5.3 Energy Storage at utility scale as an enabler for CO_2 Mitigation

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This report is part of the study:
Technology Roadmap and Mitigation Potential of Utility-scale Electricity Storage in Mexico

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Executive summary

Background and context

In 2015, Mexico was the first developing country to submit their Intended Nationally Determined Contribution, which became its NDC under the Paris Agreement and is currently regarded as one of the leading countries in the Americas in the context of climate change. To fulfill its current pledge under the Paris Agreement, Mexico has committed to an unconditional greenhouse gas (GHG) emission reduction of 22% by 2030, including a 31% reduction in the electricity sector. Additionally, Mexico's Climate Change Mid-Century Strategy (SEMARNAT-INECC, 2016) points out a general goal to reduce emissions by 50% in 2050 compared to 2000 levels.

Recently Mexico´s inter-ministerial climate change commission gave its support to the Climate Change Special Program 2020-2024 (PECC, by its Spanish Acronym), reaffirming the mitigation goals, especially those of the electricity sector.

Fulfilling these targets in the energy sector requires concerted efforts and would imply a combination of energy efficiency measures, along with deployment of low-carbon technologies and renewables. In order to decrease its GHG emissions and achieve the medium and long-term climate targets, alternative pathways for decarbonization should be explored, as indicated in their General Law on Climate Change.

This study aims to estimate the CO_2 mitigation potential of utility-scale storage in Mexico, by assessing its role in an increasingly decarbonized power system thus, showcasing the impact of a large decarbonization of the electricity sector as a result of this technological change, which would support Mexico on its climate commitments.

Deep decarbonization of the power system might be achieved through diverse technologies, such as nuclear energy, carbon capture and storage and through the integration of large shares of variable renewable energy. In this sense, the availability of cheap large-scale storage systems might create a new paradigm and allow a very high integration of variable renewable energy despite its variable and intermittent nature.

Approach and model used

This study uses a modeling approach that compares alternative pathways to satisfy the electricity demand in Mexico in the least costly way until 2050, subject to specific greenhouse gas emissions caps related to power generation.

The modeling approach combines the restrictions of different GHG emissions caps or targets and their associated carbon price, in order to identify the mitigation potential that could be allocated to storage technologies, considering generation and storage technologies' cost reductions in the mid- and long term.

This potential is calculated by quantifying the difference in emissions after applying a carbon price (estimated as the shadow value of the carbon emissions caused by electricity generation in a first run) to scenarios with and without energy storage.

The study identifies whether electricity storage technologies allow a larger integration of variable renewable energy while decreasing system costs, which would imply a mitigation potential that could be allocated to storage. Additionally, it carries out sensitivity analyses to varying a. o. carbon prices, renewable energy costs, storage costs, and natural gas prices to see its effect on the mitigation potential of energy storage, within the modelled scenarios.

The study is part of a larger analysis of storage technologies in Mexico, which also includes other publications related to electricity storage. The data used for this modeling assessment with regard to electricity storage technologies comes from the "Storage Technology Catalogue" report, whose elaboration has been accompanied by a consultation and participation process with multiple stakeholders, in order to identify the most likely development of electricity storage technologies, in terms of techno-economic data projections, based on the best scientific knowledge.

Balmorel (an energy system and socioeconomic optimization model, open-source) was applied to assess the impact and mitigation potential of storage and to identify main drivers, challenges, and opportunities of storage technologies.

For this purpose, different long-term scenarios of the Mexican electricity system were developed to assess the role of electricity storage in enabling a larger integration of variable renewable energy and subsequently identifying the mitigation potential that could be allocated to storage systems.

Balmorel is an optimization model with a bottom-up approach, i.e. with a detailed representation of the power sector, whose objective is to satisfy the electricity demand in Mexico at the lowest cost. The Mexican power system in Balmorel is represented with 53 regions, and hourly simulation of generation and demand. Data inputs rely on official and updated sources publicly available, including the aforementioned Storage Technology Catalogue.

Since the model minimizes the total costs of the system, it acts as a social planner and does not consider each individual deployment of any technology, i.e. a business plan, but the model chooses what is best for society at the overall level.

Scenario analysis with detailed energy system modeling to assess the mitigation potential of storage

This analysis explores the impact of storage technologies on a "Reference scenario", which could be considered as an unconstrained scenario driven by least-cost optimization (i.e. it will find the cheapest way to satisfy all the electricity demand in every region and hour), and on a "Climate" scenario that would limit GHG emissions from electricity generation in Mexico through carbon pricing.

In order to evaluate the different alternatives, four scenarios are modeled, as shown in Figure 1, considering the availability of storage systems and the use of carbon pricing to limit GHG emissions. The carbon price is set at a level that in the "Climate scenario without storage" would allow achieving an emission target of 124 $MtCO_2e$ by 2030, consistent with Mexico's NDC and the sectoral goal for electricity generation established in the General Law on Climate Change. Furthermore, on 2050, the target is set at 75 $MtCO_2e$, representing a goal of 35% GHG emissions reduction compared to 2000 level.

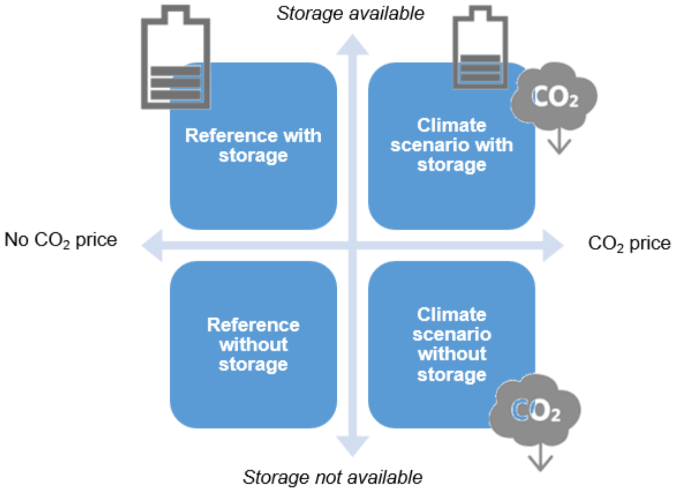

Figure 1. Main scenario set-up.

