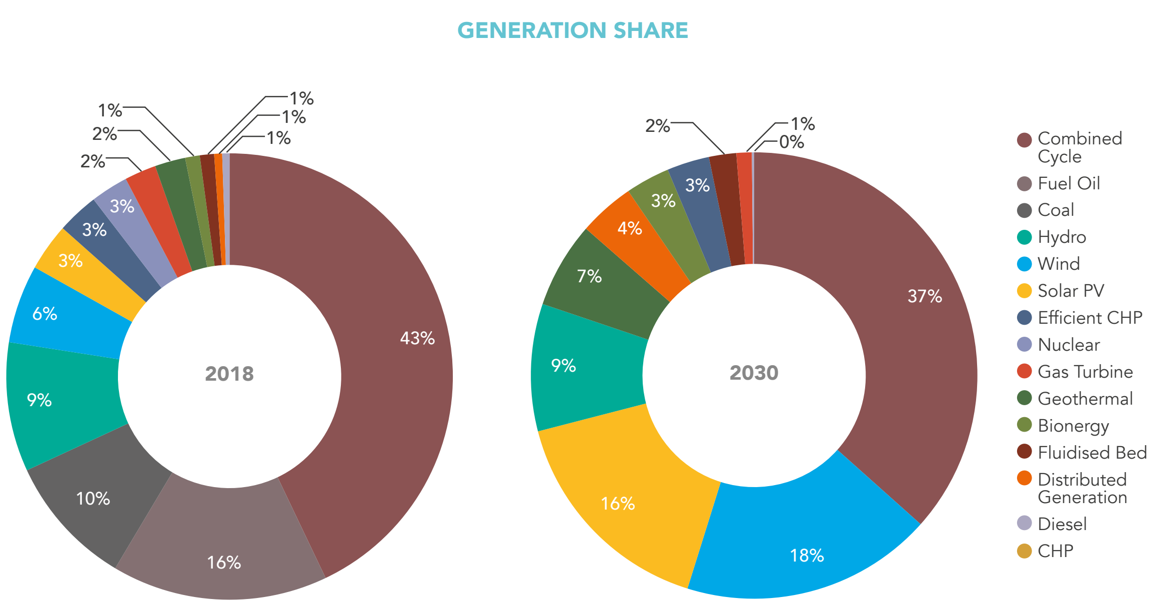


Figure 34. Evolution of the electricity matrix for the Decarbonisation

The diversification factor reduces from 1.90 in 2019 to 1.85 in 2030, because of the disappearance of fuel oil, coal and fluidised bed combustion technologies. As presented in Figure 35, carbon mitigation technologies considerable reduce GHG emissions with a growth rate of -6.4% per year. In 2030 GHG emissions represent less than half of GHG emissions in 2019.

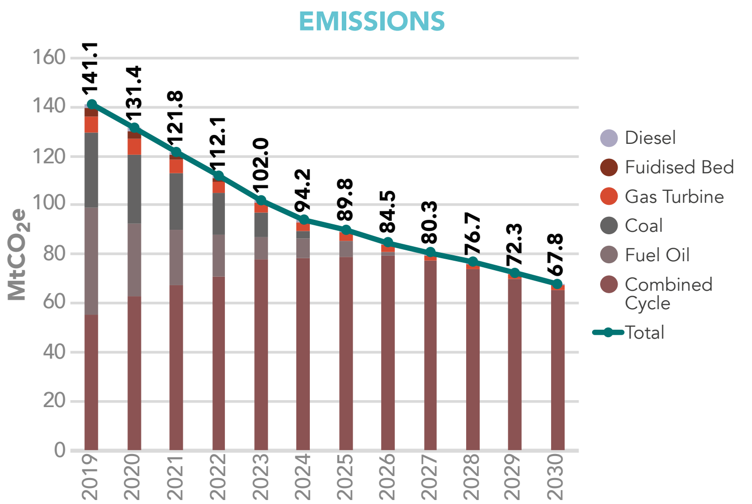


Figure 35. Annual emissions of GHG for the Decarbonisation scenario ($MtCO_2e$)

The estimated costs for this scenario amount to 192.5 billion USD for the entire period. From these costs, 57% correspond to investment funds while 34% to fuel costs and 9% to operation costs (Figure 36). Investment costs are higher in 2019 and were estimated in 15 billion USD with operation costs of 3.2 billion USD and fuel costs of 5 billion USD. By 2030, investment costs reduce to 7.8 billion USD while fuel costs reduce to 1.1 billion USD with an increase of operation costs to 4.5 billion USD. Detailed cost information is presented in the Annex of this document.

Implications of the mitigation measures

The comparative analysis of the scenarios shows the transition required towards a low carbon electricity sector. Figure 37 presents that renewable energy requires to double its participation (solar PV from 17 GW to 35 GW, wind from 14.7 GW to 29.9 GW and distributed generation from 4.6 GW to 8.9 GW). Additionally, bioenergy needs to increase by 1.7 GW. The penetration of fossil-based technologies has to decrease in 29.4 GW including 9.9 GW of natural gas combined cycles, 5.5 GW of coal and 10.6 GW of fuel oil. It is also required to reduce 242 MW of CHP.

The Decarbonisation scenario resulted in a total installed capacity that is 11% higher compared to the Baseline scenario. The reason for this is that the

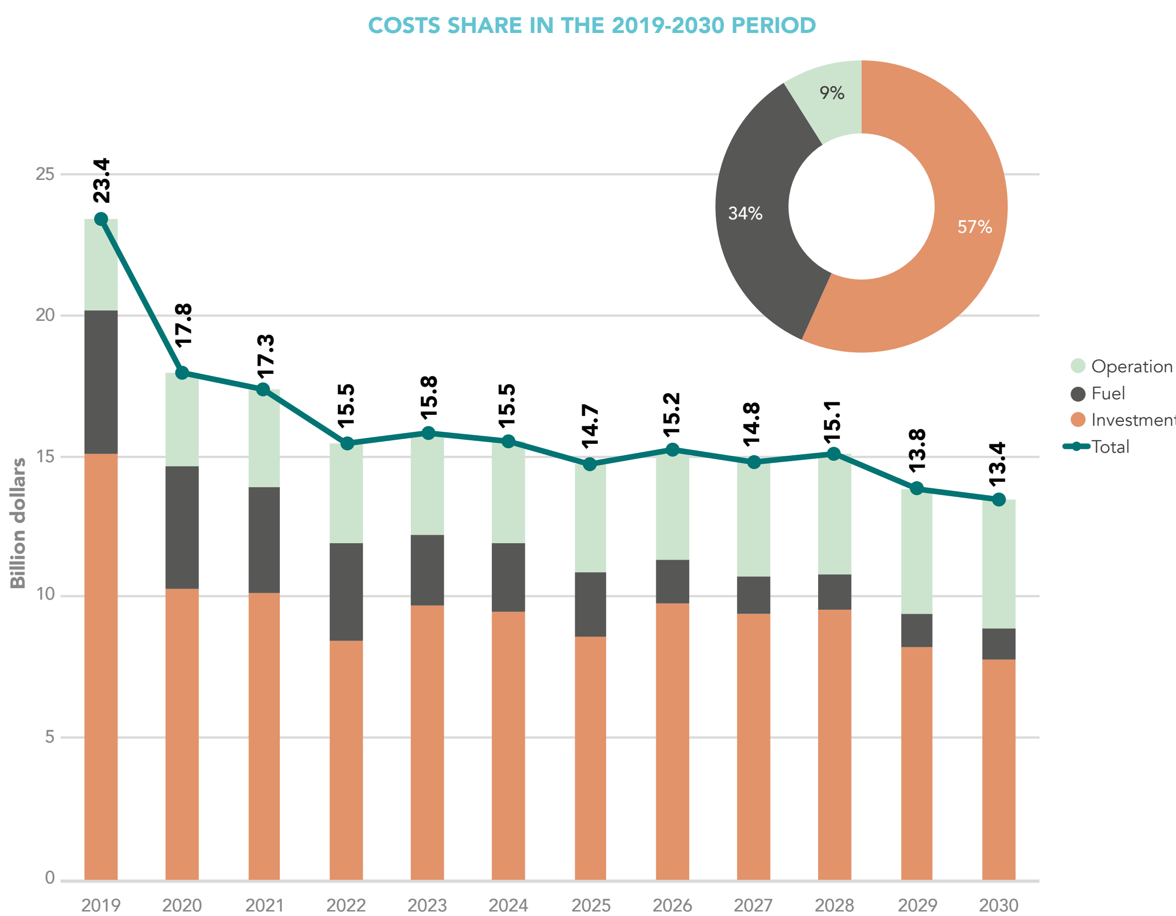


Figure 36. Total costs for the Decarbonisation scenario in billion USD

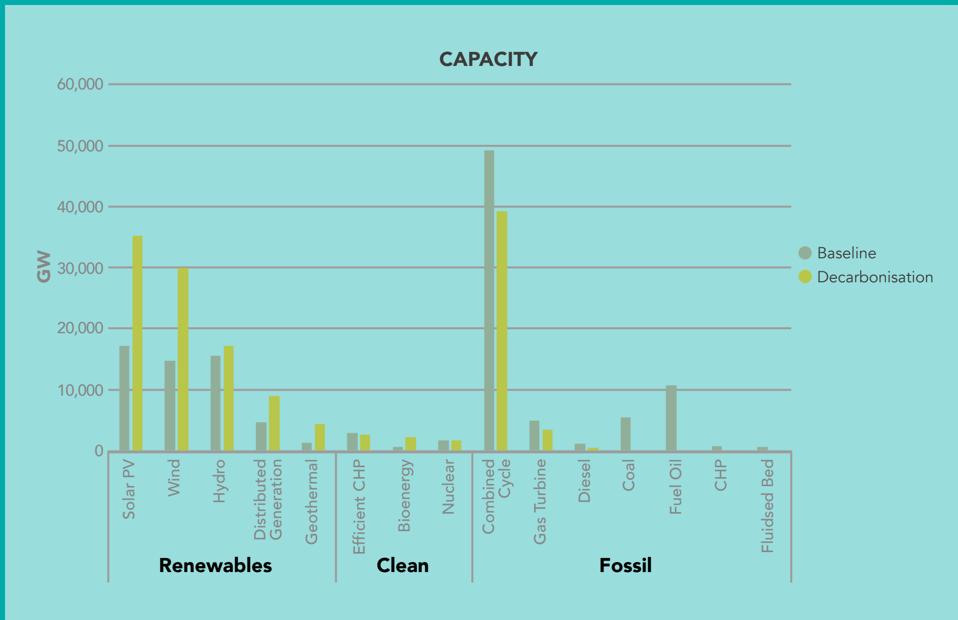


Figure 37. Comparison of the installed capacity in 2030

Decarbonisation scenario requires a higher penetration of renewable energy, includes the retirement of fossil-based technologies and a higher demand due to a higher penetration of electric vehicles (Figure 38).

The decarbonisation of the transport sector increases demand in the Decarbonisation scenario of the electricity sector. Electricity demand of electric vehicles could account for 23.7 TWh in 2030. The increase in the penetration of distributed generation could reduce distribution losses by reducing demand. In the Decarbonisation scenario there is an increase in transmission investment which reduces transmission loses by 33% compared to the Baseline scenario. Figure 39 presents the additional energy that has to be generated in order to cope with grid losses. As observed, the reduction of losses due to an increase in distributed generation penetration and an increased investment in transmission, compensates the existing losses in the Baseline scenario. The latter shows the importance of expanding the transmission network and distributed generation.

Investment in renewable energy is required in order to comply with carbon budget trajectory and must be doubled by 2030 generating 277 TWh covering 53.7% of demand. In the Baseline scenario, renewable energy generation corresponds to 146 TWh which is only 28.2% of total demand. In the case of non-renewable clean energy sources, an additional 8% is needed for the decarbonisation scenario which translates to 12% for the entire period. Additionally, it is required that fossil fuel generation technologies decrease their participation every year, so that by 2030 these technologies reduce 42% their participation in comparison to the baseline and 20% for the entire simulation period.

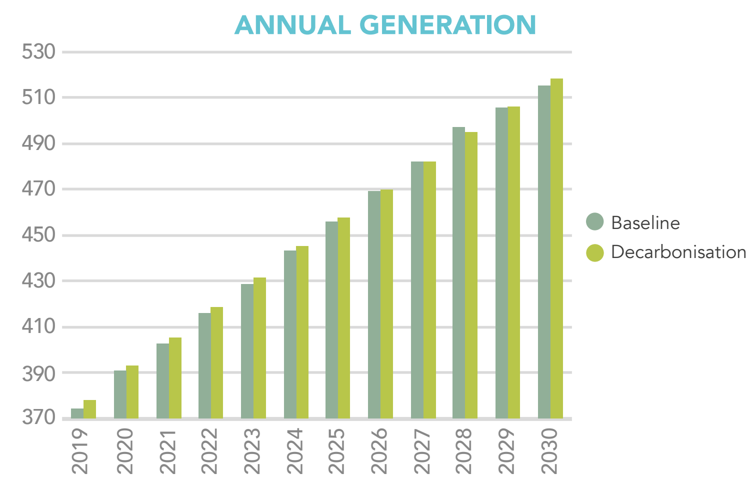


Figure 38. Comparison of the annual generation

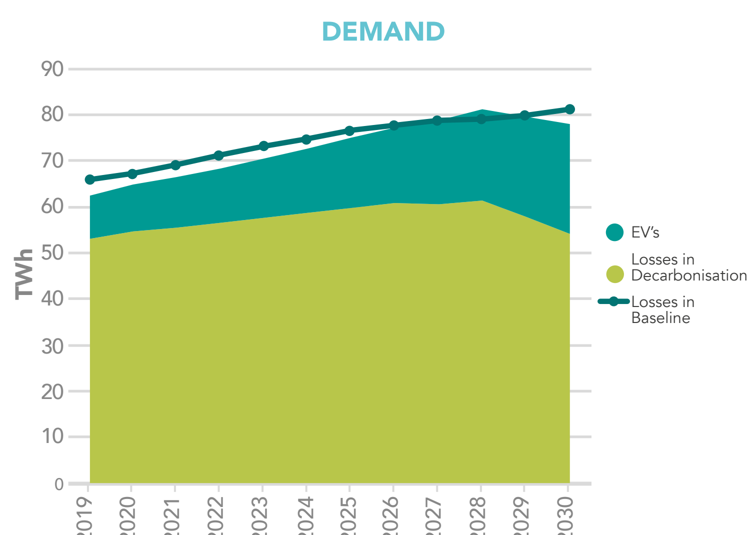
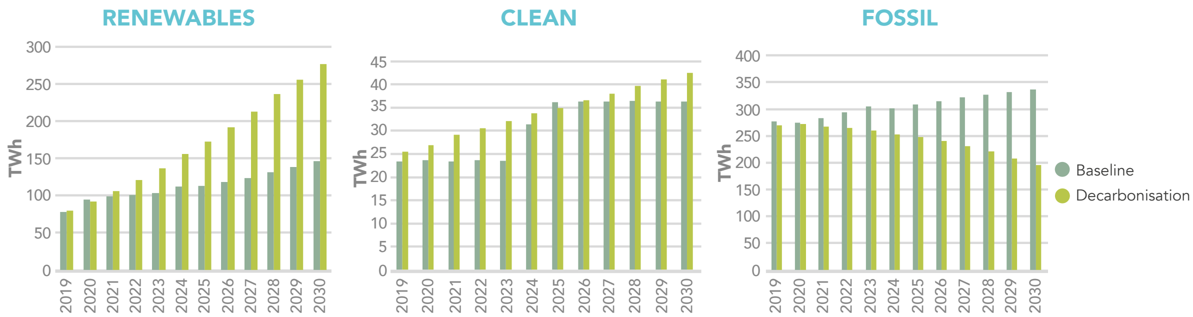


Figure 39. Comparison of the components of the demand that vary in each scenario

Figure 40. Comparison of the generation of renewables, clean and fossil energies



As previously observed, the Baseline scenario does not comply with the NDCs and remains far from the required carbon budget scenarios (both the 2°C and 1.5°C). However, in the case of the Decarbonisation scenario, emissions decrease and are lower than the NDC required emissions after 2021. In this scenario (S2), emissions are lower than the carbon budget scenarios after 2023 (2°C) and 2024 (1.5°C). The cumulative emissions for the Decarbonisation scenario are below the carbon budget by 64 MtCO2e for the 1.5°C scenario while the cumulative emissions remain below the 2°C scenario by 118 MtCO2e (Figure 41).

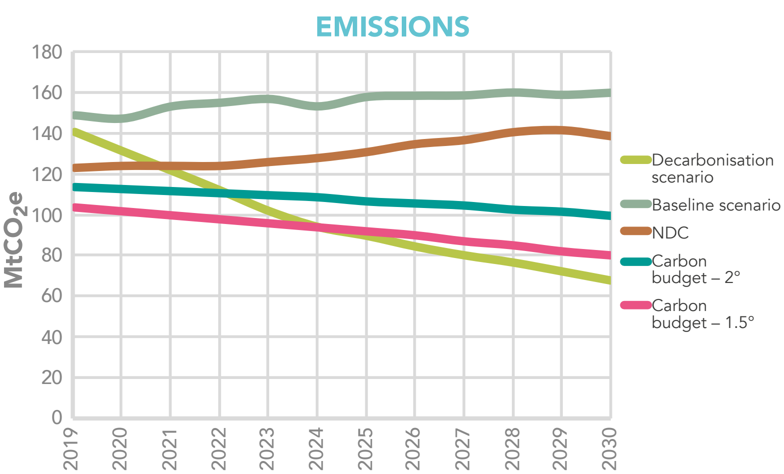


Figure 41. Comparison of the emissions

For the 2019–2030 period, in most years, the total costs of the electricity system are higher in the Decarbonisation scenario (Figure 42). Only at the beginning (2019 and 2020) and the end of the simulation period (2029 and 2030) total costs are lower in the Decarbonisation scenario. The total cumulative costs of the Decarbonisation scenario are only 5% higher in comparison to the Baseline scenario, by 9 billion USD (Figure 43). The reason for the latter relies on the fact that the required increase in investment of 45 billion USD is compensated by a decrease in operation costs that could be saved from avoiding the use of fuels. In the case of operation costs, they almost remain the same.

Operation of the power system in 2030

One of the main issues regarding the operation of a low carbon electricity system is related to the impact of a high penetration of renewable intermittent technologies. With this regard, the model used for this study can simulate the hourly operation of the system, satisfying demand with the combination of power plants that minimise operation costs and considering operational limitations of these plants. The economic dispatch model also considers transmission lines, and, in this case, curtailment issues are analysed. Curtailment refers to the reduction in intermittent energy due to the following reasons:

- The combination of the available intermittent technologies and the existing traditional sources have a larger generation in comparison to demand but conventional technologies cannot reduce their output due to operational minima.

- The transmission capacity is insufficient to handle the generation from renewable energy sites.

The following sections present two weeks of the year that present the lowest and highest demands in the system. The low demand week corresponds to January between the 1st and the 6th, while the high demand week corresponds to June between the 17th and the 23rd. The two cases represent a 168-hour week and show the operation of the system considering the National Electricity System (SEN) with its elements: The National Interconnected System, and the Baja California and Baja California Sur systems.

Operation in the SEN

The demand projections rely on three factors:

- This exercise does not consider changes in electricity consumption behaviour.

- Transmission and distribution losses.

- Electric vehicle demand (section 5.5.2.7) assuming a random vehicle charging.

Figure 44 shows the demand pattern for the minimum demand week. As observed, the lowest demand occurs at 5 am of the 1st of January with a demand of 43.7 GWh/h while the demand peak for this

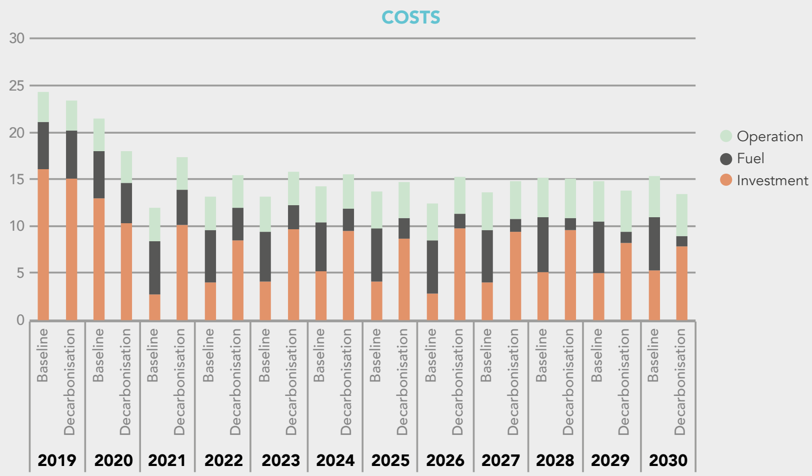


Figure 42. Comparison of the total costs by year

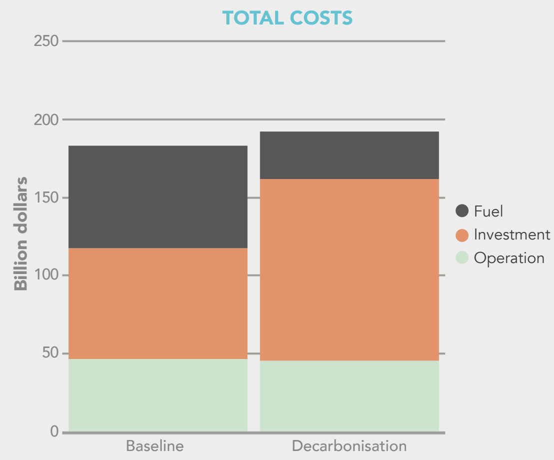


Figure 43. Comparison of the total period accumulated costs

week occurs on the 3rd of January at 8 pm with 62.7 GWh/h. Figure 45 shows the demand pattern for the maximum demand week. For this week, the demand peak corresponded to 6 pm on the 20th of June with 71.9 GWh/h. The lowest demand for this week was on the 23rd of June at 8 am with 57.7 GWh/h.

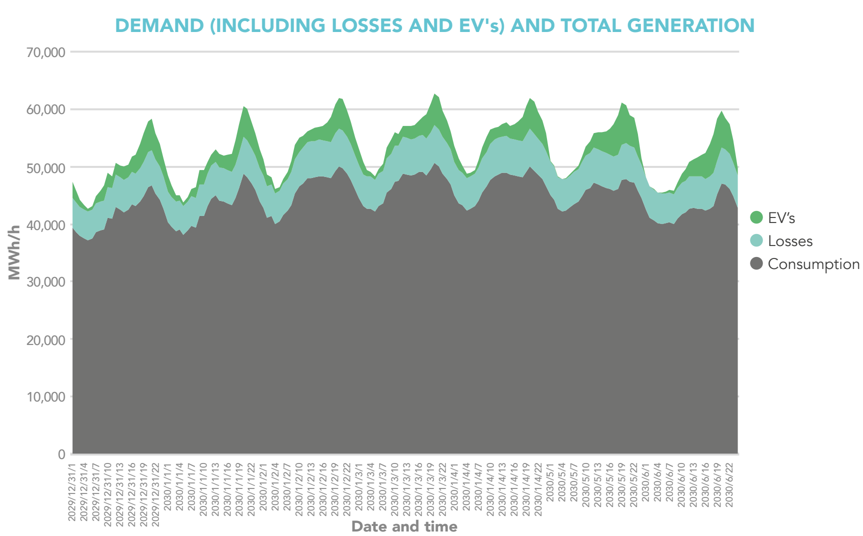


Figure 44. Demand components for the minimum demand week

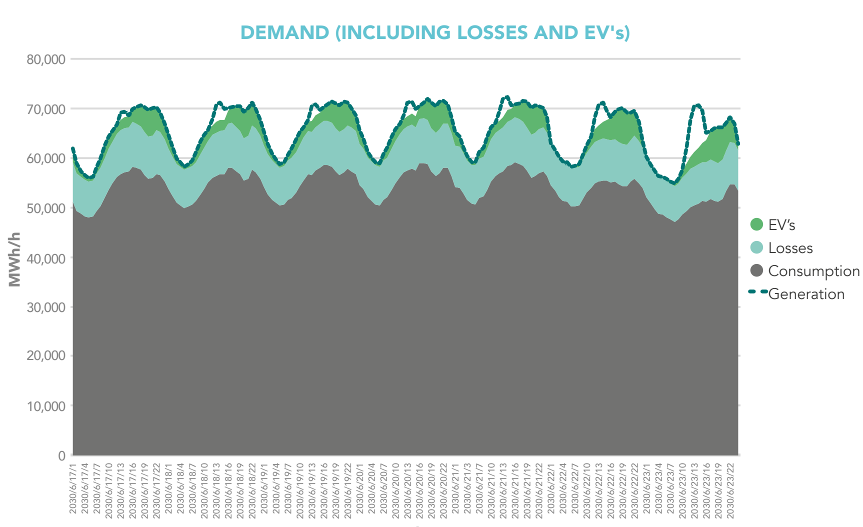


Figure 45. Demand components for the maximum demand week

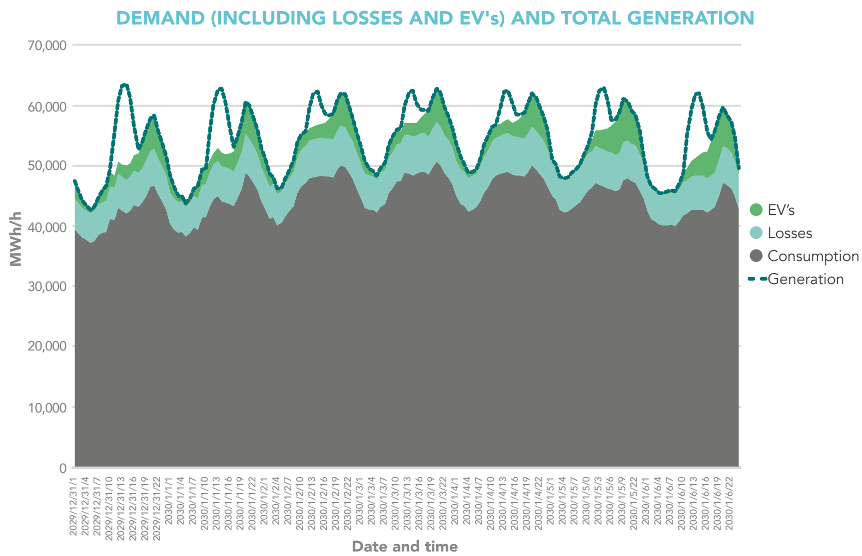
On the basis of the previous demand, Figure 46 presents the generation technologies required to cover the demand. As observed, there are hours of the week that have a higher generation in comparison to demand. Curtailment represents the gap between demand and generation.

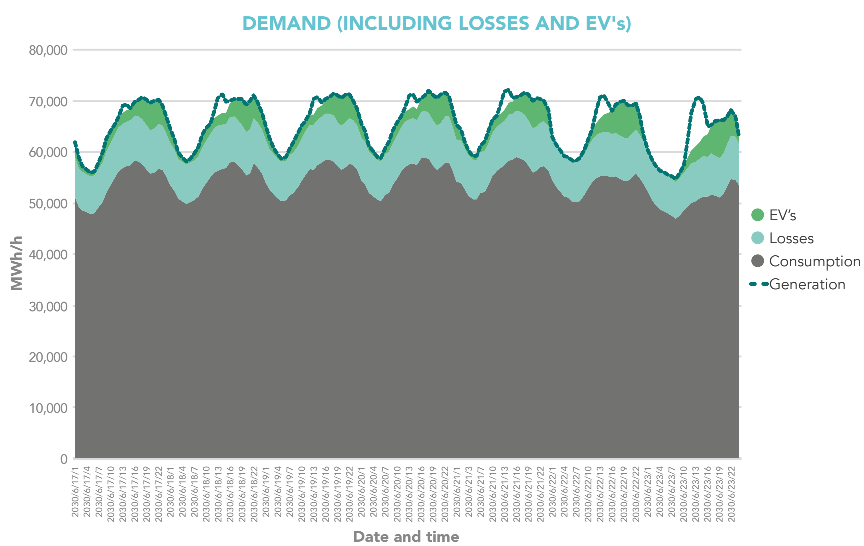
The generation curve shows that 20.8% of energy is generated from intermittent sources in the minimum demand case while this number corresponds to 18% in the maximum demand case. As observed in Figure 47, the introduction of solar PV and distributed generation reduces the generation from natural gas combined cycles in 10 GWh/h between 8 am and 11 am. In the evening, between 3 pm and 8 pm, this technology increases its participation by 18 GWh/h because solar technologies decrease their participation and demand increases (peak at 8 pm). In the case of the maximum demand, natural gas combined cycles reduce their participation by 15 GWh/h between 8 am and 1 pm and increase their participation by 20 GWh/h between 2 pm and 8 pm. Hydro produces approximately 18 GWh/h between 8 pm and 10 pm.

The maximum curtailment occurs in the same day with the lowest demand (1st of January) at 2 pm. In general, curtailment occurs between 10 am and 6 pm with a maximum at 2 pm (hours with sun). Solar energy (both PV and distributed generation) has the largest curtailment. In the case of the maximum demand case, the same patterns are observed. However, curtailment is lower in energy quantities and in hours since it is only necessary between 11 am and 5 pm.

An important factor in the need for curtailment corresponds to the difference between maximum demand and its previous level during hours of sun. Electric vehicle charging patterns affect demand, reaching a peak at 7 pm (see section 5.5.2.7). For the

Figure 46. Demand and generation





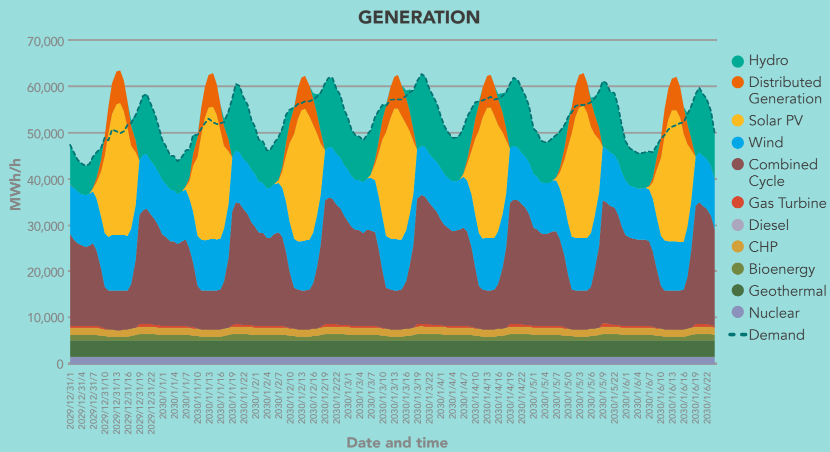


Figure 47. Generation matrix in the minimum-demand week

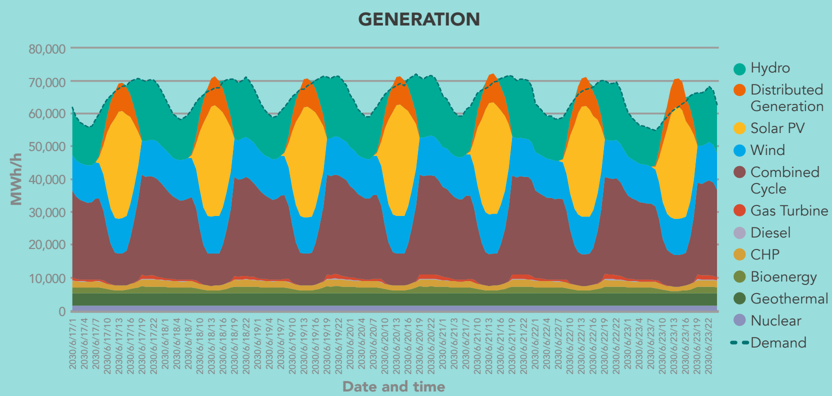


Figure 48. Generation matrix in the maximum-demand week

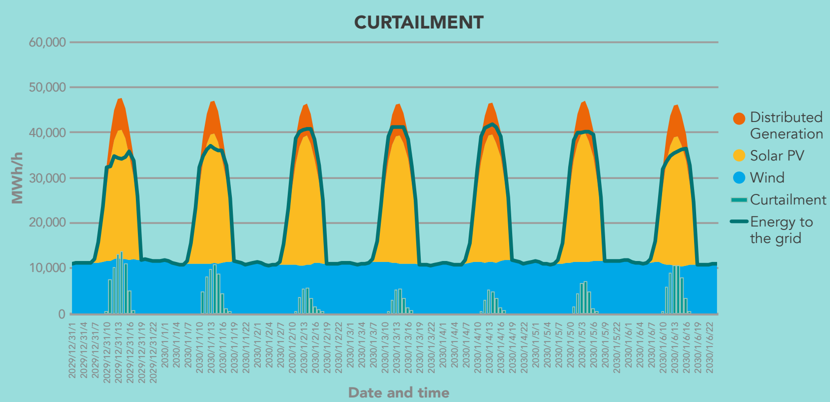


Figure 49. Curtailment in the minimum-demand week

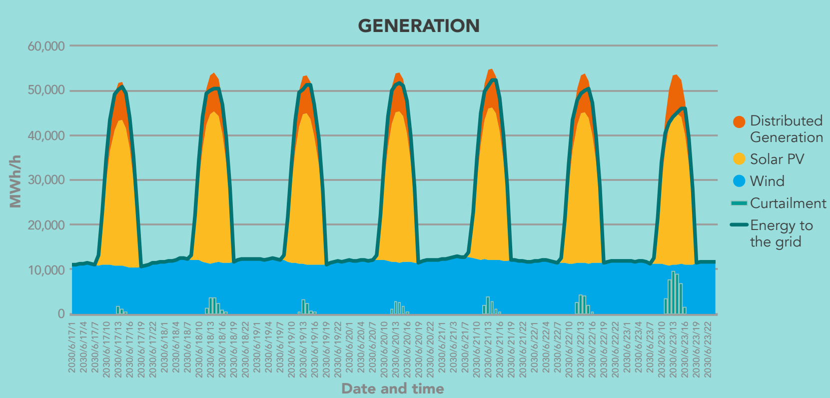


Figure 50. Curtailment in the maximum-demand week

SEN, (Figure 46) demand has a maximum value of 7.2 GWh/h at 7 pm and one hour later, electric vehicle charging requires 6.4 GWh/h. The blank space between the dotted line and demand, represents the amount of energy that has to be reduced. However, this energy could not be reduced if there are elements that could increase the flexibility of the network. There are several technologies that can contribute to the latter including energy storage technologies such as batteries or hydro, or regulatory mechanism that could act on vehicle charging and flatten the curve.

Operation in BC

The electricity system in Baja California (BC) is a small system compared to the SEN. As shown in Figure 51, the minimum load corresponds to 2–7 GWh/h on the 2nd of January at 4 am and a maximum load of 3.7 GWh/h on the 5th of January at 7 pm (electric vehicle charging is at a maximum). In the case of the maximum demand (Figure 52), the minimum load occurs on the 18th of June at 7 am with a demand of 3.1 GWh/h, while the maximum load occurs on the 22nd of June at 6 pm and corresponds to 4.7 GWh/h.

As observed in Figure 53, solar generation is responsible for having an electricity supply of 1 GWh/h higher than demand during the hours of sun (12 pm and 6 pm). For the maximum demand week, this supply excess is lower. However, as observed in Figure 54, at evening, it is necessary to add 805 MWh/h to cover the demand peak. In both cases, geothermal serves as a baseload technology, while most of the demand is met by using solar PV and natural gas combined cycles, with a baseload generation of 513 MWh/h in the minimum demand case and 627 MWh/h in the maximum demand case.

Given the fact that the Baja California system is isolated, during the minimum demand week, curtailment is considerable for each day, as seen in Figure 55. In this system, solar PV represents the most important intermittent technology, while distributed generation and wind have a small participation in the system. Curtailment closely follows the solar supply curve.

Figure 51. Demand components in the minimum-demand week in BC

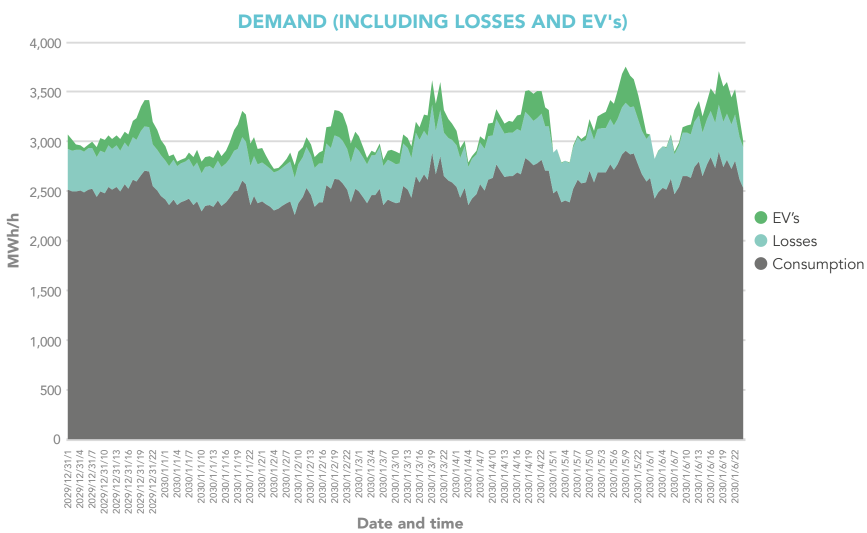
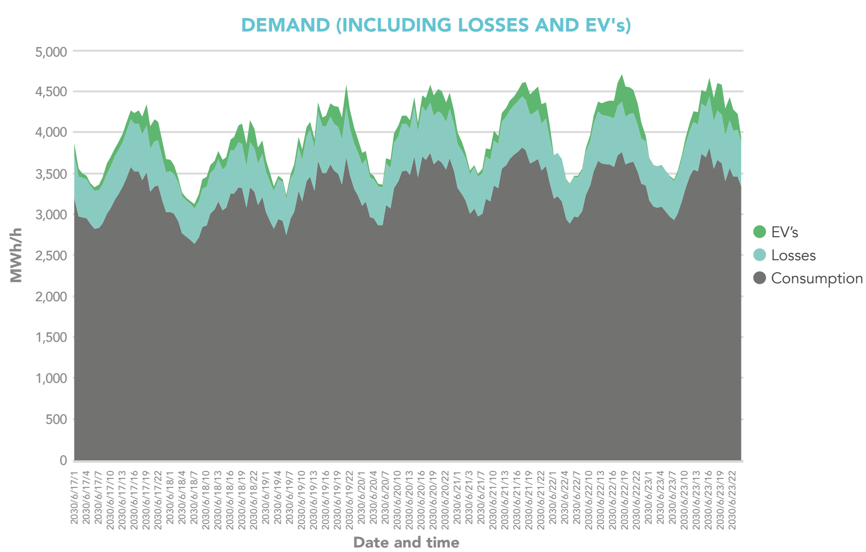


Figure 52. Demand components in the maximum-demand week in BC



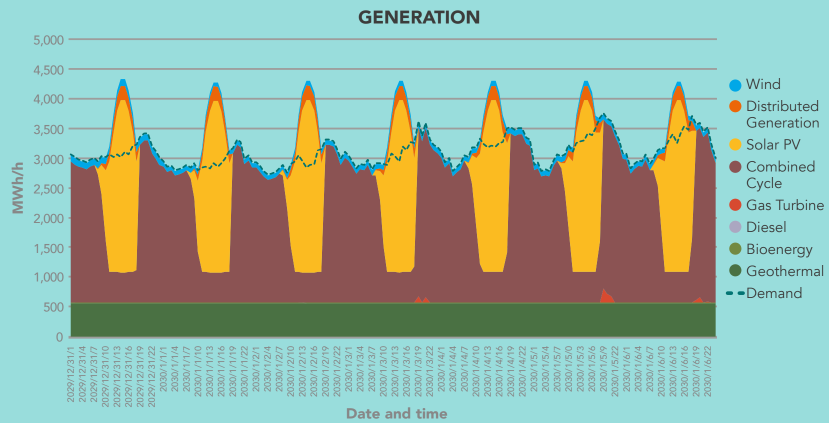


Figure 53. Generation matrix in the minimum-demand week in BC

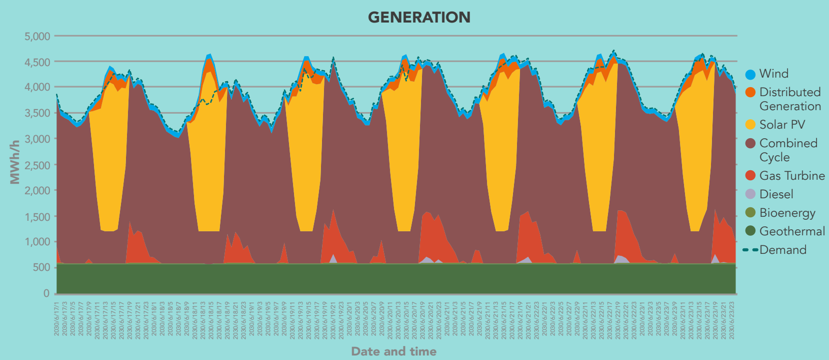


Figure 54. Generation matrix in the maximum-demand week in BC

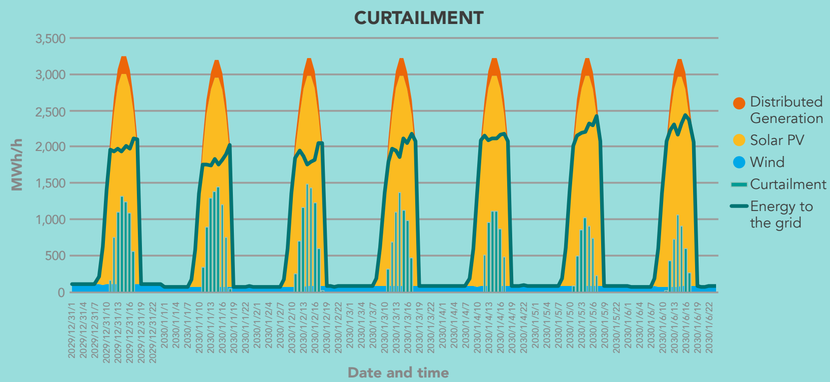


Figure 55. Curtailment in BC system in the minimum-demand week

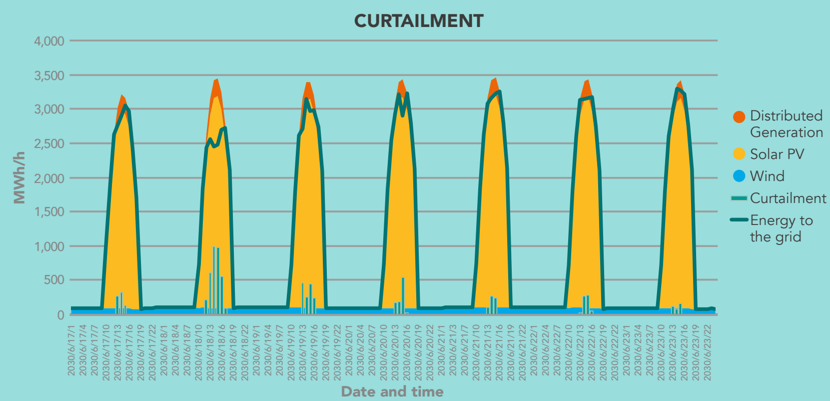


Figure 56. Curtailment in the BC system in the maximum-demand week

In total, during the week, it is necessary to reduce 39.5 GWh with a maximum of 1.5 GWh/h a 2 pm. For the maximum demand week, the highest curtailment corresponds to 976 MWh/h at 2 pm on the 18th of June (Figure 56).

Operation in BCS

The electricity system of Baja California Sur (BCS) is a smaller system in comparison to Baja California, and its demand is one third of Baja California's demand. The demand in this system is not larger than 1 GWh/h. In the case of the minimum demand week, the maximum demand was 920 MWh/h on the 6th of January at 8 pm while the minimum demand was 747 MWh/h on the previous day at 5 am. In the maximum demand case, the peak took place on the 22nd of June at 6 pm at 1,132 MWh/h while the minimum demand was 952 MWh/h in the same day at 8 am. As observed in Figure 57 and Figure 58 maximum and minimum daily values have a low variability. Furthermore, as in Baja California, there are two peaks in the same week. In the case of the minimum demand week, there is only one peak and there is a higher difference between the demand during hours with sun and peak demand during the night.

Generation in BCS is similar to BC. Geothermal is an important technology that serves as a baseload technology in both weekly cases. As there are no combined cycles in BCS, gas turbines substitute solar PV (this technology generates most energy during the day) and given its fast response capability, they shut down while solar PV operates. At night, gas turbines enter the generation matrix and reach approximately 500 MWh/h. For the maximum demand week, gas turbine capacity is not enough to cover demand and diesel combustion systems enter the system reaching 195 MWh/h (Figure 59 and Figure 60).

The curtailment in BCS in the minimum demand week occurs every day, with a maximum of 270 MWh/h at 2 pm (Figure 61). In the case of the maximum demand case curtailment is lower and the maximum is 162 MWh/h at 2 pm as well (Figure 62).

Figure 57. Demand components in the minimum-demand week in BCS

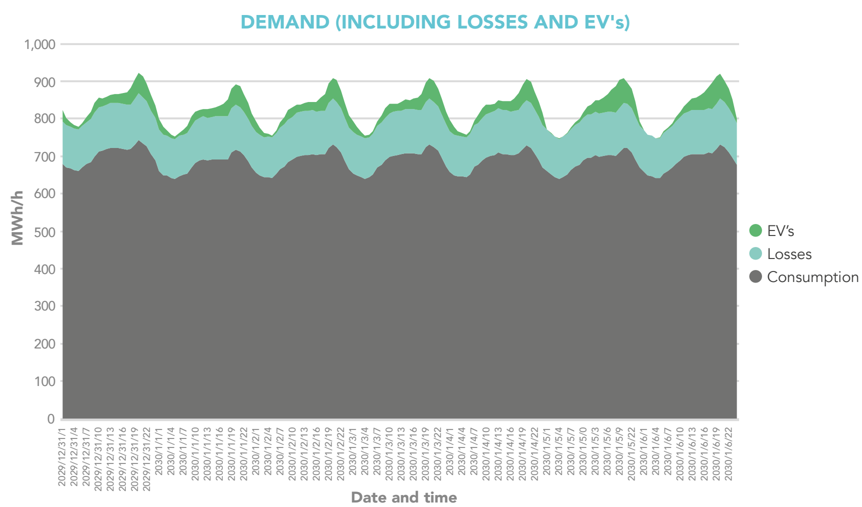
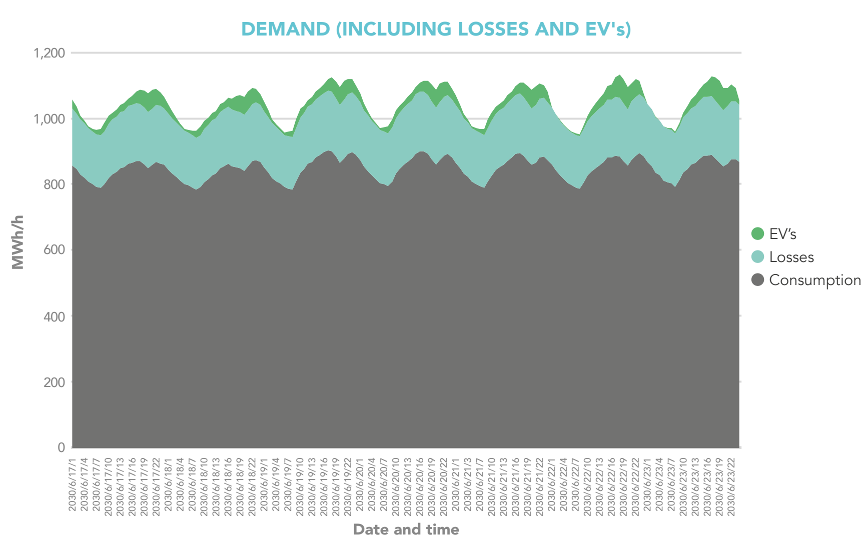


Figure 58. Demand components in the maximum-demand week in BCS



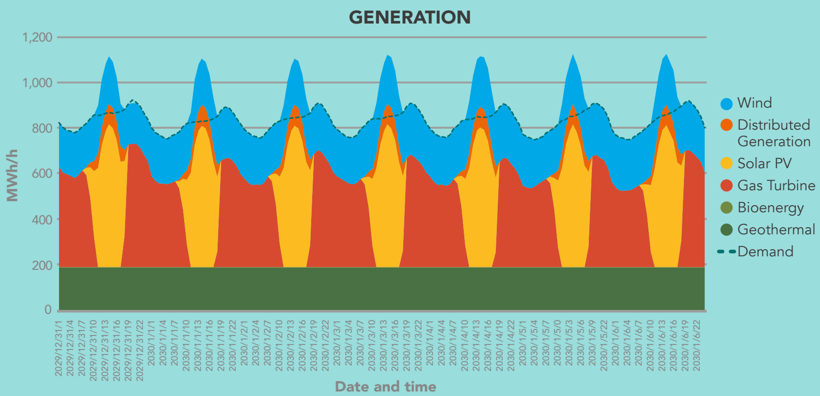


Figure 59. Generation matrix in the minimum-demand week in BCS

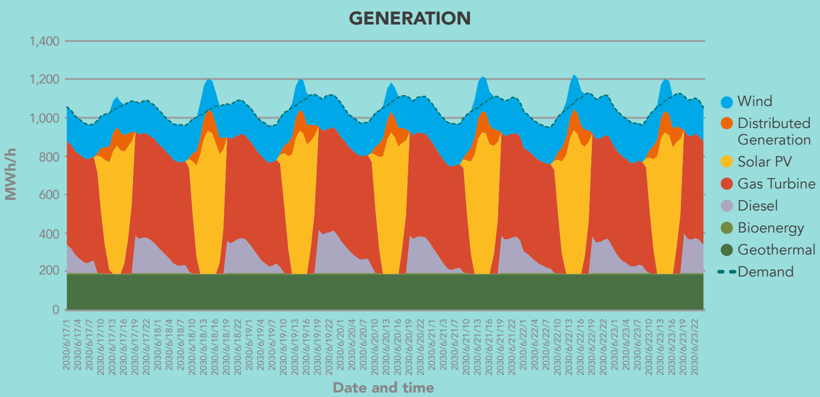


Figure 60. Generation matrix in the maximum-demand week in BCS

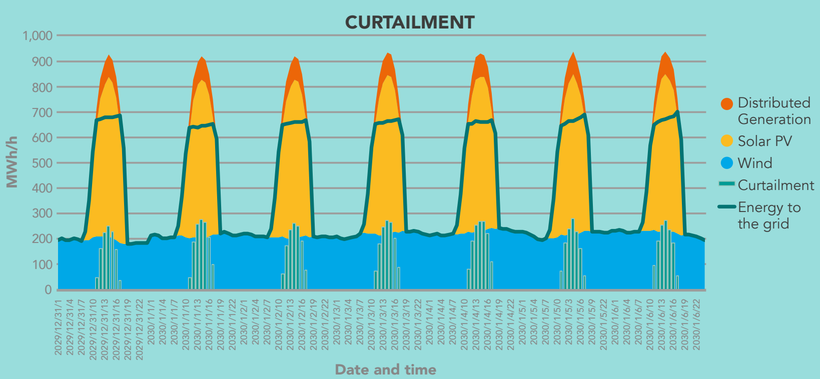


Figure 61. Curtailment in the BCS system in the minimum-demand week

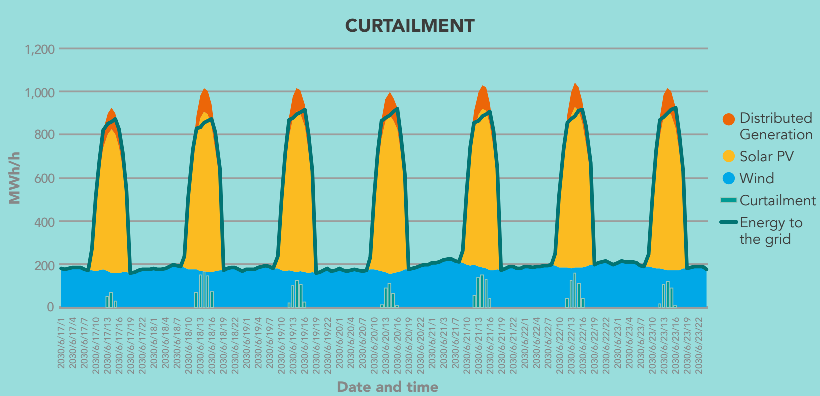


Figure 62. Curtailment in the BCS system in the maximum-demand week

Natural gas turbines provide flexibility to the system, because of their fast response contrary to natural gas combined cycles which cannot be shut down and started in a fast way. While curtailment in the BC system for the maximum demand week is 4.5% of electricity generated by intermittent sources (solar, wind and distributed generation), for the BCS system corresponds to 3.6%. In the case of the minimum demand week, curtailment represents 22.4% in the BC system and 12.1% in the BCS system. In these systems, investment in natural gas turbines could be an alternative to natural gas combined cycles, reducing the need to increase transmission lines.

Operation in the SIN

The National Interconnected System (SIN), corresponds to all the interconnected regions without the BC and BCS systems. In the minimum demand week, the peak takes place on the 3rd of January at 8 pm with 58.4 GWh/h. The minimum demand occurs on the 1st of January at 5 am with 40.2 GWh/h (Figure 63). In the case of the maximum demand week the peak occurs on the 20th of June a 6 pm with 66.3 GWh/h while the minimum occurs on the 23rd of June at 8 am with 50.3 GWh/h (Figure 64).

In the case of the SIN, solar PV is not the dominant technology as in the isolated systems and there is a higher diversification of the electricity mix. Nuclear and geothermal are baseload technologies while bioenergy and CHP have daily variations. Hydro and natural gas combined cycles adjust their generation so that the compensate for reductions in generation when solar PV and distributed generation are not operating. These latter technologies contribute to a maximum of 25 GWh/h at 2 pm. During the day, wind remains within the 10.6 and 11.1 GWh/h generation margin. In the case of natural gas combined cycles, they generate a minimum of 9 GWh/h at 2 pm and a maximum of 23.8 GWh/h at 8 pm. Hydro generated 14.4 GWh/h to satisfy peak demand (Figure 65). During the maximum

Figure 63. Demand components in the minimum-demand week in the SIN

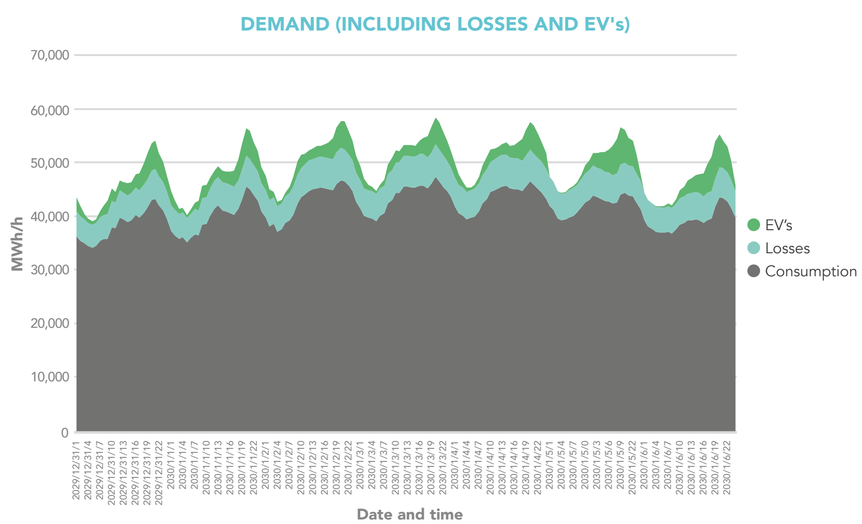
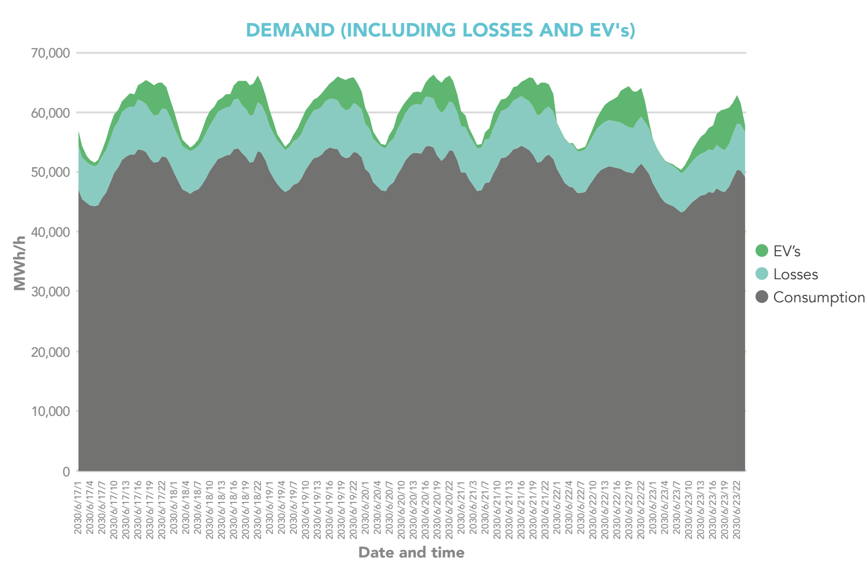


Figure 64. Demand components in the maximum-demand week in the SIN



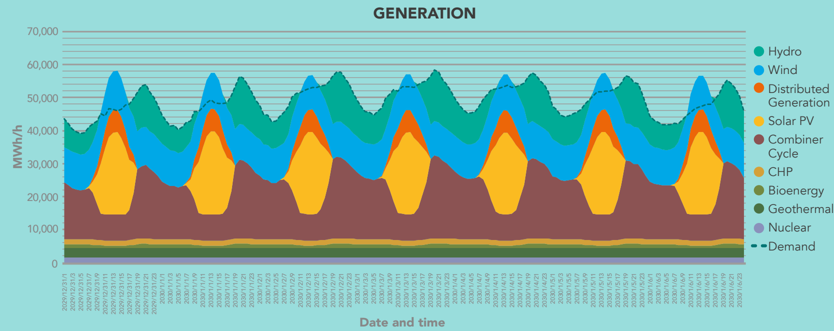


Figure 65. Generation matrix in the minimum-demand week in the SIN

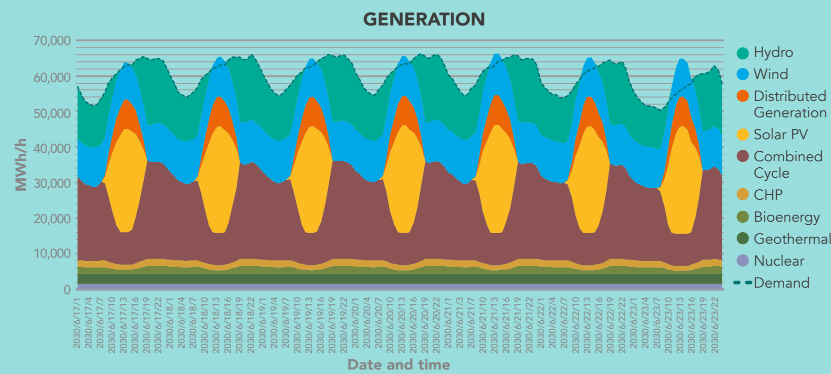


Figure 66. Generation matrix in the maximum-demand week in the SIN

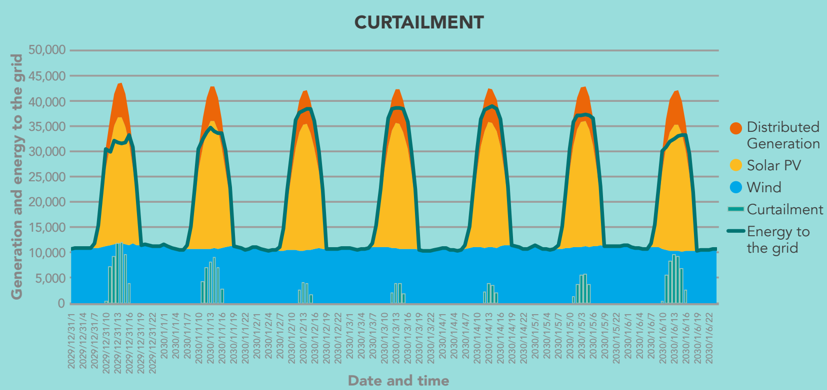


Figure 67. Curtailment in the SIN system in the minimum-demand week

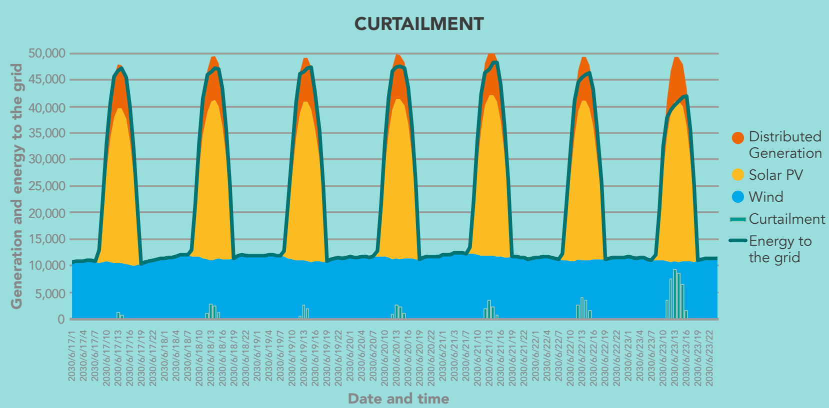


Figure 68. Curtailment in the SIN system in the maximum-demand week

demand week, the electricity matrix does not change drastically but a higher generation is needed. Natural gas combined cycles need to generate 27 GWh/h during the maximum peak hour while hydro needs to generates 18 GWh/h at the same hour. Wind generates within a range of 11 and 11.8 GWh/h during the day and solar PV and distributed generation participate with a maximum of 38.2 GWh/h at 2 pm (Figure 66).

During the minimum demand week, curtailment is higher, representing one fifth of the electricity supply from intermittent sources and equivalent to 9-5 GWh/h at 2 pm (Figure 67). In the case of the week with the maximum demand, curtailment is lower at 9 GWh/h at 1 pm (Figure 68). For this week, the cumulative curtailment is 1.9% of intermittent supply while curtailment in the minimum demand week is 5.3%.

5.7.2.2. DECARBONISATION TOWARDS 2050

While the 2030 decarbonisation pathway has taken the electricity sector towards a 1.5°C pathway, it is necessary to analyse the evolution of the sector to 2050 so that greenhouse gas emissions stay in the correct trend. The uncertainty for any simulation study considering long term, requires the careful analysis of the results, and for this reason, this section explores how the electricity system should look like according to a 1.5°C route. The scenarios to 2050 consider an inertial trend for demand growth without considering technological advances, regulatory or social changes but is aimed at achieving the required emissions for a 1.5°C pathway. Along this analysis, the decarbonisation of other sectors such as the transportation sector limits the capacity of the electricity sector to achieve a higher decarbonisation due to the increase in electricity demand by electric vehicles. As shown in Figure 69, the electricity demand of electric vehicles (green section of the graph) increases drastically from 2030 while electricity demand from other sectors increase in a slower pace. Electric vehicle demand in 2050 corresponds to 30% of total electricity demand and is equivalent to total electricity demand of 2016 (SENER, 2019).

The impact of electric vehicles in electricity demand is such that even if energy efficiency is considered, there could only be a slight reduction in total demand, as presented in Figure 70. In this graph, the red solid curve represents total demand if energy efficiency is not considered while the black solid line represents total demand if energy efficiency is considered.

In order to understand the required radical change in the generation of electricity, Figure 71 shows changes in the participation of different energy technologies. Natural gas combined cycles must reduce their participation in the electricity sector reducing from 52% in 2023 to 14% in 2050. Moreover, other fossil fuel technologies must stop operating. The required electricity to cope with the increasing demand must be generated by wind and

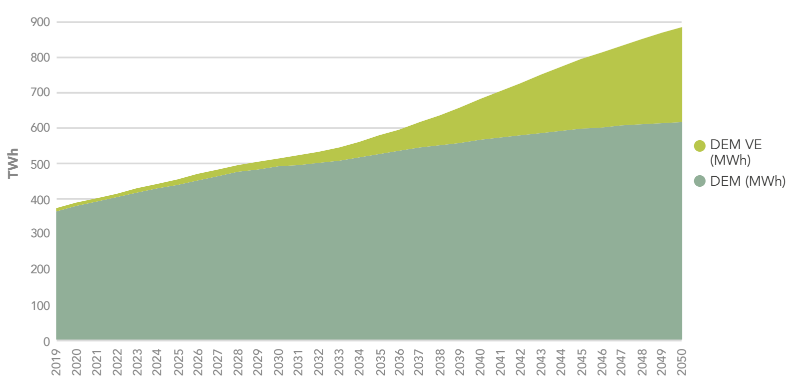


Figure 69. Impact of the EV's in the demand

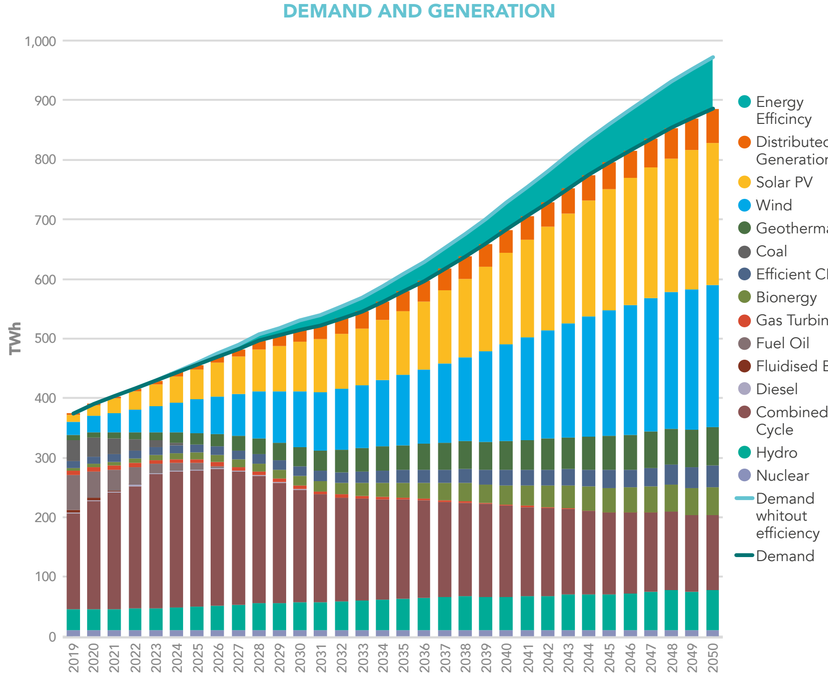


Figure 70. Demand, generation and energy efficiency for the decarbonisation

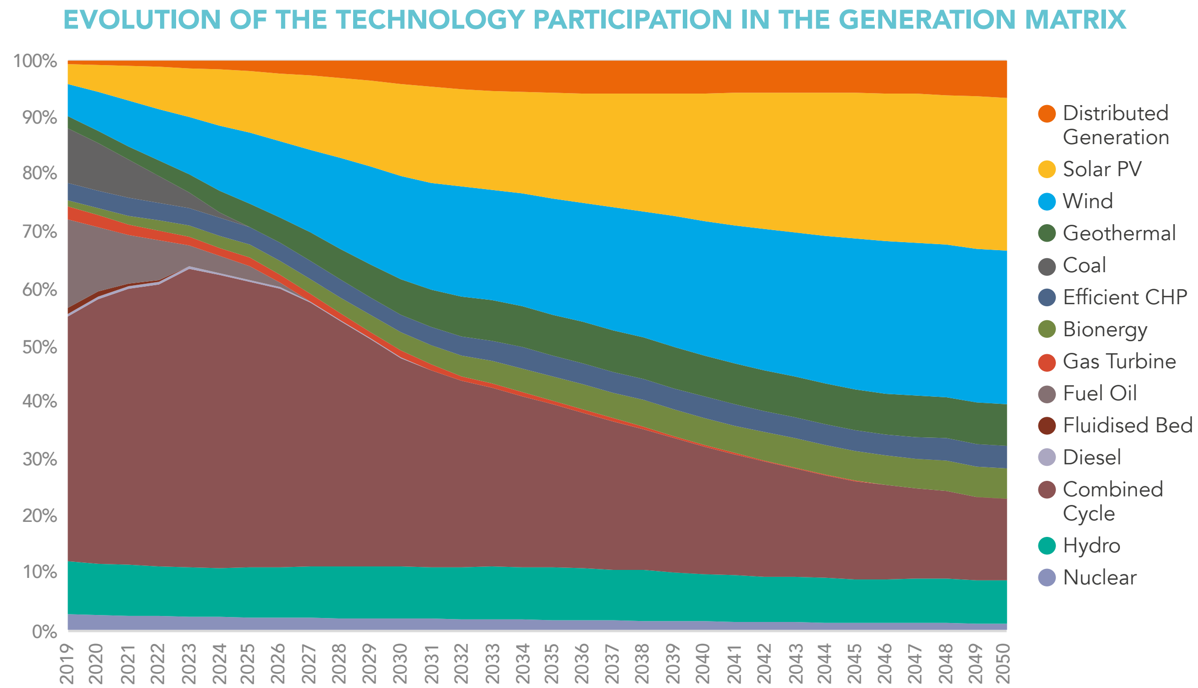


Figure 71. Evolution of the technology participation in the generation matrix to 2050

solar PV which could account for 27% each by 2050. Hydro maintains its participation between 8 and 9%, while geothermal, distributed generation and bioenergy account for 7, 6 and 5% respectively.

In terms of installed capacity (Figure 72), it must be 4 times larger compared to 2018 levels, and 2 times compared to 2030 levels. In the specific case of solar PV, 99.7 GW are required (correspond to an additional capacity of 29.7 GW compared to installed capacity in 2018). For wind, additional 70.8 GW are required while hydro and distributed generation require an additional capacity of 24 GW each. In the case of natural gas combined cycles, this technology will have 39.2 GW of installed capacity in 2050 which represents a 48% increase in comparison to 2019.

The proposed electricity system can reduce greenhouse gas emissions to 44 $MtCO_2e$ in 2050 from 141 $MtCO_2e$ in 2019 and 67 $MtCO_2e$ in 2030. As shown in Figure 73, the Decarbonisation scenario, has lower emissions between 2024 and 2041 in comparison to the required 1.5°C emissions trajectory. From 2041 to 2050, the emissions of the decarbonisation scenario are above the required target (1.5°C emissions trajectory). Despite this, cumulative emissions for the 2019–2050 period

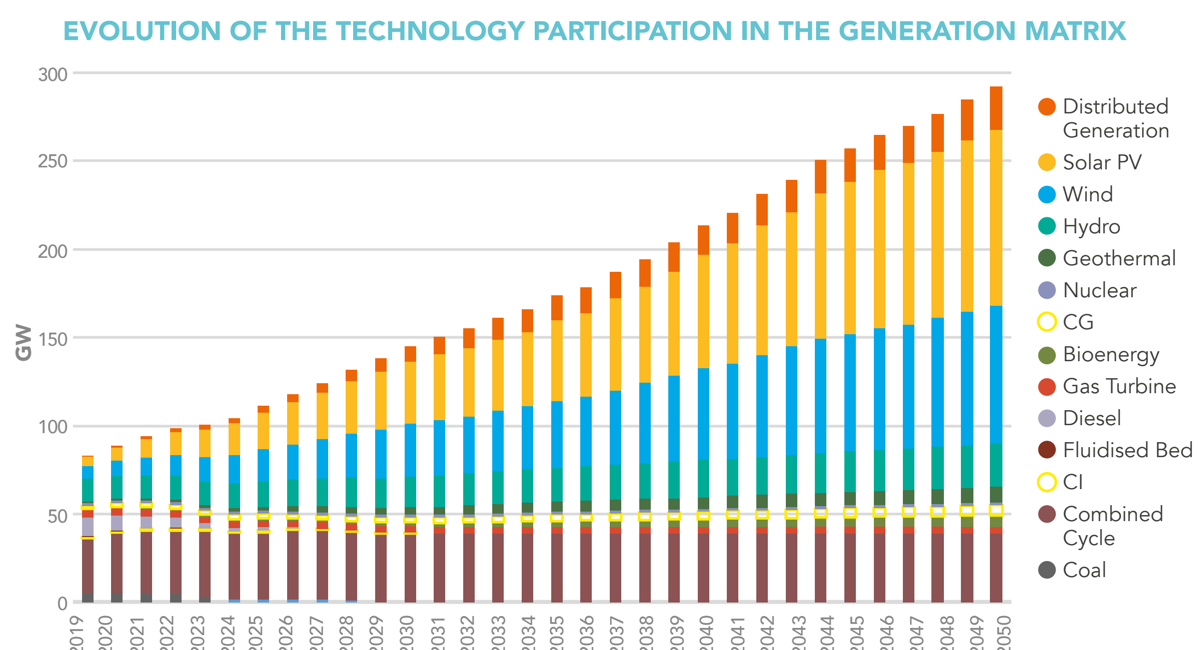


Figure 72. Evolution of the installed capacity to 2050

Figure 73. Emissions of the Decarbonisation scenario and the 1.5 °C route to 2050

are 9 $MtCO_2e$ lower than the required carbon budget. It is important to highlight that while the carbon budget trajectory requires the complete decarbonisation of the electricity sector, the simulated pathway for the sector stabilises by the end of the period.

As observed, the emissions trajectory of the Decarbonisation scenario between 2019 and 2025 present the highest reduction rate of the simulated period. The latter relies on the fact that the decommissioning of coal and fuel oil power plants rapidly reduce emissions during this period. Later reductions in emissions slow down because of the gradual substitution of natural gas burning assets by renewable energy sources. The gradual reduction of emissions achieves lower emissions than the 1.5°C trajectory. For the 2032–2050 period, the reduction of emissions slows down remarkably because natural gas combined cycles are still in the system. As shown in Figure 69, electricity demand by electric vehicles increase between 2028 and 2034, when emission reductions in the electricity sector decrease. The impact of electric vehicles is significant and reduces the potential emission reductions in the electricity sector. For the latter reason, by the end of the simulation period, emission reductions are smaller.

The reduction of emissions will require an electricity system with a high penetration of clean energy technologies and even requires a 100% renewable energy system. However, there are operational challenges in the operation of a fully renewable energy system are high and there are still uncertainties in the mechanisms that could relax the stresses imposed by these technologies to the system such as the charging regulation of electric vehicles, regulation of energy storage, demand control, smart grids and behavioural changes in energy consumption, just to mention some examples. The transition of the electricity sector requires the latter but also the understanding and improvement in the use of energy at all levels.

5.7.3. MARGINAL ABATEMENT COST AND MITIGATION POTENTIALS

The estimation of the marginal abatement cost curve (MACC) was based on the Decarbonisation and Baseline Scenarios. The calculation of marginal costs compares the present value costs of a base technology in comparison to those of the alternative technologies for an additional reduction of CO2e emissions. In the case of the electricity sector, the Baseline Scenario was compared to the Decarbonisation Scenario. In first place, the cost of implementation of renewables was calculated by considering their penetration in the Decarbonisation Scenario and the levelised costs incurred by those technologies. The cost information was taken from the PRODESEN 2018 – 2032 and in this case wind, solar PV, distributed generation, geothermal and hydro were considered as mitigation measures. The costs of the business-as-usual technologies were also calculated considering their penetration in the electricity matrix from the Baseline Scenario and their levelised cost of electricity. For this case, an average cost for the fossil fuel technologies was calculated. The marginal abatement costs considered the present value costs of renewable technologies and were compared to the present value costs of fossil fuel technologies that would be required in order to satisfy the electricity generation provided by renewable technologies. The latter was subsequently divided by the potential emissions reduction. It is important to mention that the marginal costs considered costs in 2030 base on 2018 price levels.

Two additional technologies were introduced into the calculation (solar thermal and storage). While their current costs are high, and the optimisation model does not consider them because of this, these technologies could play a larger role in the future and for this reason were included as additional mitigation alternatives. In the case of solar thermal, the penetration to 2030 was taken from IRENA (2015) that considers a total installed capacity of 1.5 GW and a generation of 3.6 TWh in 2030. In this case, a capacity factor of 27% was considered and costs were also taken from PRODESEN 2018 – 2032. It is important to mention that there is one solar thermal project in northern Mexico with an installed capacity of 14 MW. In the case of storage, from the curtailment calculations presented in the previous sections, the storage potential to 2030 was estimated in 4.9 TWh. In this case, cost data was taken from Lazard's analysis (2019) and a grid scale system was considered. Additionally, an installed capacity of 100 MW with a capacity factor of 17% were introduced into the calculations. For this specific case, investment costs were considered in 898 USD per kW with operation and maintenance costs (including charging) of 80 USD per kWh. Figure 74 presents the marginal costs. As observed, geothermal, wind and solar PV present negative costs, indicating that these technologies are

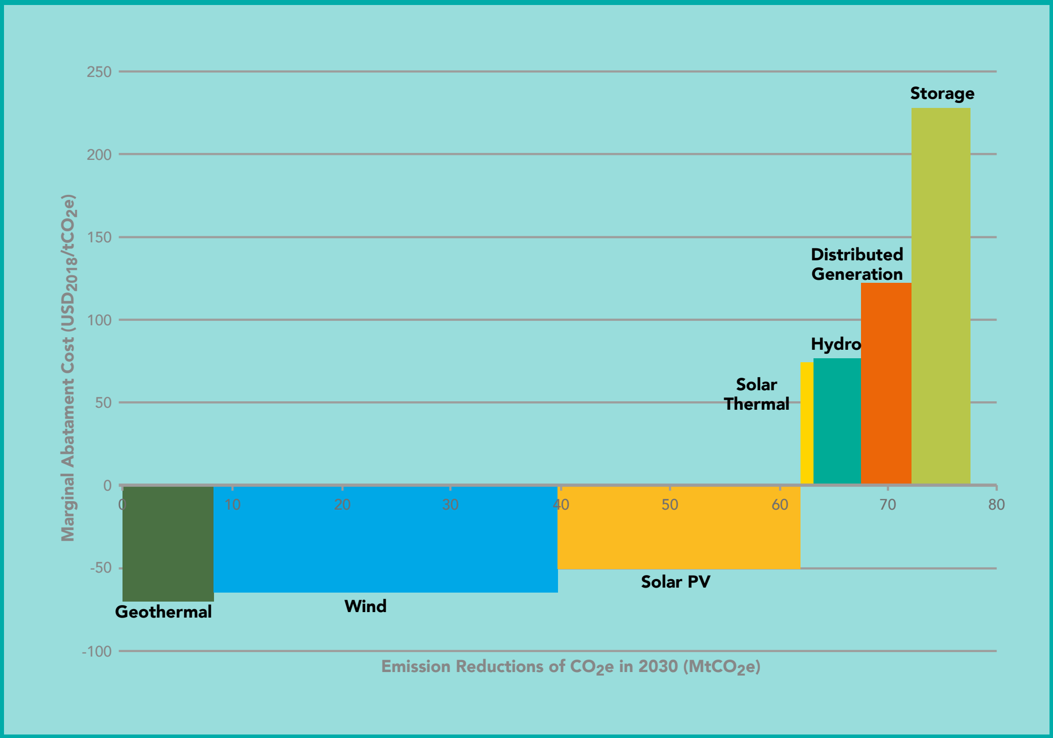


Figure 74. Marginal abatement cost curve for the electricity sector

cost effective and provide benefits. It is important to consider that there is a degree of uncertainty in the estimation of geothermal and hydro costs because their costs depend on the specific location of projects. Additionally, even though distributed generation has a positive marginal cost, the implementation of financial schemes such as the *Bono Solar* (*Hogares Solares*) Programme can represent an alternative that could make this technology cost-effective.

5.8. CONCLUSIONS

There is no doubt that the electricity sector represents a strategic sector for the Mexican economy and will play an important role in the future decarbonisation of the country. This section analysed greenhouse gas mitigation alternatives and pathways in line with the required decarbonisation for avoiding a global temperature increase of 1.5°C. With this regard, reaching the carbon budget is feasible with a high penetration of renewable energy, particularly in the case of solar (16% of total generation), and wind (18% of total generation) in 2030. Moreover, the electricity sector can reduce between 2019 and 2030 almost 700 MtCO2e of cumulative emissions, which represents a 37% reduction from the baseline scenario. This decarbonisation will require significant investments. However, savings from operation and maintenance costs (mainly fuels) can make these investments feasible and even represent a reduction in electricity generation costs.

In addition to a high penetration of renewable technologies, the decarbonisation of the electricity sector will require the decommissioning of high CO2 emitting technologies that have been operating for more than 40 years. In the first place, the coal power generating technologies must retire from the electricity matrix by 2024 and all thermal power plants based on fuel oil must do the same by 2025. In the case of natural gas combined cycle, it remains as the main electricity generating technology and increase 9 GW between 2019 and 2030. This technology would generate 50% of electricity during peak hours in 2024, 2025 and 2026, representing 37% of generation by 2030. Natural gas combined cycles could serve as a bridge for the energy transition because of their flexibility (rapidly change from a baseload-generating technology to a peak-following technology) capable of substituting intermittent renewable technologies when natural resources are not available. The increase in the penetration of intermittent sources will pose a challenge to the electricity system which will need to have a larger flexibility to cope with an increasing demand. Together with the intermittency of renewable energy sources, the increased penetration of electric vehicles will pose a challenge for the electricity system and technical and regulatory actions will be required. With this regard, a better understanding of the electric vehicle charging patterns will be required in order to establish the required regulations.

The electricity system will require a flexible network in which transmission and distribution can cope with the increasing demand. The existing infrastructure will have to be greatly expanded and updated, and reducing energy demand trough energy efficiency and distributed generation will be fundamental. In the case of energy efficiency, there are still barriers that will have to be attended through policy, such as a lack of information. The promotion of distributed generation must be enhanced through the establishment of innovative financial mechanisms and better regulation. This technology has a high potential to not only provide investment alternatives to transmission and distribution, but also to provide direct benefits to the user by democratising electricity.

Innovation is a key aspect of the electricity sector, thus Mexico should be looking for increasing investment in cost-effective measures such as wind and solar PV, and in new technologies such as energy storage, solar thermal, and carbon capture and storage (CCS). It is important to mention that energy storage technologies are advancing at an accelerated pace and might become cost-effective in the near future. Additionally, Mexico started implementing a solar thermal project (Agua Prieta II) which could represent an initial step for implementing this technology in a larger scale. Finally, while CCS technology has taken a slow development pathway, its potential in the long term should also be considered to further decarbonise the electricity sector.

As one of the main greenhouse gas emitters in Mexico, the electricity sector has the enormous challenge of following a decarbonisation pathway while it copes with a growing electricity demand. However, as presented in this document, the electricity sector has also a significant mitigation potential which will require the best technical and regulatory instruments. If these necessary technical and regulatory actions are taken, the electricity sector will not only reduce emissions greatly but will bring economic benefits and wealth for the entire population. ◆

6. OIL AND GAS SECTOR DECARBONISATION PATHWAY

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KEY POINTS
OIL AND GAS SECTOR

- Government estimates an increase in both oil and natural gas production that would translate into higher greenhouse gas emissions.

- There are huge opportunities for the decarbonisation of the oil and gas sector in Mexico. Mitigation measures can reduce emissions and provide important economic benefits.

- The total abatement potential in 2030 corresponds to 25.3 million tonnes of CO_2e per year. From this mitigation opportunity, 57% corresponds to cost effective measures with economic benefits.

- With the aid of international financial mechanisms, mitigation could be increased to 83% of its total potential.

- Methane fugitive emissions reductions are also important for mitigation/ reaching the targets, therefore and the existing regulations for reducing methane fugitive emissions should be enforced and further restrictions encouraged.

- To achieve a deeper decarbonisation of the sector in the long term, and given the current development stage of CCS technology, it is necessary to maintain unconventional resources unburned.

- The current stage of development of electric vehicles could increase their penetration in the future, and oil refining assets could no longer be necessary.

The oil and gas sector in Mexico has historically played a fundamental role in the economic development of the country. This sector is a symbol of national pride that has guided the energy policy since its nationalisation in the 1930's, its liberalisation in 2013, and the current attempts to return control of the sector to the state monopoly (*Petróleos Mexicanos*, PEMEX) (Jano-Ito and Crawford-Brown, 2016).

In Mexico, primary production of energy was 7,000 PJ in 2017. Almost 85% of this energy came from hydrocarbons for which oil accounted for 62%, natural gas for 22% and condensates for 1%. During the past 11 years, the annual growth rate of primary energy production in Mexico has been steadily decreasing by 3.3% per year. In 2017, 2,000 PJ (oil) were exported while only 300 PJ (coal) were imported. In the case of secondary sources of energy, there were considerable imports that accounted for 4,116 PJ in the same year. Exports of secondary energy were only 366 PJ. It must be remarked that while oil exports have been decreasing, imports of natural gas and gasoline have significantly increased and represent 26% and 46% of the total imports of secondary energy (SENER, 2019).

6.1. BACKGROUND OF THE OIL INDUSTRY

The history of the oil industry in Mexico begins in 1900 when the Mexican Petroleum Company founded by Edward Doheny started drilling at the Ébano Field. Parallel to this, the English company Pearson and Son in the year 1902 found oil in the Isthmus of Tehuantepec and founded El Águila Mexican Petroleum Company, which years later built a refinery in Minatitlán with a process capacity of 1,886 barrels per day (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

In December 1901, President Porfirio Díaz issued the Petroleum Law, which was intended to boost oil activity by granting ample facilities to foreign investors; however, upon Diaz's fall, the government of President Francisco I. Madero issued, in June 1912, a decree to establish a special tax on oil production and, subsequently, ordered the registration of companies operating in the country, which controlled 95% of the business (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

With the oil boom, the companies expanded and as a consequence, Venustiano Carranza's government decided that all oil companies and agents who were dedicated to the exploration and exploitation of oil should register with the Secretariat of Development. In 1915, the Technical Commission on Petroleum was created, and later, in 1918, a tax on oil lands and contracts was established to control the industry and reverse the concessions made by Porfirio Díaz. This caused protests and resistance to foreign companies. (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

The first oil boom ended in 1921 while production reached 193 million barrels in that year. During this time, more than 200 companies were already operating in the country. The discovery of oil reservoirs in Texas, California and Oklahoma reduced international oil prices, slowing down production in Mexico. In 1925, the reorganisation of oil companies at the international level ended the dominance of individual companies giving power to the newly formed international consortia. In 1932, El Águila Mexican Petroleum Company started the operation of a new oil refinery in Mexico City and found oil reservoirs in the state of Veracruz. During this time, the national company Compañía Petróleos de México (PETROMEX) was created in order to guarantee the supply of oil and refined products (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

The creation of a single union for all workers in the petroleum industry, and the rejection of a collective agreement by the oil companies, led to a strike that lasted two weeks, paralysing the economy. After the workers resumed their activities, the Conciliation Board condemned the foreign companies to comply with the recommendations made by an expert's report. However, oil companies did not comply, and in 1938, President Lázaro Cárdenas del Río decreed the expropriation of the oil industry (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

As a consequence, Petróleos Mexicanos (PEMEX) was created to manage and operate the nationalised oil industry. Likewise, an article was added to the Constitution so that this industry could not be acquired, owned or exploited by individuals, thus eliminating the granting of concessions in the industry and leaving these activities solely to the Mexican State (Álvarez de la Borda, 2005; 2006; Colmex, 2008).