The **"Reference"** and **"Climate"** scenarios with the possibility to deploy storage assume the techno-economic characteristics of Li-ion technologies; however, results should be understood in a broader context, as other technologies that achieve the same efficiencies and costs could also be deployed. Furthermore, a sensitivity analysis with pumped hydro storage is also performed.

Storage technologies can support RE-expansion and have a large CO_2 mitigation potential

Results show that renewable energy generation would become increasingly cost-efficient to satisfy a growing electricity demand, and it could play a larger role in the future power system as it would be cheaper than traditional fossil-based electricity supply, even with no carbon pricing. Furthermore, when attaining climate targets through the use of carbon pricing, renewable technologies become even more cost-efficient than fossil-based plants, as they do not emit greenhouse gas emissions, and the share of variable renewable energy would be even larger.

Currently, the total installed capacity of solar PV technologies is of approximately 5.5 GW, and modeling results show that even without a climate ambition, solar PV generation would be 63% higher with storage than compared to a scenario without storage by 2030, and 25% larger by 2050. The total optimal storage capacity in 2030 would be of 16 GWh (volume) and 5 GW (power), and it would rise up to 69 GWh (volume) and 23 GW (power) by 2050. Results show that it would be cheaper to satisfy the electricity demand by investing in renewable energy and storage capacity, than by investing in gas-based power plants. The mitigation potential of storage would be up to 6 $MtCO_2$ by 2030 and up to 15 $MtCO_2$ by 2050 (see Figure 2, left), while decreasing total costs of satisfying the electricity demand in the country by 1% in 2030 and 3% in 2050.

Attaining a climate cap of 75 $MtCO_2$ by 2050 considering a linear reduction from current emissions level, would imply a carbon price of 6 USD/tCO_2 in 2030 and 47 USD/tCO_2 in 2050, under the reference conditions of this modeling approach and the possibility to invest in storage. Solar generation would 23% and 105% higher by 2030 and by 2050, respectively, when comparing a scenario with storage and without storage with the same level of carbon pricing. Solar PV capacity could optimally rise up to 194 GW by 2050, achieving the target of 75 $MtCO_2$ while supplying the electricity demand in the most cost-efficient way. By

2030, the total optimal storage capacity would be of 19 GWh (volume) and 6 GW (power), and by 2050 it would be of 410 GWh (volume) and 70 MW (power).

The share of natural gas-based generation in the power system in 2050 would still be around 37% without storage systems–compared to a level of 13% that could be achieved when storage systems are deployed, as storage technologies would largely displaced gas-based generation. The mitigation potential associated to storage technologies would be of 4 $MtCO_2$ in 2030 and up to 63 $MtCO_2$ by 2050 (see Figure 2, right). Hence, the level of emissions without storage would be of 138 $MtCO_2$, in spite of a carbon price of 47 USD/tCO_2, which would restrict Mexico's ability to comply with their overall goal to decrease their total greenhouse gas emissions by 50% compared to 2000. Therefore, modeling results show that electricity storage systems could allow a reduction equivalent to 46% of total emissions in the electricity sector compared to the *Climate* scenario without electricity storage. Furthermore, total system costs would be reduced by 10% annually in 2050 if storage technologies are deployed.

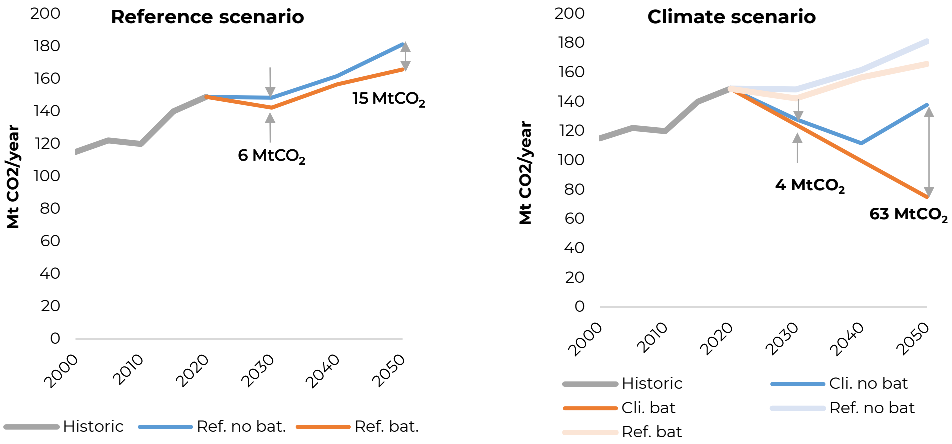

Figure 2. Annual CO_2 emissions and CO_2 mitigation potential (arrow) in the Reference and Climate scenario

In addition, a few sensitivity analyses were carried out in order to assess the impact on uncertainties in some of the inputs that could affect significantly the results:

- The emissions of the electricity sector are very sensitive to variations in the natural gas price throughout the whole period. When using a carbon price of 47 USD/tCO_2 by 2050, the emissions of the scenario with storage would increase from 75 $MtCO_2$ to approximately 101 $MtCO_2$, if the natural gas price is 2 USD/GJ lower than the defined value. On the other hand, if the price of natural gas is higher than expected (+1 USD/GJ), the emissions of the electricity sector would be 52 $MtCO_2$ by 2050. Higher gas prices make renewable technologies more cost-efficient, even at low carbon prices, and vice versa.
- The impact of the uncertainty in the solar PV investment cost would only have a large influence in 2030, and by 2050 the difference would be between +5 $MtCO_2$ (slow learning) and -2 $MtCO_2$ (fast learning) in comparison to the base case.
- Uncertainty in the learning rate of the battery investment cost would have a high impact on the CO_2 mitigation potential. If batteries become cheaper than the central estimate, the mitigation potential would grow from 63 $MtCO_2$ to approximately 72 $MtCO_2$ by 2050.