6.1.1. THE EVOLUTION OF PEMEX (1938–2013)

Already nationalised, the oil industry began to grow from 51 million barrels produced in 1940 to 86 million in 1950. Exports in the latter year exceeded 12 million barrels. This increase in production was due to intense exploration work, with the most relevant result being the discovery, in 1952, of the first fields in the new Gold Belt (located in Veracruz) (Colmex, 2008).

During the 1950's, the refineries of Poza Rica, Salamanca, Ciudad Madero, the new Minatitlan refinery and the Azcapotzalco refinery were built. Also, the operation of a basic petrochemical plant in Poza Rica began, thus starting the petrochemical industry in Mexico. Between 1964 and 1970, exploration and drilling activities were promoted, leading to the discovery of the Reforma field on the borders of Chiapas and Tabasco, the Arenque field in the Gulf of Mexico, and in 1966 the creation of the Mexican

Petroleum Institute (Colmex, 2008). In the 1970's, a new hydrocarbon-producing region was discovered in the State of Chiapas, (Cactus I and Sitio Grande I wells). It was the most important finding at that time (CMM, 2008).

From 1976 onwards, in response to the political strategy of President José López Portillo, greater activity was promoted in all areas of the industry, making oil the country's main source of foreign currency. The increase in production at that time was linked to the discovery of the Sonda de Campeche fields, considered to date as the most important oil province in the country and one of the largest in the world. In the 80's, the strategy of the national oil industry was to consolidate the productive plant through growth, particularly in the industrial area, with the expansion of productive capacity in refining and petrochemicals. However, the fall in international prices led to a severe economic crisis (Colmex, 2008).

In 1992, Congress approved the Organic Law of Petróleos Mexicanos and its Subsidiary Agencies, through which an administrative and organisational restructuring was undertaken. With this law, PEMEX decentralised and deconcentrated functions and resources to fulfill all the implicit activities of the oil industry and its strategic areas; PEMEX Exploration and Production (PEP), PEMEX Refining, PEMEX Gas and Basic Petrochemicals (PGPB), and PEMEX Petrochemicals (PPQ) (Colmex, 2008).

The year 1997 marked the beginning of a new phase of expansion of the Mexican oil industry, through the execution of important projects to increase the production volumes of crude oil and gas, and to improve the quality of fuels. The Cantarell complex is positioned as the sixth most important oilfield in the world, due to its proven hydrocarbon reserves (Colmex, 2008).

In 2001 Burgos project was launched in the north of the country to increase natural gas production. In 2002, the IMP established as one of its new research programs, the exploration and production of deep-water resources. In 2003, the reconfiguration of the refineries in Salamanca and Cadereyta was completed and the construction of marine platforms began. In 2005, in order to expand the company's oil production and restore hydrocarbon reserves in the face of the decrease in production at Cantarell, Pemex intensified its oil activities in Chicontepec, the Ku-Maloob Zaap complex, and in deep-water reservoirs of the Gulf of Mexico (CMM, 2008).

In 2007, the Ku-Maloob-Zaap complex, the Floating Production, Storage and Offloading Unit (FSPO) "Señor del Mar" came into operation, with a storage capacity of 2,200,000 barrels of crude. This vessel allowed the mixing of crude oil to obtain a greater economic value in international sales. Also in that year, the swing plant in the Morelos Petrochemical Complex began operations, with a production capacity of up to 300,000 tonnes of polyethylene, with the purpose of stopping the import of up to 40% of these products at the national level (CMM, 2008).

Despite the previous efforts, the decrease in oil production and the urgency to restructure PEMEX led the administration of President Felipe Calderón to propose an energy reform in 2008. The proposal aimed at allowing the participation of private companies in oil and gas exploration and production. After several expert discussions and an intense negotiation, the initial proposal of the reform was rejected but some minor reforms were passed by the Mexican Congress. The changes were mainly focused on the oil industry and allowed the participation of private companies through service contracts with PEMEX. However, private companies were not allowed to directly participate in oil exploration and production activities (Payan, 2013; Jano-Ito and Crawford-Brown, 2016).

6.1.2. THE ENERGY REFORM OF 2013

In 2013, President Enrique Peña Nieto enacted the energy reform which represented a drastic change to the existing sector at that time, since it now allowed the participation of private actors in the exploration and production of oil and natural gas. Private participation was also allowed in the refining of oil and in the basic petrochemical sector. The energy reform aimed at increasing oil production and reverting the production decrease, which had been constant since 2004. Additionally, it was aimed at reducing the fiscal burden to PEMEX and improve its financial situation which has been severely damaged by the dependence of the government budget on revenues from oil exports (IEA, 2017). With the reform, PEMEX remained as the productive company of the State and was organised in the following units (PEMEX, 2017).

- **PEMEX Exploration and Production (PEP).** Petroleum and hydrocarbons (solid, liquid and gaseous) exploration and extraction.

- **PEMEX Drilling and Services (PPS).** Provides drilling, completion and repair services to onshore and offshore wells. PPS also provides services to wells such as cementation, registration and flexible pipeline, among others.

- **PEMEX Industrial Transformation (PTRI).** Engages in activities regarding refining, transformation, processing, imports, exports, commercialisation of hydrocarbons, petroleum-based products, natural gas and petrochemical products.

- **PEMEX Logistics (PLOG).** Provides transport and storage services for hydrocarbons, petrochemicals and petroleum-based products, and other services related to PEMEX, subsidiaries, and third parties through pipeline and maritime and terrestrial vehicles.

- **PEMEX Ethylene (PE).** Methane, ethane and propylene derivatives production, distribution and commercialisation.

- **PEMEX Fertilisers (PF).** Ammonia, fertilisers and their derivatives production, distribution and commercialisation, as well as provision of services related to these products.

The previous paragraphs briefly described the energy legislation that was derived from the energy reform. However, section 6.2 presents a greater description of the existing regulatory framework which currently rules the oil and gas sector.

6.1.3. CURRENT POLICIES IN THE OIL AND GAS SECTOR

Despite the reform, the administration that took office in late 2018, has suspended several instruments such as the oil and gas auctions that allowed the association between PEMEX and private companies. Government control of the energy sector and the dismantling of the energy reform have been guiding elements of the energy policy of the country. The four-point plan proposed by López Obrador focuses on increasing the production of oil and natural gas, modernising the existing oil refining assets, the construction of a new oil refinery and investment in expanding the lifetime of decommissioned power plants. The new government's National Plan, presented in July 2019, maintains energy self-supply of the country as its main guideline in order to reduce the sector's dependency on foreign energy products. While the four points are included in the National Development Plan, other policies include the transition towards renewable energy technologies, the vertical integration of the oil and gas supply chain, the enhancement of the financial situation of PEMEX, the promotion of transparency of energy regulation entities, the capacity building of human resources in the national energy sector and the establishment of policies to foster the efficient use of energy (Morena, 2018).

While the main legislation of the 2013 reform has not been changed (further described in the following sections), the current administration has taken several actions in order to increase its participation in the energy sector with the general objective of increasing power of the energy monopolies (PEMEX and CFE) and reduce the participation of private companies. For instance, this government has taken control of the independent energy regulator (CRE), by appointing commissioners who share the views of government intervention in the energy sector and has tried to dismantle other mechanisms established in the energy reform such as the long-term electricity auctions and the tradable clean energy certificates market.

6.2. REGULATORY FRAMEWORK OF THE OIL AND GAS SECTOR

6.2.1. OIL EXTRACTION AND PRODUCTION

As previously presented, before the Energy Reform, PEMEX was the only company allowed to participate in oil and gas production related activities. The Reform allowed investment activities in exploration and extraction by granting contracts to PEMEX, and also to private companies, either alone or in joint ventures with PEMEX. The secondary legislation established different types of contracts that could be used in order to secure government revenues. The contracts are granted for contractual areas and can be for the provision of services, for production or profit sharing, or as licenses. The Government may choose the type of agreement that is most attractive to the country, depending on the features and benefits (Gobierno de la República, 2013).

The Ministry of Energy (SENER) is responsible for the development of guidelines for the contracts as well as for the technical guidelines that will be mandatory for the participants. The Ministry of Treasury and Public Credit (SHCP) defines the fiscal terms of the contracts and bids, while the National Hydrocarbons Commission (CNH) acts as the regulatory agency, conferring the contracts to the winners, overseeing and managing the agreement over its lifetime and determining if the contracts shall be modified. As strongly remarked by the government, the winners of the bidding rounds do not acquire the ownership of the hydrocarbon resources (Gobierno de la República, 2013).

Under the Energy Reform, a new international practice regarding arrangements, known as rounds, was incorporated to the energy sector processes. The assignees can only be State Productive Enterprises (SPE) —PEMEX— and the contractors can be SPE and private enterprises. Arrangements can be contracts or assignments. A contract, or agreement, is a legal act signed by the State, through the CNH, to allow SPEs, private companies or both in a joint venture, to explore and extract the hydrocarbons from a contractual area and for a limited amount of time. The assignees and contractors are selected by a bidding process. An assignment is the legal administrative act in which the Federal Government grants exclusive rights to the assignee in order to engage in exploration and extraction of hydrocarbons in a contractual area for a specific time. The new categories —assignment and contract—

of the Reform also suppose a new scheme for the tax collection regime regarding assignees and contractors (Centro de Estudios de las Finanzas Públicas, 2014a; Centro de Estudios de las Finanzas Públicas, 2014b).

The auctions from Round One and Two resulted in more than 90 signed contracts, with hundreds of millions of USD in bonuses offered by the winning bidders, and up to 150 billion USD anticipated over the course of the contracts (Wilson Center, 2018). SENER reports that until July 2018, 9 public bidding rounds have taken place, with the assignment of 104 blocks (87,079 m2). With regards to the strategic associations of PEMEX, there have been 3 farm-outs, 2 migrations with partners and one without partners (SENER, 2018). According to the National Hydrocarbons Commission (CNH), Round One resulted in 38 contracts, Round Two in 50 contracts, Round Three in 16 contracts and there have been 3 farm-outs. In total, the government assigned 107 exploration and extraction contracts (48 onshore, 28 in deep-water and 31 in shallow water).

6.2.1.1. ROUND ZERO

Round Zero was designed to define the migration of PEMEX production to new contracts and farm-outs (Global Data, 2014). This round was established to provide PEMEX the advantage to define its portfolio (Gobierno de la República, 2013). Round Zero was held in 2014 and PEMEX determined which assets were to remain under its control, based on the company's financial and technical capabilities for exploration and extraction. PEMEX was assigned 83% of Mexico's total proved and probable hydrocarbon (2P) reserves (100% of what PEMEX requested), as well as 21% of total prospective resources (67% of what the company requested). (Centro de Estudios de las Finanzas Públicas, 2014b; PEMEX, 2014; Wilson Center, 2018).

As part of Round Zero, private sector partnerships with PEMEX were also considered, through a farm-out or association process. In this case, PEMEX was able to invite private companies to partner on the development of specific projects –blocks which PEMEX has already started to develop. The partner would commit to make future capital contributions and to cover operational expenses. Farm-out opportunities would be managed through the government's auction and public bidding modality, with PEMEX keeping the authority to provide technical input (Wilson Center, 2018). Farm–outs allowed PEMEX to enhance its operational capabilities and also lower the financial, technological and geological risks, in order to stabilise its production and then increase it gradually. PEMEX and its partners had to sign a contract with CNH to complete the association or migration processes (SENER, 2018).

The joint venture project Trion (deep–water) was added to the auction processes in July 2017, allowing PEMEX to find a partner to develop the area. It was the first–ever PEMEX farm–out, and was assigned to BHP Billiton (Australia) (second place was BP Exploration Mexico), based on a winning payment of 624 million USD and tied with BP in terms of additional royalty commitments (4% each bid). There were four more farm–out biddings: Ogarrio, for onshore resources, held in October 2017 and won by DEA Deutsche Erdoel AG (California Resources–Petrobal was in second place); Ayin–Batsil (in the Southeast Basins region, shallow water), which was declared void; Nobilis–Maximino (deep–water), which was cancelled; and Cárdenas–Mora, an onshore resource granted to Cheiron Holdings Limited (Egypt) in October 2017 (Gran Tierra y Sierra Blanca was in second place) (Wilson Center, 2018; Oil Business Mexico, 2019; CNH, 2019).

On April 27th, 2018, the CNH announced a call for associations, for PEMEX Exploration and Production (PEP). The partners and PEMEX would execute exploration or extraction activities under a license contract in the several blocks including: Artesa, Bedel–Gasifero, Bacal–Nelash, Cinco Presidentes, Giraldas–Sunuapa, Juspí–Teotleco, and Lacamango. The opening for proposals was supposed to take place in February 2019. (SENER, 2018; CNH, 2019).

There also have been farm–outs granted under the migration concept in the production sharing scheme. The first contract was granted in May 2017 and did not include any partners (PEMEX Exploración y Producción) corresponding to the Ek–Balam site (in shallow water). The second contract was granted to Petrofac México, S.A. de C.V., in December 2017 for the Santuario El Golpe area (onshore). In March 2018, Servicios Múltiples de Burgos, S.A. de C.V. was granted with the third contract, for the Misión onshore block. The last migration occurred in August 2018, when DS Servicios Petroleros and D&S Petroleum, S.A. de C.V. were conceded the operational rights for the Ébano onshore block (Oil Business Mexico, 2019; CNH, 2019; SENER, 2018).

6.2.1.2. ROUND ONE

The first public round is known as Round One, and its first auction was held by the government in July 2015. It had four bidding processes, or auctions. SENER announced that it would bid 169 blocks, 109 for exploration and 60 for production.

Round 1.1 Shallow water

This was the first auction for hydrocarbon exploration and extraction production–sharing contracts. The stage comprised 14 areas, or blocks, located in the shallow water of the Gulf of Mexico, in the Southeast Basins Oil Province. This is the most explored oil province, with the largest cumulative production in the country. Two blocks (2 and 7) were awarded to Sierra Oil&Gas in consortium with Talos Energy and Premier Oil. Blocks 1, 5, 8, 9, 10, 11, 13 and 14 were not auctioned because there were no company proposals. Blocks 3, 4, 6 and

Table 10. Results of Round 1.3

BLOCK	FIELD	WINNER
Block 1	Barcodón	Diavaz Offshore, S.A.P.I. de C.V.
Block 10	La Laja	Geo Estratos, S.A. de C.V.-Geo Estratos Mxoil Exploración y Producción, S.A.P.I. de C.V.
Block 11	Malva	Renaissance Oil Corp S.A. de C.V.
Block 12	Mareógrafo	Consorcio Manufacturero Mexicano, S.A. de C.V.
Block 13	Mayacaste	Grupo Diarqco, S.A. de C.V.
Block 14	Moloacán	Canamex Dutch B.V. -Perfolat de México, S.A. de C.V. -American Oil Tools S. de R.L. de C.V.
Block 15	Mundo Nuevo	Renaissance Oil Corp S.A. de C.V.
Block 16	Paraíso	Roma Energy Holdings, LLC-Tubular Technology,S.A. de C.V. - Gx Geoscience Corporation, S. de R.L. de C.V.
Block 17	Paso de Oro	Geo Estratos, S.A. de C.V. - Geo Estratos Mxoil Exploración y Producción, S.A.P.I. de C.V.
Block 18	Peña Blanca	Strata Campos Maduros, S.A.P.I. de C.V.
Block 19	Pontón	Geo Estratos, S.A. de C.V. - Geo Estratos Mxoil Exploración y Producción, S.A.P.I. de C.V.
Block 2	Benavides-Primavera	Sistemas Integrales de Compresión, S.A. de C.V. - Nuvoil, S.A. de C.V. y Constructora Marusa, S.A. de C.V.
Block 20	Ricos	Strata Campos Maduros, S.A.P.I. de C.V.
Block 21	San Bernardo	Sarreal, S.A. de C.V.
Block 22	Secadero	Grupo R Exploración y Producción, S.A. de C.V. -Constructora y Arrendadora México, S.A. de C.V.
Block 23	Tajón	Compañía Petrolera Perseus, S.A. de C.V.
Block 24	Tecolutla	Geo Estratos, S.A. de C.V.-Geo Estratos Mxoil Exploración y Producción, S.A.P.I. de C.V.
Block 25	Topén	Renaissance Oil Corp S.A. de C.V.
Block 3	Calibrador	Consorcio Manufacturero Mexicano, S.A. de C.V.
Block 4	Calicanto	Grupo Diarqco, S.A. de C.V.
Block 5	Carretas	Strata Campos Maduros, S.A.P.I. de C.V.
Block 6	Catedral	Diavaz Offshore, S.A.P.I. de C.V.
Block 7	Cuichapa-Poniente	Servicios de Extracción Petrolera Lifting de México, S.A. de C.V.
Block 8	Duna	Construcciones y Servicios Industriales Globales, S.A. de C.V.
Block 9	Fortuna Nacional	Compañía Petrolera Perseus, S.A. de C.V.

References: CNH (2019).

12 were not assigned because proposals were rejected to Murphy Worldwide Inc. (U.S.) and Petronas Carigali International E&P B.V. (3 and 4) and ONGC Videsh Limited (India) (6 and 12) (CNH, 2019).

Round 1.2 Shallow water

This was the second invitation to bid for hydrocarbon extraction production-sharing contracts. It comprised 9 fields in 5 areas located in shallow water in the Gulf of Mexico (in the Southeast Basins Oil Province). The five shallow water blocks were offered to a wide range of international companies: Eni (Italy), Lukoil Overseas Netherlands, Pan American Energy of Argentina (partially owned by BP)-E&P Hidrocarburos y Servicios, Statoil E&P México, DEA Deutsche Erdoel AG, Petronas Carigali International E&P–Galp Energia E&P (Portugal), CNOOC International Limited, Talos Energy LLC–Sierra Oil and Gas–Carso Oil and Gas-Carso Energy, Fieldwood Energy (U.S.), and PetroBAL (Mexico) (CNH, 2019).

Round 1.3 Onshore

This was the third invitation to bid for hydrocarbon extraction license contracts. Blocks were grouped in three geographical zones identified as Burgos Fields, North Fields and South Fields. This auction, informally known as the Mexico round due to the boosted participation of Mexican firms by the authorities, included less onerous financial requirements and bidding terms. The offerings consisted of 25 onshore blocks, of which 18 were conceded to Mexican companies (Table 10).

Round 1.4 Deep-Water

Finally, this was the fourth invitation to bid for hydrocarbon exploration and extraction license contracts. The auction was held in December 2016 and involved offshore deep-water resources in the Gulf of Mexico, particularly in the Perdido Fold Belt and Saline Basin Oil Provinces, comprising 10 blocks (8 were awarded contracts). Four blocks corresponded to the Perdido region and were assigned to CNOOC (China National Offshore Oil Corporation) (2 blocks); ExxonMobil (U.S.)–Total (France) and Chevron (U.S)–PEMEX–INPEX (Japan). The remaining four blocks, from the saline basin, were awarded to: Statoil (Norway)–BP (UK)–Total (France) (2 blocks); Petronas (Malaysia)–Sierra Oil&Gas (Mexico), and Murphy (U.S.)–Ophir (UK)–Petronas (Malaysia)–Sierra Oil&Gas (Mexico) (PEMEX, 2014; Wilson Center, 2018; CNH, 2019; Oil Business Mexico, 2019).

6.2.1.3. ROUND TWO

For Round Two there were four processes, consisting of 29 blocks, of which 19 were successfully tendered.

Round 2.1 Shallow water

This round was held in 2016 and included 15 contractual areas located in the shallow water regions of Tampico-Misantla, Veracruz and Southeast Basins in the Gulf of Mexico. For Tampico-Misantla one block was granted to DEA Deutsche-PEMEX (ENI México-Lukoil International in second place). For the Southeast Basins blocks were granted as follows: One for PC Carigali (a subsidiary of Malaysian Petronas)-Ecopetrol Global (Murphy Sur-Talos Energy-Ophir Mexico was in second place); one for ENI México-Capricorn Energy (subsidiary of British Cairn Energy)-Citla Energy (Mexico) (Repsol Exploración-Premier Oil-Sierra Perote was in second place); one for PEMEX-Ecopetrol, one to Capricorn Energy-Citla Energy E&P (ENI in second place); one for ENI México (DEA Deutsche-Diavaz GyP in second place); one for Repsol Exploración (Spain)-Sierra Perote (Mexico) (COOC E&P México in second place); one for Lukoil International Upstream Holding (Russia); one for ENI México-Citla Energy and one for Total E&P (France)-Shell (Dutch). There were no offers for the Verecruz block. The winning bidders paid 525 million USD to the government as part of their offers to get blocks (Wilson Center, 2018; Oil Business Mexico, 2019; CNH, 2019).

Round 2.2 Onshore

The second round was for hydrocarbon exploration and extraction licenses, integrated by 12 contractual areas: 9 in the Burgos Basin, 2 in the Chiapas Fold Belt and 1 in the Southeast Basins. For the Burgos Basin one license was granted to Iberoamericana (Spain)-PJP4 (Mexico) and five to Sun God (Canadian)-Jaguar (Mexico) (Iberoamericana-Newpek-Verdad Exploration, Iberoamericana-PJP4, Newpek-Verdad Exploration were second places in three of the blocks). For the Southeast Basins, the only block was awarded to Sun God-Jaguar (Perseus Exploración Terrestre was second place) (Wilson Center, 2018; Oil Business Mexico, 2019; CNH, 2019).

Round 2.3 Onshore

The third auction was held in 2016, for hydrocarbon exploration and extraction licenses. It included 14 blocks located in the following oil provinces: Burgos, Tampico-Misantla, Veracruz and Southeast Basins. For Burgos, one license was awarded to Iberoamericana-PJP4 (second place for Shandong-Sicoval-Nuevas Soluciones), two to Newpek-Verdad Exploration (Petrosynergy-Química Apollo in second place) and one for Iberoamericana-PJP4. For Tampico-Misantla, the only block was awarded to Jaguar Exploración y Producción (DEP PYG in second place). For Veracruz, one was awarded to Shandong-Sicoval-Nuevas Soluciones (second place was Roma-Tubular-Sum. Marinos y Golfo) and two to Jaguar Exploración y Producción (Petrosynergy-Química Apollo in second place in one of them). For the Southeast Basins, two blocks were awarded to Jaguar Exploración y Producción (second places were Promotora y Operadora-Consorcio 5M and Perseus Exploración Terrestre), two to for Shandong-Sicoval-Nuevas Soluciones (DEP PYG and Tonalli Energía were second places), and two to Carso Oil and Gas (Shandong-Sicoval-Nuevas Soluciones was second place) (Wilson Center, 2018; Oil Business Mexico, 2019; CNH, 2019).

Round 2.4 Deep-water

The last bidding round of Round Two took place in February 2018 and consisted of 29 license contracts for hydrocarbon exploration and extraction in the oil provinces of the Perdido Area, the Mexican Mountain Ranges and the Saline Basin. For this round, 19 of the 29 blocks were allocated. For the Perdido Area, one block was assigned to Shell-PEMEX (COOC E&P Mexico was second place), three to Shel-Qatar Petroleum (second places were PEMEX-China Offshore, PEMEX Exploración y Producción, none and China Offshore-PC Carigali). For the Mexican Mountain Ranges, two were granted to Repsol-PC Carigali-Ophir (subsidiary of the Malaysian Medco Energy, but formerly British) (Shell-Qatar Petroleum in second place), one to PC Carigali-Ophir-PTTEP (Shell-Qatar Petroleum in second place) and one tp PEMEX Exploración y Producción. For the Saline Basin four blocks were allocated to Shell Exploración y Extracción de México (second places to PEMEX Exploración y Producción, Chevron-PEMEX-ONGC Videsh, Chevron-PEMEX-Inpex and PC Cargail Mexico Operations), one to Chevron-PEMEX-Inpex (BHP Billton Petróleo Operaciones de México), one to Eni-Qatar Petroleum, two to PC Carigali México Operations (the first block had BP-Statoi as second place) and one to Repsol-PC Carigali-Sierra-PTTEP(Thailand) (Eni-Qatar Petroleum-Citla Energy in second place) (Wilson Center, 2018; Oil Business Mexico, 2019; CNH, 2019).

6.2.1.4. ROUND TWO

The first auction of Round Three was announced in September 2017, with the intention of assigning marine resources with the objective to restore reserves. During the first half of 2018 35 blocks located in shallow water were offered including Burgos, Tampico-Misantla-Veracruz and Southeast Basins (26,042 km^2 in total) of which 16 were assigned. Sharing contracts were granted for hydrocarbon exploration and extraction-production. The cash bonuses presented to the Mexican government by winning bidders were higher than 124 million USD, and total investment in projects were expected to surpass 8.5 billion USD over the life of the contracts. The areas had around 1,998 million barrels of crude oil equivalent and a remaining volume of 219 million barrels of crude oil equivalent. For the Burgos region, bidding winners were: Repsol Exploración México (2 blocks of which PEMEX Exploración y Producción was second place), Premier Oil Exploration and Production México (2 blocks). For the Tampico-Misantla-Veracruz región, one block was granted to Capricorn–Citla, two to PEMEX–Deutsche–Compañía Española and one to PEMEX–Compañía Española. In the case of the Southeast Basins, one was granted to Eni–Lukoil (México) (Deutsche–Premier in second place), one to PEMEX Exploración y Producción (Deutsche–Premier–Sapura in second place), one to Deutsche–Premier–Sapura (Malaysia) (Eni–Lukoil was second place), one to Pan American Energy (Argentina) (Eni–Lukoil in second place), two to Total–PEMEX (Sapura–Galem and Eni–Lukoil in second place), one to Total–BP–Pan American (Shell–Pemex in 2nd place) and one to Shell–PEMEX (Total–BP–Pan American in second place) (Oil & Gas Magazine, 2018; El Financiero, 2019; Comisión Nacional de Hidrocarburos; Secretaría de Energía, 2018). There were two additional auctions contemplated before the end of 2018 (Wilson Center, 2018).

Round 3.2

Round 3.2 was presented in January 2018. It included 37 contractual onshore blocks comprising 9,513 km^2 in total and in three regions: Burgos (21 blocks), Tampico–Misantla–Veracruz (9 blocks) and the Southeast Basins (7 blocks). The license contracts were for hydrocarbon exploration and extraction. The prospective resources were estimated in 260 million barrels of crude oil equivalent and a remaining volume of 219 million barrels of crude oil equivalent (Oil & Gas Magazine, 2018; El Financiero, 2019; CNH, 2019; SENER, 2018).

Round 3.3

Round 3.3 was announced in March 2018 and comprised 9 contractual areas in Burgos (onshore: conventional and non–conventional) under the concept of license contracts for hydrocarbon exploration and extraction. The blocks constituted a total area of 2,704 km2. In July, the CNH approved the last adjustments to the rules of the tender and disclosed that the presentation and opening for proposals of the two bidding processes would be programmed for February 2019. Nevertheless, SENER instructed the CNH to cancel the auctions and postpone the farm–outs. For Round 3.2, 15 companies were registered until December 2018 to participate in the bidding process, such as DEA, Jaguar, PetroBAL, PEMEX, Tecpetrol, Newpek and Pacific Rubiales. As for Round 3.3, only 9 companies showed interest, of which only PEMEX and Southerngeo Mexico signed up. The rationale for these cancellations was to review the Energy Policy and evaluate the results and progress of the contracts (Oil & Gas Magazine, 2018; El Financiero, 2019; CNH, 2019; SENER, 2018).

6.2.2. OIL REFINING

Under the new framework of the Energy Reform and the Hydrocarbons Law of 2016, SENER is the governmental body that grants licenses to any company, national or foreign, interested in the treatment and refining of crude oil. Among other requirements, those who are seeking to obtain a refining license must receive an authorisation document from ASEA, indicating that the plant will comply with article 51, fraction I of the Hydrocarbons Law, which stipulates that the applicants should present to the authorities the design of the plant, machinery and equipment, according to the applicable laws and best practices. A social impact assessment is also required (Gobierno de la República, 2013; SENER, 2019).

6.2.3. TRANSPORT AND STORAGE

The Hydrocarbons Law authorised the Energy Regulatory Commission (CRE) to authorise permits to private companies interested in the hydrocarbons retail sector. In August 2016, CRE announced the guiding principles in the development of activities in the hydrocarbons retail sector. In 2017, the gasoline, diesel and jet fuel markets in Mexico went from a model of only one provider (in charge of the supply for the whole country) to an open and competitive scheme in which many players are able to distribute fuels. Until June 2018, CRE has granted 294 retail permits (including PEMEX and its subsidiaries), and 22 oil products combined retail permits (which entails hydrocarbons, oil products and petrochemicals) (SENER, 2018).

SENER has the obligation to determine the energy-related public policies applicable to the storage and the security in the supply of hydrocarbons and oil products, in order to preserve the nation's interests and energy security. One way to do that is by means of building strategic storage points (in charge of the Federal Government) and assuring the existence of commercial inventories. SENER has defined policy for establishing minimum levels for the strategic storage and commercial inventories, so the country can respond quickly and correctly in case of a contingence in the fuel reserves (SENER, 2018). The oil refineries are required to report on a weekly basis, if the market conditions are normal, and on a daily basis if the country is under an emergency. SENER and CRE are responsible for the installation of the necessary communication channels to generate the supply-demand aggregate reports for every product and sub-product, on a national and regional scale. SENER has the mandate to collect and publish all the relevant data (SENER, 2018). The minimum mandatory reserves will be determined by regions and will come into effect in January 2020 (First Stage), increasing in 2022 (Second Stage) and 2025 (Third Stage). The minimum reserves are expressed in days. The country was divided in regions, based on the products import logistics, the current infrastructure for transport (pipelines and roads) and the storage capacity in land and marine terminals. The regions are shown in the following map (SENER, 2018).

For all regions, the first minimum mandatory reserves shall be enough to cover 5 days. In 2022, the minimum mandatory reserves must be of 8 days, and

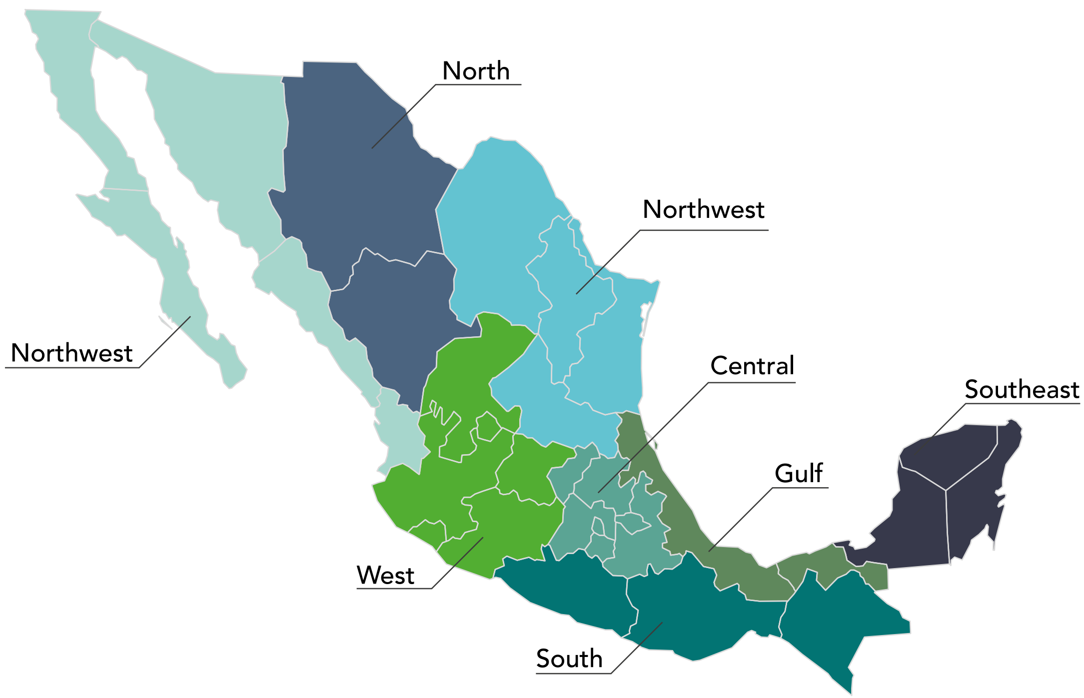


Figure 75. Regions considered for the minimum reserves and statistical reports

References: SENER (2018).

the quarterly average must be of 9 days for all regions except for South and Southeast, which must be 10 days. In 2025, Northeast, Central and Gulf regions must have a minimum of 10 days; Northwest, North and West must count with 11 days; and South and Southeast will require 13 days. As for the quarterly averages, North, Northeast, Central and Gulf regions must have 12 days of reserve; Northwest and West 13 days; Southeast 14 days and South 15 days (SENER, 2018).

PEMEX, through its subsidiary PEMEX Logistics, can offer its storage and pipeline transport infrastructure capacity to third parties interested in the retail of oil products. The method for doing this is referred as Temporada Abierta (Open Season), and consists of a transparent and competitive procedure, as indicated by Hydrocarbons Law and determined by CRE. During November and December 2016, CRE approved the first procedure of Open Season, and announced the first call for the first stage, presenting the Rosarito and Guaymas systems as available for third parties. In May 2017, the required capacity for the two systems was assigned, and in October, Tesoro/Andeavor started its operations. In December of 2017, CRE approved another procedure in the Open Season, for the Sistema Norte Zona Frontera, Sistema Pacífico Zona Topolobampo and Sistema Norte Zona Madero areas. In January 2018, it was announced the call for participants for the Sistema Norte Zona Frontera, while the call for Sistema Pacífico Zona Topolobampo was announced in February 2018. The agenda, procedures, requirements, forms, references and other information that the participants may need is made publicly available by PEMEX Logistics. Those participants who comply with the requirements will have access to a Data Room with more detailed information to support the decision-making processes (SENER, 2018).

6.2.4. NATURAL GAS PRODUCTION, TRANSPORT AND STORAGE

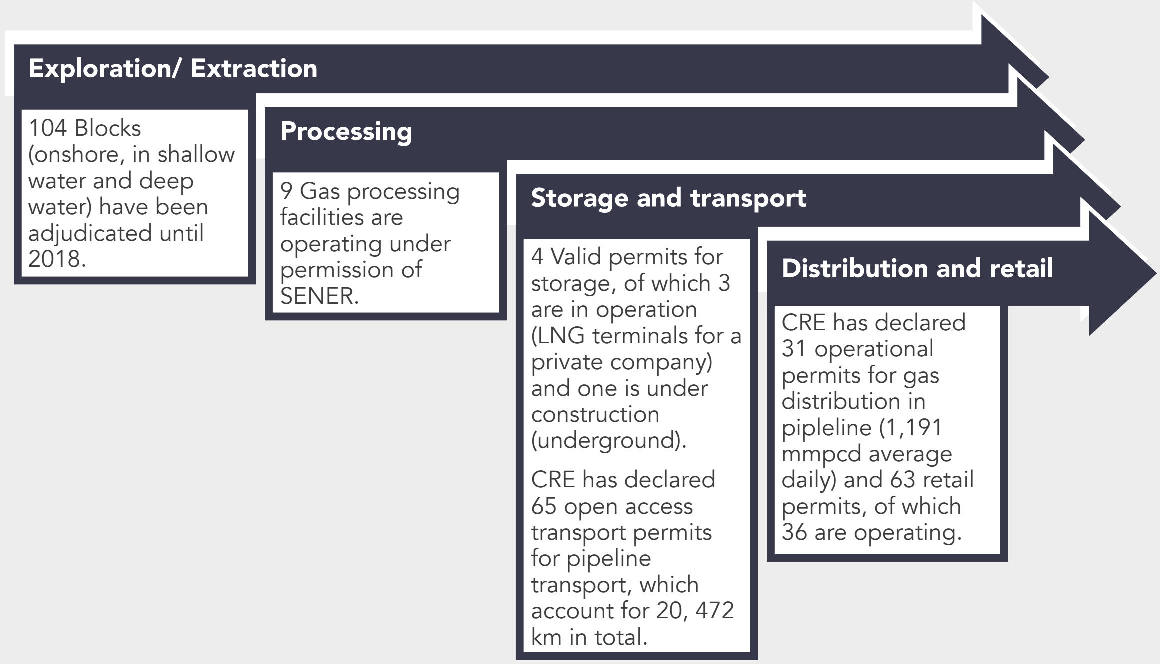
The Federal Government, through SENER, developed a strategy[20] in August 2013 to deal with the natural gas deficit in Mexico and secure a reliable, safe and continuous supply, at a competitive cost. Under the new Energy Reform, plans and public policies have been developed to modernise the national natural gas industry. Such plans and policies[21] have demanded a collaborative action between many energy-related institutions[22] (Figure 76) (SENER; 2018a).

20 The Natural Gas Supply Integral Strategy (Estrategia Integral de Suministro de Gas Natural).

21 Five Year Plan for Exploration and Production of Hydrocarbons 2015-2019, Public Policy for Implementing the Natural Gas Market in Mexico, Five Year Plan for the Expansion of Natural Gas Transportation and Storage Systems and the Public Policy for Natural Gas Storage

22 CNH, CRE, CENAGAS, PEMEX.

Figure 76.
Operation permits in the natural gas supply chain



References: SENER (2018a).

The CNH issues regulations regarding surface analysis of resources and exploration and grants permits for exploration activities. Such permits refer to the studies executed onshore or offshore to identify the possibility of hydrocarbons to be found in a certain area. These studies are the main input for the characterisation of the areas that will comprise future bidding rounds for exploration and production contracts. Until September 28th, 2018, CNH had authorised 73 projects, of which 58 were seismic assessments. The authorised companies can profit from the information (SENER, 2018a).

The gas extracted from the fields can be wet gas (sour or sweet) or non-associated gas (sweet or sour). After the extraction of natural gas, it must be processed to comply with the requirements of the regulations and standards for final use. Each field is unique, so the composition of the gas will be different from field to field and the treatment to meet the standards can vary. In general terms, gas processing consists of removing water, solid particles, heavy hydrocarbons, sulphur, nitrogen oxides and carbon dioxide. If a company is interested in processing natural gas, it must be authorised by SENER. Until 2018, SENER has granted 9 valid permits to gas processing facilities (SENER, 2018a).

CENAGAS (created in August 2018), is the decentralised agency of the Federal Government, linked to SENER, in charge of managing the National Natural Gas Pipeline Network (SISTRANGAS). CENAGAS also serves as a transporter, operator and provides maintenance to its own pipelines. SISTRANGAS is an integrated network of gas pipelines with an effective open access and a variety of users, but there are also other gas pipelines in the country that are operated by private companies. CENAGAS must issue proposals for planning instruments and revisions of new practices to SENER through the Five-Year Expansion Plan of the SISTRANGAS (SENER, 2018a).

The storage of natural gas is a key element in the supply chain infrastructure, because it aims to build and strengthen the energy security of the natural gas system as well as the stability in supply. Due to these characteristics, SENER announced the Public Policy on Natural Gas Storage in March 2018, in order to establish the incentives that are needed for the country to have strategic and operational inventories, an efficient use of the existing infrastructure and to develop new infrastructure. There are four technologies for natural gas storage in Mexico presented in the following diagram (Figure 77) (SENER, 2018a).

CENAGAS is responsible for the management of strategic storage, and thus, has to bid the projects to build the needed capacity to guarantee 5 days of minimum reserves. In 2018, CRE approved a bidding process of the four fields (SENER, 2018a).

The retail activities of natural gas are regulated by CRE, and grants permits to the companies. In order to allow new players in the market, a regulation was implemented to start a gradual contract transfer program to the new regulatory scheme. From 2017, the price of natural gas is determined according to market conditions. CRE generates and publishes a national reference index for natural gas bulk prices. This index is

Technique	Description
LNG Terminals	High capacity for delivery, can help with peaks in demand quickly and effectively. It has a limited storage capacity and the highest capital and operational costs.
Not feasible fields for hydrocarbon extraction	Lowest capital and operational costs due to the existing infrastructure. Well known geology. Needs constant maintenance because most of the sites are old.
Confined aquifers	High storage capacity, but currently there is few information about projects in these areas.
Saline reservoirs	This technoloy allows for high rates of extraction and injection, requires low levels of cuchion gas. It has higher costs for strategic storage than fields or aquifers.

Figure 77. Natural gas storage techniques

References: SENER (2018a).

informative and reflects the average prices of the free and voluntary transactions made by the retailers in the Mexican market. Since there is no fixed price, the indexes are not mandatory. In August 2017, CRE approved the methodology for the monthly index calculation, based on the average prices observed in the Mexican market. The indexes are issued for six regions, each of them having their own supply patterns, infrastructure of the gas market, tariff zones, SISTRANGAS flows, prospective projects (transport and connections), as well as prices and marketing volumes (SENER, 2018a). The regions are:

- Region I. Baja California, Sinaloa and Sonora
- Region II. Coahuila, Chihuahua and Durango
- Region III. Nuevo León and Tamaulipas
- Region IV. Aguascalientes, Colima, Jalisco and Zacatecas
- Region V. Ciudad de México, Estado de México, Guanajuato, Guerrero, Hidalgo, Michoacán, Morelos, Puebla, Querétaro, San Luis Potosí and Tlaxcala
- Region VI. Campeche, Chiapas, Oaxaca, Quintana Roo, Tabasco, Veracruz and Yucatán

6.3. OIL, NATURAL GAS, AND OIL PRODUCTS PRODUCTION

6.3.1. OIL AND GAS SECTOR INFRASTRUCTURE

Infrastructure for hydrocarbon production is diverse and involves a significant number of processing equipment in different regions of the country along the oil and gas supply chain. The following table presents the number of oil and natural gas production, processing, transportation and storage facilities in Mexico, and Figure 78 presents their location.

6.3.2. OIL AND GAS PRODUCTION

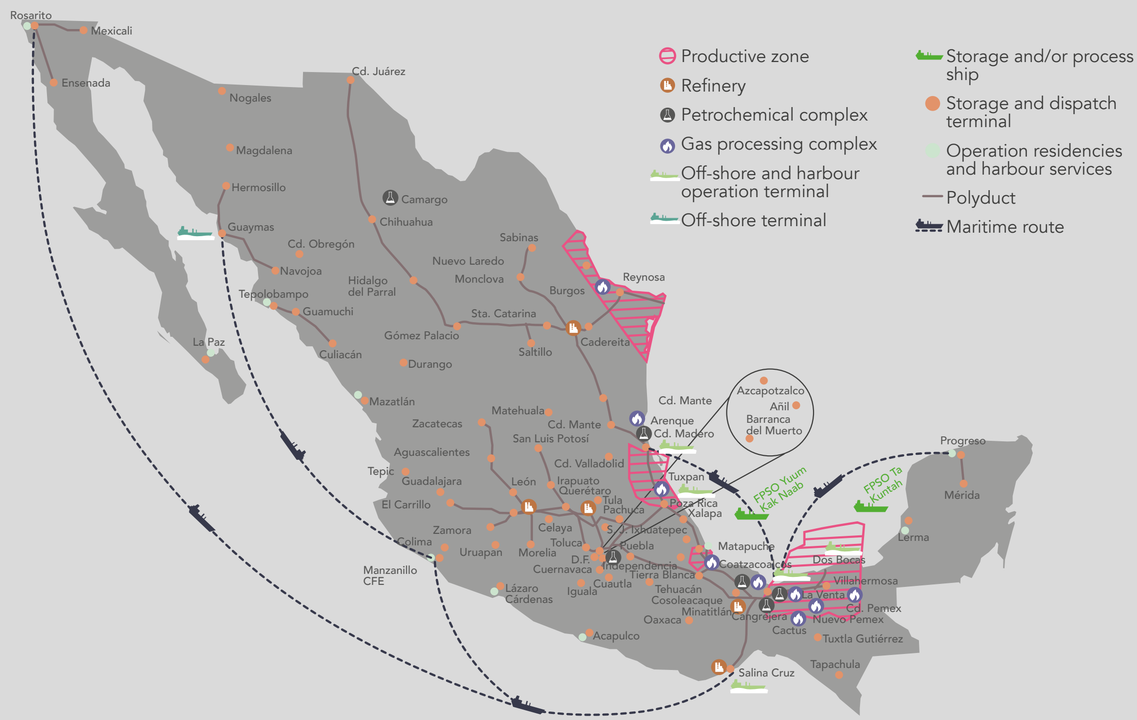
The production of oil mainly depends on two regions located in the Gulf of Mexico: Cantarell and Ku Maloob Zaap. The discovery of oil in the 1970´s in the Cantarell field, marked the beginning of an extensive programme for oil production that reached its peak in 2004. Natural gas has been mostly produced as a by-product of oil, and in some natural gas fields located in the northern part of the country. As observed in Figure 79, there is a decreasing trend in both oil production and reserves while natural gas production presents a peak between 2008 and 2015 and a slight decrease in reserves. Given this decrease, unconventional resources both offshore and onshore have been considered to complement conventional production. One of the main purposes of the energy reform of 2013 was to allow private investment to complement PEMEX's efforts in the

Table 11. Crude Oil, natural gas and oil products infrastructure 2018

FACILITIES	NUMBER
Crude oil land fields	340
Average productive wells in operation	7,811
Associated gas and crude oil wells	4,785
Non-associated gas wells	3,026
Off-shore platforms (PEP)	270
Natural gas compression stations	22
Refineries	6
Gas processing complexes	9
Liquefied gas distribution terminals	10
Petroleum based products storage and disposal terminals	74
Off-shore terminals	6
Operation residencies and harbour services	10
Tankers	16
Truck Tanks	1,485
Tank Car	525
Gas pipelines (km)	22,575

References: Created with information from PEMEX (2019) and IICNIH (2019).

Figure 78. Oil and natural gas facilities



References: SENER (2018).

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23 It includes Complejo Procesador de Gas y Aromáticos Área Coatzacoalcos, that comprises facilities located in Pajaritos and in the petrochemical complexes Cangrejera and Morelos.

24 Pemex Ethylene: Cangrejera and Morelos; Pemex Fertilizers: Cosoleacaque and Camargo and Pemex Industrial Transformation: Independencia (San Martín Texmelucan).

25 It includes 2 owned, 13 in financial leasing, and 1 rented.

26 It includes crude oil, gas and multiple products.

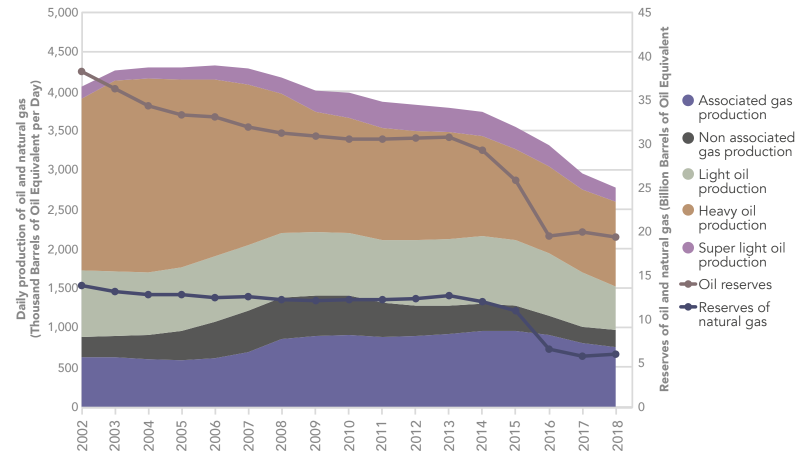
27 This figure does not include private pipelines and pipelines under construction. Considering these projects, pipeline infrastructure extends to 26,382 km.

development of these resources (EDF-CMM, 2015). Several oil auctions took place after the reform. However, the new government has cancelled the remaining oil auctions and announced the financial strengthening of the oil monopoly.

In 2018, oil production represented 1,811 thousand barrels per day, which was 6.8% less than the previous year (CNH, 2019a). As can be observed, crude oil production in Mexico is mainly based on offshore shallow water which comprised 82% of total production in 2018. With regards to the type of oil produced, in 2018, 60% of oil produced was heavy oil, 30% was light oil and 10% was superlight oil.

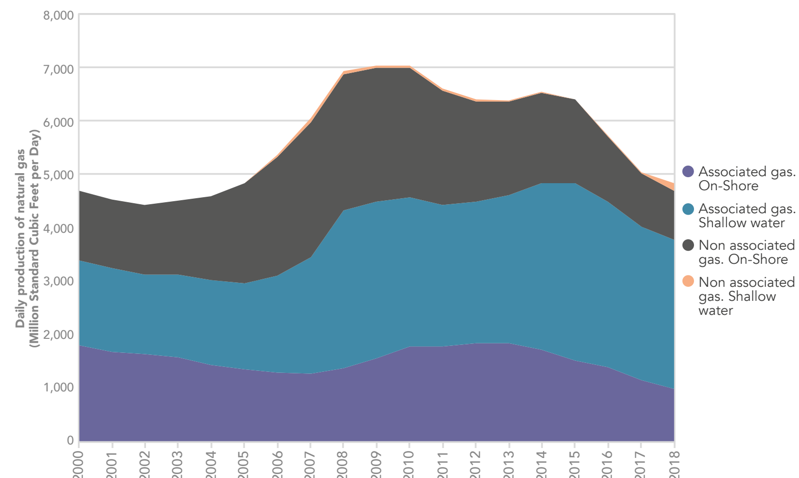
In the case of natural gas, as previously mentioned, production has primarily relied on the oil production fields of the Gulf of Mexico. In 2018, natural gas production decreased 4% compared to 2017 levels due to a 6% reduction in the production of oil-associated gas. Contrastingly, there was a 4% increase in non-associated gas production, as observed in Figure 80.

As mentioned, one of the aims of the Energy Reform of 2013 was to increase production of natural gas through the exploitation of unconventional sources. According to estimates, natural gas from shale deposits amounts to figures between 150 trillion ft³ and 459 trillion ft³ (SENER, 2013). Since the Reform, PEMEX started the exploration and production of gas from shale deposits and as of 2019 has completed the construction of 22 wells for hydraulic fracturing. From these wells, 6 are still operational with an average production of 2 million standard cubic feet per day (CNH, 2019a). The remaining 16 wells have been retired.



References: CNH (2019a) and SENER (2019).

Figure 79. Oil and natural gas production and reserves



References: CNH (2019a).

Figure 80. Natural gas production

6.3.3. OIL AND GAS PRODUCTION PROCESS

Oil and natural gas are found in specific geological structures or reservoirs, which can be mainly classified according to the type of traps and stored fluid. Reservoirs can also be classified according to the type of fracture. In México, 80% of the extracted oil comes from naturally fractured reservoirs. Exploration is always the first step in the oil production process in order to determine whether there are oil and gas reserves and whether the extraction is viable or not (Miranda-Martínez et al, 2006).

6.3.3.1. EXPLORATION

The exploration is the first step in the process of producing crude oil, natural gas and petroleum products. This activity or set of activities are comprised by direct or indirect methods with the aim of identifying, discovering, and evaluating the geologic structures capable of containing underground hydrocarbons. These methods include previous recognition, surface studies and underground studies by means of well perforation. The purpose of this stage is to evaluate the existing oil potential in a certain region. Some of the indirect methods are (SENER; 2015):

- **Superficial Geology** which includes zone´s previous studies, maps, aerial photos, satellite imagery and camp geology.
- **Potential methods** that include magnetic and gravimetric studies which compile information that enables underground rock classification and the identification of possible basement deformations that affect the formation of geological structures.
- **Seismic regional** which is the process of seismic acquisition in marine, terrestrial and transition zone environments, and the most used geophysical method worldwide for hydrocarbon exploitation.

The direct method used in the exploratory phase is:

- **Exploration wells perforation** which is the only way to validate the hydrocarbons existence.

6.3.3.2. PRODUCTION

Once a hydrocarbon deposit is located, the extraction takes place in the following stages (SENER, 2015):

- **Conditioning.** It includes roads construction, access routes, and a multi-well drilling pad construction.

- **Well perforation.** The well perforation takes place with a drill starting from the most superficial layer until the reservoir is reached. As the drill makes its way through the ground layers, a pipe that allows the oil and gas extraction is placed. In offshore production, platforms and ships make the exploration and drilling process possible (Artigas, 2010).

There are different types of wells according to their function. Exploration wells are drilled to confirm or deny the existence of oil. Once hydrocarbons are found, the well is named as development well which in turn can be classified in production, injection or observation well. On the other hand, if no hydrocarbons are found, the well is known as dry well (CMM, 2017).

In general terms, the perforation can be inshore or offshore. In land the drilling might be conventional or moveable (self-propelled, on wheels or on tracks). On the other hand, offshore drilling might be floating (ships, submersible or semi-submersible platforms) or supported (platforms or Jackups). The rotary drilling is the most commonly used method for the exploration and production wells, and can reach depths over 7,000 m. The equipment is mounted on a platform with a 30 to 40 m high tower, and a transmission rod is rotated, connected to the drill pipe. The rod has a mud shuttle connected to blowout safety valves at the top of the rod. The drill pipe rotates at a speed of 40 to 250 revolutions per minute and turns a fixed cutting-edge friction drill, chisel type, or a roller drill with hardened tooth rotating blades (Artiguas, 2010; EM, 2015).

The production is generally made through water or gas displacement. At the beginning of the extraction, the crude is under pressure, and diminishes as the oil and gas are extracted. The production can be understood in three stages (Speight, 2015):

1. Emerging or primary production: The stream is controlled by the reservoir's natural pressure, due to the gas dissolved in the oil and the hydraulic pressure exerted by the water caught underneath the crude.

2. Artificial pressure or secondary production: The extraction is carried out by means of the injection of high-pressure gas into the reservoir when the natural pressure is too low.

3. Exhaustion: The well can only produce in an intermittent way, so enhanced (or improved) oil recovery methods are used.

Improved oil recovery refers to all processes used to recover more oil from a field than is achieved by primary methods. Most of them consist of gas or chemical liquid injection and/or the use of thermal energy. Among the first, the most used are: gaseous hydrocarbons, CO_2, nitrogen and combustion gases. The chemical liquids include polymers, surfactants, alkalis and solvent hydrocarbons. Typical thermal processes refer to the use of steam or hot water, or in-situ generation of thermal energy by burning oil in the rock of the field and finally injection of bacteria (Baldras, 2013).

- **Separation and recollection.** The stream extracted from the well is a mix of hydrocarbons, nitrogen, carbon dioxide, hydrogen sulphate and water, and it must be sent to a separation process to recover the crude oil which is the most valuable portion of the mixture (Reinicke & Hueni, 2013).

The crude is separated from gas by an industrial agitation process, and from water. The crude oil is transported through pipelines to different terminals, some of it is loaded to tankers for exports. The rest is transported to a platform (linkage), where different platforms pump their crude oil (Gómez, 2000).

The crude oil enters the platform from the linkage platform and is divided in two streams. Each one of them passes through a heat exchanger, where the heat is transferred to a closed-circuit cooling water system until the temperature decreases to 176°F. Each of these streams enter a first stage separator which operates at 100 psig. A corrosion inhibitor and an antifoam are added to the separator. The separated gas goes to the compression system, but if the separated gas exceeds the system's capacity or if it is not operating, it is sent to the burner. The water that is separated from this first stage is measured and sent to the bitter water system for its processing. The separated crude oil is measured and sent to the second separation stage, which operates at 25 psig. The separated bitter water and gas run the same fate as the ones separated in the first stage. The crude oil separated is pumped out and directed at 174°F to the dehydrators where some high voltage grids coalesce and separate the oil from emulsified water, which is sent to bitter water system for its processing. Both streams leave the dehydrators to enter a heat exchanger to reach a temperature of 150°C and are pumped at 1050 psig out of the platform after being measured and filtered, and sent to the linkage platform. At this point crude oil is ready to be sent to the National Refinery System (SNR) or exported for abroad processing (Gómez, 2000).

- **Abandonment and dismantling.** Its main objective is the plugging of wells in order to isolate the surface from the underground formations crossed by the well, preventing oil and gas from migrating to the surface. It is necessary to remove the equipment and installations on the surface, in order to restore it to the original state (prior to the start the extraction) (SENER, 2015).

6.3.3.3. GAS PRODUCTION AND PROCESSING

The gas contained in the underground reservoirs can be found either associated or non-associated to oil. It is conformed mainly by methane, which represents between 63% and 99% of the molecular weight. Nonetheless, traces of ethane, propane, butane, pentane and other heavier hydrocarbons can be found, known as the gas liquids and from which most of the productive chains of basic petrochemistry and liquefied petroleum gas (LPG) are formed. In the gas stream there are also some impurities such as nitrogen and hydrogen sulphur which have to be removed due to damages in the distribution system (CMM, 2008).

PEP extracts gas from de productive reservoirs and is segmented in separation batteries at the well's exit, along with some vaporised crude oil components, which separate from gas by condensation when cooled down, generating the so-called natural gasolines or condensates. At this point, the gas is bitter due to the impurities and corrosive components in the mixture (CMM, 2008).

PTRI is in charge of natural gas (and its liquids) processing, as well as transportation, commercialisation and storage. There are nine gas processing complexes: La Venta, Poza Rica, Cactus, Ciudad PEMEX, Arenque, Burgos, Matapionche, Nuevo PEMEX and IPG Cangrejera. Each of them has different capacities. For instance, Cactus has ten sweetening plants which account for a capacity of 1,990 million standard cubic feet per day (MMSCFD), while La Venta, Burgos and Cangrejera have none. The total sweetening capacity is 4,553 MMSCFD, liquid recuperation accounts for 5,905 MMSCFD, liquid fractioning for 551 thousand barrels per day and 3,343 tonnes per day for sulphur production (IICNIH, 2019).

After bitter gas is separated from crude oil and is free of condensate, it is sent to the gas processing centres for its treatment. The first stage consists of the gas sweetening, in which hydrogen sulphide and carbon dioxide are removed from natural gas by amines. These amines are in an aqueous medium and are continuously regenerating in a closed loop. The hydrogen sulphide in changed into elemental sulphur through thermic and catalytic reactors. The obtained gas is called humid sweet gas, which is then passed through a dehydration section. Afterwards, in the second stage methane and the liquid components form the humid gas are recovered in a cryogenic plant (PEMEX, 2006). Natural gas is then ready to be injected into the transport system, which accounts for 22,575 km of gas pipelines (IICNIH, 2019).

6.3.4. REFINERY INFRASTRUCTURE AND OIL QUALITY

The National Refinery System (SNR) is comprised by 6 refineries owned by Pemex Industrial Transformation. These refineries satisfied the national demand up until 1990. After that year, imports increased due to the reduction of oil availability and processing problems in the country. The refineries are Madero, Salamanca, Minatitlán, Tula, Salina Cruz and Cadereyta. The first one (Madero) began operations in 1914 and the last one (Cadereyta) in 1979. Three of these refineries have been reconfigured to improve SNR efficiency by improving the heavy oil conversion by means of the construction of catalytic disintegration plants[28], diesel hydro-treatment[29] and coking[30]. Madero and Cadereyta were reconfigured in 2003 and Minatitlán in 2011. Figure 81 shows SNR refineries (SENER, 2018b).

It can be seen in Figure 82 (units in thousand barrels per day) that the installed capacity has not been totally used in any of the years shown.

Figure 81. SNR Refineries Location

Reference: SENER (2018b).

28 Complex diesel molecules disintegration process into simpler ones to improve gasoline yield.

29 Process whose objective is to eliminate contaminant components in petroleum by making it react with hydrogen.

30 This process converts the vacuum distillation residual products into products with greater added value, which increases the production of light hydrocarbons and diminishes the heavy oil production.

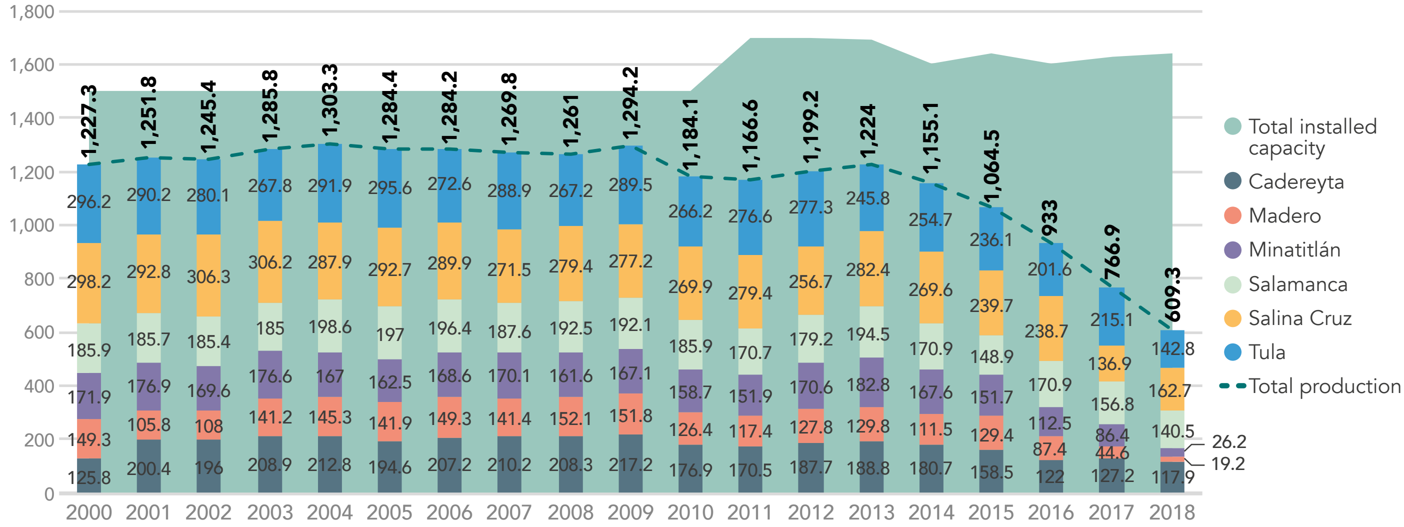


Figure 82. Crude Oil Processing by Refinery (2000–2019)

References: SIE (2019).[31]

Since 2013 the production has declined notoriously and in 2018 only 37% of the installed capacity was used. This was due to the increase in scheduled maintenance and rehabilitation projects in the Minatitlán, Salina Cruz and Madero refineries (SENER, 2018b).

Table 12. Properties of Mexican oil

	EXTRA-LIGHT OLMECA	LIGHT ISTMO	HEAVY MAYA	EXTRA-HEAVY KMZ
Average production 2018: 1,813 thousand barrels per day	188	553	557	516
°API	40	32.6	21.9	12
Sulphur%	0.81	1.5	3.5	5

Reference: Based on Guevara (2019).

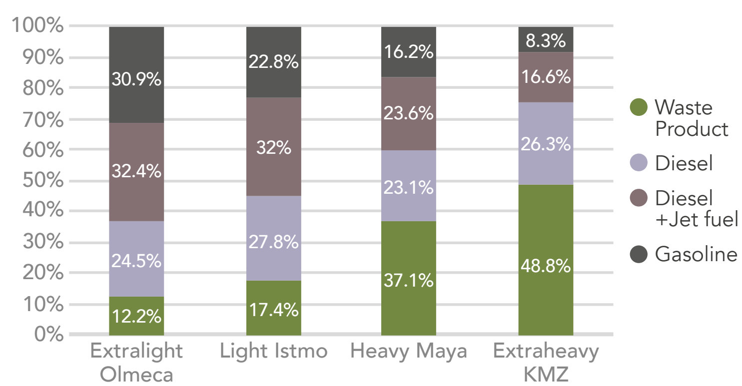


Figure 83. Types and quality of oil in Mexico

References: Based on Guevara (2019).

Figure 83 shows oil quality. The lighter the oil, the lesser waste products and the greater the amount of gasoline produced (e.g. the Extra light Olmeca produces the greatest amount of gasoline and the least waste products). However, this type of oil had the smallest production in 2018. Table 12 presents the 2018 average production for different types of oil produced in Mexico.

In 2019, 35% of the crude oil production was destined for the SNR. In 2018 the refineries received 33%, which is 6% less than in 2017 and 10% less than in 2016. Regarding the quality of the crude oil, in 2019 48% has been heavy oil (13% more than in 2018) and 52% light oil (13% less than in 2018) (SENER, 2019).

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6.3.5. OIL PRODUCTS PRODUCTION

The Energy Reform of 2013 allowed private investment in not only oil exploration and production, but also in other segments of the industry, including oil refining. Despite the fact that the country is among the key players in the oil and gas industry, from the oil boom in the decade of 1970, the oil refining industry in Mexico has declined because of the succeeding economic crises that limit spending in maintenance of the existing assets. As a result, oil refining has decreased from 1,227 thousand barrels of processed oil per day in 2000 to 609 thousand barrels of processed oil per day in 2018. It has to be remarked that existing processing capacity corresponds to 1,640 thousand barrels of

31 The American Petroleum Institute (API) stablished the API as a unit to measure oil´s purity, the less API degrees the heavier the oil is. The oil´s purity determines its value in the market, a lighter oil is more valuable than a heavier one. Table 12 shows the types and quality of the different oils in México. As it can be seen in the year 2018 oil production was 30% Heavy Maya, 30% Light Istmo, 28% KMZ Extra heavy oil, and 10% Extra light Olmeca.

oil per day. In 2018, only 37% of total capacity was used. Table 12 presents the production of oil derived products from 2000 to 2018. As observed, in 2018, 33% of total production corresponded to gasoline (regular and premium), 19% to diesel, 30% to fuel oil, 6% to kerosene, 6% to natural gas, 3% to petroleum coke, the rest to liquid products, asphalt, and lubricants. Table 13 shows that petroleum derived product production in 2018 was 20% less than in 2017, with reductions in gasoline production (20%), kerosene (15%) and diesel (23%) (PEMEX, 2019; SENER, 2019).

6.3.5.1. OIL REFINING PROCESS

Crude oil by itself has no use, so it has to be sent to a refining process in order to obtain valuable products. The refining process is a set of chemical and physical processes through which determined hydrocarbons and products are extracted from crude oil (Gobierno de la República, 2008).

The general refining process is shown in Figure 84. Distillation is the first step in the process, and the obtained fractions are converted through a chemical process and finally, to enhance production, the residue is treated with technology capable of processing heavy compounds. In Mexico, there are only three refineries that can process heavy oil. This is because these refineries were reconfigured and thermal cracking technology was implemented (Guevara, 2019).

Figure 84 presents the types of processes for each of the steps. The distillation stage is formed by the oil desalination process, and the atmospheric and vacuum distillation units. Oil desalination is the unit that washes the salt contained in the oil before it enters the atmospheric distillation. The atmospheric distillation process separates the crude oil in several fractions making use of the difference in volatility of each of the products obtained. The vacuum distillation separates the residual crude under vacuum conditions at the bottom of the distillation unit (Guevara, 2019).

The distillate's treatment basically consists on the sulfur removal. For instance, the naphtha's hydrodesulfurisation uses hydrogen to remove sulfur from naphtha before it enters the catalytic reformer. In a similar way, gasoline, diesel and oil suffer hydrotreatments to remove sulfur. LPG and dry gas must also be purified by removing sulfur (sweetening) (Guevara, 2019).

The chemical conversion is an important part in the refinement process, because molecules react under certain conditions to become more ramified, and heavy oil is transformed into lighter products to conform the final gasoline pool. More specifically, naphtha´s reforming improves the quality of naphtha by increasing the content of octane. Naphtha is an important component on the final gasoline blend. The reformation produces hydrogen as a byproduct, and it is used in the hydrotreatment unit. The alkylation unit uses sulfuric or hydrofluoric acid to produce high octane gasoline components.

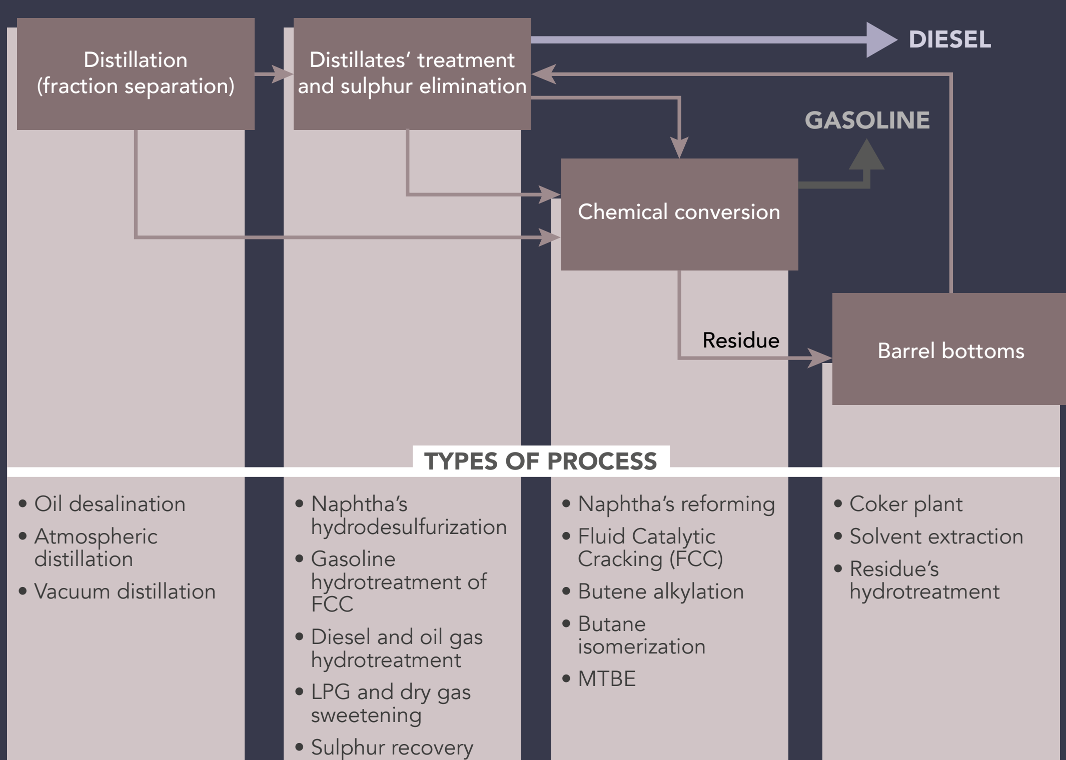


Figure 84. Refinery's Processes

References: Based on Guevara (2019).

The isomerisation unit changes linear molecules into ramified ones to increase the amount of octane, which is then fed to the alkylation units or to the final gasoline blends. Fluid catalytic Cracking (FCC) is a process that employs a riser reactor for the catalytic conversion of heavy oil fractions into lighter products. The riser reactor is fed with the so-called 'equilibrium catalyst' which comes from the regenerator. In the riser reactor coke is deposited on the catalyst, thereby lowering the activity. At the end of the riser reactor, the coked catalyst is separated from the hydrocarbon products, stripped, and sent to a fluidised bed regenerator to burn the coke and reactivate the catalyst (Den Hollander et al, 2001).

Methyl tert–butyl ether (MTBE) and tert–Amyl methyl ether (TAME) are oxygenates that are used as additives to increase the octane content in gasoline, and their use depends on environmental legislation regarding the composition and quality of the gasolines (Gobierno de la República, 2008).

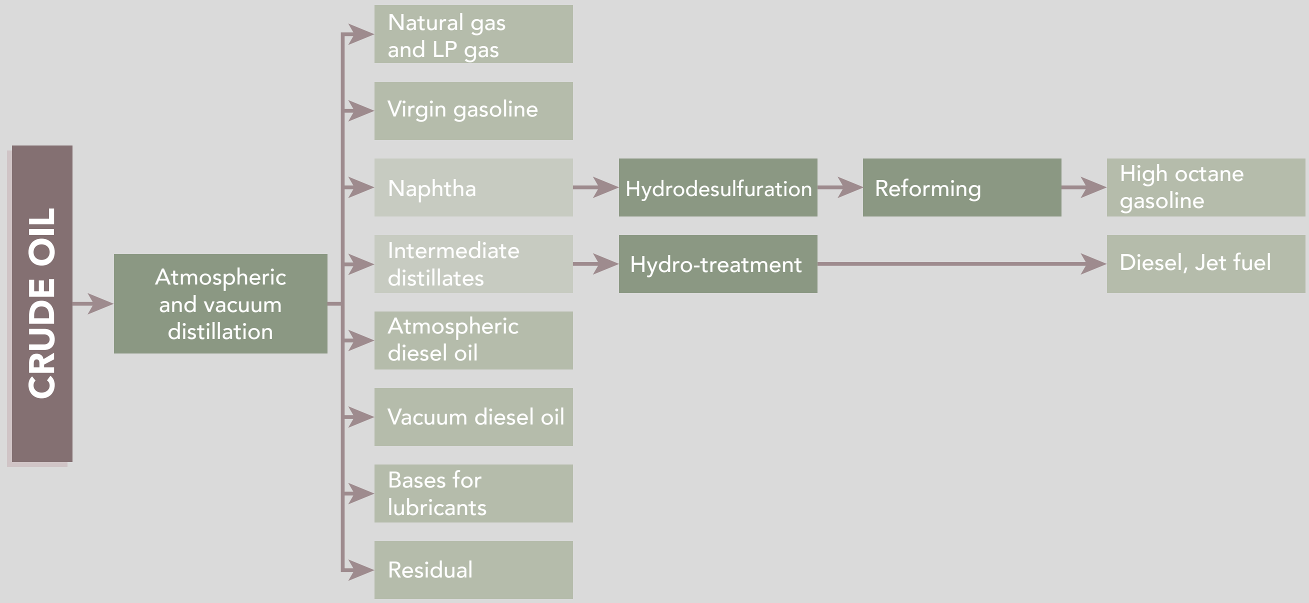
The barrel bottom technologies process the residual heavy oil to turn it into lighter products. The coker plant changes residual heavy oil into crude coke, and naphtha and diesel oil byproducts. There is also solvent extraction and hydrotreatment to obtain valuable products out of residues, increasing the refinement´s yield (Guevara, 2019).

Figure 85 and Figure 86 show the general process for extra light oil and heavy oil refinement respectively. Extra light oil is easier to process than heavier types of oil. For instance, after the atmospheric and vacuum distillation (which is the first step required in any type of refinement) of the extra light oil, must of the final products are obtained. The naphtha and the intermediate distillates must be further treated. After obtaining naphtha a hydrodesulfurisation takes place to eliminate sulphur and a reforming process to improve the amount of octane in gasoline. Similarly, the intermediate distillates must be submitted to hydrotreatment to eliminate sulphur from diesel (Guevara, 2019).

Figure 86 shows that heavy oil refining requires more steps than light oil refining in order to obtain valuable products. The final consumer gasoline includes many different components that are obtained through different processes. These components are isomerised, direct gasoline, alkylate, reformed and catalytic gasoline. Diesel, coke and lubricating bases are obtained as well (Guevara, 2009).

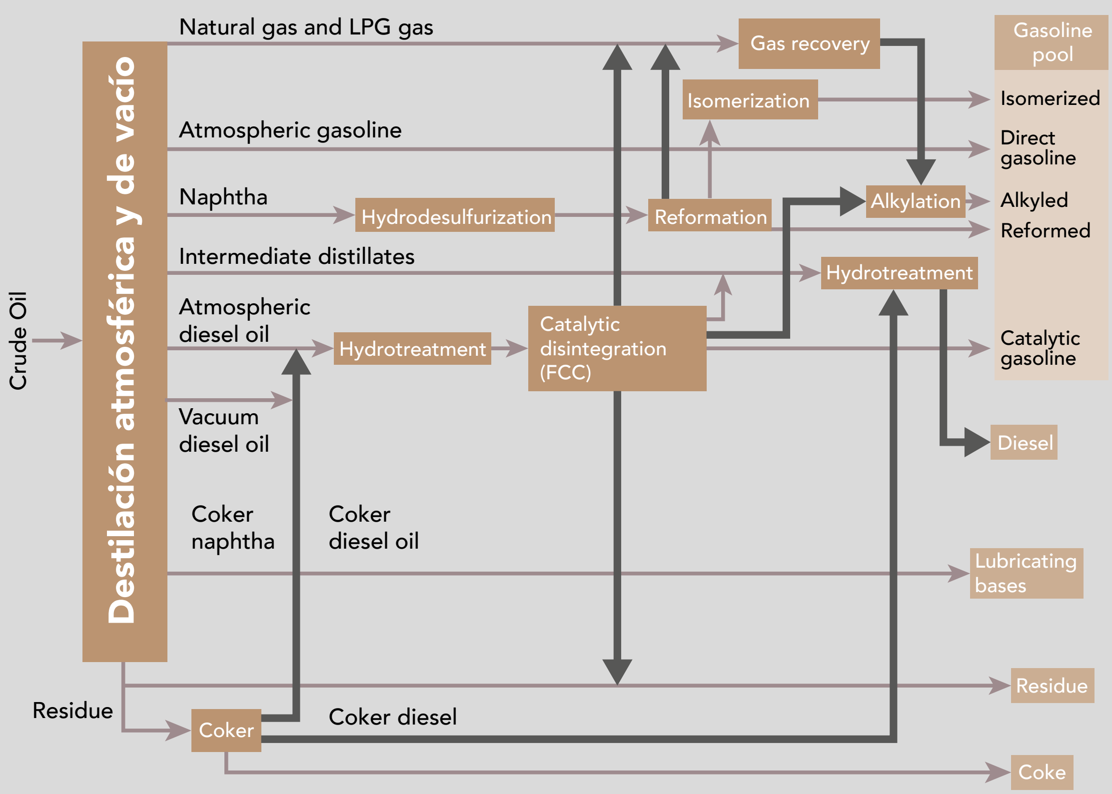
6.3.6. IMPORTS AND EXPORTS

Historically, Mexico's oil exports have represented a significant part of the government income. In 2018, Mexico exported 1,184 thousand barrels of crude oil. From these exports 97% corresponded to heavy oil (Maya). The decline in oil reserves and production has reduced exports in almost 700 thousand barrels of oil from 2004 levels. In the case of natural gas, exports are almost zero, but imports have grown from 231 million standard cubic feet per day in year 2000 to 1,317 million standard cubic feet per day in 2018. For oil derived products, the situation is similar, and imports have constantly grown because of a reduced processing capacity in the existing refineries. Gasoline and diesel are the main products imported. In the case of gasoline, imports increased from 91 thousand barrels per day in 2000 to 594 barrels per day in 2018. For diesel, imports increased from 28 thousand barrels per day in 2000 to 239 thousand barrels per day in 2018. Table 14, Table 15 and Table 16 present exports and imports data (PEMEX, 2019; SENER, 2019).



Reference: Based on Guevara (2009).

▲ **Figure 85.** Extra light Oil Refining



◀ **Figure 86.** Heavy Oil Refining.

Reference: Based on Guevara (2009).

Table 13. Petroleum Products 2000–2018

THOUSAND BARRELS PER DAY	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Petroleum Products	**1245.90**	**1267.14**	**1275.91**	**1342.89**	**1361.17**	**1338.26**	**1329.67**	**1312.43**	**1306.86**	**1342.69**	**1229.14**	**1190.22**	**1225.89**	**1275.76**	**1206.05**	**1114.27**	**977.18**	**786.58**	**628.51**
Dry gas (1)	41.81	38.95	37.38	51.34	49.86	51.91	56.73	55.24	54.95	54.92	54.15	62.58	67.83	70.72	63.91	62.18	61.94	47.89	34.80
Liquid gas (2)	24.87	27.76	31.33	33.79	28.02	30.63	25.41	26.64	25.89	27.09	25.52	21.44	25.21	25.15	26.43	21.39	17.22	16.09	10.14
Gasoline	**393.02**	**390.24**	**398.19**	**445.18**	**466.65**	**455.12**	**456.24**	**456.39**	**450.68**	**471.55**	**424.15**	**400.27**	**418.13**	**437.31**	**421.57**	**381.41**	**325.27**	**256.98**	**207.11**
Pemex Magna	360.54	362.02	359.39	396.52	418.49	411.99	413.67	425.72	418.75	445.78	408.56	385.89	398.36	417.23	390.01	360.95	316.03	249.63	205.22
Magna	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	341.25	324.17	336.84	360.48	290.92	272.54	150.56	10.98	8.85
Magna ULS (3)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	81.79	67.31	61.72	61.52	56.75	99.09	88.41	165.48	238.65	196.37
Pemex Premium	17.92	17.30	21.77	37.60	43.83	38.20	34.97	26.09	25.37	22.72	12.47	13.70	19.74	19.84	30.77	16.84	7.68	5.58	1.89
Base	13.32	9.75	16.36	10.48	3.94	4.78	7.46	4.47	6.51	2.99	3.05	0.66	0.03	0.24	0.79	3.62	1.56	1.77	0.00
Others	1.25	1.17	0.66	0.58	0.39	0.15	0.14	0.12	0.06	0.05	0.08	0.02	0.00	N/D	0.00	0.00	0.00	0.00	0.00
Kerosene	**55.58**	**56.96**	**56.66**	**59.56**	**62.13**	**63.29**	**64.80**	**66.30**	**64.02**	**57.06**	**51.86**	**56.29**	**56.62**	**60.81**	**53.40**	**47.84**	**42.80**	**40.50**	**34.65**
Jet fuel	55.32	56.70	56.66	59.56	62.13	63.29	64.80	66.30	64.02	57.06	51.86	56.29	56.62	60.81	53.40	47.84	42.80	40.50	34.65
Others	0.26	0.26	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	0.00	0.00	0.00	0.00	0.00
Diesel	**265.41**	**281.62**	**266.90**	**307.78**	**324.66**	**318.19**	**328.12**	**334.04**	**343.50**	**337.00**	**289.51**	**273.77**	**299.61**	**313.42**	**286.62**	**274.66**	**216.21**	**153.62**	**116.81**
Pemex Diesel	254.52	266.64	246.69	290.81	319.59	312.25	318.33	326.22	336.07	291.45	220.97	193.64	225.93	217.68	186.87	191.49	130.14	87.42	67.81
Diesel ULS (3)	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	44.53	67.72	80.07	72.65	92.08	97.85	83.01	85.07	63.85	48.87
Load at HDS	9.69	13.90	19.46	16.41	5.06	5.94	9.79	7.82	7.43	1.02	0.81	0.06	1.03	3.66	1.91	0.16	0.99	2.35	0.13
Desulfurized	1.20	1.07	0.74	0.56	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	0.00	0.00	0.00	0.00	0.00
Industrial fuels	2.43	0.00	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	0.00	0.00	0.00	0.00	0.00
Fuel oil (4)	**422.58**	**435.87**	**449.56**	**396.51**	**368.04**	**350.81**	**325.20**	**301.45**	**288.66**	**316.19**	**322.27**	**307.47**	**273.45**	**268.81**	**259.23**	**237.39**	**228.09**	**217.26**	**185.10**
Heavy	421.88	435.37	449.13	396.19	367.59	350.24	324.92	301.10	287.92	315.74	321.87	307.14	273.28	268.81	259.23	237.39	228.09	217.26	185.10
Intermediate products	0.70	0.50	0.43	0.32	0.46	0.58	0.28	0.35	0.74	0.44	0.41	0.33	0.17	N/D	N/D	0.00	0.00	0.00	0.00
Asphalt	31.06	28.68	28.79	25.64	27.18	29.26	32.29	31.93	34.32	31.91	24.86	26.07	23.12	18.70	23.92	17.66	16.87	16.47	13.78
Lubricants	5.98	5.21	4.92	5.47	5.40	5.17	5.10	5.18	5.11	4.20	4.27	3.73	3.88	4.38	3.69	2.29	2.97	1.89	1.88
Coke	1.53	0.28	0.75	16.19	27.65	29.06	31.15	32.23	35.79	37.45	28.84	31.07	49.08	60.73	57.60	58.26	48.16	31.65	19.67
Others	1.63	1.56	1.45	1.42	1.58	4.81	4.61	3.01	3.95	5.32	3.70	7.53	8.97	15.71	9.69	11.19	17.66	4.22	4.56

References: SENER (2019).

(1) Crude equivalent thousand barrels per day. (2) Excludes liquid butane gas blend. (3) Production started in 2009.

Table 14. National Crude Exports 2000–2018

THOUSAND BARRELS PER DAY	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total	1603.69	1755.65	1705.12	1843.93	1870.33	1817.12	1792.68	1686.15	1403.37	1222.13	1360.55	1337.73	1255.46	1188.77	1142.23	1172.39	1194.29	1173.86	1184.15
Olmeca	397.55	317.38	244.85	215.64	221.42	215.80	230.61	172.72	129.56	143.45	211.71	202.86	193.67	98.60	91.22	124.22	107.98	18.94	N/D
Istmo	109.75	86.84	45.79	24.91	27.36	80.97	68.29	41.14	23.02	14.15	74.86	99.27	99.44	102.73	133.68	193.96	152.67	85.76	30.66
Maya	1096.39	1351.43	1414.48	1603.38	1621.55	1520.35	1493.79	1472.30	1250.79	1064.53	1073.98	1035.60	962.35	987.44	917.33	854.21	933.65	1069.15	1153.49

References: SENER (2019).

Table 15. Natural Gas Exports and Imports 2000–2018

MILLION STANDARD CUBIC FEET PER DAY	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Exports	23.58	24.87	4.40	N/D	N/D	23.91	32.74	138.70	107.37	66.54	19.26	1.31	0.92	3.08	4.14	2.68	2.17	1.75	1.36
Imports	231.37	292.24	592.46	756.91	765.62	480.37	450.89	385.61	447.13	422.03	535.76	790.82	1089.30	1289.68	1357.79	1415.84	1933.87	1766.05	1316.53

References: PEMEX (2019).