Alternative Climate targets

Since the CO_2 price is derived from the climate target, alternative CO_2 targets could change the mitigation potential of storage, as an effect of changing CO_2 prices. In addition, the level of carbon pricing would change the dynamics of the system, thereby also changing the mitigation potential that could be allocated to storage technologies.

If this climate target is strengthened from 75 down to 50 $MtCO_2$ in 2050, this would imply a carbon price of 106 USD/tCO_2, and the mitigation potential of storage would decrease from 63 to 38 $MtCO_2$. A very high carbon price would make clean energy cost-efficient compared to fossil-based generation without storage. Hence, there would be a relatively smaller impact from storage technologies in terms of mitigation, but highly significant in terms of costs, as clean energy generation would become cheaper. Total costs of satisfying the electricity demand would be 16% lower by 2050 if storage technologies are deployed.

If the climate target loosens up from 75 to 100 $MtCO_2$ in 2050, this would imply a carbon price of 30 USD/tCO_2, and the mitigation potential of storage would also decrease from 63 to 55 $MtCO_2$. The mitigation potential is smaller as at lower carbon prices solar PV plus storage systems are a little less advantageous than fossil fuel generation. Nevertheless, total costs of satisfying the electricity demand would be 6% lower by 2050 if storage technologies are deployed.

At moderate carbon prices, the possibility to invest in storage systems would allow to achieve larger levels of decarbonization, increasing the cost-efficiency of solar PV and storage systems compared to fossil-based generation. At low-moderate carbon prices, storage would mostly displace fossil-based generation, while at high carbon prices, storage would also displace more expensive clean energy sources.

Pumped hydro storage and Li-ion batteries

This study considers as a reference technology for storage Li-Ion batteries, but there are other technologies that could potentially be highly relevant in a Mexican context, especially Pumped Hydro Storage (PHS). The deployment of PHS would promote the efficient integration of variable renewable energy, compared to a scenario without storage, and would have a mitigation potential of 46 $MtCO_2$ in 2050. Nevertheless, due to the expected large cost-reduction of Li-ion batteries in the mid-term, the mitigation potential associated to only pumped hydro storage is lower than the one associated with only Li-ion batteries after 2040.

The deployment of both technologies might be the preferred solution, combining the advantages of PHS (inter-seasonal and inter-annual storage, and a lower user/import of mineral resources) and Li-ion batteries (lower costs higher round trip efficiencies and fast response for ancillary services), where PHS would store energy during larger periods of time.

If there are any limitations to the Li-ion battery volume (MWh), the role of PHS could increase but the role of storage technologies would be in an overall way smaller. Scenarios with Li-ion limits of two-to-four hours duration range, would imply optimal investments of 1.2 GW of PHS by 2030 and 5.0-5.3 GW of Li-ion batteries, which would increase substantially towards 2050.

Regulatory and financial barriers slow-down the effective deployment of storage technologies

Regulatory and financial barriers to storage systems would influence the pace of its effective deployment, hence affecting the level of renewable energy integration. Nevertheless, as the cost of storage technologies (Li-ion batteries used in this modeling approach as reference technology) are predicted to fall sharply, they would become economically attractive even with the prevalence of some existing barriers. Therefore, an adequate regulation can facilitate a faster and larger integration, thereby further reducing the cost of storage, which would result in a decrease of the overall cost of satisfying the electricity demand in Mexico while fulfilling climate obligations. Modeling results show that:

- High electricity transmission costs to and from storage sources could decrease solar PV generation by 3% to 5% in 2050, resulting in 3 $MtCO_2$ of additional induced emissions.
- If storage devices with a volume/capacity ratio above 6 hours can participate in a more favorable way in the electricity market than storage devices with a lower ratio, emissions could increase by up to 4% in 2040 and 10% in 2050, equivalent to an 8 $MtCO_2$ increase.
- If investments are associated with a higher risk perception of storage technologies, emissions could likewise increase.

Knowledge-based input for decision-making and climate- and energy planning

This study is not a prognosis about how the future will evolve, but a scenario assessment of what could happen if storage technologies can be integrated in the system under different climate ambitions. Modeling results show that the role of storage technologies could be key in a future Mexican power system that is increasingly decarbonized and fulfills Mexico's climate goals.

If storage systems evolve in a way similar to how it has been assessed, they could be a game changer regarding the integration of variable renewable energy, as it allows to address the concern, "what happens when the sun is not shining and the wind is not blowing?".

This study shows that storage technologies could have the potential to disrupt the electricity system. Storage technologies would decrease costs, facilitate the integration of renewables and would have a considerable CO_2 mitigation potential.

1. Introduction

Climate Change

Accumulation of anthropogenic greenhouse gas (GHG) emissions in the atmosphere is “extremely likely to have been the dominant cause” of the observed increase of average global temperatures since the mid-20th century (Intergovernmental Panel on Climate Change, 2014). This change in climatic conditions impacts natural and human systems, and threatens to cause substantial damages in the short, medium, and long term. Negative effects are becoming more evident year by year (World Metereological Organization, 2020).

As a global response to the threat of climate change, in the Paris Agreement, all signatory countries agreed to limit the increase in global average temperature to well below 2°C above pre-industrial levels (UNFCCC, 2015). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C shows there are pathways that could allow limiting warming to 1.5 °C, reducing the likelihood of extreme weather events, but they all require urgent action, far more immediate than previously anticipated (IPCC, 2019). The 1.5°C IPCC report indicates that the share of primary energy from clean and renewable sources (including biomass, hydro, solar, wind, and geothermal) should be between 38-88% in 2050 on all routes that limit the increase in global temperature by 1.5°C. More specifically, the report indicates that the share of electricity supplied by clean and renewable should increase to 59-97% in 2050. Climate change, air pollution, increasing dependence on fossil fuels and volatile fuel prices are making our society and economy vulnerable, setting the world at a crossroads concerning the future of energy (Jacobson, 2017).

Energy security and self-sufficiency

The electricity sector is experiencing a radical transformation worldwide. These changes in generation are in part responsible for the decoupling of emissions from economic growth apart from energy efficiency. In 2019, energy-related CO_2 emissions fell by 3.2%, while growth in advanced economies[1] reached 1.7%. Power sector emissions declined by 1.2% around the world (IEA, 2020), thanks to a larger generation from renewables and nuclear power, and fuel switching from coal to gas.

Mexico’s greenhouse gas emissions totaled 733.8 $MtCO_2e$ in 2017 (INECC, 2019), and ranks 12th with respect to the world’s most emitting countries. The emissions associated to electricity generation account for approximately 21.15% of the country’s GHG emissions. In this context, and to live up to international commitments, Mexico has pledged to reduce its GHG emissions. In fact, Mexico was the first developing country to submit its intended climate plan before the Paris Agreement and formalized it into Nationally Determined Contributions (NDC). As stated in its NDC communicated to the United Nations Framework Convention for Climate Change (UNFCCC) in 2016, Mexico commits in its General Law of Climate Change (DOF, 2018) to reduce in an unconditional manner its emissions in 2030 by 22% in terms of GHGs, including a 31% reduction by 2030 of the electricity sector.

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[1] Australia, Canada, Chile, European Union, Iceland, Israel, Japan, Korea, Mexico, Norway, New Zealand, Switzerland, Turkey, and United States (IEA, 2020).

Additionally, Mexico's Climate Change Mid-Century Strategy (SEMARNAT-INECC, 2016) points out a general goal to reduce emissions by 50% in 2050 compared to 2000 levels.

In 2018, Mexico generated 317,278 GWh of electricity (SENER, 2019), of which 51% was generated in combined cycle power plants, whereas 4.6% through variable renewable sources (solar and wind). At the same time, Mexico imported approximately 40% of its natural gas consumption and 50% of its coal consumption (SENER, 2020), while experiencing a decrease in its Energy Independency (SENER, 2019b). In this context, a transformation in the Mexican electricity sector might bring climate gains while promoting energy self-sufficiency; and therefore, energy security.

The role of storage in VRE integration, as sustainable back-up capacity might be limited

Clean energy, including Variable Renewable (VRE), as well as energy efficiency, both in production and consumption, will play a fundamental role in reducing greenhouse gas emissions. The cost of VRE, especially solar and wind, has decreased dramatically in recent years, while its integration into electrical systems increases (IRENA, 2017). Between 2010 and 2018, the global weighted average levelized cost of electricity from solar PV fell by 77%, while the cost of electricity from onshore wind declined 36% (IRENA, 2020a). However, because generation using these technologies is unequally distributed through the geographical space (especially in the case of wind), as well as it is intermittent and uncontrollable, their deployment will "bring new challenges for policy makers, regulators and power utilities in terms of system planning and operation" (IRENA, 2020b).

Currently, 10% of the power generation at a global level comes from variable resources (solar PV and wind), and countries are integrating variable renewable energy (VRE) at a share of over 30% on an annual basis (IRENA, 2020a). Flexibility in power systems is a key enabler for the integration of high shares of VRE. This flexibility can be achieved through technologies, business models, market design, and system operation. Most of these challenges would be overcome by upgrades in the transmission infrastructure, demand-side management, or the so-called smart grids. On a technology level, the Global Renewable Outlook published by IRENA (2020a) highlights that "both long-term and short-term storage will be important for adding flexibility, and the amount of stationary storage (i.e. excluding batteries from electric vehicles) would need to expand from around 30 GWh today to over 9,000 GWh by 2050."

Electricity storage as enabler of cost-effective integration of VRE, and thus facilitating greenhouse gas emissions reduction

The International Renewable Energy Agency (IRENA) (2020b) concluded that "storage services help to manage the variability and uncertainty that solar and wind use introduce into the power system" helping to address key technical and economic challenges related to variable renewable energy integration. Therefore, storage technologies could play a role in enabling a higher integration of VRE. The need arises to assess whether storage technologies could contribute to the efficient integration of VRE in Mexico, and thus promote a decrease of greenhouse gas emissions and other environmental impacts associated with fossil fuel-based electricity generation.

Storage of electricity allows excess energy generated when renewable resources are available, to be stored and used subsequently, once the resource availability is low and/or the demand for electricity is high. This allows increasing the dispatch and distribution capacity in the network, enabling electricity produced in periods of low demand to be stored and used later to satisfy peak demand. This reduces the use of technologies that cover peak demand, such as single cycle gas plants, as well as the needs for spinning reserves and the use of fossil-based power plants to provide ancillary services. When stored energy comes from renewable sources, storage technologies have the potential to contribute to greenhouse gas mitigation by facilitating a larger cost-efficient integration of renewable sources.

The assessment of electricity storage technologies in a Mexican context

During the last years, Mexico has increased substantially its renewable energy capacity. Furthermore, Mexico has a large untapped potential for solar and wind energy. However, to embark onto a low carbon development pathway, Mexico also faces several challenges. A larger increased participation of VRE causes challenges in power system flexibility, operation, transmission networks, and reserve requirements and for ancillary services.

In the case of Mexico, GHG emissions have been growing in the electricity sector. This is caused by drivers such as population growth and the growth of energy intensive economic activities. Emissions in the electricity sector have grown by 40% between 2000 and 2017, from 116.07 $MtCO_2e$ to 162.56 $MtCO_2e$ (INECC, 2019). The combination of increased national energy consumption, the decrease in national energy intensity (in KJ/USD of GDP) and the decreasing Energy Independency (SENER, 2019b) show the urgency to continue taking measures to mitigate GHG emissions.

In recent years, technological change in the electrical system has been accentuated, reducing the use of fuel oil and increasing the use of natural gas. Although this trend has reduced emissions, it has not offset the emissions associated to the increase in demand associated to the increase in population, and industrial and economic activities. Currently, approximately 50% of the generation comes from the use of natural gas. Although this technological change has been environmentally favorable, today it might also become an energy dependency problem.