Table 16. Petroleum Products Exports and Imports 2000–2018

THOUSAND BARRELS PER DAY	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
EXPORTS																				
Petroleum Products	**111.48**	**103.73**	**155.88**	**177.24**	**152.94**	**187.04**	**188.00**	**179.73**	**191.98**	**243.95**	**192.78**	**184.75**	**147.40**	**181.47**	**201.24**	**194.80**	**185.51**	**158.04**	**132.81**	**80.41**
Liquid gas	5.54	3.14	0.38	0.30	0.24	1.77	2.09	1.02	0.11	1.09	0.09	1.49	0.11	0.18	1.30	0.02	4.45	5.67	1.25	N/D
Pentanes	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Gasoline	69.73	73.05	70.68	70.73	76.24	79.03	86.65	79.70	68.79	71.44	67.70	75.17	69.38	66.75	65.97	62.89	52.66	44.96	37.74	24.43
Jet fuel	3.64	2.52	6.34	7.62	6.80	6.95	6.29	3.40	5.72	4.22	1.31	1.76	N/D	1.20	N/D	N/D	N/D	N/D	N/D	N/D
Diesel	4.45	8.95	7.99	2.92	7.69	0.83	2.55	8.81	6.45	4.79	0.41	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Vacuum gas oil	N/D	0.82	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Fuel oil	0.05	3.87	24.87	21.44	2.64	0.82	35.63	33.58	59.03	121.23	122.29	100.85	69.74	95.17	128.80	123.94	113.25	103.51	89.78	47.54
Asphalts	7.37	5.70	4.39	1.16	0.32	0.33	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Oil residues	20.69	5.68	41.22	72.87	57.53	92.05	52.04	53.22	50.45	41.17	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Other	0.00	N/D	N/D	0.21	1.48	5.26	2.76	0.00	1.43	N/D	0.97	5.49	8.16	18.17	5.17	7.95	15.15	3.90	4.04	8.45
IMPORTS																				
Petroleum Products	**363.21**	**335.31**	**243.64**	**199.85**	**234.19**	**333.72**	**368.89**	**494.63**	**552.54**	**519.27**	**627.30**	**678.20**	**670.83**	**602.94**	**640.26**	**739.75**	**799.46**	**935.40**	**983.31**	**632.60**
Liquid gas	58.12	74.58	59.85	55.55	50.32	45.64	48.24	53.63	49.27	51.56	50.14	39.91	44.17	44.71	41.30	50.42	14.98	8.51	11.89	9.81
Propane	62.57	25.23	41.70	29.79	34.31	27.30	27.38	29.27	39.45	28.48	28.89	42.48	41.46	34.77	43.28	54.82	35.67	34.08	49.94	28.75
Gasoline	90.58	136.00	89.72	54.38	94.54	169.39	204.24	307.56	340.01	329.07	379.11	404.66	395.24	358.27	370.05	426.64	504.70	570.18	594.32	391.87
Naphtha	N/D	3.28	5.87	14.68	17.94	20.96	9.95	7.78	5.58	5.98	30.66	25.65	1.08	16.89	19.64	13.43	6.08	12.36	8.90	12.63
Diesel	27.67	6.69	17.22	3.93	2.94	21.36	40.55	52.73	68.04	47.69	108.02	135.67	133.59	107.12	132.89	145.33	187.85	237.47	238.80	135.78
Fuel oil	116.47	85.21	16.41	18.59	17.75	26.43	14.32	16.99	32.91	39.19	11.00	25.02	44.62	31.32	13.01	16.96	10.69	24.43	16.48	9.90
Other	7.79	4.33	12.87	22.94	16.40	22.65	24.22	26.67	17.30	17.29	19.48	4.80	10.68	9.88	20.10	32.15	39.50	48.38	62.98	43.87

References: PEMEX (2019).

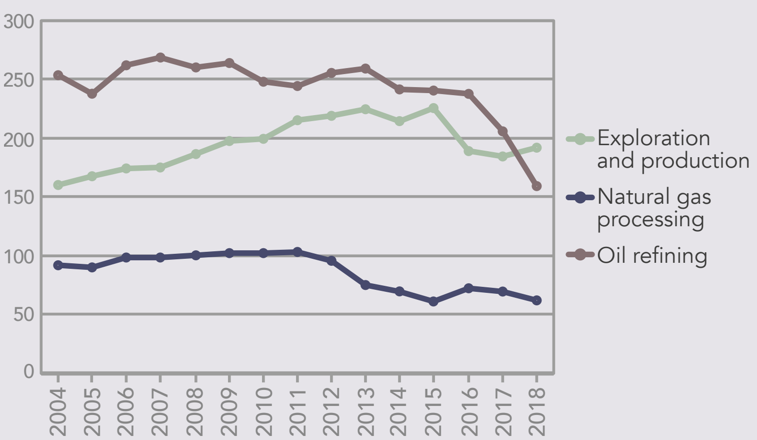
6.4. ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS

Energy consumption for oil and gas activities in 2018 accounted for 192 PJ for exploration and production, 62 PJ for natural gas processing and 160 PJ for oil refining. Energy consumption increased between 2017 and 2018, by 4% for exploration and production, decreased by 11% for natural gas processing and 22% for oil refining. It must be highlighted that energy consumption reductions were due to a decrease in production. However, in the last years PEMEX has been implementing energy saving programmes in its facilities (PEMEX, 2017a). Figure 87 presents energy consumption between 2004 and 2017.

According to PEMEX (2017a), greenhouse gas emissions in 2018 accounted for 16.0 million tonnes of CO_2e for exploration and production, 4.5 million tonnes of CO_2e for natural gas processing and 9.5 million tonnes of CO_2e for oil refining. As it can be observed in Figure 88, in the case of natural gas processing and oil refining, greenhouse gas emissions have remained relatively constant. However, there have been changes in greenhouse gas emissions for exploration and production. In 2009, there was a decrease in greenhouse gas emissions because of the implementation of a flaring and venting reduction programme in the Cantarell field. Additionally, there was a decrease in total greenhouse gas emissions of 6.6% between 2017 and 2018, emissions because of natural gas saving programmes implemented by PEMEX but also because a reduced production of refined products (PEMEX, 2010; 2017a).

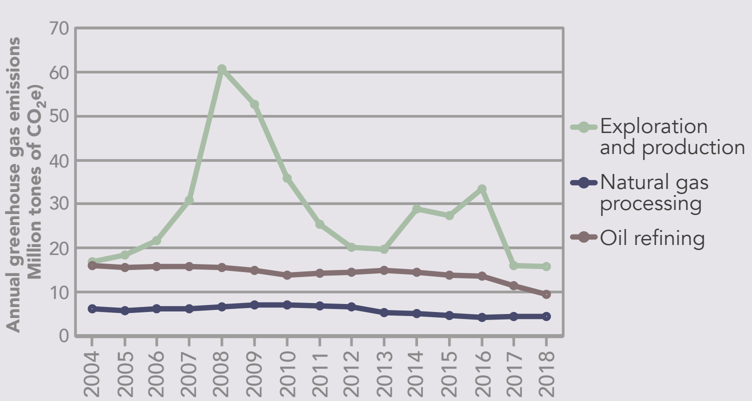
It is important to remark that the above historical emission trajectories correspond to estimates by PEMEX. However, the National Greenhouse Gas and Compound Inventory of 2017, presents a different estimation for fugitive emissions along the oil and gas supply chain. For instance, PEMEX reported methane emissions for 3.3 million tonnes of CO2e in 2018 while the National Inventory 18.4 million tonnes of CO2e in 2017 (PEMEX, 2018; INECC, 2019). For this reason, for 2018, CO2 emissions reported by PEMEX were combined with fugitive emissions reported by INECC. For 2018, fugitive emissions were estimated considering oil and gas production in 2018 and an average methane emissions factor from historical emissions and oil and gas production. Figure 89 presents the historical greenhouse gas emissions trajectory for the oil and gas sector in Mexico.

Figure 87. Historical energy consumption in oil and gas activities



References: PEMEX (2006; 2008; 2010; 2015; 2017a; 2018).

Figure 88. Historical greenhouse gas emissions reported by PEMEX



References: PEMEX (2006; 2008; 2010; 2015; 2017a).

6.5. FUTURE DEVELOPMENT OF THE OIL AND GAS SECTOR AND THE CARBON BUDGET

In order to estimate the future development of the oil and gas sector and its greenhouse gas emissions, three scenarios were analysed considering government projections, the natural depletion pathway of oil and gas resources in Mexico, and the required emissions trajectory for limiting a temperature increase of 1.5°C. The scenario assumptions are presented in the following sections.

6.5.1. GOVERNMENT ESTIMATES (CNH SCENARIO)

Federal Government expansion plans were taken from the National Hydrocarbons Commission (CNH) and the Ministry of Energy (SENER). In the case of oil and gas production, the CNH recently published its oil and gas production prospects for 2033 (CNH, 2019a). This information was used to estimate, for instance,

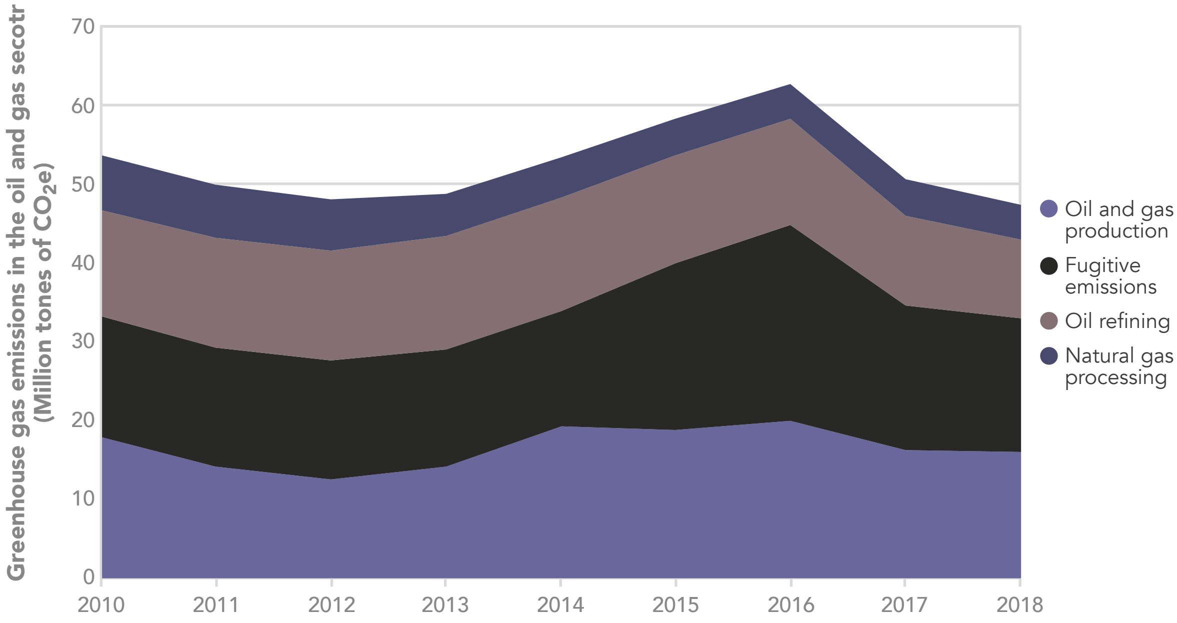


Figure 89. Historical greenhouse gas emissions in the oil and gas sector

References: PEMEX (2006; 2008; 2010; 2015; 2017a; 2018; INECC, 2019).

future venting and flaring, and its potential emission reductions. Furthermore, oil refining upgrading, and capacity expansion was also included and taken from SENER (2017) and PEMEX (2019a). In the latter case, the refining capacity of the Dos Bocas refinery project was included in the calculations (processing capacity of 340 thousand barrels of oil per day). Figure 90, Figure 91 and Figure 92 present the production forecasts.

In order to expand the CNH scenario to 2050, annual growth rate estimates from the depletion scenario were considered. It has to be mentioned that CNH presents estimates for oil and natural gas contracts up to 2045 (Porres-Luna, 2019). However, they were not taken due to a higher decrease in production which was 12% per year from 2033 to 2045. The depletion scenario, which will be presented in the following section, considered an annual growth rate of -6% which is similar to the historical production decrease following the production peak in 2004 (-4%).

6.5.2. DEPLETION SCENARIO

This scenario was estimated considering peak production theory proposed by M. King Hubbert (1956). Hubbert's theory considers that the exploitation of natural resources such as oil and natural gas will gradually deplete the stock of these limited resources. Hubbert proposed that production of natural resources followed a Gaussian curve, reaching a production peak depending on existing reserves and future discoveries. Following Hubbert's theory and using the work of Ayala-Chávez (2017) and Towler (2014), a production curve for oil and gas was estimated for Mexico. For this purpose, historical information of total hydrocarbon production and reserves was taken from PEMEX (1977; 1988; 1999; 2010; 2017; 2018).

Figure 93 presents the historical data for hydrocarbons production from 1938 to 2018, and the projected production using Hubbert's theory. As observed, historical production of oil and natural gas follows a production trend similar to the Gaussian from proposed by Hubbert. It is important to consider that the estimation of the projection uses existing estimates of oil and gas reserves and does not consider the potential implications of unconventional production of oil and natural gas which are considered in CNH estimations.

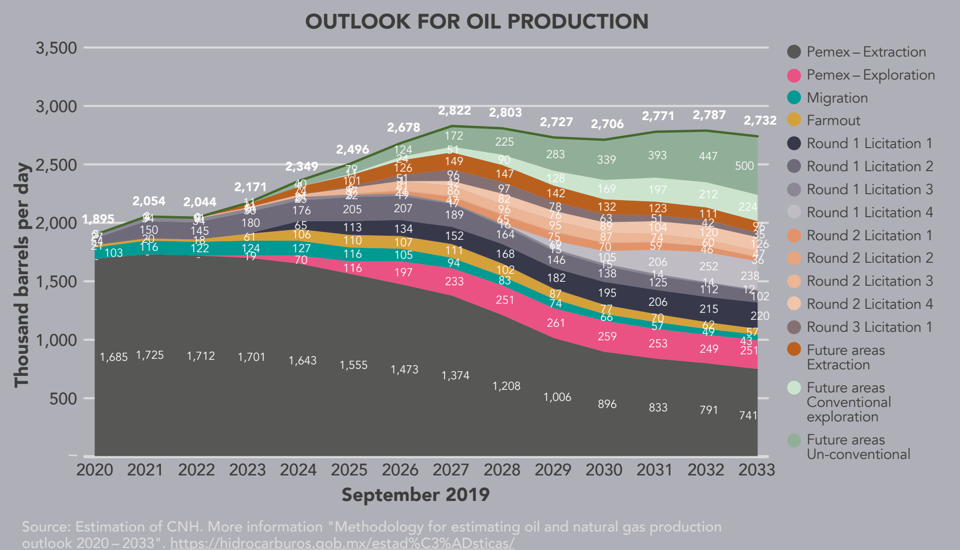
6.5.3. DECARBONISATION SCENARIO

For this scenario, the estimations of the required emission trajectories to limit the average temperature increase to 1.5°C were taken from ICM. Additionally, the estimations took 2010 as the initial year and emissions were adjusted considering this year's emissions of CO_2e in the sector. The estimated carbon budget for the 2019-2030 period corresponds to 510 million tonnes of CO_2e while this figure increases to 989 million tonnes of CO2e for the 2019-2050 period. For the 2010-2018 period, the carbon budget was estimated in 461 million tonnes of CO_2e. Historical emissions for the same period were 471 million tonnes of CO_2e, and for that reason the budget can be adjusted to 500 million tonnes of CO_2e for the 2019-2030 period and to 979 million tonnes of CO_2e for the 2019-2050 period.

6.5.4 EMISSIONS FOR THE 3 SCENARIOS

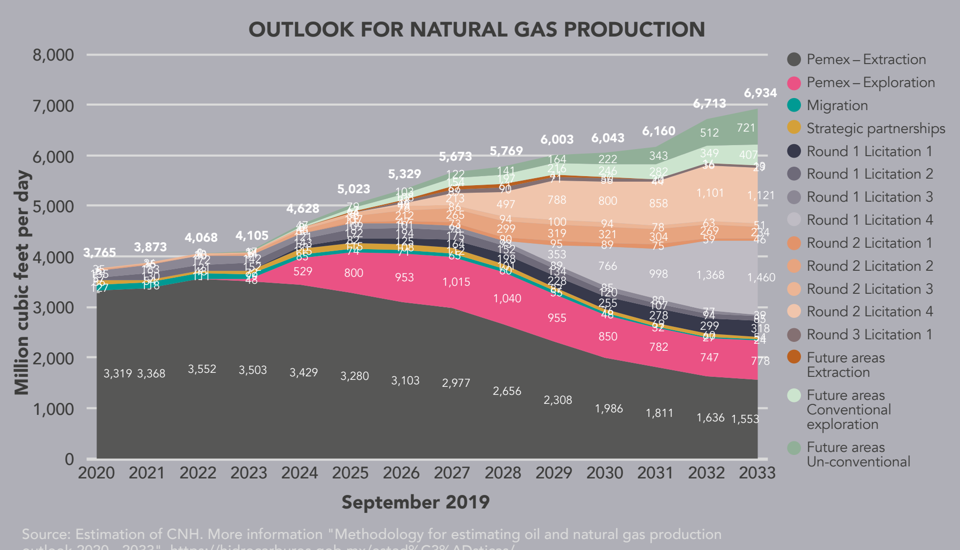
The emissions from the scenarios are presented in Figure 94. Mitigation measures will be described in the following sections.

Figure 90. Oil production (2020–2033)



References: CNH (2019a).

Figure 91. Natural gas production (2020–2033)



References: CNH (2019a).

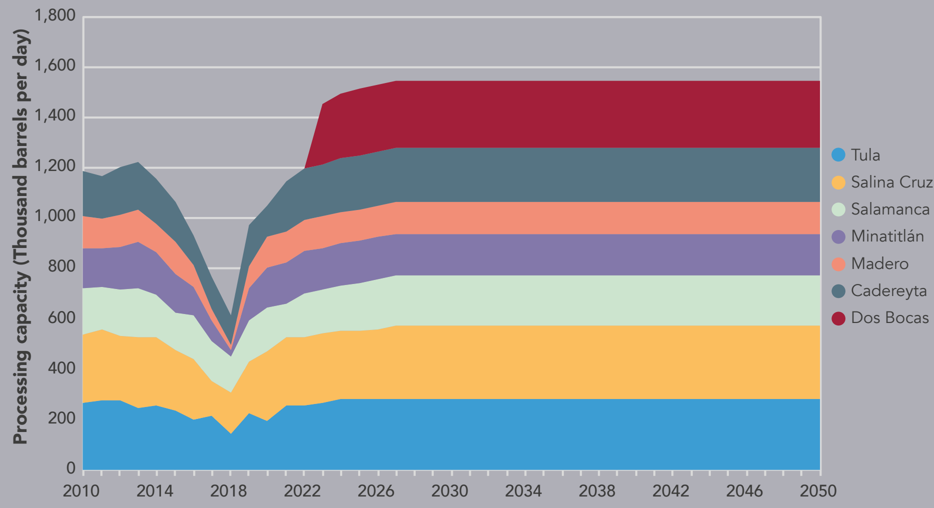


Figure 92. Crude oil processing (2017–2030)

References: SENER (2017) and PEMEX (2019a).

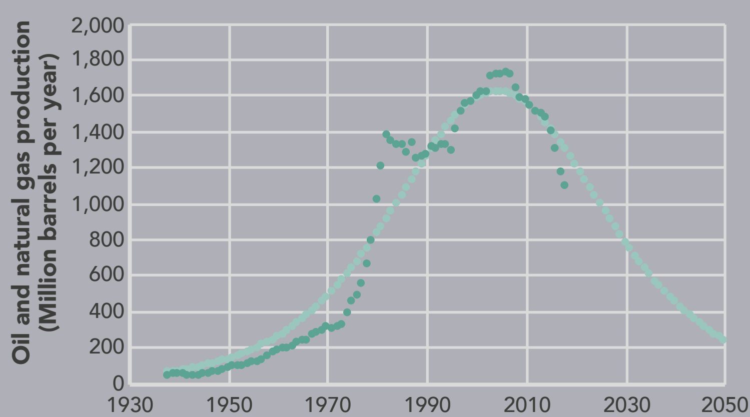


Figure 93. Historical and projected oil and gas production

References: PEMEX (1977; 1988; 1999; 2010; 2017; 2018).

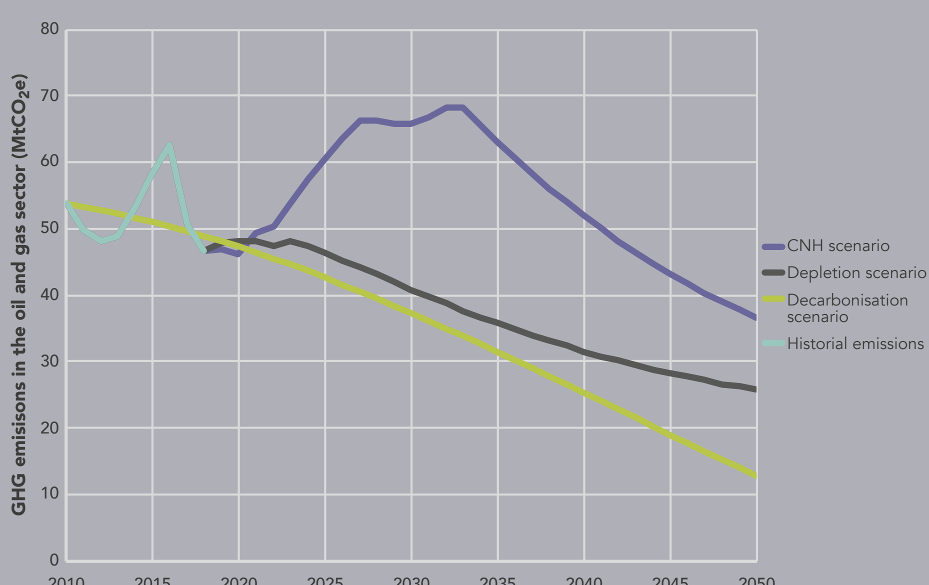
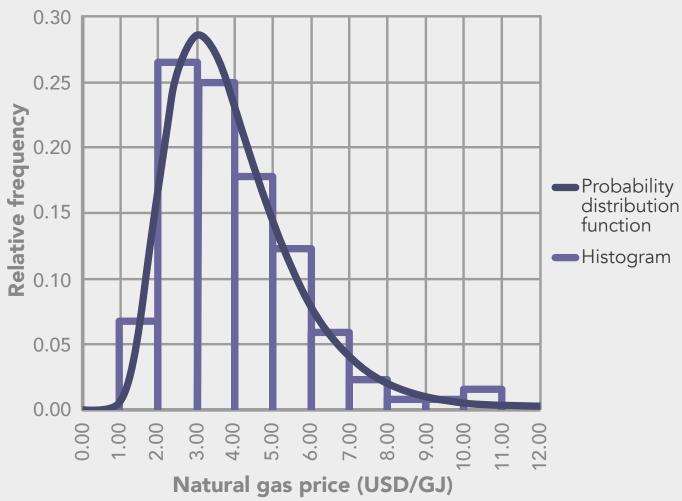


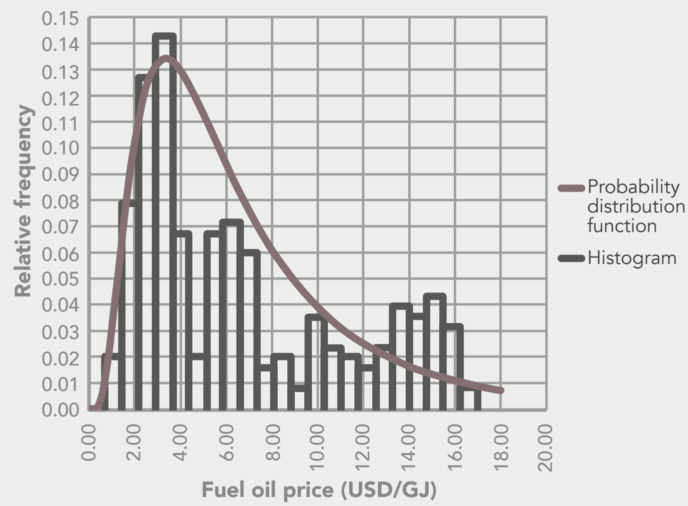
Figure 94. Emission for the scenarios

Figure 95. Distribution of historical natural gas prices



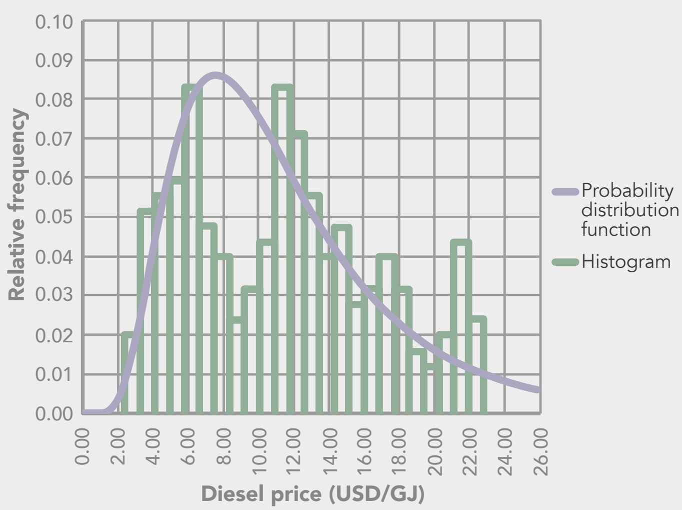
Data obtained from SENER (2019).

Figure 96. Distribution of historical fuel oil prices



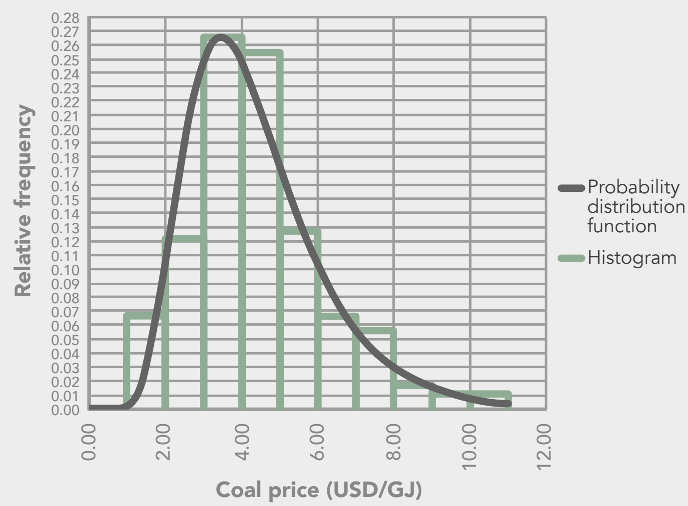
Data obtained from SENER (2019).

Figure 97. Distribution of historical diesel prices



Data obtained from SENER (2019).

Figure 98. Distribution of historical coal prices



Data obtained from SENER (2019).

6.6. ECONOMIC ASSUMPTIONS

In order to estimate greenhouse gas emission reduction potentials, several common economic assumptions were included in the calculations. In the case of fuel price trajectories, information from the Ministry of Energy (SENER) was used, together with electricity prices and trajectories from the planning scenarios of the electricity sector presented in the National Electricity System Development Programme 2018–2032 (EIA, 2019; SENER, 2018). In the specific case of fuel prices, a historical data was used to estimate the volatility and growth trends of fossil fuels for the 1997–2018 period (Figure 95, 96, 97 and 98). The evolution of fuel prices was simulated by using a geometric Brownian motion (GBM) with drift algorithm assuming that the prices followed a log–normal distribution which can be observed in the following graphs (Dixit and Pindyck, 1994).

The fuel price trajectories were simulated using the following equation (Jano-Ito and Crawford-Brown, 2017):

$$dF_h = \varphi_h F_h dt + \mu_h F_h dz$$

The term dF_h in the latter equation represents a change in the trajectory of fuel prices for fuel h, whereas dz a change in $z(t)$ which follows a Wiener process in time t; and dt a change in t. The constant values that were used for the drift (φ_h), variance parameter (μ_h) and initial fuel price were assumed to portray the long term as in Yang and Blythe (2003) and Yang et al (2008).

The following graphs show the evolution of natural gas, fuel oil and diesel prices for the 1997–2050 period and the evolution of coal prices for the 2002–2050 period. In the case of uranium, fuel loading in nuclear plants takes place every 18 to 24 months and the price is subject to long term contracts that are not affected by spot market uranium prices showing a low volatility (Fernández et al, 2009; Jano-Ito, Crawford-Brown and De Vries, 2019). For this case, data from SENER (2018) was used. Fuel prices were adjusted to 2018 prices. In the case of crude oil prices, data from the United States Energy Information Administration (EIA) was used to estimate the evolution of Mexican crude oil prices. The crude oil price for 2018 was taken from the Bank of Mexico (2019). Industrial electricity prices were taken from SENER 2018 and adjusted to 2018 prices. It has to be mentioned that crude oil and electricity prices were considered for the oil and gas sector and for this sector costs were only calculated for the 2018–2030 period.

For all the considered mitigation measures, a discount rate of 10% was used. For project lifetimes, different time periods were considered depending on the nature of the project. For instance, in the case of cogeneration a 30-year lifetime period was considered while a 15-year period was considered for the other mitigation measures. Investment and operation and maintenance costs were adjusted to 2018 values using the Chemical Engineering Plant Cost Index (CEPCI) and the producer price index (PPI) reported by the OECD for Mexico.

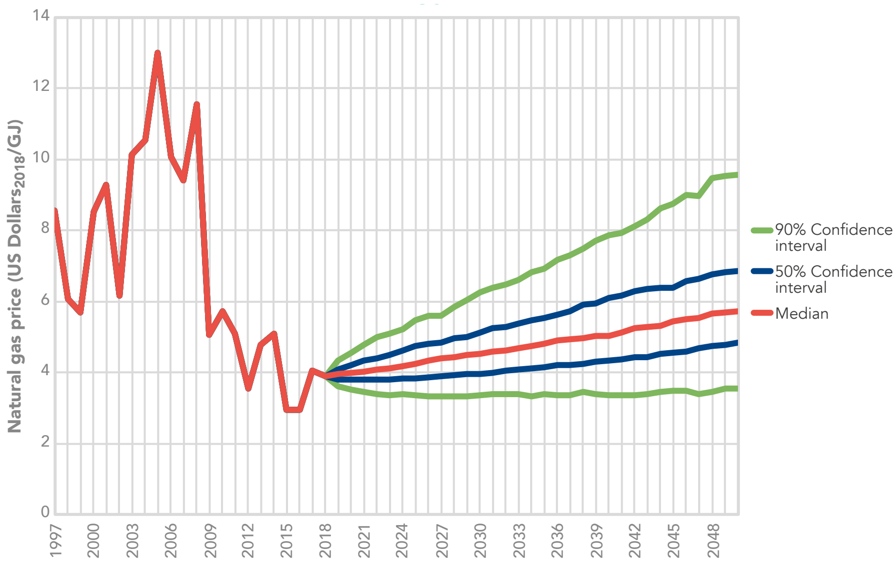


Figure 99. Natural gas price trajectories

Data obtained from SENER (2019).

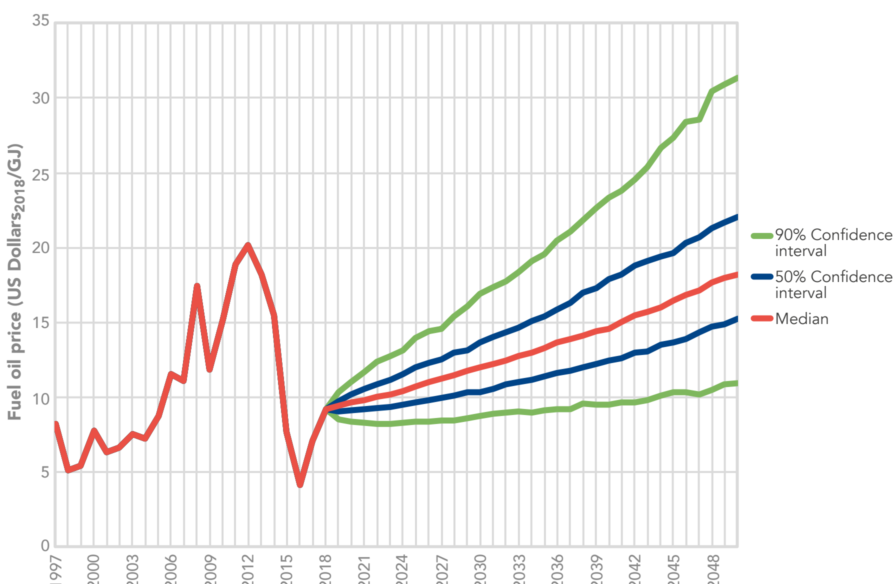
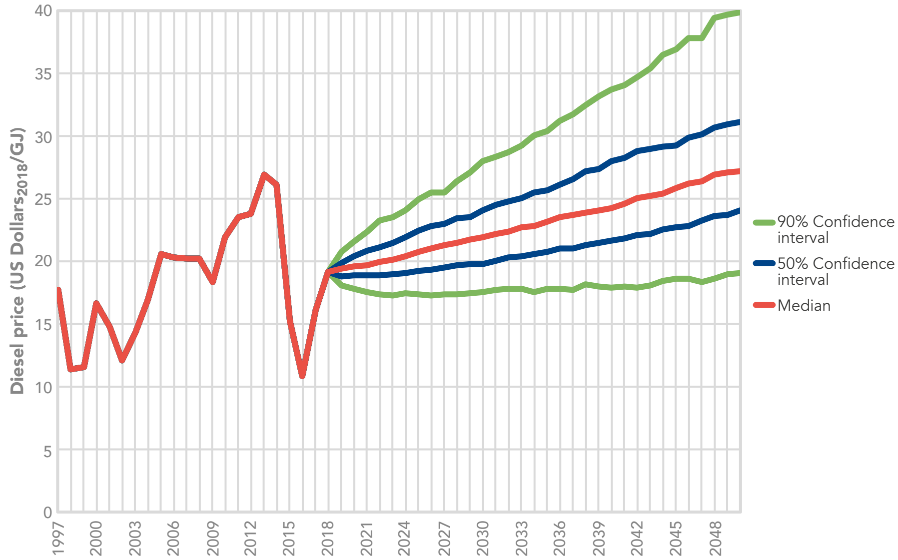


Figure 100. Fuel oil price trajectories

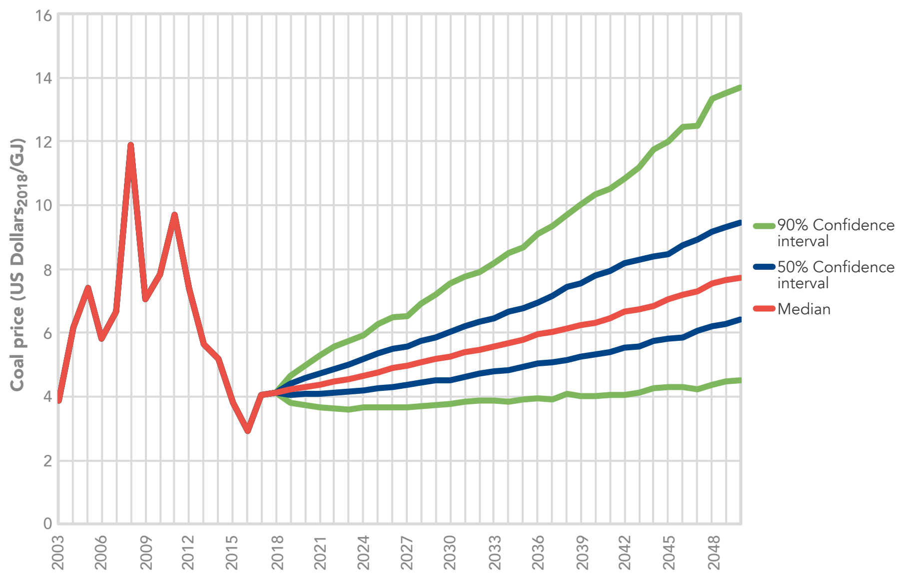
Data obtained from SENER (2019).

Figure 101. Diesel price trajectories



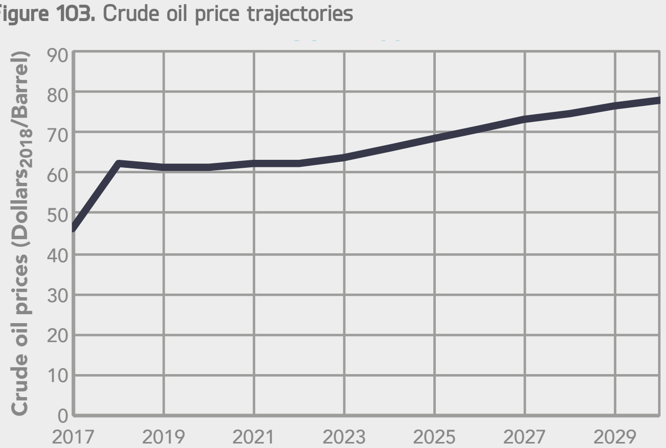
References: Data obtained from SENER (2019).

Figure 102. Diesel price trajectories



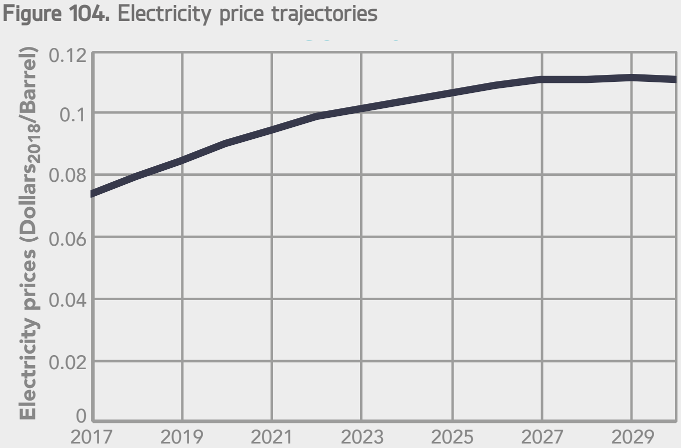
References: Data obtained from SENER (2019).

Figure 103. Crude oil price trajectories



Data obtained from BANXICO (2019) and EIA (2019).

Figure 104. Electricity price trajectories



Data obtained from SENER (2018).

6.7. MITIGATION MEASURES IN THE OIL AND GAS SECTOR

Table 17. PEMEX Cogeneration Projects

	ELECTRIC ENERGY (MW)			
	CAPACITY	PEMEX CONSUMPTION	VAPOUR (T/H ANNUALLY)	INVESTMENT (MILLION USD)
Cactus	633	29	480	877
Nuevo PEMEX Third stage	262	0	140	288
Tula	444	267	1,150	489
Cadereyta	525	135	850	638
Salina Cruz	436	120	800	569
Minatitlán	541	90	800	405
La Cangrejera	512	102	899	747
Morelos	516	89	788	785

References: PEMEX (2017b).

Table 18. Steam and electricity generation assumptions

ASSUMPTION	VALUE
Gas turbine efficiency	0.35
Furnace efficiency	0.8
Heat recovery efficiency	0.8
Useful time (years)	10
Capacity factor	0.8

In the following sections, a brief description of mitigation measures is presented. The considered measures include energy saving and greenhouse gas mitigation technologies including natural gas recovery and compression, an improvement in the efficiency of flaring, enhanced oil recovery (EOR) with and without carbon capture and storage (CCS) technology, replacement of wet seals with dry seals in centrifugal compressors, methane leak detection and repair, installation of vapour recovery units in storage tanks, energy efficiency in gas processing boilers and cogeneration. In the latter case, projects corresponding to refineries are included. In the specific case of oil refining, different mitigation measures were considered including thermal integration, economisers, fouling reduction, heat recovery, from regenerators, air excess control, air preheating, and vacuum pumps.

6.7.1. COGENERATION

Cogeneration consists of a set of facilities that simultaneously generate electrical and thermal energy from the same primary energy source. The advantage of cogeneration is its greater energy efficiency, since both heat and mechanical or electrical energy are produced in a single process, replacing the need to use a conventional power plant for electrical requirements and a conventional boiler for steam needs. Cogeneration projects contemplated by PEMEX in the 2019–2023 Business Plan, in the 2017–2021 Business Plan and in the Special Climate Change Program 2015–2018, as part of the update of the mitigation and adaptation goals of the oil and gas sector. Table 17 presents the general characteristics of the projects presented by PEMEX.

In order to estimate greenhouse gas emissions mitigation potentials, typical steam temperature and pressure were assumed. Steam conditions generated for the natural gas processing facilities Cactus and Nuevo PEMEX were assumed as 104 kg/cm^2 and 444°C; while 60 kg/cm^2 and 482°C were assumed for the other plants (Alcaraz-Calderón, et al., 2014; Mireles-Bravo, 2016; Barragán-Hernández, 2011). Table 18 presents the assumptions considered for the electricity and steam generation efficiencies (CMM, 2017).

Due to the lack of specific information on fuel consumption at PEMEX plants, it was assumed that cogeneration systems would replace gas turbines for electricity generation and natural gas boilers for steam generation. The gas consumption required to generate electricity and steam separately was determined, as well as with the cogeneration system. The difference between these consumptions represented the saving of energy and natural gas. This saving was finally multiplied by the emission factor for natural gas combustion. The natural gas consumption for the three cases was calculated with the following equations (CMM, 2017):

$$F_{GT}=\frac{E_{Total} * FP}{n_{GT}}$$

$$F_{GT}=\frac{V_{Total} * (h_{Process} - h_{Initial}) * FP}{n_{GT}}$$

$$F_{Cogen} = F_{GC} + \frac{V_{Additional} * (h_{Process} - h_{Initial}) * FP}{n_{GT}} - F_{GT}\,(1 - = n_{GT}) * n_{HR}$$

In the previous set of equations, F_{GT} is the natural gas consumption in the gas turbine, E_{Total} the annual generated electricity, FP the capacity factor, n_{GT} the gas turbine efficiency, F_{GC} the natural gas consumption in the boiler, V_{Total} the annual required steam, $h_{Process}$ the vapour enthalpy required in the process, E_{Total} the liquid water enthalpy to be heated for steam generation, n_{GC} the steam boiler efficiency, F_{Cogen} the amount of natural gas for the cogeneration system and $n_{HR}$the heat recovery efficiency. The additional amount of steam was calculated from the difference between

Table 19. CO_2 emissions, efficiency and abatement costs from cogeneration

FACILITY	BASELINE EMISSIONS ($MTCO_2E$ PER YEAR)	COGENERATION EMISSIONS ($MTCO_2E$ PER YEAR)	EMISSION REDUCTIONS ($MTCO_2E$ PER YEAR)	EFFICIENCY WITHOUT COGENERATION	EFFICIENCY WITH COGENERATION	MARGINAL ABATEMENT COST IN 2030 (USD/TCO_2E)
Cactus	3.29	2.05	1.24	0.45	0.72	-169.56
Nuevo PEMEX	1.58	1.06	0.52	0.34	0.51	-229.17
Tula	3.64	2.70	0.93	0.58	0.78	-103.51
Cadereyta	3.48	2.38	1.10	0.64	0.77	-170.28
Salina Cruz	3.04	2.13	0.92	0.56	0.80	-161.72
Minatitlán	3.47	2.33	1.14	0.52	0.77	-214.10

the amount of steam required in the process and the amount of steam that can be harnessed from the gas turbine. The difference represents the amount of steam that must be additionally heated in order to meet the process steam requirements. In the gas processing facilities, the steam generated from the combustion gases in the turbine was sufficient to meet the process steam requirements. Table 19 presents the main results obtained, including the estimation of the annual CO_2 emissions reduction.

6.7.2. REDUCTION OF GAS FLARING AND VENTING

The calculation for the reduction of gas venting and flaring was initially made from the estimation of emissions by gas venting and flaring. Data on gas venting and flaring by asset was taken from the National Hydrocarbons Commission (CNH) for 2018. The annual averages are presented in Table 20.

Table 20. Gas venting and flaring in 2018

OIL FIELD	VENTING AND FLARING IN 2018 (MILLION CUBIC FEET PER DAY)
Activo de Producción Abkatun-Pol-Chuc	5.0
Activo de Producción Bellota-Jujo	3.2
Activo de Producción Cantarell	37.8
Activo de Producción Cinco Presidentes	6.0
Activo de Producción Ku-Maloob-Zaap	52.9
Activo de Producción Litoral de Tabasco	11.7
Activo de Producción Macuspana-Muspac	27.3
Activo de Producción Poza Rica-Altamira	28.2
Activo de Producción Samaria-Luna	4.2
Activo Integral Aceite Terciario del Golfo	4.7
Activo de Producción Veracruz	0.3

References: CNH (2019a)

It was assumed that the values in Table 20 correspond to natural gas, although it is possible that they contain CO_2 generated from the non-constant flaring of the gas. The recovery and compression of gas from oil fields has been an alternative that has not been fully implemented in PEMEX and wastes significant amounts of natural gas that could be used to increase the supply of this fuel at the national level. Various investments have been made in compression infrastructure in the Cantarell and Ku Maloob Zaap oil fields (PEMEX, 2012), (PEMEX, 2012a). Since Ku-Maloob-Zaap represents the largest source of vented and flared gas, calculations were performed considering this oil field. Investment costs were estimated in 0.24 USD per m^3 of gas while operation and maintenance costs were estimated in 0.008 USD per m^3 of gas injected (IEA, 2006). It was assumed that 83.7% of the gas was burned, and it was calculated that the reduction of CO2e emissions could be 6.6 million tonnes of CO2e per year (CMM, 2017). It was also assumed that 10% of the gas to be compressed would be used to cover the compressor energy requirements. The marginal cost of abatement is 3.3 USD per tonne of CO_2e in 2030.