The report is part of a larger analysis of storage technologies in Mexico, which also includes several other publications, for example a *Technology Catalogue* for storage technologies, an analysis of *Barriers and enablers to the implementation of storage technologies in Mexico*, and the results of five case studies among others.

This report assesses the impact that selected electricity storage technologies could have on the Mexican electricity sector towards 2050. By using an energy systems analysis approach, the study attempts to identify the main drivers, challenges, and opportunities of this technology, especially with regard to greenhouse gas emissions mitigation.

Brief introduction to the approach used

Energy storage technologies can potentially contribute to a more cost-effective introduction of VRE and provide to the electrical system services to improve the stability and reliability thereof, which reduces CO_2 emissions by displacing fossil fuel-burning technologies. Storage couples with VRE, because it enables the transfer across time of energy and might thereby support an efficient large-scale VRE integration and decarbonization of the electricity sector. Storage can also provide other important energy system services, such as frequency and voltage control.

Therefore, studying the mitigation potential of storage technologies is relevant from an energy and environmental policy point of view. This study focuses on the possible deployment of storage in the Mexican power system through four main modeling scenarios: two *Reference scenarios* with and without Lithium-Ion batteries, and two *Climate scenarios* with a CO_2 price with and without Lithium-Ion batteries.

The study is organized as follows: Sections 2 and 3 describe the electrical system and the data used in modeling the electrical system through the optimization model Balmorel. Section 4 describes the applied methodology, as well as the scenarios and premises used in the modeling. Section 5 describes the results for each of the scenarios regarding the mix of technologies, mitigation potential and system costs. Section 6 shows the mitigation potential associated to different mitigation goals (different CO_2 prices) and compares the mitigation potential of Pumped Hydro Storage instead of Lithium-Ion batteries. Part 7 shows how regulatory and financial barriers can affect the level of storage deployment and thereby the level of CO_2 emissions reduction. In section 8, a sensitivity analysis is carried out for three parameters: the cost of VRE, the cost of batteries and the price of natural gas. Finally, Section 9 summarizes the main conclusions from the study. Additionally, Appendix A compiles all data sources, Appendix B describes the results of the sensitivity analysis for selected parameters and Appendix C introduces the mathematical framework of the model Balmorel.

2. The Mexican power system

Overview

The electricity sector in Mexico has undergone important changes in its generation mix during the past two decades, as Figure 2.1 shows, going from a system largely relying on fuel oil to a system heavily dependent in natural gas. The increase in natural gas generation has covered both the increase in electricity demand and a decrease in fuel oil consumption in thermoelectric plants.

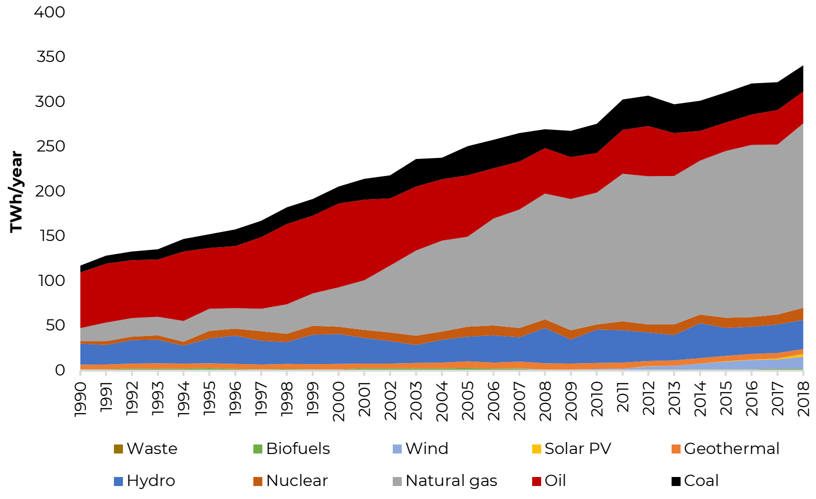

Figure 2.1. Electricity generation by source in Mexico during 1990-2018. Source: IEA (2020).

Figure 2.2 shows the installed capacity by technology in the electricity sector in Mexico in 2018 (SENER, 2019). At the end of 2018, the total installed capacity of the Mexican power sector was approximately 70 GW, where the main technologies were combined cycle (36.5%), hydropower (18%), conventional thermal plants (17%), coal (7.7%) and single cycle gas turbines (4.6%). Other VRE sources, such as wind and solar, start playing a role in the Mexican electricity matrix, and at 2018 their share in the installed capacity was 6.8% and 2.6%, respectively (SENER, 2019).

Low-carbon electricity ("clean energy[2]" under the Mexican Electricity Law) has been dominated by hydropower, nuclear and geothermal electricity, with a more recent increase of wind and solar PV generation. Solar and wind technologies were the fastest growing sources of electricity in the past decade, with a 68% average growth for wind and 103% for solar PV in the 2012-2017 period (SENER, 2020).

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[2] Clean Energy definition in the Energy Transition Law includes: wind, solar radiation, ocean energy in its various forms, geothermal reservoirs, bioenergy sources, methane and other gases associated with waste disposal sites, livestock farms and waste-water treatment plants, hydrogen through combustion or used in fuel cells, hydroelectric plants, nuclear power, agricultural waste and municipal solid waste, efficient cogeneration plants and sugar mills, thermal power plants with carbon dioxide capture processes and geological storage, and other technologies considered as low-carbon (DOF, 2015).

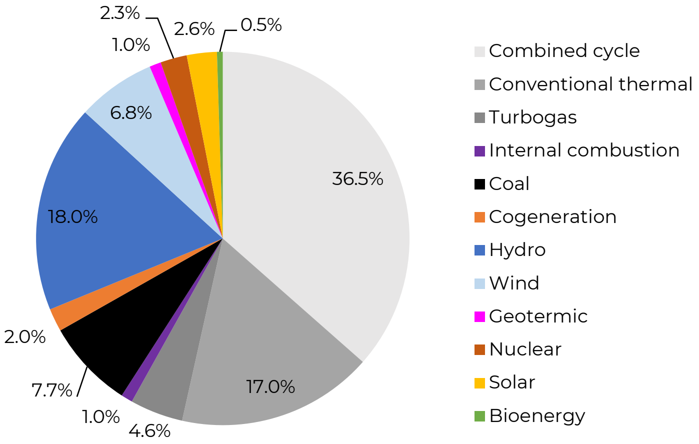

Figure 2.2. Installed capacity by technology in Mexico in 2018. Source: SENER (2019).

While clean energy installed capacity accounted for around one third of the total installed capacity of Mexico, these sources represented 23.2% of annual generation in 2018 (SENER, 2019). Figure 2.3 shows the generation in 2018 by technology, where total electricity generation reached 317 TWh (SENER, 2019). The participation of natural gas in the Mexican electricity system reached 53.7% in 2018 considering combined cycle and single cycle gas turbine plants ("turbogás").

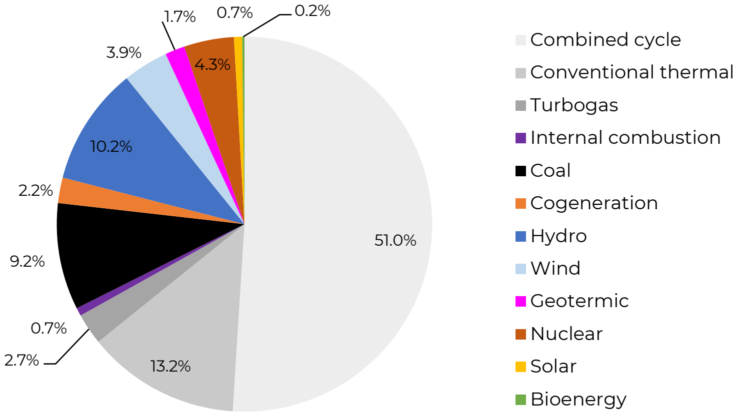

Figure 2.3. Generation by technology in Mexico in 2018. Source: SENER (2019).

Figure 2.4 shows the evolution of clean energy technologies in the past decades in Mexico.

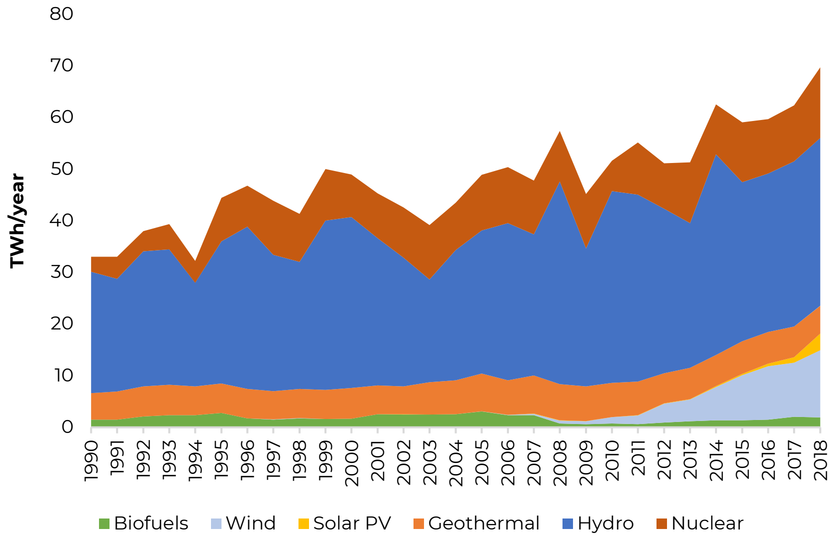

Figure 2.4. Low-carbon electricity generation by source in Mexico. Source: IEA (2020).

Transmission/congestion

Figure 2.5 shows the distribution of transmission capacity in 2018 in the control regions of the National Electric System (SENER, 2019). The total capacity of the system was about 78,239 MW. In the past three years, the capacity has grown by approximately 5.4%. In some of the control regions with increasing demand, the transmission capacity has reached its maximum limit or is already surpassed. An example of this is the Yucatan peninsula (SENER, 2019), whose transmission capacity is limited with respect to the flow of energy imports from the eastern control region, which includes the southeast of the country.

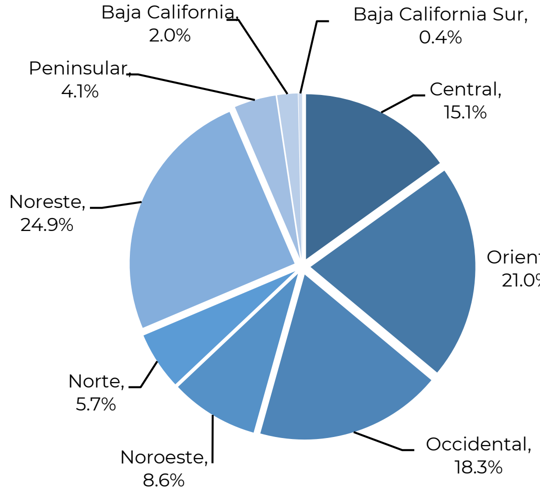

Figure 2.5. Transmission capacity by control region in Mexico in 2018. Source: SENER (2019).

An increasing demand and limited investments in the transmission grid amid a growing share of VREs poses challenges to the electrical system and transmission network. It is presumed that all this has created problems of congestion, and an increase in the reserve requirements as well as for ancillary services to ensure the reliability of the system. The next figure shows that there are bottlenecks between transmission regions, which would increase marginal local prices[3] and might even result in generation curtailment (SENER, 2019).