6.7.3. INCREASED EFFICIENCY IN FLARING

For the calculation of the emissions reductions from the use of efficient burners, it was assumed that combustion could have an efficiency of 98% (API, 2009; EDF-CMM, 2015). The emission reduction potential was calculated for the Canterell, Litoral de Tabasco, Macuspana-Muspac and Poza Rica-Altamira oil fileds; and was calculated as the difference between the emission generated from an efficient combustion and the emissions generated by burners with an efficiency of 83.7%. Investment costs were assumed to be 0.012 USD per million cubic feet burned, while operation and maintenance costs were assumed to be 0.0009 USD per million cubic feet burned (EPA, 2003; EDF-CMM, 2015; CMM, 2017). Emission reductions can be as high as 2.7 million tonnes of CO_2e per year, while the marginal cost of abatement corresponds to 34.8 USD per tonne of CO_2e in 2030.

6.7.4. ENHANCED OIL RECOVERY (EOR)

Enhanced oil recovery is used to increase recovery of oil through the injection of CO_2 at high pressure in producing wells with the benefit of eliminating emissions of $CO_2$2 that are otherwise vented to the atmosphere. It has been estimated that CO_2 injection can increase oil production by 11% (Lajous, 2009). EOR could be used in several fields including Cantarell, Ku–Maloob–Zaap, Bermúdez Complex, Jujo–Tecominoacán, Chicontepec deposits and Cinco Presidentes (CMM 2009; Lacy, Serralde, Climent, & Vaca, 2013). The scenario proposed for these calculations includes the use of the CO_2 generated in the production of ammonia in the Petrochemical Complex of Cosoloecaque. The calculations considered that the CO_2 would be injected into the Cinco Presidentes oil field located 65 km from the petrochemical complex. The information used for the calculations was obtained from Mitsubishi Heavy Industries (2016), Morales–Mora, Pretelín–Vergara, Leiva, Martínez–Delgadillo, & Rosa-Domínguez (2016), IEA (2004) and McCollum and Ogden (2006) (CMM, 2017).

In order to calculate investment and operation and maintenance costs, it was assumed that the petrochemical complex required a CO_2 compression system, together with a pumping station and a CO_2 transportation pipeline. The required investment costs were estimated in 41 million USD and operation and maintenances costs of 2.2 million USD per year. It was also assumed that one tonne of CO_2 injected could produce 1 barrel of oil. Oil prices used in the calculations are presented at the beginning of this section. Emission reductions can be approximately 0.8 million tonnes of CO_2e per year (considering two ammonia production units); while the marginal cost of abatement corresponds to -19.6 USD per ton of CO_2e in 2030.

6.7.5. EOR WITH CARBON CAPTURE AND STORAGE

From Mitsubishi Heavy Industries (MHI) (2016), it is possible to implement a CO_2 capture unit in the petrochemical complex of Cosoleacaque, so that emissions from the primary reformer are not vented. MHI (2016) estimated that 346,750 tonnes of CO_2 are emitted annually from the primary reformer of every unit. This CO_2 could also be used for EOR operations. The calculations considered the compression and transport of this CO_2 together with the addition of a CO_2 recovery unit. For this, MHI (2016) considered an investment of 150 million USD (2018 prices). Total investment costs were estimated in 167 million USD with operation and maintenance costs of 11 million USD per year (solvent replacement is included). Emission reductions can be approximately 0.5 million tonnes of CO_2e per year (considering two ammonia production units); while the marginal cost of abatement corresponds to 91.3 USD per ton of CO_2e in 2030.

6.7.6. METHANE LEAK DETECTION AND REPAIR (LDR)

A leak detection and repair program includes several operational factors that should be considered such as the inspection time of facilities, the number of inspectors needed, the potential to reduce leakage losses, and the time needed to perform repairs. Programs also include improvement of operation practices within the facility and constant monitoring of equipment such as valves, pumps, and connectors. (EPA, 2007). The most important sources of equipment emissions from natural gas processing plants are valves and connectors. The main cause of leaks in this type of equipment is due to failures in seals or gaskets, or by wear and improper maintenance. Leaks can be detected through visual inspections, sound, odours, or infrared cameras (EPA, 2007; CMM, 2017).

For this measure, information from EDF–CMM (2015) was used, considering fugitive methane emissions in onshore production wells, compression stations, storage facilities and processing centres. The data presented in EDF–CMM (2015) was used, and the emissions reduction corresponded to 0.6 million tonnes of CO_2e per year. The total investment costs were 3 million USD (CMM, 2017). The marginal abatement costs considering the economic benefits of gas savings were estimated at -5.3 USD per tonne of CO_2e.

In the case of platforms, the LDR programme costs and mitigation potential were estimated from Bylin et al (2010) for 209 exploration and production platforms. For the calculation, typical methane emissions per platform (4.9 million cubic feet per year) were considered. LDR programmes in platforms can reduce approximately 70% of methane emissions and investment costs can be around 55 thousand USD per platform (Bylin et al, 2010). From this data, 0.4 million tonnes of CO_2e can be reduced per year. Marginal abatement costs were -2.8 USD per tonne of CO_2e.

6.7.7. VAPOUR RECOVERY UNITS

Vapour emissions in storage tanks can vary widely depending on the type of fluid being stored, the number of filling cycles, or the amount of oil handled in the tanks. In general, the main component of these vapours is methane found in 40% to 60%. The implementation of vapour recovery units can reduce vapour emissions by more than 95%. Vapours contain a significant amount of liquefied gas, so vapour recovery is additionally valuable due to the recovery of higher calorific value products (EPA, 2003a; CMM, 2017).

In order to calculate Information from EDF–CMM (2015) was used, considering fugitive methane emissions in crude and condensate storage tanks, and dehydrators. The data presented in the study was taken, and the emissions reduction corresponded to 0.5 million tonnes of CO_2e per year. The total investment costs were considered as 20.9 million USD. The marginal abatement costs were estimated at -18.3 USD per tonne of CO_2e.

In the case of platforms, the VRU costs and mitigation potential were estimated from Bylin et al (2010) for 209 exploration and production platforms. For the calculation, typical methane emissions from oil storage tanks per platform (9.7 million cubic feet per year) were considered. VRU in platforms can reduce approximately 95% of methane emissions and investment costs can be around 200 thousand USD per platform (Bylin et al, 2010). From this data, 1.1 million tonnes of CO_2e can be reduced per year. Marginal abatement costs were 22.5 USD per tonne of CO_2e.

6.7.8. CENTRIFUGAL COMPRESSION WET SEALS

Oil is used as a seal in centrifugal compressors to prevent high pressure gas leakage. However, the oil captures some of the gas flowing through the compressor. This gas has to be separated from oil to maintain proper operation but is normally vented into the atmosphere (EPA, 2006). An alternative technology corresponds to the replacement of wet seals by dry seals. Dry seals do not use oil provide additional benefits by offering lower operating and downtime costs (EDF-CMM, 2015; CMM, 2017).

Based on publicly available information, a current count of 85 centrifugal compressors was considered for natural gas processing facilities while 23 compressors were considered for natural gas compression platforms and 24 compressors for natural gas compression stations. In the case of marine platforms, it was assumed that there were 3 compressors per platform. It was considered that the change from wet to dry seals can reduce 57 cubic meters of methane per hour per compressor, which was obtained from various studies that estimate that the maximum value of emissions in a compressor with wet seals is 68 cubic meters per hour per compressor and that of a dry seal is 11 cubic meters per hour per compressor. The investment costs of this measure were taken from (EDF-CMM, 2015; CMM, 2017), as 375 thousand USD per compressor and a reduction in operation and maintenance costs of 5 thousand USD per compressor. The volume of gas savings was estimated as well as the economic benefits of its savings using the projection of prices of this fuel. The emissions that could be avoided correspond to 0.9 million tonnes of CO_2e per year for natural gas processing facilities, 0.2 million tonnes of CO_2e per year for platforms and 0.3 million tonnes of CO_2e per year for compression stations. Marginal abatement costs were estimated in -1.3 USD per tonne of CO_2e.

6.7.9. GAS CAPTURE IN CENTRIFUGAL COMPRESSOR WET SEALS

As presented in the previous section, natural gas is vented from wet seals in centrifugal compressors. Another alternative for methane emissions mitigation, consists in capturing the natural gas in the oil seals. A recovery system can be implemented so that natural gas is captured, and the clean oil is returned to the compressor. In this case, it was considered that 68 cubic meters per hour per compressor of natural gas are emitted. As in the previous section, a total of 132 centrifugal compressors were considered. The investment costs of this measure were taken from (EDF-CMM, 2015), as 75 thousand USD per compressor. The volume of gas savings was estimated as well as the economic benefits of its savings using the projection of prices of this fuel. The emissions that could be avoided correspond to 1.2 million tonnes of CO_2e per year for natural gas processing facilities, 0.3 million tonnes of CO_2e per year for platforms and 0.3 million tonnes of CO_2e per year for compression stations. Marginal abatement costs were estimated in -6.9 USD per tonne of CO_2e.

6.7.10. REPLACEMENT OF PNEUMATIC DEVICES WITH AIR SYSTEMS

Several pneumatic control instruments along the oil and natural gas supply chain use high pressure natural gas. These devices are used to regulate pressure, temperature, liquid levels and flow and present leaks. The use of compressed air systems can avoid these emissions additionally improving operational safety. Typical air systems use a compressor to increase the pressure of atmospheric air. The compressed air is stored in a tank and later filtered and dried. In some applications such as small pneumatic pumps or gas compressors, compressed air does not need to be dried. The calculation of the mitigation potential and costs were taken from EPA (2004). It was considered that a medium size facility presents 35 control loops with an emission of 45 standard cubic feet per day of methane. Additionally, EPA (2004) estimates that 1 cubic foot per day per control loop is required. The required investment costs for this system are approximately 80 thousand USD with additional operation and maintenance costs of 18 thousand USD per year. The calculation considered the addition of the required facilities including an air compressor. In the case of offshore and onshore oil production facilities, 2 control loops were considered for 209 platforms and 340 onshore oil fields (Bylin et al, 2010). The emissions that could be avoided correspond to 0.4 million tonnes of CO_2e per year for natural gas processing facilities, 0.3 million tonnes of CO_2e per year for platforms and 0.2 million tonnes of CO_2e per year for onshore oil and gas production facilities. Marginal abatement costs were estimated in -6.7 USD per tonne of CO_2e.

6.7.11. THERMAL EFFICIENCY IN NATURAL GAS PROCESSING

Energy efficiency can be improved in boilers within gas processing facilities of PEMEX. This mitigation measure was estimated considering data from CMM (2008) and PEMEX (2011) and for three gas processing facilities (Poza Rica, Cactus and Nuevo PEMEX). CMM (2008) estimated that boiler efficiency could be increased by 5 and 10% through the modernisation of steam generation units. Maintenance programmes in PEMEX were revised in order to only include boilers that have not received upgrading operations. For instance, units CB-2522 and CB-2524 in the Nuevo PEMEX complex received engineering and upgrading work in 2015. From this revision, in the case of Poza Rica, BW-1, BW-3 and BW-4 units were considered while units CB-10, CB-11, CB-12 and CB-13 for Cactus; and units CB-2501, CB-2502, CB-2521 and CB-2523 for Nuevo PEMEX were used for the calculations. Total investment was estimated in 116 million USD and CO_2e mitigation potentials were calculated in 25 thousand tonnes of CO_2e for Poza Rica, 42 thousand tonnes of CO_2e for Cactus and 53 thousand tonnes of CO_2e for Nuevo PEMEX. Marginal abatement costs are 50.0 USD per tonne of CO_2e for Poza Rica, 43.6 USD per tonne of CO_2e for Cactus and 68.7 USD per tonne of CO_2e for Nuevo PEMEX.

6.7.12. EXCESS AIR CONTROL IN REFINERIES

In the combustion chamber of the boiler, the air is mixed with the fuel, providing the oxygen needed for combustion. Ideally, only the exact amount should be supplied, but in practice, a small excess of air is required to ensure that all fuel is burned in the boiler. If there is too much air, the efficiency of the boiler is reduced, because additional air is heated in the chamber and heat is lost in the exhaust gases. Efficient air inlet control increases overall efficiency, providing energy savings. Fuel savings with this measure can be more than 5% (Seamonds, Lowell, Balon, Leigh, & Silverman, 2009). One of the most common techniques to control air quantities in boilers corresponds to control systems that monitor the amount of oxygen in the exhaust gases and adjusting the air intake (The Carbon Trust, 2012; CMM, 2017).

For the calculation of this mitigation measure, the production of steam in the six PEMEX refineries was estimated. Additionally, 47 operating boilers were considered and together with their average steam production. The investment and operation and maintenance costs for the excess air control system were considered in 13,628 USD per boiler and 3,253 USD per boiler per year, respectively (Colket et al, 2012; CMM, 2017). The CO_2e emission reduction of this measure was estimated in 0.2 million tonnes of CO_2e per year with a marginal abatement cost of -101.8 USD per tonne of CO_2e.

6.7.13. AIR PREHEATING IN REFINERIES

Preheating combustion air is one of the most effective ways to improve efficiency and energy savings in industrial process heaters (DOE, 2007). The heat of the exhaust gases is used, by means of heat exchangers located at the outlet of these gases. The recovered heat is transferred to the combustion air, thereby reducing the energy demand of the furnace. Typical fuel savings are between 8% and 18% and may be economically attractive for furnaces with a flue gas temperature of 343°C or higher, and with capacities of at least 50 Million BTU per hour (Garg, 1998; CMM, 2017).

For the estimation of the mitigation potential, information was available from the process diagrams for the Cadereyta, Salamanca, Minatitlán and Tula refineries. According to these diagrams, some furnaces already have an air preheating system. Information was obtained in relation to the capacity of the reforming and distillation furnaces and their preheating system. The energy savings of the measure were assumed to be 10% in the fuel consumption of the furnaces. The investment costs were estimated at 83,429 US USD per million Btu per hour of thermal capacity of the preheating system (NYSERDA, 1985). Operating and maintenance costs were estimated at 2% of the initial investment. The emission reduction of this measure was estimated in 0.3 million tonnes of CO2e per year with a marginal abatement cost of -64.5 US USD per tonne of CO_2e.

6.7.14. ECONOMISERS IN REFINERIES

Economisers are heat exchangers that recover heat from combustion gases which is used to preheat feed water in boilers. The amount of heat recovered depends on the temperature of these gases and the liquid to be heated (Barma, Saidur, Rahman, Allouhi, Akash, & Sait, 2017). Economisers can improve total heat recovery and efficiency of the steam system by more than 10% (DOE, 2012). Calculations for the control of excess of air in boilers were used. Investment costs for a boiler economiser with a capacity of 225.8 t/h steam correspond to 32,287 USD (EPA, 2010; CMM, 2017). Based on data from PEMEX, an average boiler capacity of 200 t/h of steam was considered. Annual operating and maintenance costs of 2% of the initial investment were assumed. The emission reduction of this measure was estimated in 0.5 million tonnes of CO_2e per year with a marginal abatement cost of -73.2 USD per tonne of CO_2e.

6.7.15. FOULING MITIGATION IN REFINERY EQUIPMENT

Fouling corresponds to the accumulation of solid material on the surfaces of heat exchangers. Fouling is a complex phenomenon that is not yet fully understood. However, some causes of its occurrence are particles process flows, crystallisation, chemical reactions, corrosion processes and accumulation of biological material (Master, Chunangad, & Pushpanathan, 2003). Fouling decreases the area of flow and heat exchange, resulting in significant amounts of energy that are lost (Díaz-Bejarano, 2015). It is therefore important to have effective scale mitigation methods in refineries. The most used methods are the addition of chemicals, the use of equipment designed to mitigate fouling and regular cleaning (Smaili, Vassiliadis, & Wilson, 2001; CMM, 2017).

The input data used in the calculations were taken from the work of Panchal and Huangfu (2000) and a regular maintenance program of exchangers with three cleanings per year was assumed. The estimated cost for cleaning was 25,539 USD for each unit, including the costs associated with the drop-in production due to unit shutdown during cleaning. The estimated savings, considering a typical preheating train for a distillation unit of 100,000 barrels per day was 5.5 MJ per barrel of processed crude (CMM, 2017).

Estimates of crude oil processed in distillation units were used in the six refineries. Due to the nature of the measure, it was considered that there are no capital costs, as all costs are for operation and maintenance procedures. The emission reduction of this measure was estimated in 0.2 million tonnes of CO_2e per year with a marginal abatement cost of -28.1 USD per tonne of CO_2e.

6.7.16. HEAT RECOVERY FROM REGENERATORS IN FCC UNITS

Fluidised-bed Catalytic Cracking (FFC) is widely used to convert high molecular weight hydrocarbon fractions into lighter products, such as gasoline and diesel. FCC uses catalysts to carry out cracking reactions. During the process, coke accumulates over the catalysts. Therefore, it is necessary to regenerate the catalysts continuously for reuse. This is achieved by burning the coke in a regeneration reactor, commonly called a regenerator. The flue gases can reach very high temperatures at the outlet of the regenerator, thus containing a large amount of energy. Heat recovery boilers are commonly installed at the outlet of the gases, to use some of this heat and produce steam and/or electricity (Worrell, Corsten, & Galitsky, 2015; CMM, 2017).

Information was available from PEMEX regarding the number and capacity (in thousands of barrels per day) of FCC units in the six refineries. A utilisation factor of 71% was assumed to calculate the number of barrels processed annually in the FCC units (SENER, 2016). The considered investment was 42 million USD for a power recovery system in an FCC unit of 100 thousand barrels per day capacity (New Energy and Industrial Technology Development Organization [NEDO], 2008). The operating and maintenance costs were assumed to be 2% of the total investment, representing 0.08 USD per barrel of oil processed per year. The energy saving potential considered was 17.28 MJ/barrel processed in the FCC (New Energy and Industrial Technology Development Organization [NEDO], 2008). It was also assumed that thermal efficiency in electricity generation was 35% and considering this percentage the fuel savings of the measure were calculated. The emission reduction of this measure was estimated in 0.4 million tonnes of CO2e per year with a marginal abatement cost of 62.2 USD per tonne of CO_2e.

6.7.17. THERMAL INTEGRATION IN ATMOSPHERIC DISTILLATION

Atmospheric distillation units process all crude entering the refinery. In these units, crude oil is separated into several fractions taking advantage of its different boiling points. This process consumes large between 35 and 45% of the total energy used (Szklo & Schaeffer, 2007). Because of this, the energy efficiency methods applied in these units are of great relevance from both an economic and an environmental point of view. One of the most common ways of increasing this efficiency is thermal process integration. Heat transfer between the hot products and the feed through a heat exchanger network reduces the energy demands in cooling systems and furnaces. The optimisation of these networks can be carried out from the original design of the plant, or by adapting existing installations (CMM, 2017).

The proposed measure is based on the work of Kamel, Gadalla, & Ashour (2013), and considers changes in the structure and operating conditions of the exchanger network and modifications in the reflux currents of the atmospheric distillation column. It was assumed that the measure could be applied in the SNR atmospheric distillation plants that have not been converted to combined plants (specifically in the refineries of Salamanca, Tula, Madero and Salina Cruz). The total capacity of the distillation plants (7 plants), according to PEMEX data, is 645 thousand barrels of oil per day. Energy savings potential for this measure typically lies between 10 and 20% (Worrell, Corsten, & Galitsky, 2015). The investment cost considered was 407 thousand USD for a plant with a processing capacity of 100 thousand barrels per day (Kamel, Gadalla, & Ashour, 2013; CMM, 2017). The operation and maintenance costs were taken as 2% of the initial investment. Both costs were related to process capacity and considered constant. The calculated reduction in emissions from this measure was 0.08 million tonnes of CO_2e per year with a marginal abatement cost of -70.8 USD per tonne of CO_2e.

6.7.18. THERMAL INTEGRATION IN ATMOSPHERIC DISTILLATION/VACUUM DISTILLATION

Combined plants involve the integration of atmospheric and vacuum distillation units, seeking to maximise heat recovery, avoid operational inefficiencies (such as cooling and then heating the same currents), and maintain the operation of the processes under optimum thermodynamic conditions. One of the most widely used tools in thermal process integration is pinch analysis, which is a methodology for minimising energy consumption in chemical processes. The latter achieved by calculating energy targets, which are achieved by optimising the heat recovery system, energy supply methods and process operating conditions (Ateeq, Taher, & AL Salam, 2017).

This measure considers thermal integration between atmospheric and vacuum distillation units in refineries in which PEMEX does not have combined plants. The input data used in the calculations were taken from previous studies conducted at PEMEX for the Tula refinery (Briones, et al., 1999). Energy consumption in the atmospheric distillation and vacuum distillation units were estimated and the processing capacity and energy consumption of the combined plants were determined as the sum of the individual units (CMM, 2017).

For this mitigation measure, investment costs were calculated in 88 thousand USD per thousand barrels of processed oil (Briones, et al., 1999). Operation and maintenance costs were considered 2% of the initial investment. The emissions reduction from this measure was calculated in 0.2 million tonnes of CO_2e per year with a marginal abatement cost of -17.5 USD per tonne of CO_2e.

6.7.19. VACUUM PUMPS UN VACUUM DISTILLATION UNITS

Vacuum distillation units use the atmospheric distillation residues to recover additional hydrocarbon fractions avoiding thermal decomposition that would occur if the temperature of the crude oil was increased above the operating parameters of atmospheric distillation. The vacuum distillation units use systems that create and maintain the necessary vacuum conditions. These systems may consist of steam ejectors, liquid ring vacuum pumps, or a combination of both (European Integrated Pollution Prevention and Control Bureau [EIPPCB], 2015). It is common to have multi-stage ejector systems, with a vacuum pump in the last stage. The ejectors consume medium to high pressure steam in large quantities, as well as cooling water. Their technology is relatively inexpensive, sound and reliable, and they require little maintenance, but their efficiency is low (Birgenheier & Wetzel, 1988). Replacing steam ejectors with vacuum pumps can increase the electricity consumption for vacuum generation, but reduces heat requirements, the consumption of cooling water and the use of conditioning agents, as well as the consumption of electricity for cooling pumps (European Integrated Pollution Prevention and Control Bureau [EIPPCB], 2015). The final energy balance can therefore represent significant savings (CMM, 2017).

The measure considers the replacement of the steam ejector system in the vacuum distillation towers by liquid ring vacuum pumps. An investment cost of 487 thousand USD was estimated for a vacuum system (Valero Energy Corporation, 2003; DOE, 2005). The energy savings considered were equal to the 8% of the total energy consumed in the refineries (Morrow III, Marano, Sathaye, Hasanbeigi, & Xu, 2013). The emissions reduction of this measure was estimated in 0.7 million tonnes of CO_2e per year with a marginal abatement cost of -71.2 USD per tonne of CO_2e.

6.7.20. STEAM TRAP REPAIR

The adequate functioning of heat traps is key in avoiding steam leaks and thus improving energy efficiency in oil refinery operations. Substituting leaking traps can reduce steam use in approximately 8%, reducing fuel use. For the estimation of mitigation potentials from this measure, it was assumed that 6,000 steam traps could be fixed or replaced in PEMEX oil refineries. Additionally, it was assumed that this measure could reduce steam leaks in 15 kg per hour for every steam trap operating 8 thousand hours per year (CMM, 2017). Investment costs were taken from Rossiter and Beth (2015) who estimate that replacing a steam trap costs 400 USD. From this, CO_2e emission reductions were calculated in 0.2 million tonnes of CO_2e with marginal abatement costs of -72.0 USD per tonne of CO_2e.

6.8. MARGINAL ABATEMENT COSTS, MITIGATION POTENTIALS AND DECARBONISATION PATHWAYS TO 2030

Based on the previous assumptions and calculations, Figure 105 presents the marginal greenhouse gas abatement costs and emissions reduction potentials for 2030. As it can be observed, the total abatement potential in 2030 corresponds to 25.3 million tonnes of CO_2e per year.

The emission reduction trajectories (including the mitigation pathways for the previously described measures) of the analysed scenarios are presented in Figure 106. Considering the CNH Scenario, after 2024 greenhouse gas emissions increase above Decarbonisation Scenario (represents the 1.5°C trajectory) levels because of the increase in oil and gas production from unconventional resources. The cumulative emissions for the CNH Scenario correspond to 524 million tonnes of CO_2e (2019-2030 period) exceeding the required carbon budget by 24 million tonnes of CO_2e. In the case of the Depletion Scenario, the natural depletion trend and production of oil and natural gas heavily contributes to achieve lower emissions

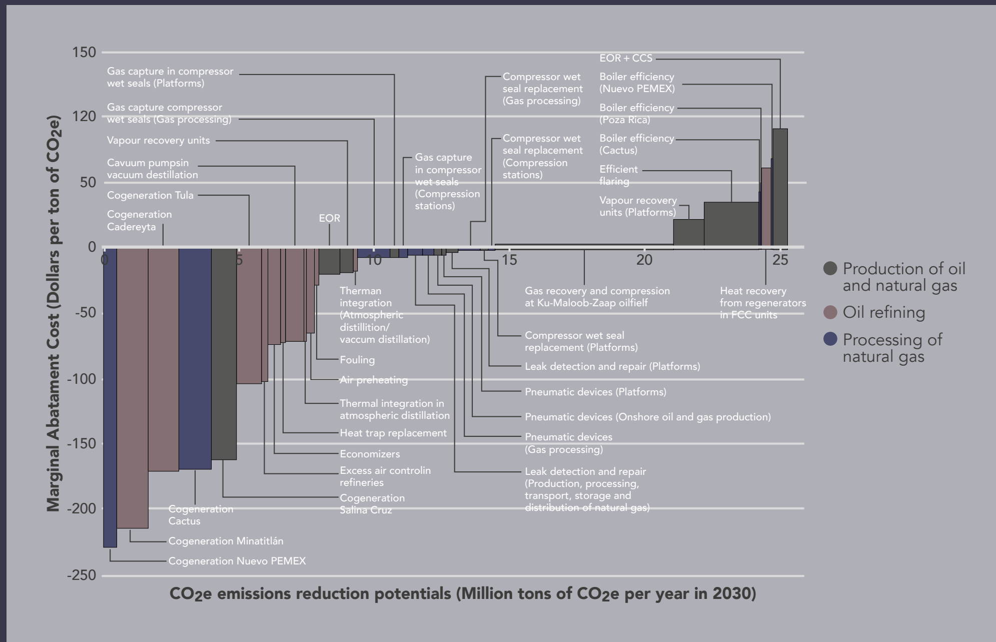
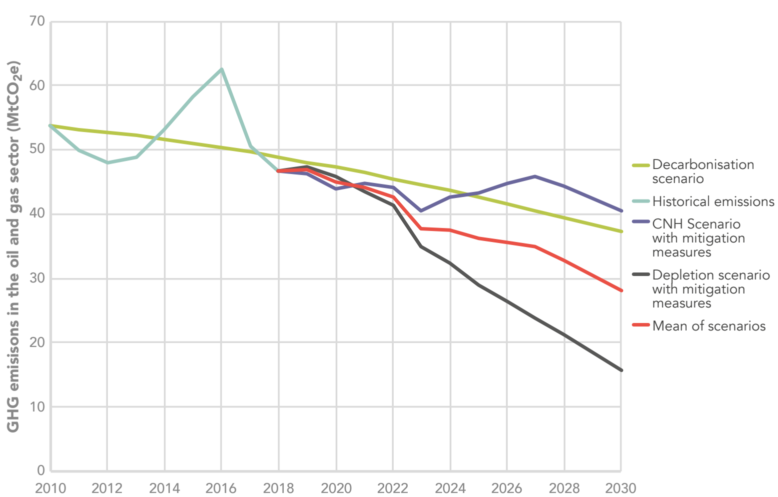


Figure 105. Marginal abatement cost curve for the oil and gas industry

compared to the Decarbonisation Scenario. The latter will be further analysed in the following section. For this scenario, the resulting cumulative emissions between 2019 and 2030 is 380 million tonnes of CO_2e. If a mean trajectory (shown in Figure 106) between the CNH Scenario and the Depletion Scenario is considered, the estimated cumulative emissions correspond to 452 tonnes of CO_2e for the 2019–2030 period.

Figure 106. Decarbonisation scenarios for the oil and gas sector



6.9. DECARBONISATION OF THE OIL AND GAS SECTOR TOWARDS 2050

As presented in the previous sections, there is no doubt that in order to decarbonise the oil and gas sector in Mexico, several mitigation measures must be implemented in the shorter term. However, to achieve a more ambitious decarbonisation of the sector, further alternatives must be analysed. One of the main challenges to achieve this relates to the high uncertainty around the economic and climate policy for 2050 and the technological development required for alternatives such as carbon capture and storage, or the penetration of electric vehicles. Because of this, this section of the study explores alternatives that may be implemented given the sector's current situation.

Carbon capture and storage and un-burnable oil

Carbon capture and storage technologies have proved not to have a significant role in decarbonisation (Beck, et al., 2020). McGlade and Ekins (2014) modelled two different scenarios to determine the degree of exploitation of possible reserves worldwide in order to keep the world's temperature increase down to 2.0 degrees. The results suggest that on a global scale nearly 600 billion barrels of oil reserves must remain unused by 2035 in a scenario where carbon capture and storage (CCS) is unavailable, representing around 45% of total available reserves. Contrastingly, in a scenario allowing the wide-spread and rapid adoption of CCS in both the electricity and industry sectors, nearly 500 billion barrels of oil must remain in situ. In a scenario with no CCS, no region can fully exploit their reserves although some regions must leave greater proportions of their reserves unused than others (McGlade and Ekins, 2014).

This study also suggests that exploration efforts should be called into question. Arctic oil, for instance, is classified as un-burnable oil, and the development of these reserves are incompatible with limiting average global temperature change to 2°C. In the same way, the exploitation of light, tight oil or any type of unconventional oil extraction is not consistent with the established goals. Moreover, at least 40% of deep-water resources that are yet to be found must remain undeveloped, which rises the required use of CCS to 55%. For these reasons the development and exploitation of all and every oil resource discovered, or the discovery of more expensive resources should not be encouraged by policy makers (McGlade & Ekins, 2014).

The oil and gas production for the depletion scenario in this work presents the production reduction trend without considering the development of unconventional resources, while the CNH scenario presents the development of unconventional resources until 2030. As observed in the depletion scenario, in order to achieve a deeper decarbonisation of the sector, and given the current development stage of CCS technology, it is necessary to maintain unconventional resources unburned as presented in Figure 107.

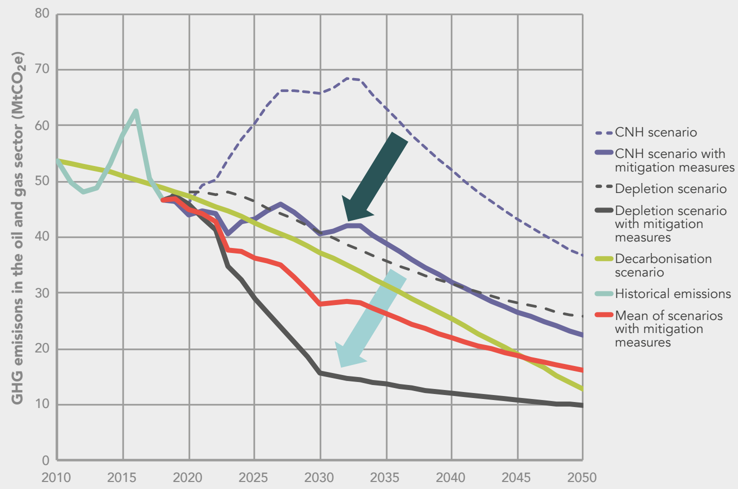


Figure 107. Mitigation scenarios towards 2050

Reduction in fuel demand

The decarbonisation scenarios prepared by the World Resources Institute (WRI) Mexico for the transportation sector were used in order to analyse gasoline and diesel demand and supply. The following graphs (Figure 108 and 109) present the production and demand projections for gasoline and diesel. In the case of production, it was considered that oil refining capacity could operate at their optimum level with constant maintenance and upgrading. The demand scenarios projected by WRI consider the business as usual, NDC and decarbonisation scenarios.

Based on the data presented in the previous graphs, it can be observed that there would be an overcapacity for gasoline production. However, in the case of diesel, the existing capacity and considering the decommissioning of some refining assets could be enough to satisfy diesel demand in the decarbonisation scenario. Despite of this, it is important to mention that the current stage in the development of electric vehicles could increase their penetration in the future and oil refining assets could no longer be used.

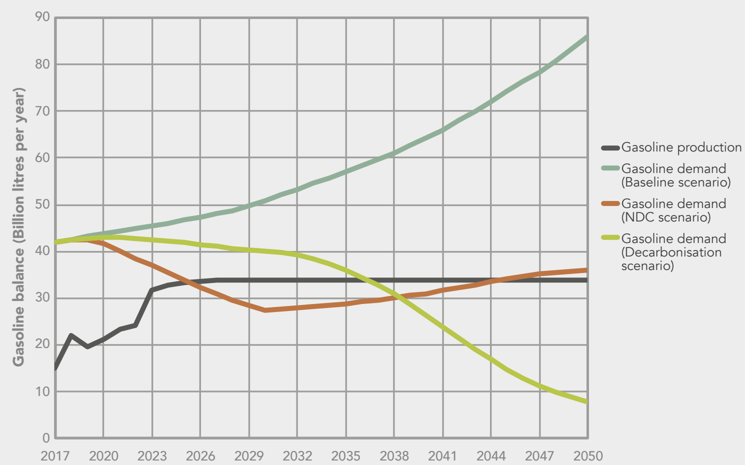


Figure 108. Gasoline balance of demand and production

6.10. CONCLUSIONS

This study evaluates the decarbonisation possibilities given the current administration's plans, which are based on the use of hydrocarbons and the increase of production of gasoline and diesel. The CNH Scenario, which is based on government estimates, highlights an increase in both oil and natural gas production that would translate in higher greenhouse gas emissions. This scenario would exceed the required carbon budget by 177 million tonnes of CO_2e for the 2019-2030 period.

There are huge opportunities for decarbonisation of the oil and gas sector in Mexico, and several mitigation

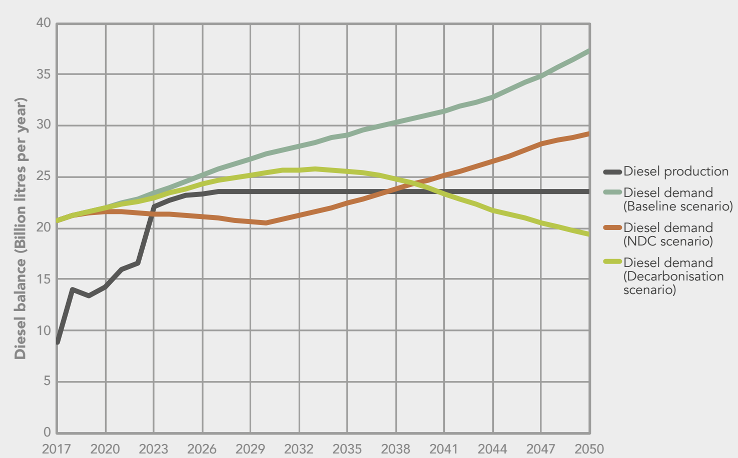


Figure 109. Diesel balance of demand and production

measures can reduce emissions and provide important economic benefits. From the mitigation strategies analysed, 57% correspond to cost effective measures with economic benefits, which are equivalent to an emissions reduction of 14.5 million tonnes of CO_2e in 2030. It is important to highlight that the latter figure can increase to 83% if natural gas capture platforms are included in marine oil and gas fields. With regards to this strategy, and as observed in the marginal abatement cost curve, it has a positive marginal cost. However, its cost is lower compared to other technologies such as carbon capture and storage and could be implemented with the aid of international financial mechanisms. This strategy could represent an increase of approximately 6.5 million tonnes of CO_2e in emissions reduction. Methane fugitive emissions reductions are also important, and the existing regulations should be encouraged and enforced. In addition to this, the rational and efficient use of energy within PEMEX facilities is necessary and key to reduce greenhouse gas emissions and cogeneration could provide a cost-effective solution. ◆

7. TRANSPORT SECTOR DECARBONISATION PATHWAY

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KEY POINTS
TRANSPORT SECTOR

- The transport sector made up 23% of Mexico's GHG emissions in 2015, making it the largest GHG emitter nationally. This emissions grow faster than any other sector in absolute terms and under the business as usual scenario, they are projected to duplicate by 2050.
- While all transport modes grow in activity, individual road transport is the fastest growing category. It is projected to reach 58% share of all passenger kilometres travelled by 2050.
- The Avoid–Shift–Improve framework provides a way for governments and other actors to consider policies and actions to reduce emissions in transport in three key areas: Avoid and reduce the need for motorized travel; Shift passenger and freight travel to more environmentally and socially sustainable modes; and Improve the energy efficiency of transport modes.
- Barriers to reduction in travel and modal shift include access to financial resources, capacity building, and overcoming old models. On the other hand, barriers to vehicle electrification comprise conditions on electrification of transport fleets (i.e. renewable energy procurement), electric vehicle barriers, such as vehicles, batteries, and charging infrastructure; and electric freight barriers.
- Transport sector decarbonisation brings co-benefits in the sustainable development agenda by addressing air quality, road safety, physical activity, access to opportunities, and economic development.
- The proposed decarbonisation pathway for the transport sector results in GHG emissions of 140 $MtCO_2e$ by 2030 (30% below BAU) and 44 $MtCO_2e$ by 2050 (86% below BAU). Following this route, more than 75,000 human lives could be saved, considering a reduced exposure to particulate pollution by midcentury.

The transport sector in Mexico is composed of vehicles in passenger or freight activities within four main transportation modes: road, rail, aviation and shipping. While all transport modes grow in activity, individual road transport is the fastest growing category and is projected to reach 58% share of all passenger kilometres travelled by 2050. Freight operations are dominated by medium and heavy trucks with 70% of all freight-ton kilometres travelled and exhibit a sustained 2.7% growth.

In terms of energy, the transport sector consumed 2,454 PJ in 2018, this represents 46% of final energy consumption in 2017 and grew 4% compared to the previous year. Road transportation is the most relevant mode with almost 90% of the sector's energy consumption, followed by aviation with 7.8%, shipping and rail with 1.1% each.

This massive energy consumption makes this sector a critical element for Mexico's decarbonisation. GHG emissions from transport grew at an annual rate of 2.1% from 2005 to 2015 (SEMARNAT, 2017), and are expected to continue that trend due to multiple elements that increase demand for travel. Among these elements, are sprawling urban development, economic growth and globalization (cargo moves farther), fleet growth, ageing fleet, and insufficient infrastructure across all modes except individual passenger transport (cars) which still receives a disproportionate investment when compared to its benefits.

In this section, we will cover the causal chain of emissions that defines the approach used to simulate the sector in Mexico. This is followed by a framework that conceptualizes the decarbonisation approach and guides the implementation of mitigation actions. The impact of such measures will be presented and contrasted against the current business-as-usual (BAU) trends the sector displays.

7.1. RESEARCH APPROACH

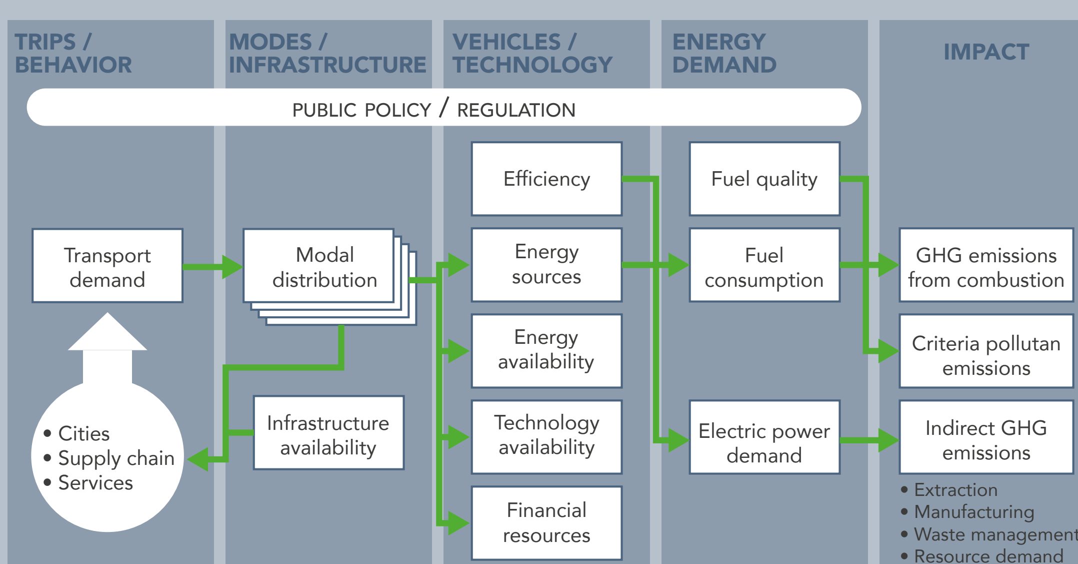
The transport sector has direct emissions from fossil fuel feedstock burned in internal combustion engines (ICE) of varying levels of efficiency and technology, and indirect emissions from the consumption of other energy sources like electricity, from a long vehicle manufacturing chain with multiple material and energy-dependent steps (material mining, component production, assembly, and distribution). An effective decarbonisation strategy requires an analysis of all GHG sources to avoid shifting emissions to another sector.

7.1.1. CAUSAL CHAIN

A causal chain of sector emissions is shown in Figure 110. This diagram portrays how the sector emits GHG, and how each component can be mapped with the Avoid-Shift-Improve framework (further discussed in section 7.5). The causal chain can help visualize how the decarbonisation actions can impact emissions and what are the main conditions and requirements for implementation.

Travel demand refers to the use of any mode of transportation to satisfy any need. It requires vehicle infrastructure (roads, tracks, ports, airports, sidewalks

Figure 110. Transport sector GHG emissions causal chain



Source: WRI Mexico

or trails), a vehicle energy to power it, and energy infrastructure to produce, distribute and supply that energy (usually as fuel). The use of this energy to satisfy our demand for travel results in GHG and criteria pollutant emissions and infrastructure congestion, which may bring about other social and demographic effects.

Travel demand: is a function of urban development, economic activity, supply chains, purchasing power and behaviour.

Modal distribution: is a function of public policy, regulations, existing and planned infrastructure, capabilities.

Energy/emissions: a function of energy consumption, technology, and efficiency.

Additional factors:

- Prices and availability of fuels and other resources;
- Policy and regulatory framework;
- Sociodemographic and cultural effects; and,
- Financial options for infrastructure development and technological alternatives.

The development of a decarbonisation pathway for the transport sector was based on the Energy Policy Solutions (EPS) Mexico model and the identification of the effective decarbonisation levers. The methodology included analysing financial and technical feasibility, and avoiding technological lock-in. This means avoiding short or medium-term GHG abatement solutions that could block the implementation of decarbonisation measures.

7.1.2. THE ENERGY POLICY SOLUTIONS (EPS) MODEL

The EPS was developed by Energy Innovation LLC, as part of its Energy Policy Solutions project (EI, 2015). It is an effort that aims at informing policymakers and regulators about the most effective and cheapest climate mitigation and energy emission-reduction policies. The model is open source and widely documented. The model and the files for running and editing it, as well as and extensive documentation, can be obtained online[32] (Figure 111).