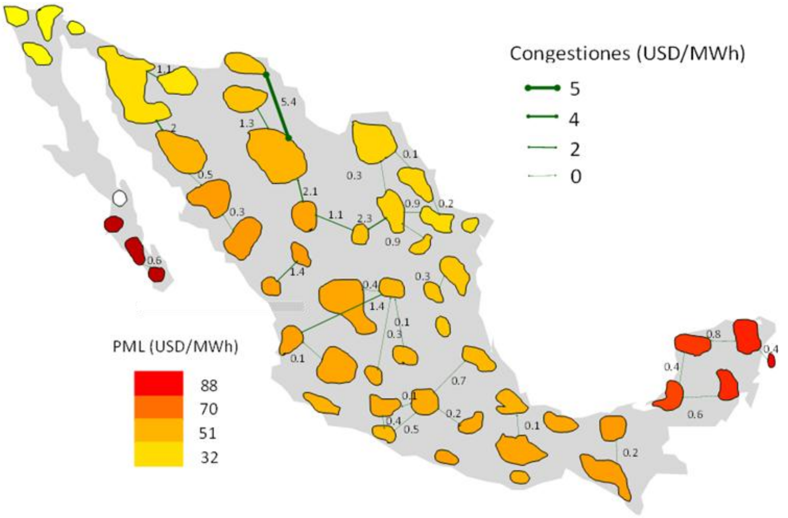

Figure 2.6. Congestion and Marginal Local Prices (PML) by transmission region in Mexico in 2017 (Working Group, 2019).

Renewable energy potential and policies to increase its participation

Mexico is one of the countries with the highest potential for solar generation, with a mean solar irradiation higher than the ones of China, Germany or Japan (Oseguera, 2010), countries that lead in installed capacity of these technologies (IRENA, 2020). In addition, Mexico also has good wind resources. The wind potential is concentrated in the Tehuantepec Isthmus (Oaxaca), but it is also spread in the northwestern part of Mexico and in the Baja California peninsula (World Bank, 2020).

RE regulation and climate policies

Increasing the generation of clean and renewable generation technologies for the decarbonization of the sector is mandated by law. The Energy Transition Law, which came into effect in December 2015, mandates that Mexico must generate at least 35% of its energy from clean sources by 2024 (DOF, 2015), and the clean energy share reached 23% in 2018. The Law also entails the modernization of plants (fuel-change), energy-efficiency measures, and technical losses reduction.

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[3] Working Group, 2019. Congestion in the electric power transmission network study. Presentation. Not published.

Other policies seek to price carbon to incentivize investments in clean energies and energy efficiency, and to internalize the negative externalities caused by emissions. Such policies are:

a) Fossil fuel special tax instituted in 2014: a tax levied on each unit of consumption of fossil fuels, exempting natural gas. The tax is proportional to the social cost of carbon and the carbon content of the fuel (DOF, 2019).

b) The Clean Energy Certificates (CELs) market, which requires “load-centers” (the demand side) to acquire a yearly percentage of CELs out of the total consumption they make. Each CEL certifies that a MWh of clean energy has been produced. The requirement increases yearly, in line with the 35% objective for 2024 (CRE, 2016). In addition, the latest National Strategy for Energy Transition and Sustainable Energy Use states a target of 39.9% clean energy by 2033 and 50% 2050 (SENER, 2020a).

c) The recent launching of a three-year pilot program of the Mexican Emissions Trading System, which covers installations of the electricity and industry sector that emit more than 100 thousand tons of CO_2 a year (SEMARNAT, 2019).

3. Energy storage, technologies and Technology Catalogue

Energy storage technologies allow transferring energy across time. The technology can be utilized to store surplus energy and feed it to the electricity grid when demand is high. The energy stored may come from the grid or from an electricity generation installation, due to surplus production, unavailability of the system to absorb energy, or market optimization strategies –including price arbitrage.

While the energy storage at utility scale is incipient in Mexico, in the last years, stakeholders have recognized the possible value of storage (Delgado, Ramiro, & Jimenez, 2018) and proposed creating policies that further improve the adoption of storage. A working group integrated by CRE, CFE and private sector developed a document with recommendations for storage technologies (Working group CRE, 2018).

According to the *Overview of the Energy Storage Possibilities to Support the Electrical Power System* by ERRA (2016), energy storage technologies support energy security and enable the achievement of climate change goals by providing valuable services to the energy systems. Some of the benefits that storage can provide are:

- Balance generation from renewables;
- Ensure continued grid stability by substitution of fossil-based plants in delivering ancillary services;
- Improving energy system resource use efficiency;
- Supporting greater decentralization of energy production;
- Reducing system costs of electricity generation.

The specific array of services needed to be provided by storage has implications on which electricity storage technologies are most suitable to do so. Therefore, the decision to invest in a specific storage technology depends on the service required as well as the economic and social benefits it could provide. In Figure 3.1, and array of services that can be provided by storage are enlisted.

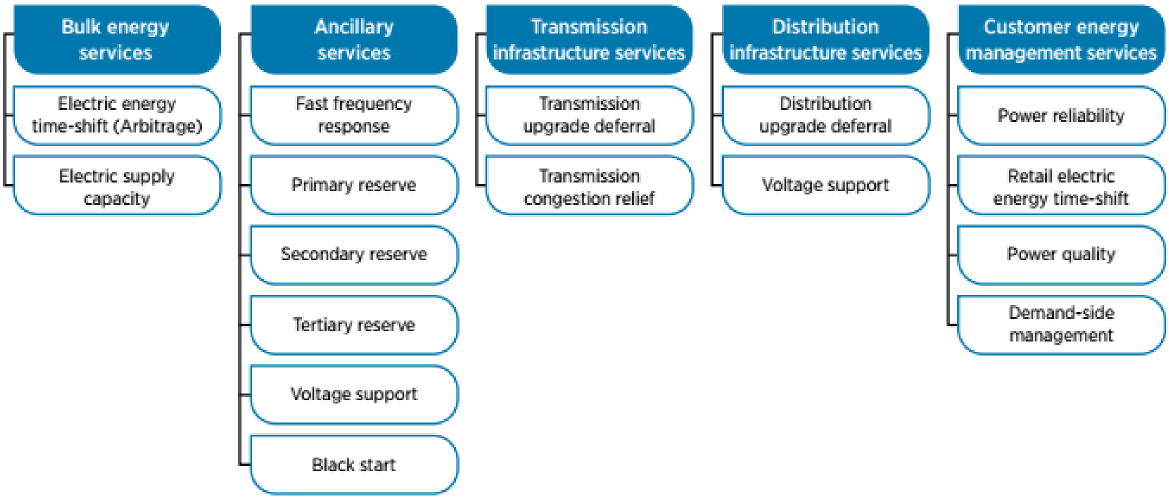

Figure 3.1. Services that can be provided by electricity storage. Source: IRENA, 2020.