The EPS uses a business as usual scenario, that is affected by policy settings applied by the user. This reference case is built into the model from official reports such as the National GHG Emissions Inventory (INECC, 2018b), the National Forestry and Soil Inventory (CONAFOR, 2009), energy use data from the Secretariat of Energy (SENER) prospective

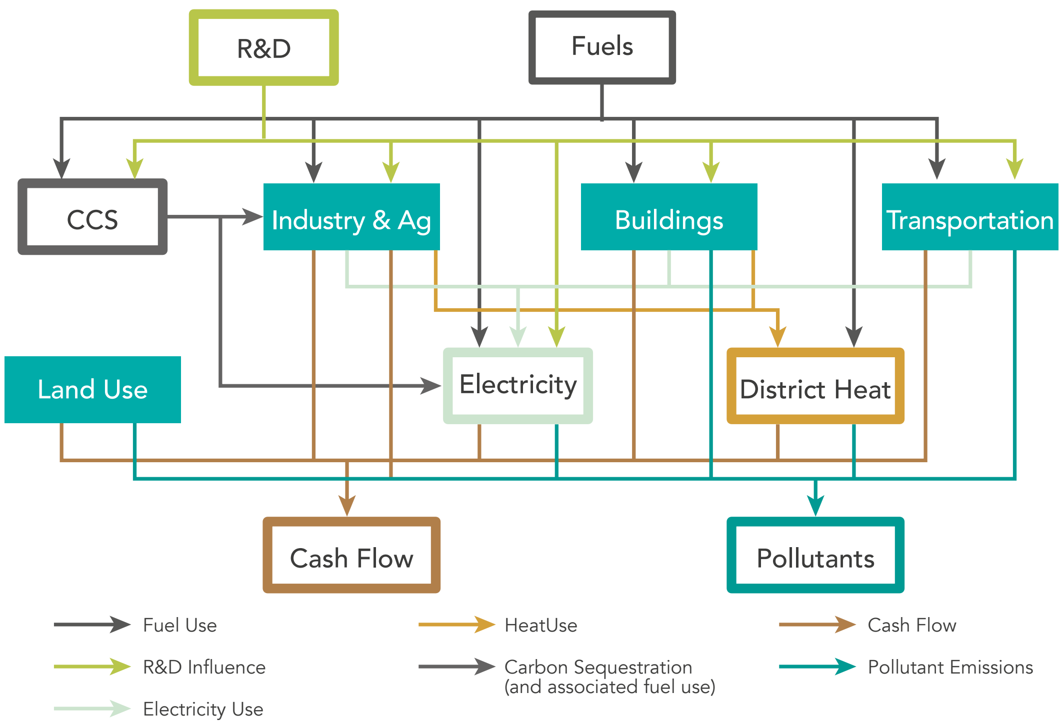


Figure 111. Simplified EPS structure diagram

Note: Energy demand is determined in each sector (industry, buildings and transportation) and fulfilled from fuel stocks or electricity generation which in turn determines pollutant emissions and cash flows.

Source: EI, 2015

32 Energy Policy Solutions Mexico – https://Mexico.Energypolicy.Solutions

studies (SENER, 2018); and from recognized technical studies, such as the Poles baseline model (Danish Energy Agency, 2015) or the EPA Moves Mexico fleet projection (INECC, 2016b). This approach enabled the use of existing work and official data, while providing novel capabilities to analyse policy options.

The EPS allows the user to control 58 different policies that impact energy use and emissions. Among them, a carbon tax, fuel economy standards for vehicles, control of methane leakage from industry, and accelerated research and development advancement of various technologies. The model allows customized implementation schedules for different policies, to better represent possible actions.

The model produces the following outputs:

- Emissions of 12 different pollutants: carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur oxides (SO_x), fine particulate matter ($PM_{2.5}$), and eight others, aggregating GHGs according to their carbon dioxide equivalency (CO_2e).

- Direct cash flow impacts (costs or savings) for consumers, industry, and the government.

- Health benefits from reduced exposure to criteria pollutants.

- Electricity generation capacity and output by technology and fuel.

- Energy consumption by technology and fuel.

System Dynamics

A variety of approaches exist for representing the economy and the energy system in a computer simulation. The Energy Policy Solutions is based on a theoretical framework called "system dynamics." As the name suggests, this approach views the processes of energy use and the economy as an open, ever-changing, nonequilibrium system. This may be contrasted with approaches such as computable general equilibrium models, which regard the economy as an equilibrium system subject to exogenous shocks, or disaggregated technology-based models, which focus on the potential efficiency gains or emissions reductions that could be achieved by upgrading specific types of equipment.

The use of a system dynamics model, allows for stock carry-over between periods, allowing to register changes in capacities, populations/fleets, and accumulated benefits in comparison to a reference scenario; it also allows for a gradual change in parameters that does not require to re-calculate a general parameter for a specific sector, this is useful in the industry sector to allow for progressive improvements in efficiency.

Source: EI, 2015.

7.1.3. INPUT DATA

The model has significant input data requirements from a variety of data sources. To maximize model consistency, the following prioritization criteria was followed:

1. Data from Mexican government sources.

2. Data specific to Mexico published by reputable sources, such as the International Energy Agency and the U.S. Environmental Protection Agency.

3. Regional or international data was used to represent Mexico by proxy, adjusted by population, GDP, or other factors where applicable.

4. Finally, extrapolated present-day values using projections of Mexico's GDP, population, or other relevant scaling factors.

Due to interactions and cross sector effects, it is important to analyse the complete energy system in order to ensure that GHG emissions are not just shifted from one sector to another. The model is designed to operate at a national scale, considering all sectors reported in Mexico's climate change policy, and shown in table 21. Output is reported at annual intervals, from 2017 to 2050.

Table 21. EPS Mexico – Sector Aggregation

EPS COMPONENT	INCLUDES:	ENERGY FLOW OR AREA
Electricity	Electricity	Energy generation
Industry	Oil and gas	Energy generation / use
	Industry	Energy use
	Agriculture	Energy use / land use
	Waste management	Energy use / cities
Buildings	Buildings	Energy use / cities
District heat	Not used in Mexico model	Energy use / cities
Transport	Transport	Energy use / cities
LULUCF	Land use, land-use change and forestry	Land use

Source: EPS Mexico, 2020.

The transport sector reflects fuel demand and emissions from both on-road and non-road public and private transportation. On-road transportation includes light duty vehicles (LDV), heavy duty vehicles (HDV) for passenger and freight use, and motorcycles. Non-road transportation includes rail, ship and air modes.

The use of the EPS for the analysis presented in this report may have the following limitations:

- The Energy Policy Solutions model relies on various scientific studies and results to establish the effects of policies on physical quantities and costs. The studies typically investigated these relationships under a set of real-world conditions. These conditions cannot reflect all possible policy settings a user might select. Generally, the model's business as usual scenario is likely to be closest to the conditions under which the various policies were studied by the creators of the data. Therefore, the uncertainty of policy effects is likely smallest when policy levers are set at low values; uncertainty increases as the policy package includes a greater number of policies and the settings of those policies become more extreme. The decarbonisation effects required to achieve carbon budget emissions depend upon extreme settings to change current trends and the heavy BAU growth.

- Due to limits on available data that represent Mexico, and the necessary use of scaled U.S. values for certain variables, certain policy responses may be larger or smaller in magnitude in the model than in reality. For example, because average household income is lower in Mexico than in the United States, many price elasticities might be lower in the United States than in Mexico (that is, wealthier consumers are less price-sensitive), causing the estimated effects of these policies for Mexico to be conservative.

7.2. BUSINESS AS USUAL SCENARIO (BAU)

The model works with a business as usual (BAU) scenario (called the reference case within the EPS model) and compares the effects of applied policies to such scenario. The BAU is built from historical data and represents Mexico's current emissions trajectory across the modeled sectors, with no interference from additional policies and abatement actions.[33] This BAU scenario can be summarized as follows:

Planning horizon: base year 2016, modeling horizon 2017 through 2050 determined from prospective studies on energy demand (fuels and electricity), emission factors for all pollutants and emissions from LULUCF. Detailed information from Mexico's prospective studies usually reaches 2032, so trends were extended from the available data values to reach 2050.

National scale: Mexico was modelled countrywide with no regional/political divisions. National data was obtained from studies reporting a national total. The model includes every major sector of the economy.

Assumptions: compatible data was used as much as possible from prospective studies covering the same planning horizon and using the same base assumptions of population, gross domestic product, fuel prices, cost of capital and set of policies and standards. The energy prospective considers Mexico's recent energy reform and energy transition legislation, current carbon tax and no carbon market.

BOX 7.1.3. / Main sources of data for the transportation sector

Transportation

- EPA MOVES Mexico on-road transport fleet database – **INECC**
- Vehicle prices and fleet composition – **INEGI**
- Annual railway statistics – **SCT**
- Commercial aviation in numbers – **SCT (1991-2016)**
- Annual marine transportation statistics – **SCT**

Cross-sector

- Energy Technology Perspectives (CCS) – **International Energy Agency**
- Air Quality Program for the Central Mexico Megalopolis 2017-2030 – **CAME**
- Air pollution impacts – **INECC**

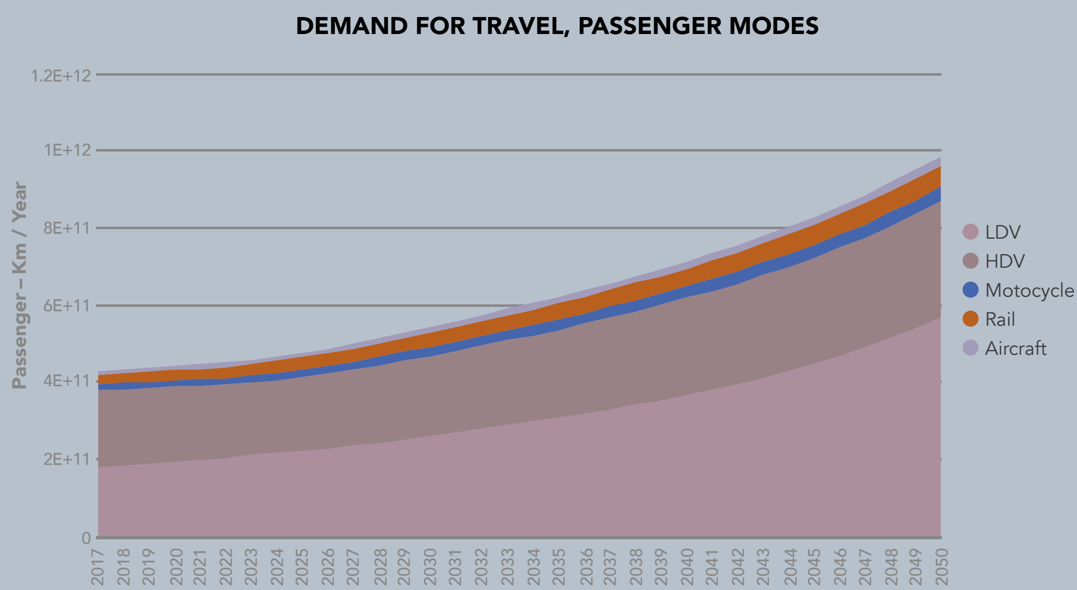
Source: EPS Mexico, 2020.

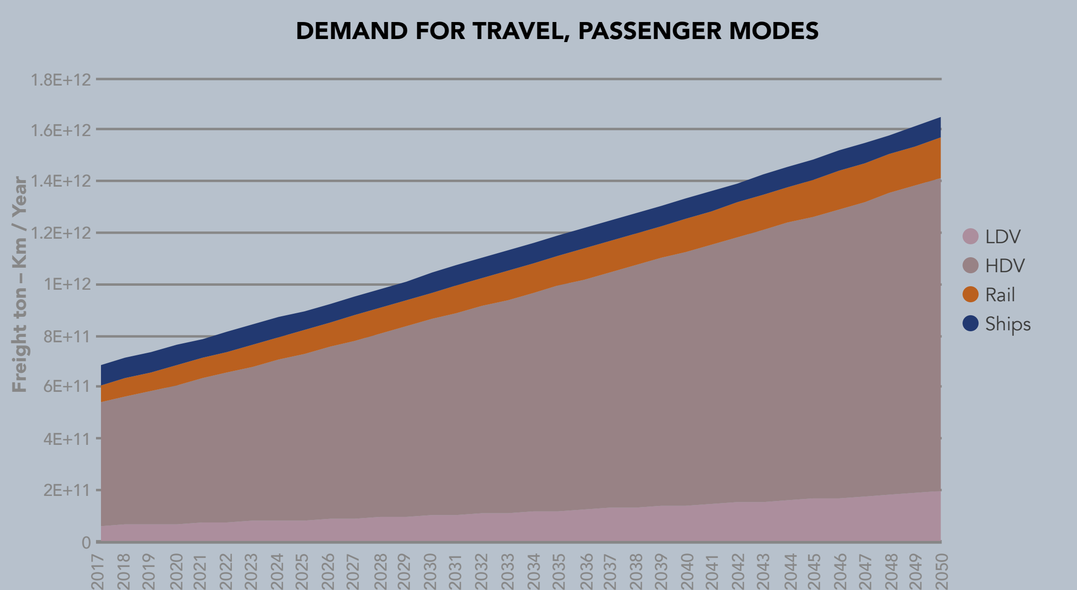
7.2.1. TRAVEL DEMAND AND MODAL SHARE

Business as usual projections estimate a steep growth in individual road transport, which grows from 42% in 2017 to 58% of all passenger kilometres travelled and becomes the single most important mode of passenger transport. Freight modes exhibit a sustained 3% annual growth until 2030 which tapers slightly to 2.7% by 2050. Freight modes are dominated by medium and heavy trucks with 70% of all freight-ton kilometres travelled. Travel demand for passenger and freight modes in the BAU scenario is shown in Figure 112.

33 EPS Mexico reference case (BAU) and Mexico's GHG emissions baseline are not compatible due to differences in methodologies, data sources and availability. Mainly an updated GHG inventory and energy prospective scenarios. Any differences between them do not imply an increase or abatement in emissions, since most deviations correspond to differences in data, emission factors, activity levels and methodologies.

Figure 112. Demand for travel, passenger and freight modes





Source: EPS Mexico, 2020.

Table 22. Modal distribution – BAU

		2017	2030	250
PASSENGER MODES	Cars and SUVs	42%	48%	58%
	Buses	47%	38%	31%
	Motorcycle	3%	4%	4%
	Rail	6%	7%	6%
	Aircraft	2%	3%	2%
FREIGHT MODES	Light and medium trucks	9%	10%	12%
	Heavy trucks	69%	73%	74%
	Rail	10%	10%	10%
	Ships	11%	7%	5%

Source: EPS Mexico, 2020.

Figure 113. Fleet size by vehicle type

Source: EPS Mexico, 2020.

7.2.2. FLEET SIZE

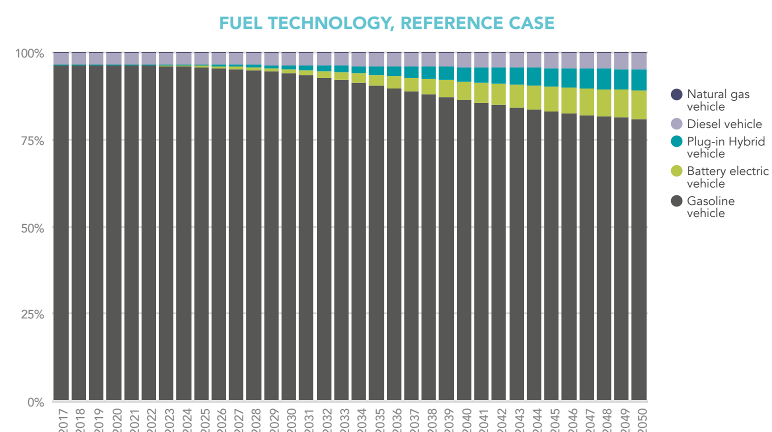
Fleet size varies widely by vehicle type, the most numerous are light duty vehicles (LDV), which numbered over 26 million in 2017, reach 64 million by 2050, growing at 2.8% per year. The only other vehicle displaying such growth are motorcycles which go from 2 million to over 4 million in the same period (Figure 113). Heavy duty vehicles (HDV) and aircrafts both grow at 1.6% annual rate. Transport emissions increase from 1.8% per year in the 2020 to 2030 period to 2.4% per year in the 2030–2050 period.

7.2.3. FUEL TECHNOLOGY

In the business as usual scenario, gasoline vehicles make up 96% of the vehicle fleet in 2017. By 2030, gasoline still makes up 94% of all vehicles, with plugin hybrid and electric vehicles reaching only 2%. In 2050 plugin hybrid and electric vehicles make up 11% of all vehicles, while gasoline vehicles retain 81% of share, with over double the fleet by 2050 this means a doubling of gasoline vehicles and no reduction in absolute terms (Figure 114).

7.2.4. FUEL EFFICIENCY

Fuel efficiency by vehicle type for the business as usual scenario is shown on Figure 115. Note how efficiency



Source: EPS Mexico, 2020.

Figure 114. Fuel technology, BAU

increases at a much faster rate for lighter vehicles, this is due to a higher growth and a shorter lifespan, which results in a higher exchange rate that raises the average vehicle efficiency from a higher share of new vehicles.

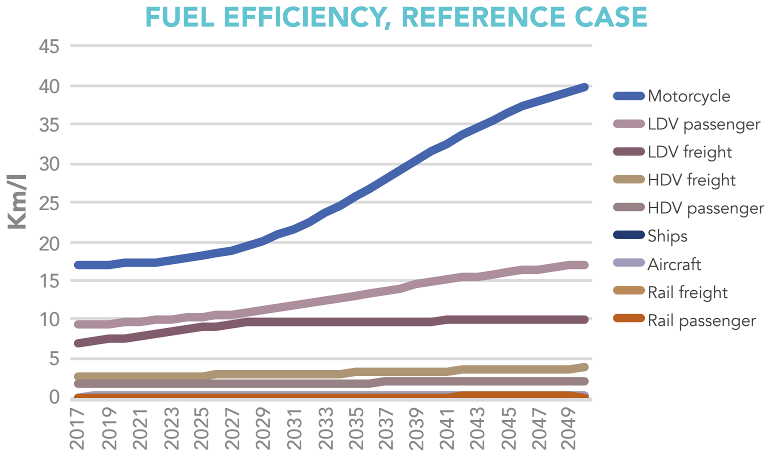


Figure 115. Fuel efficiency by mode

Source: EPS Mexico, 2020.

7.3. TRANSPORTATION SECTOR GHG EMISSIONS PROJECTIONS

The transport sector made up 23% of Mexico's GHG emissions in 2015. With almost a quarter of all emissions, it is an important element of Mexico's path to decarbonisation. Additionally, transportation emissions in Mexico grow faster than any other sector in absolute terms, climbing at an annual rate of 2.1% per year from 2005 to 2015 (SEMARNAT, 2017).

These emissions stem first from light-duty passenger vehicles (32%) followed by heavy trucks (27%), light and medium trucks (21%).

Under the business as usual scenario, GHG emissions from the transport sector could grow from 166 million tonnes (MtCO_2e) per year in 2017 to 317 Mt by 2050, shifting from 21 to 24% of total emissions by 2050. Under this scenario, transport sector emissions in Mexico are projected to duplicate by 2050, as shown in Figure 116.

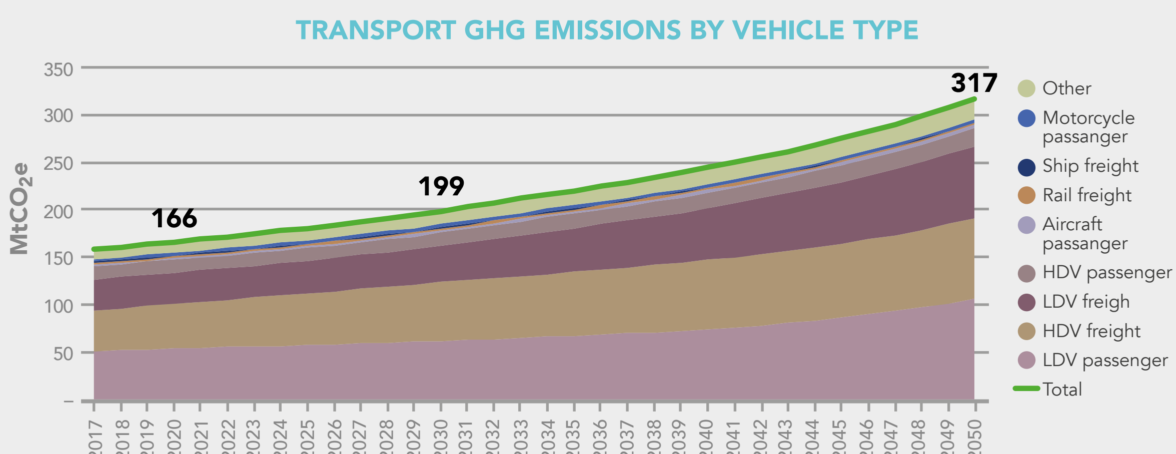
7.4. DECARBONISATION MEASURES FOR THE TRANSPORT SECTOR

Proposed decarbonisation measures will be presented through the avoid-shift-improve framework. The framework provides a way for governments and other actors to consider policies and actions to reduce emissions in transport in three key areas.

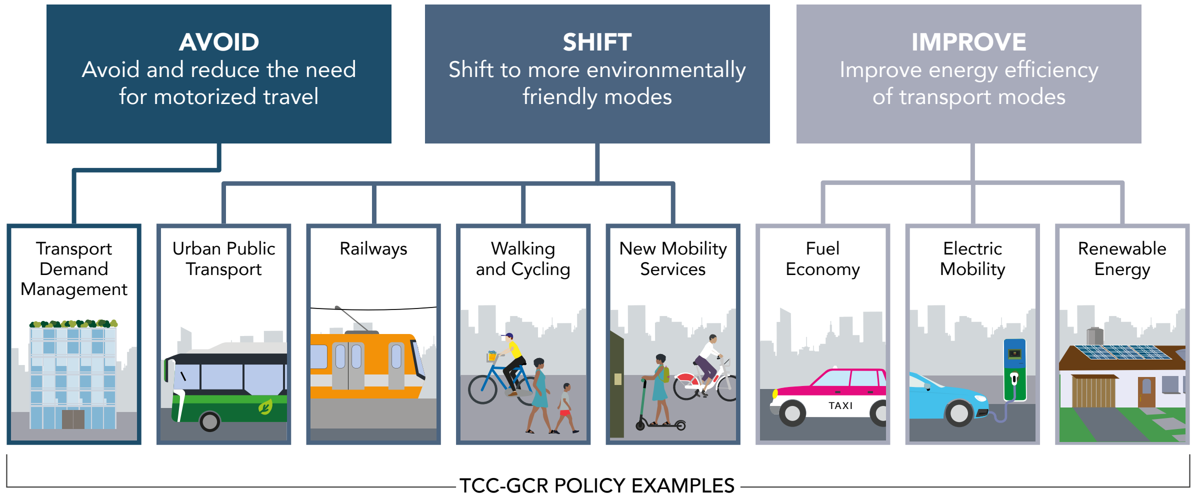
- Avoid passenger trips and freight movement or reduce travel distance by motorized modes of transport through regional and urban development policies such as integrated transport, spatial planning, logistics optimization, and travel demand management.
- Shift passenger and freight travel to more environmentally and socially sustainable modes, such as public transportation, cycling and walking (for passenger transport), and railways or inland waterways (for freight transport). Low-carbon modes of transport should be retained. Encourage new mobility services such as bicycle and electric scooter sharing.
- Improve the energy efficiency of transport modes through fuel economy, low-carbon fuel, electric mobility, and vehicle technologies, increased vehicle load factors, and better managed transport networks with nonpetroleum, low-carbon fuels playing a more significant role, particularly before 2030.

The avoid-shift-improve framework provides a strategy to decarbonise the transport sector through a comprehensive approach that draws on the full range of solutions (Figure 117).

Figure 116. Transport GHG emissions by vehicle, BAU scenario



Source: EPS Mexico, 2020.



Note: TCC-GSR = Transport and Climate Change – Global Status Report (see SLoTCaT 2018)

Source: Dalkmann and Brannigan, 2007.

Figure 117. Avoid–Shift–Improve framework

Amplify Avoid and Shift Solutions reducing demand for travel and concentrates use of most efficient modes

This includes a host of complementary policies on land use and mobility planning, public transportation, alongside strong behavioural changes that promote walking, and cycling. Meeting carbon reduction targets means going beyond efforts to improve efficiency of growing fleets, particularly for motor vehicles. Decarbonisation plans are only comprehensive if they consider efforts to reduce unnecessary travel and shift to low-carbon transport modes.

7.4.1. AVOID AND REDUCE DEMAND FOR TRAVEL

Strategies in the avoid phase aim at reducing motorized trips and trip lengths, as well as encourage trips in low-carbon transport. These strategies can play a significant role in achieving sectoral benchmarks, through encouraging cities where people need fewer or shorter vehicle trips and can travel more by public transportation, cycling, or walking. These strategies can also contribute to providing rural areas with better access to services and opportunities.

Managing transport demand

The objective of managing demand for transport is to disincentivise the use of motorized transport, particularly individual transport. An example of a transport management strategy is congestion pricing, which reduces unnecessary travel by charging a fee to transit through designated areas, usually in a city's core. This particular strategy has been successfully implemented to reduce vehicle emissions and induce sustainable transport options in Singapore, Stockholm, and London. Most recently, congestion pricing was approved for New York City. Careful mobility planning should avoid unregulated transport alternatives that may steer people away from public transport and toward private vehicles, such as ride-hailing applications. Congestion pricing is just one of various forms of transport demand management, others include low-emission or car-free zones, strict parking policies, and employer-commuter policies.

Enacting sustainable land use planning and regulations

A good land use plan is a good transport plan. Land use plans and zoning regulations that promote connected streets, mixed uses, and compact development centred around public transportation discourage vehicle travel and cut emissions (Ewing, 2008). Transport planning should always be linked to national urban development policies in order to promote compact growth with connected street networks focused on urban roads rather than expressways. Commitments to national policies that encourage land use plans to favour people over motor vehicles are critical when thinking of mobility planning.

Examples of good measures are national urban growth, economic development, and housing construction programs that promote compact urban development connected to public transportation and street-based and mixed land use planning that encourages cycling, walking, and other forms of sustainable transport. Examples of actions in this area include the Colombian Nationally Appropriate Mitigation Action (NAMA) on transit-oriented development (DOTS) which integrates sustainable mobility with land use development; it focuses public and private development around transit stations and provides a strategy for implementing this approach on a larger scale (Kooshian and Winkelman 2018).

Sustainable mobility plans

Land use planning should be complemented by national sustainable transport plans and city-level sustainable urban mobility plans (SUMPs) designed along certain guidelines, potentially in connection with federal transport funding programs. Globally, more than 800 SUMPs have been identified, with over 60% being implemented in European cities (SLoCaT, 2018). The process of preparing SUMPs specifically prioritizes sustainable modes of transport: public transportation, cycling, and walking.

Removing fuel subsidies

Fuel subsidies make vehicle travel less expensive, thus inducing people to travel more and consume more fuel, regardless of the vehicle's fuel economy standards. Fuel subsidies are popular yet regressive instruments that promote unnecessary travel, induce congestion and weaken fuel efficiency initiatives. Removing all fossil fuel subsidies would cut global carbon emissions between 6.4 and 8.2% by 2050. Fossil fuel subsidies cost 5.2 trillion USD per year according to a recent study that accounts for costs, such as air pollution and climate abatement, as well as the subsidy (Coady et al. 2019). Subsidies are not effective ways to help low-income population groups, most of the resources devoted to subsidizing fuels end up benefiting people who are not overly sensitive to fuel prices (Arze del Granado et. al. 2012). Ensuring a just transition is important in this context and fuel subsidies are far from it.

Box 7.5.1. / Opportunities in freight and logistics

Globally, freight transport, mostly road freight, was responsible for 41% of total transport CO_2 emissions in 2015 (SLoCaT 2018). Under business as usual, freight demand (in metric tonnes per kilometre) is expected to grow in 100 to 230% by 2050, raising emissions along with it. Road freight emissions alone are projected to grow significantly, nearly doubling from 2.5 $GtCO_2$ in 2014 to 4.6 $GtCO_2$ in 2050 under business as usual (ETC 2018).

Despite freight's significant share in transport emissions, in the NDCs it is mentioned only a third of the times that passenger transport mentioned (SLoCaT 2018). This gap in the current NDCs —combined with significant technological advances over the past several years– sets the stage for countries to strengthen their NDCs by addressing freight emissions. Although emissions from freight can be reduced via Avoid, Shift, and Improve strategies, the largest abatement potential lies in accelerating the transition to zero-carbon fuels (Energy Transitions Commission 2018).

Source: Fransen, 2019.

Strategies to improve logistics, increase load factors and reduce backhauls

Improving logistics and operational efficiency, for example, by using information technology to optimize freight routes, improve load factors, and eliminate backhauls, has the potential to globally abate an estimated 0.8 $GtCO_2e$ in 2050 (ETC 2018). For urban freight, "last-mile" solutions, such as consolidating delivery at the city, neighbourhood, or building level, can cut emissions and improve safety and air quality in densely populated urban areas.

7.4.2. SHIFT MODES OF TRANSPORT

Shift strategies focus on switching to, or retraining, low-carbon travel. Strategies include public transportation, and non-motorized transport, or any mean other than individual motor vehicles. This effort requires the creation of policies and financial environments that allow countries and cities to plan and implement high-quality, affordable, efficient and public transportation systems, that are connected to citywide bicycle and pedestrian infrastructure that is well planned, safe and compatible with urban life.

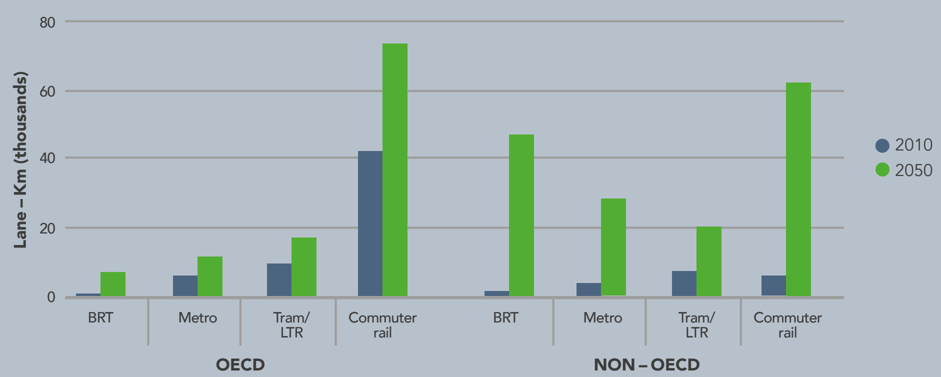
Providing high-quality public transportation

High quality public transportation is reliable, safe, frequent, direct, connected, affordable and accessible; furthermore, it is an integrated public system, that considers commuter catchments and prioritizes safe cycling and walking.

By investing in high-quality public transportation governments can shift passenger travel toward travel modes with less emissions. There is a need for consistent programs to finance efficient systems that offer people access to opportunities within cities and reduce emissions, enabling the development and use of metro systems, bus rapid transit (BRT), trams, light rail transit (LRT), and commuter rails required for shifting away from informal transit (or paratransit), such as minibus and taxi networks which do not offer safety to neither the users nor the operators. Programs to improve informal transit services should also take priority. Public transportation plays a key role in decarbonisation and urban mobility efforts, an important part of the benefits comes from investments, adding BRT, metro, LRT, and commuter rail, especially in non-OECD countries (See Figure 118). These estimates do not consider further gains that could be achieved through bus fleet electrification or upgrading informal networks.

Ambitiously expanding and retaining cycling and walking

In Mexico, there is a clear opportunity to integrate robust cycling and walking plans and policies. Given the nearly zero-carbon emissions of walking and cycling (including scooters), shifting toward these modes provides large potential benefits in mitigating emissions from transport. An in-depth analysis of global cycling potential by Mason in 2015, found that a dramatic increase in cycling could save society 24 trillion USD in energy, vehicle, and infrastructure costs cumulatively between 2015 and 2050 and cut CO_2 emissions from urban passenger transport by nearly 11% in 2050 compared with an alternative Shift scenario without a strong emphasis on cycling (Mason et al. 2015).



BRT = bus rapid transit. LTR = light rail transit.
OECD = Organisation of Economic Co-operation and Development.

Source: Repogle and Fulton 2014.

Figure 118. High shift assumptions for rapid transport system length by transport mode and region, 2010 and 2050

Many countries can build on existing policies, a 2016 UN Environment Programme report that surveyed cycling and walking issues and policies in 25 low–to middle–income countries across Africa, Asia, and Latin America found that most had a policy at some level intended to give cycling and walking more attention (UN Environment, 2016). But it also found that commitments varied widely from "relatively insubstantial" sections in a general transport or mobility policy to "standalone national walking and cycling policies." Options include commitments to develop and implement cycling and walking policies, to designate dedicated funding to such programs, and to dedicate a certain amount of transport budgets to cycling and walking infrastructure. Commitments to gather better data and to address concerns of key users such as women, children, and the elderly can also provide valuable benefits.

Shift strategies to maximize better transport modes

Shifting strategies, for example, toward lean non–motorized modes could be deployed for urban freight. Shifting diesel road freight to less carbon–intensive rail and shipping is also possible in some countries, offering an estimated 0.6 $GtCO_2e$ in global abatement potential in 2050 (ETC 2018). Policymakers have explored options such as disincentivizing road freight through heavy–duty vehicle road tolls, investing in infrastructure to reduce rail bottlenecks, and mandating longer trains on major rail corridors (Frey et al. 2014). Table 23 summarizes the main strategies to improve road freight efficiency, potential energy savings, and their enabling policies.

7.4.3. IMPROVE TECHNOLOGY, EFFICIENCY AND USE OF ENERGY

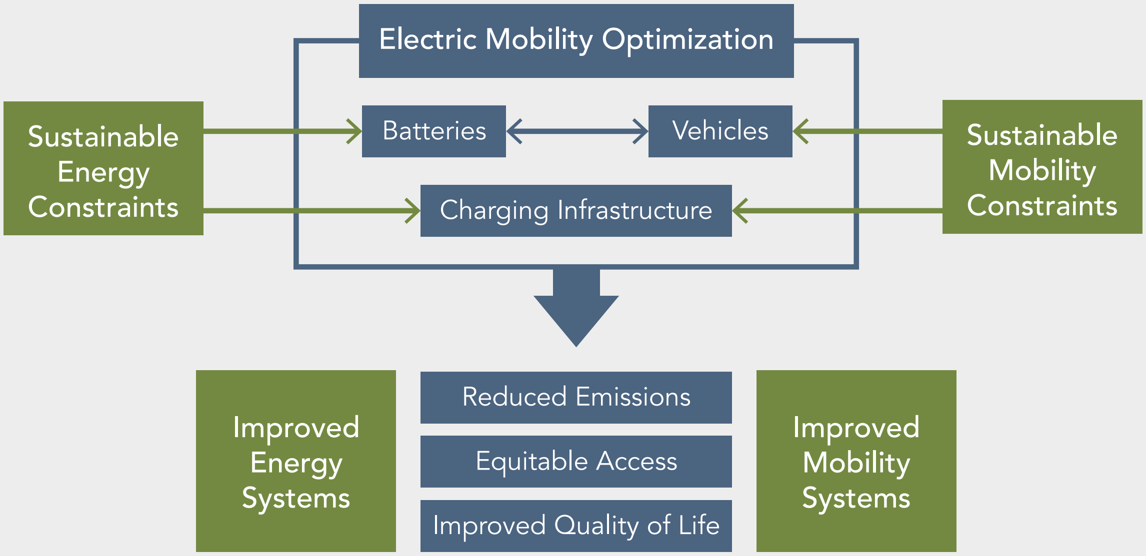
The final set of policies fall in the improve category. These strategies are aimed at the improvement of vehicle performance to reduce negative externalities.

Table 23. Road freight efficiency strategies

STRATEGY	ESTIMATED POTENTIAL ENERGY BENEFIT	ENABLING FOLICIES AND HOW REFLECTED IN NDCs
High–capacity vehicles (larger trucks that improve efficiency)	20% or more, depending on rebound effect	Performance–based standards
Optimized routing	5 – 10% intracity, 1% long haul	Real–time routing data based on geographic information systems (GIS), Easing of delivery time constraints
Platooning (driving heavy–duty trucks [primarily tractor–trailers or rigid trucks] in a single line with small gaps between them to reduce drag to save fuel during highway operations)	5 – 15%, depending on assumtions	Vehicle communication and automation technologies
Improved vehicle utilization	Substantial but difficult to quantify	Better data collection (enabled by ICT). Collaboration and alliances among carriers and logistics companies
Backhauling (using return trips formerly run without cargo to transport goods, thereby reducing trips)	Substantial but difficult to quantify	Collaboration and alliances among carriers and logistics companies (through freight exchanges)
"Last–mile" efficiency measures	1 – 5%	Allocation and prediction of dynamic demand to prepare for demand peaks. Increased competition, including market entry of freight services providers
Re–timing urban deliveries	Difficult to estimate and generalize	Incentives to shipment receivers to accept the insurance and logistical impacts of shifting to early–morning and off–hour deliveries
Urban consolidation centers (grouping shipments from multiple shippers and consolidating them onto a single truck for delivery to a given geographic region)	Vehicle activity, fuel use, and CO_2 emissions within urban centers can be reduced by 20 to 50%	City regulatory policies to reduce congestion and promote air quality
Co–loading (using supply chain collaboration within a company or across firms to increase vehicle load on outbound operations)	5 – 10%	Legal and regulatory frameworks to promote energy savings while protecting companies' intellectual property rights
Physical internet (open, global logistics system enabling efficient delivery based on sophisticated real–time data)	Work to date suggests 20% systemwide a efficiency improvement	Legal and regulatory frameworks; ICT to collect, process and protect proprietary data

Source: Fransen, 2019, adapted from IEA, 2017

Figure 119.
WRI electric mobility systems framework



Source: WRI.

Improvements are reflected in greater energy efficiency, better technology, or travel-related decisions –such as car-pooling / ride-sharing– are required to reduce polluting emissions, greenhouse gases and congestion.

An overarching framework for optimizing electric mobility systems to maximize benefits to both the power and transport sectors based on the following common sustainability goals is shown in Figurer 119 (Franzen, 2019a).

Electric vehicles 'not a panacea' without decarbonisation

In both the US and Europe, EVs represent a substantial reduction in lifecycle greenhouse gas emissions compared to the average conventional vehicle. This has been a consistent finding across most studies examined by Carbon Brief.

> "EVs are not currently a panacea for climate change, lifecycle GHG emissions from electric vehicles can be similar to or even greater than the most efficient gasoline or diesel vehicles [in the US]."

As electricity generation becomes less carbon intensive –particularly at the margin– electric vehicles will become preferable to all conventional vehicles in virtually all cases. There are fundamental limitations on how efficient petrol and diesel vehicles can become, whereas low-carbon electricity and increased battery manufacturing efficiency can cut most of the manufacturing emissions and nearly all electricity use emissions from EVs.

A transition from conventional petrol and diesel vehicles to EVs plays a large role in mitigation pathways (https://www.carbonbrief.org/qa-how-integrated-assessmentmodels-are-used-to-study-climate-change) that limit warming to meet Paris Agreement (https://www.carbonbrief.org/category/policy/paris-2015) targets. However, it depends on rapid decarbonisation of electricity generation to be effective. If countries do not replace coal and, to a lesser extent, gas, then electric vehicles will still remain far from being "zero emissions".

The implementation of improve strategies would bring the following results:

- Reducing GHG emissions in the energy and mobility sectors.
- Improving local air quality by reducing small particulate emissions in the energy and mobility sectors.
- Providing for equitable access to safe, reliable, and sustainable electricity and transportation.
- Improving overall quality of life for communities that incorporate electric mobility.

7.5. DECARBONISATION OF THE TRANSPORT SECTOR

An estimation of the impact of applying avoid, shift and improve strategies in the transport sector results in the following decarbonised scenario. This section will present the expected effects in the sector's activity from the application of GHG abatement policies and actions.

7.5.1. IMPACT ON TRAVEL DEMAND AND MODAL SHARE

Through the application of strict travel demand management policies (TDM), demand for travel in freight modes is reduced by 15% freight ton-km by 2030 and 45% by 2050 against BAU. Passenger modes do not reduce their travel demand against BAU but change their modal share as shown in Table 24.

TDM can include policies to reduce the use of inefficient forms of transit, such as congestion pricing or driving restrictions aimed at private cars. The effectiveness of these policies depends in part on how easily they can be circumvented. TDM also includes policies to make more efficient forms of transit more attractive, such as developing efficient public transit, building bike lanes, and promoting walking through better urban design. Policy and investment in transportation demand management should be targeted at the most densely populated regions of the country, where the benefits from reduced congestion and local air pollution will be the largest.

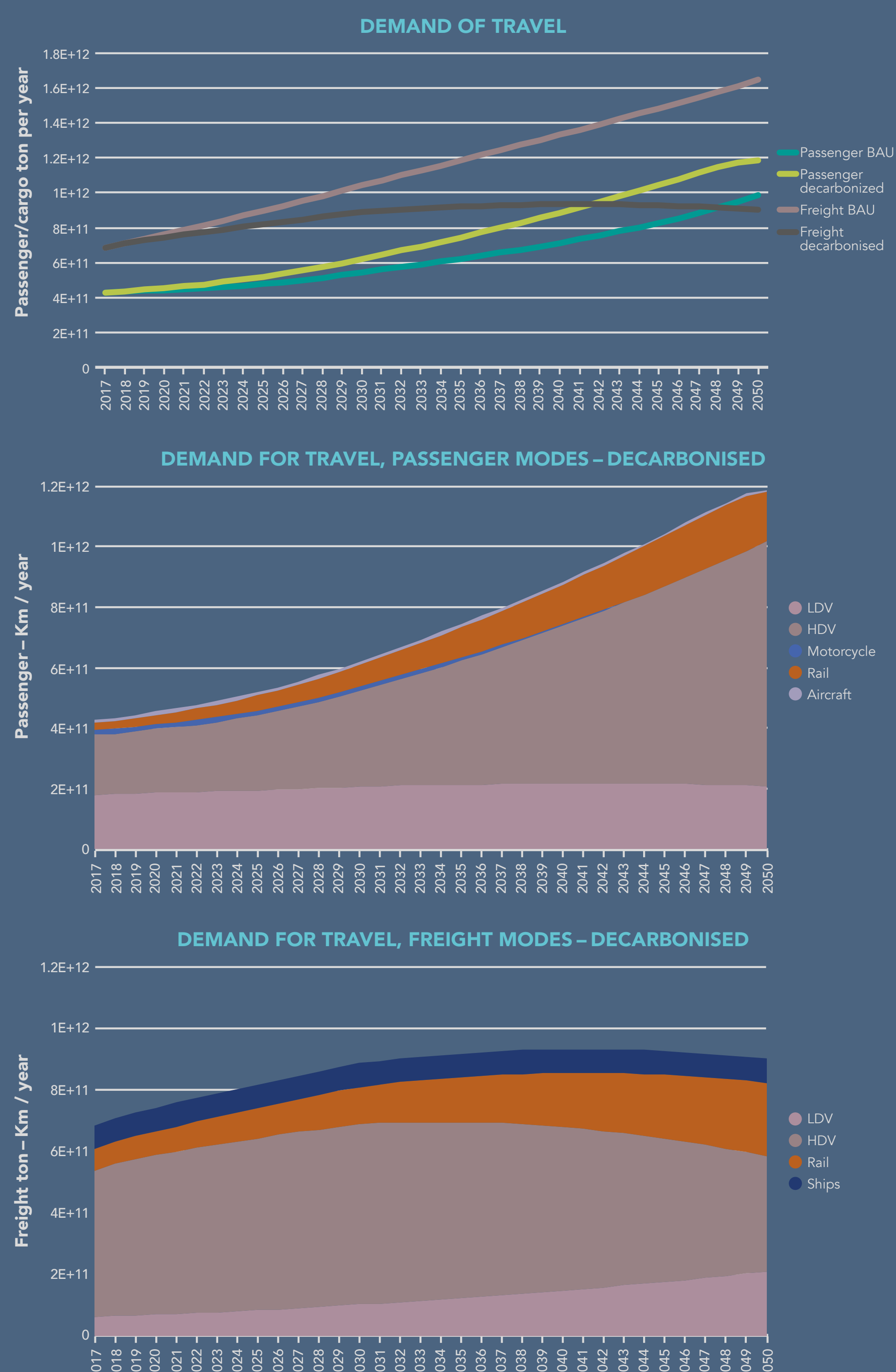


Figure 120. Travel demand–decarbonisation pathway

Table 24. Modal distribution – decarbonisation pathway

		2017	2030	250
PASSENGER MODES	LDV	42%	33%	17%
	HDV	47%	51%	68%
	Motorcycle	3%	2%	0%
	Rail	6%	11%	14%
	Aircraft	2%	2%	0%
FREIGHT MODES	LDV	9%	12%	23%
	HDV	69%	66%	42%
	Rail	10%	14%	27%
	Ships	11%	9%	9%

Source: EPS Mexico, 2020.

7.5.2. IMPACT ON FLEET SIZE AND FUEL TECHNOLOGY

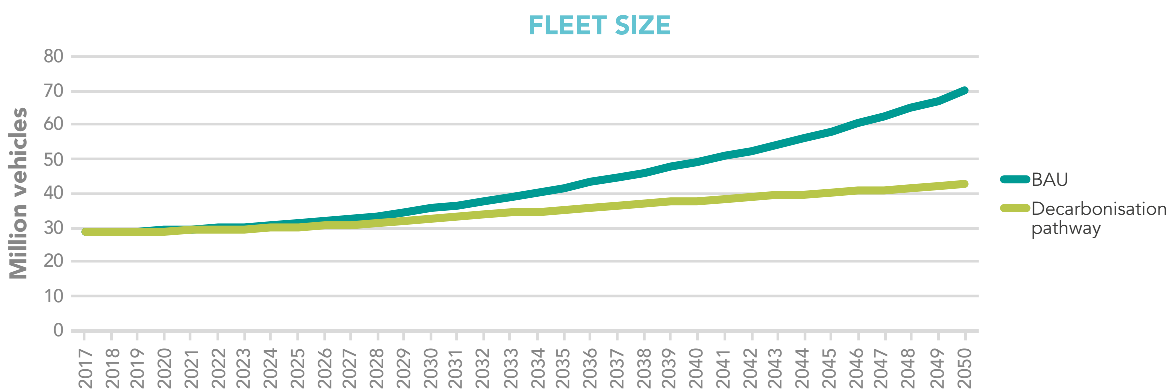
Changes in demand for travel have an impact on fleet size and composition. If the proposed decarbonisation route is followed, total fleet size would be 8% lower by 2030, almost 3 million vehicles (Figure 120). By 2050, fleet size in the decarbonisation pathway is 40% lower than BAU (27 million vehicles). This is due to reduced demand in travel and a shift to more efficient modes of transport (Figure 121).

Regarding fleet composition, electric powered vehicles in the decarbonisation pathway represent 20 additional percentage points in fleet share against BAU by 2030 and 80 additional percentage points in fleet share, reaching 91% of all fleet by 2050, as shown in Figure 122.

7.5.3. IMPACT ON FUEL EFFICIENCY

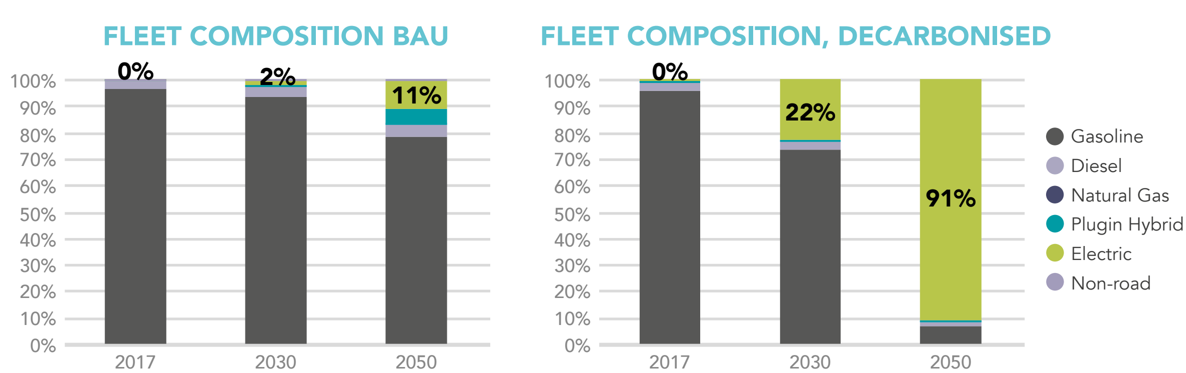
The fuel economy of newly sold vehicles is modified based on fuel prices and the combined effect of strict fuel economy standards. Fuel economy standards are minimum efficiency standards for new vehicles. These standards curb GHG emissions by improving the fuel efficiency of the new vehicle fleet. Fuel–economy standards should be administered upstream to capture 100 percent of the market for new vehicles, requiring each vehicle manufacturer to meet a fleet average fuel–economy standard for all new vehicles sold during a year. Fuel–economy standards can also be designed to provide flexibility and reward performance by allowing credit trading between manufacturers (rewarding manufacturers that offer more fuel–efficient product mixes by allowing them to sell credits to underperforming manufacturers). More stringent standards should phase in gradually with a clear ramp to meeting a final target. This approach allows manufacturers time to meet the final target while promoting continuous improvement by improving fuel economy on an ongoing basis.

Figure 121. Fleet size comparison– decarbonisation pathway vs. BAU



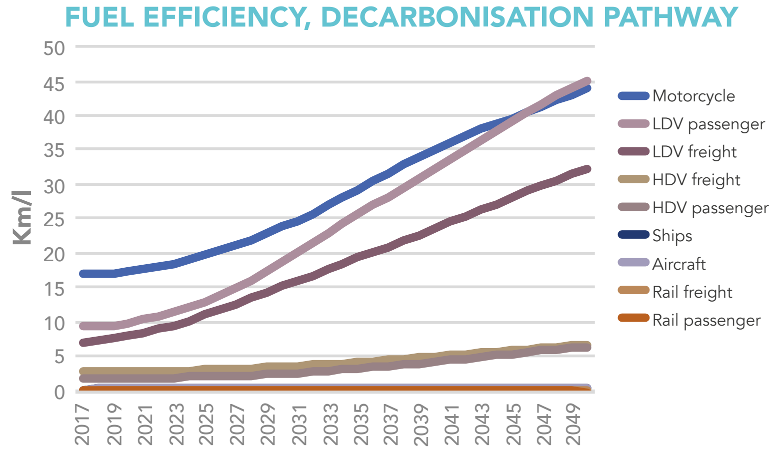
Source: EPS Mexico, 2020.

Figure 122. Fleet composition comparison



Source: EPS Mexico, 2020.

In most cases, fuel-economy standards save customers money over the lifetime of the vehicle due to reduced spending on fuel. However, many purchasers of new vehicles often do not account for lifetime fuel use in their purchasing decisions and increases in vehicle cost may be perceived as increasing costs to consumers. Fuel-economy standards improve new vehicle efficiency, but in the absence of complementary fuel-price or emissions tax policies, some of this gain may be offset by increased vehicle use due to the cheaper cost per mile of traveling. This "rebound effect" phenomenon is exacerbated if fuel is subsidized rather than taxed. Fuel taxes are thus a useful complement to fuel economy standards.

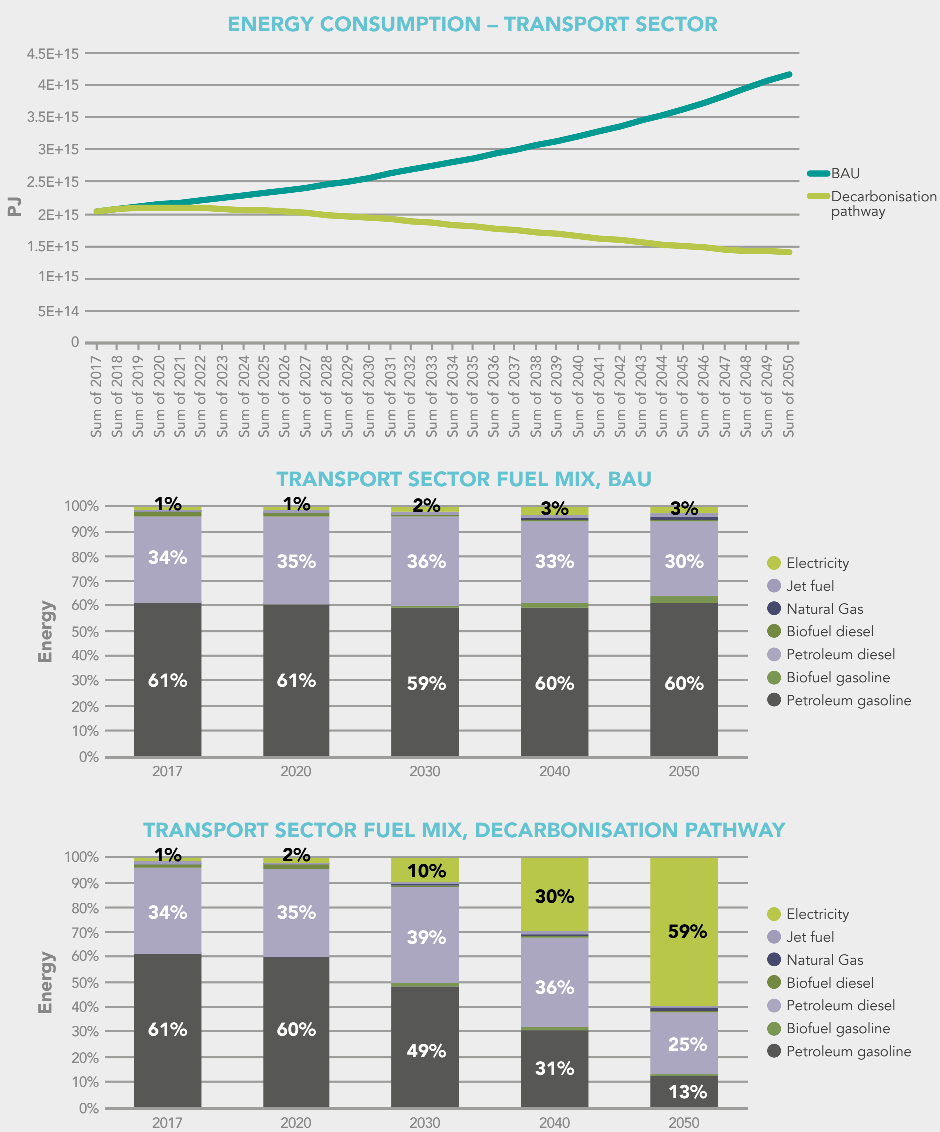


Source: EPS Mexico, 2020.

▲ **Figure 123.** Fuel efficiency, decarbonisation pathway

7.5.4. FUEL CONSUMPTION

Following the proposed decarbonisation pathway, could mean energy savings of 24% against BAU by 2030 and up to 66% by 2050. This effect comes from avoided growth in travel demand, a shift in transport modes and an improvement in energy consumption, use of electricity for transportation reaches 10% of



Source: EPS Mexico, 2020.

Figure 124. Energy consumption, decarbonisation pathway vs. BAU

transportation energy by 2030, compared to only 2% in BAU. By 2050, electricity could represent 59% of total transportation energy, displacing liquid hydrocarbons from 97% of all energy consumed in BAU to 41% in the decarbonisation pathway (Figure 124).

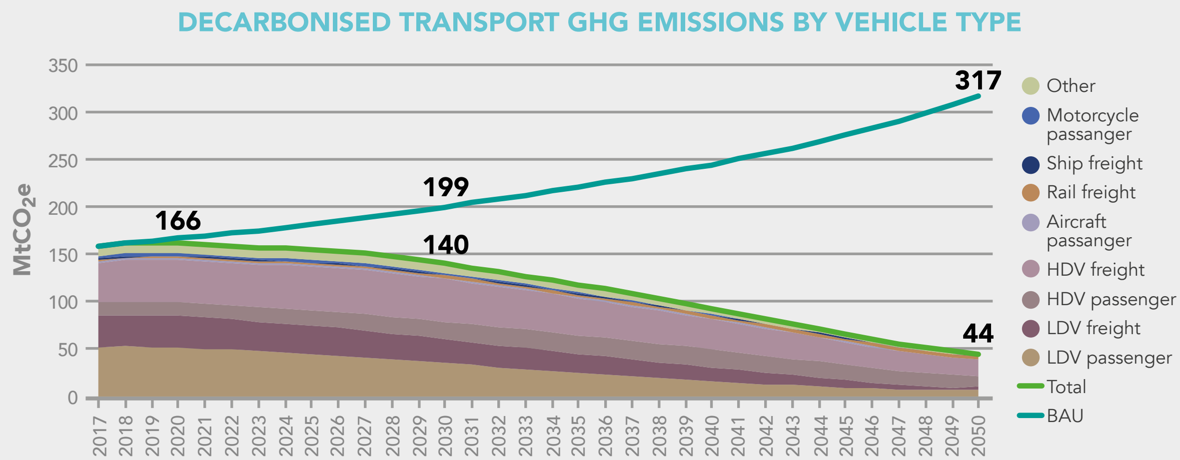
7.5.5. GHG EMISSIONS

The proposed decarbonisation pathway results in sector GHG emissions of 140 $MtCO_2e$ by 2030 (30% below BAU), and 44 $MtCO_2e$ by 2050 (86% below BAU), (Figure 124).

Transportation demand management, this refers to an extensive group of policies that span the promotion and development of active transport, increased share of more efficient modes of transport, such as mass urban transport or a higher share of the use of rail for cargo. Demand management could account for 30 $MtCO_2e$ by 2030 and remains the same throughout the modelling horizon.

Vehicle fuel economy standards add 2 $MtCO_2$ of potential reductions by 2030, due to the difficulty in the

Figure 125. GHG emissions

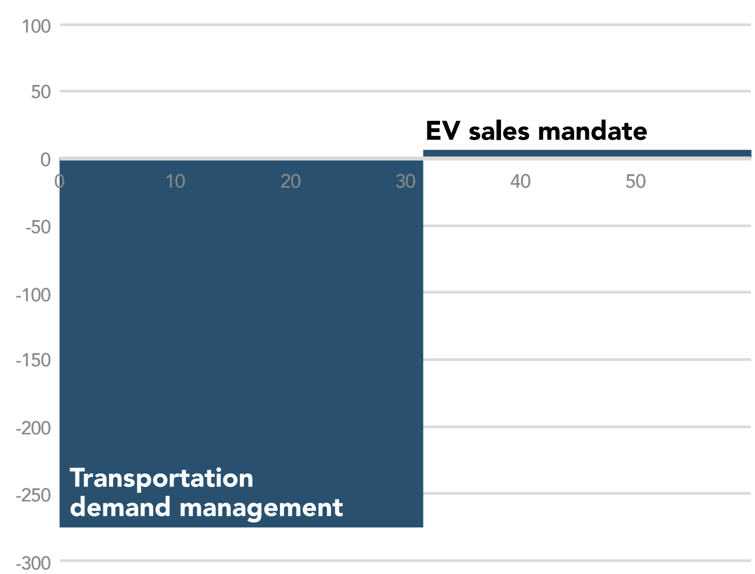


Source: EPS Mexico, 2020.

7.5.6. MARGINAL ABATEMENT COST CURVE

On the basis of the previous assumptions and calculations, figure 126 presents the marginal abatement costs curve and emissions reduction potentials for the transport sector by 2030. The 60 $MtCO_2e$ abatement (30% vs. BAU), is split into three action types.

Figure 126. Marginal abatement cost curve by 2050



Source: EPS Mexico, 2020.

implementation of fuel economy standards in the past. Nevertheless, these actions are important and become relevant in the long term, adding up to 150 $MtCO_2e$ of abatement by 2050.

A policy-driven high-penetration of electric vehicles could add considerable abatement, 28 $MtCO_2e$ by 2030 and up to 99 $MtCO_2e$ by 2050. However, this is an expensive course of action, compared to the others, so it is best to focus on avoiding demand and shift modes before investing on improving individual motorized transport.

7.5.7. CO-BENEFITS

Transport sector decarbonisation has co-benefits in the sustainable development agenda by addressing air quality, road safety, physical activity, access to opportunities, and economic development.

Air pollution and black carbon

Air pollution kills 4.2 million people around the world every year (WHO 2018b). A report by the International Council on Clean Transportation (ICCT) and Climate and Clean Air Coalition (CCAC) estimates that in 2015 transportation emissions contributed to about one in ten of these premature deaths (Anenberg et al. 2019). In addition, air pollutants other than CO2 can contribute to climate change.

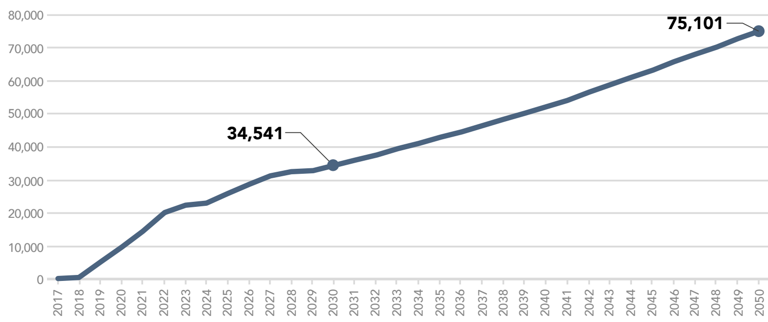
Black carbon, a component of air pollutants called particulate matter, has recently been identified as a significant contributor to global climate change (Bond et al. 2013). After CO_2 emissions, black carbon emissions are the second strongest warming influence in the atmosphere (Ramanathan and Carmichael 2008; Bond et al. 2013), and studies show that curbing these emissions may slow down the atmospheric warming expected by 2050 (Ramanathan and Carmichael 2008; Bond et al. 2013). Black carbon is also a major threat to human health because this type of particulate matter is associated with a range of respiratory and cardiovascular diseases and with premature death (Health Effects Institute 2010). Reducing emissions of black carbon presents an opportunity to slow the rate of near-term climate change and to achieve substantial public health benefits.

Freight electrification and efficiency offer important benefits in reducing urban air pollution, heavy-duty trucking is substantially and disproportionately responsible for nitrogen oxide (NO_x) emissions in particular. NO_x gases are central to the development of ground-level ozone and small particulate matter (PM2.5) (ICCT 2017). Road transport as a whole was responsible for 40% of NO_x emissions in the European Union in 2011, more than any other sector (Icopal n.d.); heavy-duty trucks contribute 55 % of NO_x emissions in India's transport sector (Guttikunda and Mohan 2014) and are expected to contribute a third of NO_x from the U.S. transport sector (US EPA 2018). Ports are already using electrification to improve air quality (Port of Los Angeles n.d.)

Road safety

Road fatalities, which globally take 1.35 million lives every year, are one of the world's top 10 causes of death (WHO 2018a). Climate and safer roads may seem like separate items, but the link between them is real and important. Making roads safe for cycling and walking is essential to enable the use of low-carbon modes of transport. In addition, public transportation, a form of low-carbon mobility, is also the safest mode of transport (Hidalgo and Dudata 2014). Countries that prioritize the safe movement of all road users, particularly through public transportation, cycling, and walking, may achieve lower carbon emissions from transport as well (Lefevre et al. 2016). The "Safe System" approach adopted by Denmark and the Netherlands, which focuses systematically on the safety of vulnerable road users such as bicyclists and pedestrians, has helped these countries achieve some of the world's lowest fatality rates for all modes (Welle et al. 2018). The International Energy Agency calls for reducing the vehicle-kilometres of travel as part of a move from a 4°C global climate change scenario to a 2°C scenario. Following this recommendation would also reduce traffic deaths by an estimated 200,000 a year (Hidalgo and Dudata 2014)

OUTPUT HUMAN LIVES SAVED FROM REDUCED PARTICULATE POLLUTION



Source: EPS Mexico, 2020.

Figure 127. Statistical lives saved. decarbonisation pathway

In Mexico, road fatalities represent the first cause of death among people from 1 to 14 years old and the fifth cause nationally.

Physical inactivity

Globally, 5.3 million deaths a year are attributed to inactivity (Lee et al. 2012). Countries such as the United States have seen steep declines in physical activity since 1965; many rapidly motorizing countries are now experiencing similar trends. China, for example, had a 45% decrease in physical activity between 1991 and 2009, and Brazil is slated to see a 34% decline between 2002 and 2030 (Ng and Popkin 2012). Cycling and walking and are the lowest-emitting modes of transport, and they also bring health benefits. Making active transport such as public transportation, cycling, and walking safe, convenient, and accessible —and thus more appealing— can encourage people to exercise. A growing body of research shows that aggressively expanding active transport is an effective, but underutilized, policy option with significant health co-benefits for mitigating greenhouse gases (Maizlish et al. 2017).

Equitable access and travel time savings

Equitable access to opportunities is an emerging goal within transport sectors, seeking to provide residents, not just with nearby transportation options, but with access to jobs and services across income levels. Focusing on access means looking at how many opportunities can be reached within a set amount of time for all residents across different modes of transport. Better access to opportunities from compact development to public transportation to cycling and walking can mean shorter trips, and thus lower emissions, as well as less time spent on congested city streets or along rural road networks. Transport improvements often disproportionately benefit wealthier residents while leaving poorer residents disproportionately impacted by the negative externalities, including poor air quality, unaffordable transport options, dangerous walking infrastructure, and exclusion from opportunities. Addressing transport poverty means taking a nuanced look at the mobility options, accessibility, transport's affordability, and negative externalities faced by a city's most vulnerable residents, including the disabled and women (Lucas et al. 2016). Currently many cities fail to offer all residents access to transit without major time delays, poor quality, or unaffordable service (Venter et al. n.d.).

7.5.8. BARRIERS TO REDUCTION IN TRAVEL AND MODAL SHIFT

Financial resources

The development of the numerous sustainable transport solutions needed for decarbonisation, will require availability of financial resources to support projects that are not just greater in number but varying in levels of magnitude, complexity and profitability. There is a need to identify and measure the finance resources available for sustainable transport solutions and channel these resources. Climate finance initiatives should ensure it is not under-prioritizing support to projects in the transport sector due to the way projects were traditionally financed and developed.

Capacity building and overcoming old models

Implementing large-scale measures to develop sustainable transport modes such as public transportation, cycling, and walking can be a challenge. All levels of government, together with universities and non-governmental organisations (NGOs), need to commit to conducting / attending capacity-building initiatives among officials involved in land-use and urban planning and the development of public transportation, local representatives and communities in general. Informing about the numerous potential benefits in developing cities with sustainable mobility solutions, and the basic elements in their effective development.

Governments need to wrench themselves free from assumptions, habits, and interests hardened by years of catering to private vehicles. This dependence on private vehicles has concentrated investments and planning that promote high-carbon modes of heavy vehicle travel. Government institutions, laws, regulations, and finance often perpetuate a legacy of directing investments and policies toward the use of private automobiles, as is evident by urban expressways, wide roads, a lack of investment in BRT or metro, and non-existent or poor cycling and walking facilities. Mexico will need policy innovations to override this tendency and will need to navigate an array of issues from establishing new finance programs to addressing the concerns of policymakers who may not be users of public transportation, to establishing capacity and knowledge of sustainable transport planning as opposed to highway planning and engineering. Implementing these actions is less about the resources available than the way existing resources are allocated. Shifting trips to sustainable transport means channelling investments toward more public transportation, cycling, and walking. A report that investigated opportunities for policy shifts ranging from fuel subsidies that foster carbon emissions to low-carbon transport notes that "by actively investing in public transportation infrastructure at the same time as reducing fossil-fuel subsidies and increasing conventional taxation on transport fuels, governments could reduce demand (energy saving) and encourage switching, and therefore could potentially influence and increase emission reductions from subsidy reform" (Merrill et al. 2015).

7.5.9. BARRIERS TO VEHICLE ELECTRIFICATION

Conditions on electrification of transport fleets

If electric vehicles are not powered through renewable energy, emissions will only be shifted to the electric power generation, a decarbonised power grid is an absolute requirement for electric transport to be effective in emissions abatement and the achievement of this pathway.

Although these opportunities are all within reach, they will require serious policy commitments and will need to overcome a legacy of dependence on and planning around carbon-intensive travel. Countries must dramatically shift policies away from private motor vehicles with internal combustion engines and unsound, unsustainable land use planning. They will need to include freight in the sweeping and wide-ranging changes needed to promote low-carbon transport. Policymakers will need to align goals and forge partnerships with ministries responsible for transport, development, health, and urban development. They must build both the capacity and knowledge needed to transform the transport sector to meet the goals of the Paris Agreement.

Electric vehicle barriers

The framework in Figure 119 links the three technical elements (vehicles, batteries, and charging infrastructure) with objectives such as fostering renewable energy and mobility to best achieve sustainability goals. It can leverage the dual nature of electric mobility systems to make sweeping improvements not attainable through traditional siloed approaches to energy and mobility. Using electric vehicles to store power is just one step planners can take to achieve more sustainable living. For example, the siting and pricing of public charging stations can be a tool to promote densification or lure drivers away from congested corridors. Planners may need to weigh competing goals. The ideal locations for public charging from a mobility perspective may conflict with the ideal locations from an energy management perspective, so a multivariate analysis is required to optimize for multiple constraints. More importantly, the failure to optimize in this manner will lead to suboptimal systems that reinforce negative externalities associated with the energy and transportation sectors.

Through the lens of dual optimization of sustainable mobility and energy, every charging point is an opportunity to shape the future characteristicsof transportation and energy management. Optimization of the entire electric mobility system requires new areas of research and standards of practice to adapt traditional principles to a modern context and gauge impacts across sectors. From this perspective, the improvement of transportation through electrification should be measured by both tailpipe emissions and net benefit to upstream emissions from the grid, rather than simply treating the energy sector as an unrelated entity with its own objectives and measures of performance. The emission reduction potential for the energy sector derived from the mobility sector (through grid-integrated EVs) should be addressed NDC content pertaining to both sectors. Integrating national policy between these sectors can be a powerful tool to force collaboration and planning that would otherwise be difficult to achieve. Moreover, calling out the ability of EVs to support energy sector emissions objectives within NDCs reaffirms the perspective that electric vehicles are both energy and mobility assets and will spur new thinking that will lead to technological advancement and economic growth.

Electric freight barriers

On the efficiency side, legal frameworks restricting anticompetitive behaviour pose barriers to backhauling, improved vehicle utilization, and the physical internet (digital transportation networks). Growing demand for just-in-time delivery affects optimized routing, "last-mile" efficiency measures, re-timing of urban deliveries, and co-loading (IEA 2017). As companies and governments experiment with the enabling policies outlined in Table 23, solutions are being developed.

Regarding electrification, one major area that merits attention is integration of charging stations with the electric grid, in terms of both generation and transmission and distribution capacity. If trucks can charge off-peak, the additional required generation capacity may be minimal, as it could benefit from unused capacity in off-peak operation, off-peak charging can be encouraged through the design of electricity tariffs. Transmission and distribution (T&D) grid integration concerns are another important implementation issue. Large truck charging stations may be connected at the transmission level rather than the distribution level. The impact of charging stations can be minimized by placing them strategically where excess T&D capacity exists; however, potential grid upgrade costs to accommodate charging loads merit further study. Charger siting and station rollout to support increasing numbers of electric trucks are related issues to address. Infrastructure siting challenges will differ for local, regional, and long-haul trucking.

7.6. CONCLUSIONS

This modelling study analyses scenarios aligned with a carbon budget compatible with global temperature increases of 1.5°C and 2°C, to propose a decarbonisation pathway for the transport sector. The transport sector has the largest GHG emissions nationally and is projected to continue on a sustained 2.2% growth in the business as usual scenario. This portrays the need of a substantial transformation of the sector in order to achieve the considerable emissions reductions required relative to current levels, and especially relative to the business-as-usual (BAU) 2050 projections.

Opportunities for decarbonisation have been framed through an **Avoid-Shift-Improve** framework.

- **Avoiding emissions** through the reduction in demand for carbon-intensive travel,
- **Shifting trips** to efficient public transportation systems and non-motorized travel like cycling, and walking, while
- **Improving on technologies** to accelerate electrification, move freight more sustainably and develop solutions for shipping and aviation.

Most decarbonisation studies for transport focus on technological changes but taking a comprehensive Avoid-Shift-Improve approach to decarbonisation will result in greater abatement. Actions will be needed in all three areas, from long-term land use planning (avoid), to inducing and implementing public transportation and cycling (shift), to fuelling vehicles cleanly and efficiently (improve), to decarbonise the sector.

Avoid and reduce the need for motorized travel

- Control rampant road transport growth, with transport demand management measures

Shift to lower / zero-carbon modes of transport

- Develop urban public transportation nationally.
- Shift freight and long-range travel to railways.
- Promote active mobility (walking and cycling).
- Introduce new mobility services.

Improve energy efficiency of transport modes

- Strengthen fuel economy standards for all transportation modes.
- Eliminate ineffective and non-progressive fossil-fuel subsidies and other incentives.

- Develop electric mobility in all modes and sizes of road transport.
- Ensure a rapid penetration of zero-emission passenger vehicles, with the last internal combustion engine car to be sold by 2035-2050.
- Technology shifts for heavy-duty road transport to Zero-carbon options, though the technology is not yet as advanced.
- Electrify all rail services.
- Aviation and shipping require a 1.5°C-compatible long-term vision, alongside the development of options and technology. In the meantime, demand management is critical to curb growth. ◆

8. METHODOLOGICAL INSIGHTS AND LEARNINGS FOR FURTHER RESEARCH

The electricity sector was modelled using a bottom-up approach and a linear programming model (PLEXOS). The limitations in the sector's characterisation were related to the lack of consideration of interactions with the country's entire economy. Even though the electricity demand was modelled using the most detailed data available for the market and forecasted with specific statistical methods, there were several uncertainties regarding the end-use, hence, how the aggregate demand could evolve. The uncertainties were more significant for the long term (2050) than for 2030. The overall growth in demand did not consider any systemic change in the consumption habits apart from the introduction of electric vehicles. Additionally, distributed generation and storage were considered as reductions in electricity consumption, and the possibility to act as electricity generators were not modelled. Contrary to a recursive dynamic model in which a myopic view of the future can be incorporated, this work considered perfect knowledge of the future by establishing the portfolio of possible plants for every year of the simulation period.

However, the modelling approach was robust, and a proven and powerful optimisation software was used. Moreover, the modelling of the electricity sector included the existing power plants in the system with their technical and economic characteristics, including transmission assets. Realistic scenarios were considered and were validated by experts in the sector, and short-term scheduling (as in the real system) was combined with long term capacity expansion decisions.

The GHG mitigation potentials and marginal abatement costs in the oil and gas sector were estimated using a bottom-up approach. This focus presents several limitations, including the lack of interaction of this sector with the entire economy and other industrial sectors. For instance, the evolution of macroeconomic variables (e.g., inflation) did not consider the impact of the sector's changes in fuel prices, and as a consequence, the effects on sector's economic variables.

Although the demand for transport fuels is analysed, fuel demand from the electricity sector and other sectors of the economy were not directly modelled but rather taken from government estimates. While hybrid modelling approaches (combining bottom-up and top-down) are desirable, given the nature of theproject, the use of a bottom-up approach had several advantages. The GHG mitigation potential and costs in this work were estimated considering a high level of detail regarding the engineering and economic characteristics of the existing oil and gas infrastructure of Mexico and real data from the sector. Moreover, the proposed measures were individually reviewed by experts and validated.

The analysis of the transport sector was based on the EPS. This model was developed by Energy Innovation LLC, as part of its Energy Policy Solutions project (EI, 2020), aiming to inform policymakers and regulators about which climate and energy policies will reduce GHG emissions most effectively and at the lowest cost. This study uses the latest version for Mexico (v.1.4.4), released in July 2018. The model is open-source and widely documented.

Projections included in this study are all derived from a computer model, which makes assumptions and simplifications. Similarly, model capabilities and results depend heavily on the quality of the input data. Although every care has been taken to validate data and calibrate model behaviour, uncertainties are to be expected. The numerical characterization of such uncertainty is not possible as almost all the input data used in the EPS lack numerical uncertainty bounds. Even if such bounds had been available, it would have been difficult to carry them through the complex model calculations to establish uncertainty bounds on the result. Nevertheless, the objective of this type of models is to inform on projected trends and the changes that can be affected in those trends, not specific numerical values. As such, EPS has proven useful in building climate change action packages and in the development of decarbonisation pathways.

A variety of approaches exist for representing the economy and the energy system in a computer simulation. The Energy Policy Simulator is based on a theoretical framework called "system dynamics". This approach views the processes of energy use and the economy as an open, ever-changing, nonequilibrium system. This may be contrasted with approaches such as computable general equilibrium models, which regard the economy as an equilibrium system subject to exogenous shocks, or disaggregated technology-based models, which focus on the potential efficiency gains or emissions reductions that could be achieved by upgrading specific types of equipment.

The use of a system dynamics model allows for stock carry-over between periods, making it possible to register changes in capacities, populations / fleets, and accumulated benefits, in comparison to a reference scenario; it also allows for a gradual change in parameters that does not require to recalculate a general parameter for a specific sector; this is useful in the industry sector to allow for progressive efficiency improvements. The EPS model development included a web application with a high-level technical architecture that facilitates and simplifies model use and review. The web interface displays the most significant results of the model in easy to read and downloadable graphs that include emissions, policy abatement wedge diagrams, marginal abatement cost curves for selected policies, financials, social benefits and specific results for each of the included sectors for each of the included scenarios. It also includes brief descriptions for each policy, extensive documentation on model calculations and architecture, and clarification on how to design each policy well. By creating a user account, the model allows to review present scenarios and to construct personalized scenarios allowing the study of results from specific policies by modifying their implementation level and even allowing a customized implementation schedule. ◆

9. CONCLUSIONS

Mexico's General Climate Change Law aims to regulate national GHG emissions according to the Paris Agreement's long-term targets; thereby, its implementation requires precise definitions and planning. For instance, the National Climate Change Strategy should internalise the ambition of Mexico's mitigation goals, including actions and objectives for the short-term, and up to the year 2050, with differentiated roadmaps among GHG sources and sectors. To advance towards this aim, this report delivered technical insights that inform policy requirements based on domestic emissions and identifying sectoral mitigation pathways in scenarios limited to 2°C and 1.5°C temperature increase.

At the technical level, this study provides a methodology based on carbon budgets for defining mitigation targets. Carbon budgets have been widely implemented as reference scenarios in international studies, guiding the design and planning of climate policies in countries such as the United Kingdom. Therefore, this methodology supplements the existing planning efforts in Mexico, delivering outputs that can inform future research and initiatives. Moreover, the cost analysis identified the actions in each sector that result in the most significant mitigation benefit at the lowest costs.

The main findings are:

- Mexico has a limited carbon budget to stabilise GHG emissions in line with the Paris Agreement's long-term targets. Achieving the carbon buget is a significant challenge considering that Mexico's emissions reached 0.7 $GtCO_2e$ in 2015, according to the National Inventory of Greenhouse Gases and Compounds 1990–2015. Mexico's carbon budget to limit global mean temperature to 2°C and 1.5°C is 22.2 $GtCO_2e$ and 8.89 $GtCO_2e$ for the 2019 to 2100 period, respectively.

- Based on the national carbon budget, the study defines sectoral budgets and decarbonisation pathways for the electricity, oil and gas and transportation sectors for the 2030 to 2050 period. The results demonstrated that mitigating the emissions of these sectors to a level consistent with the 1.5°C trajectory is feasible. Moreover, the results also showed that there are economic and technical viable measures for mitigating these sectors' emissions, which can also deliver local environmental and social benefits, such as reducing air pollution and the associated respiratory diseases.

- The decarbonisation pathway for the electricity sector (consistent with the 1.5°C scenario) requires an emissions' reduction to 64 $MtCO_2e$ by 2030. In comparison with the baseline, this path would require **i)** doubling the share of renewable energies by the year 2030; **ii)** retirement of fossil fuel-based plants with the highest GHG emissions intensity (coal and fuel oil); and **iii)** reducing the share of other fossil fuels-based technologies such as combined cycle. In the medium term, the formation of a regulatory framework and financing mechanisms that encourage the diffusion of storage technologies and distributed generation can increase the flexibility of the grid, reducing investment in transmission and distribution infrastructure. The decarbonisation pathways would require an electric power installed generation capacity 11%

higher than the baseline due to the penetration of renewables, to reach a generation of 277 TWh by 2030 (≈ 53.7% expected demand). Between 2019 and 2030, the decarbonisation pathway would only exceed 5% the total costs compared to the baseline, and its positive environmental and social externalities would outweigh the difference.

- The decarbonisation pathway for the oil and gas sector has a yearly emissions reduction potential of 25.3 $MtCO_2e$ by 2030. The mitigation measures that deliver economic benefits represent 57% of the mitigation potential (e.g., reduction of methane leaks in gas processing activities, energy efficiency in oil refining processes and cogeneration), which could increase to 83% through international financial mechanisms. Between 2030 and 2050, the expected natural depletion of conventional oil resources can reduce GHG emissions. However, the different sectoral scenarios (with or without the exploitation of unconventional resources) show that it is necessary to keep unconventional resources without burning to achieve long-term mitigation targets.

- The decarbonisation pathway for the transportation sector has a yearly mitigation potential of 210 $MtCO_2e$ by 2030 and up to 309 $MtCO_2e$ by 2050. The pathway proposes a policy strategy aimed at avoiding passenger travel and cargo mobility; shift travel to sustainable transport and improve energy efficiency through the transition to cleaner fuels. Following this approach, the vehicle fleet is 8% and 40% lower than business as usual for 2030 and 2050, and the penetration of electric and hybrid vehicles reaches 23% and 91%, respectively. The energy efficiency would increase between 10 and 15% in non-highway modes and more than double in highway modes. As a result, sectoral energy demand decreases in under 66%, reducing 80% GHG emissions in comparison to the baseline. In this path, the sector's emissions achieve a level aligned to the 2°C scenario but exceed the levels for a 1.5°C scenario. Consequently, it is critical to initiate the decarbonisation of this sector, which can strengthen in the midterm the regulatory and institutional conditions towards more ambitious mitigation targets.

This analysis delivered technical insights that can inform the design of Mexico's climate policy. The study seeks to support decision-making and enrich the design and implementation of policy tools. This effort is grounded in international experience but also in previous studies that institutional actors and civil society have carried out in Mexico.

The policy design is, by definition, a dynamic and flexible process, which must recognise and attend the most pressing needs, including facing the climate emergency. Therefore, this analysis should be expanded, discussed, reviewed and updated to guarantee its relevance and validity, for example, trough the elaboration of decarbonisation pathways for the remaining sectors (e.g., AFOLU and industry) and assessing the implications of the financial uncertainty generated by the COVID-19. Subsequent socioeconomic analysis can inform about the link between the decarbonisation pathways and other high-level political goals, such as undertaking poverty and inequity. ◆

10. ANEX

Table Investment costs (in million USD)

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal	271	0	0	0	0	0	0	0	0	0	0	0
NG-CC	5,678	4,583	563	2,793	2,561	0	1,042	0	1,026	1,892	1,895	2,544
CHP	871	678	0	0	0	0	0	0	0	0	0	0
Diesel	47	27	0	0	140	147	0	147	147	0	147	147
NG-SC	162	474	170	169	0	0	0	0	0	0	0	0
Bio	150	0	0	0	0	0	0	0	0	0	0	0
CHP-Ef	0	0	0	0	0	2,304	2,150	0	0	0	0	0
Hydro	35	0	139	269	473	190	28	1,665	1,978	1,649	350	0
Geo	109	52	0	0	0	0	0	0	0	0	0	0
Wind	3,097	3,376	1,291	743	245	1,755	135	331	262	744	1,211	1,450
PV	5,320	3,856	576	0	589	818	756	673	585	835	1,364	1,166
Total	**15,739**	**13,046**	**2,740**	**3,974**	**4,009**	**5,213**	**4,111**	**2,816**	**3,998**	**5,120**	**4,967**	**5,307**

Table Fixed O&M costs (in million USD)

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal	186	186	186	186	186	186	186	186	186	186	186	186
NG-CC	602	678	688	735	779	779	797	797	815	849	882	928
CHP	6	11	11	11	11	11	11	11	11	11	11	11
Diesel	40	40	40	40	42	44	44	46	48	48	50	52
NG-SC	21	21	21	21	21	21	21	21	21	21	21	21
Bio	381	381	381	381	381	381	381	381	381	381	381	381
CHP-Ef	48	54	57	59	59	59	59	59	59	59	59	59
Hydro	62	62	62	62	62	62	62	62	62	62	62	62
Geo	21	21	21	21	21	36	51	51	51	51	51	51
Wind	163	163	163	163	163	163	163	163	163	163	163	163
PV	309	309	310	313	318	320	320	338	358	376	380	380
Total	**126**	**129**	**129**	**129**	**129**	**129**	**129**	**129**	**129**	**129**	**129**	**129**

Table Variable O&M costs (in million USD)

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal	86	85	83	83	82	80	78	75	74	72	69	67
NG-CC	568	560	565	616	662	669	679	711	750	768	799	818
CHP	8	14	14	14	14	14	14	14	14	14	14	14
Diesel	10	9	9	8	8	8	8	9	9	8	9	9
NG-SC	12	12	11	12	12	12	12	12	12	12	12	12
Bio	172	167	189	178	165	153	169	160	150	153	142	141
CHP-Ef	36	39	39	40	44	43	44	46	42	40	38	39
Hydro	23	23	23	22	22	24	23	23	23	23	23	23
Geo	35	35	35	35	35	62	85	85	85	85	85	85
Wind	25	25	25	26	25	27	25	25	25	25	25	25
PV	0	0	0	0	0	0	0	0	0	0	0	0
Total	**975**	**970**	**994**	**1,033**	**1,071**	**1,092**	**1,136**	**1,161**	**1,184**	**1,201**	**1,216**	**1,233**

Table Fuel costs (in million USD)

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal	155	156	158	164	166	166	160	160	161	158	152	153
NG-CC	833	799	829	910	977	962	1,049	1,001	1,172	1,212	1,279	1,233
CHP	11	19	20	19	21	20	20	20	20	21	21	21
Diesel	240	233	218	192	191	197	219	236	238	226	240	238
FB	15	16	16	16	16	16	16	16	16	16	16	16
FO-Steam	3,703	3,763	4,366	4,209	3,907	3,736	4,119	4,133	3,888	4,177	3,798	3,946
NG-SC	34	36	37	38	43	42	43	47	46	45	42	44
Nuclear	6	7	6	7	7	8	7	8	8	8	8	9
Total	**4,997**	**5,029**	**5,649**	**5,555**	**5,328**	**5,147**	**5,632**	**5,621**	**5,549**	**5,864**	**5,558**	**5,660**

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NATIONAL CARBON BUDGET FOR MEXICO AND 2030 DECARBONISATION PATHWAYS

Mexico | **MMXX**