New Technology Catalogue for Storage Technologies

A Technology Catalogue shares information across relevant stakeholders to further develop technology adoption and transparency. The Technology Catalogue agglomerates relevant technical and financial information on each technology and condenses it into a single source, serving as an entrance point to analysis plans for storage projects and as information to power system modelling. The Technology Catalogue for storage technologies (Part 2 of this study) contains qualitative and quantitative descriptions of nine potential storage technologies defined in Table 3.1.

Table 3.1. Technologies considered in the Technology Catalogue.

Hydraulic	Pumped-Hydro (PHS)
Mechanical	Compressed air (CAES)
	Flywheels
Thermal	Molten salts
Electrochemical (Batteries)	Lead-acid
	Lithium-based
	Vanadium Redox
	Sodium-sulphur
Electrical	Supercapacitors

In this study, as an assessment using an exploratory approach, Lithium-ion batteries and pumped-hydro storage technologies are modelled, although all technologies in the Technology Catalogue could potentially be relevant for Mexico. The two selected technologies will not necessarily dominate the storage market, but they comprise a good initial assessment of the role and mitigation potential of storage in the electricity system. Investment costs of Lithium-ion batteries have seen a great decline in the recent decade[4] and further reductions are expected in the future (see Figure 3.2). On the other hand, pumped-hydro storage is a mature technology that is not expected to improve significantly in the future. The state-owned utility CFE currently considers pumped-hydro storage a key technology for further development.

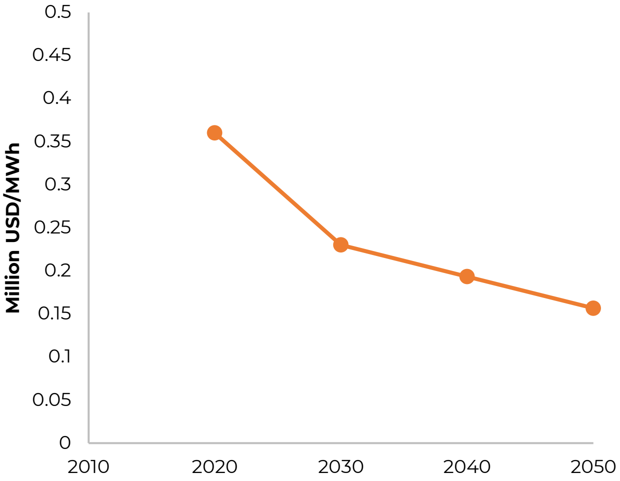

Figure 3.2. Investment cost pr. MWh for a 3-hour Li-Ion battery. Source: Technology catalogue (2020).

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[4] According to BNEF (2019), Li-ion battery prices have fallen 87% in real terms, from around USD 1,100/kWh in 2010 to USD 156/kWh at the end of 2019.

4. Methodology, data and main assumptions

Summary: Balmorel is used to assess the impact and mitigation potential of storage. The model has a highly detailed representation of the Mexican power system, with 53 demand and transmission regions and hourly simulation of generation and demand. Data inputs rely on official and updated sources, including the Energy Storage Technology Catalogue (Part 2 of this study). The analysis is framed by four main scenarios (two with storage technologies and two without storage technologies), which are used to assess the technical, economic and environmental benefits of adding storage technologies to the Mexican energy mix.

The Balmorel Energy System Model

The Balmorel energy system model is used to assess the impact and mitigation potential of storage technologies. Balmorel is a detailed techno-economical partial-equilibrium model suited for analyses of power systems. The model optimizes societal welfare across time and regions by minimizing the total cost of a given energy system, in this case the Mexican power system, when assuming inelastic demands (i.e. the electricity price does not affect the electricity demand).

Balmorel optimizes both generation dispatch and investments in generation capacity, including storage and power transmission, subject to a series of constraints, such as matching hourly power demand and supply, or restricting investments in specific areas. The results of the model *are not* a perfect prognosis, but rather an illustration of an idealized and optimal pathway from the point of view of an omniscient energy planner. The Balmorel model is open-source, it is written in GAMS (General Algebraic Modeling System) language, and the optimization problem is solved with cplex with the barrier algorithm (as in this study). More information can be obtained at the Balmorel website (Ravn, 2016).

Additional characteristics of the model Balmorel, as used in this study, are summarized below:

- The optimization is deterministic, and the parametric uncertainty of the scenarios is assessed through different local sensitivity analysis, varying one factor at a time, but without considering stochasticity as part of the optimization it-self.
- In addition, due to the fact that the full economy is not represented, as it is a partial-equilibrium model, sensitivity analysis allows considering the possible impacts of some parameters modelled as exogenous, which could get affected by the energy system.
- Balmorel might be run with different degrees of foresight between years (How much can be known or anticipated about the future?) and within the year of optimization. In this study, Balmorel-MX is run with a myopic approach between years; every year is optimized without any knowledge about how the future might evolve.

- Furthermore, the model is run with perfect foresight within the year of optimization; e.g. storage plants have the ability to foresee how the generation and demand of electricity is going to evolve over the year, in order to maximize the value of the electricity they store. Similarly, as the consumption of fossil fuels might be constraint by climate targets, its use is optimized during the year.

For further information about the equations used in the model refer to appendix C.

Input data and main assumptions

The model is calibrated to the Mexican electricity sector and represents the 53 transmission regions of the country interlinked by transmission lines (Figure 4.1). Region specific renewable energy potentials are based on the *Atlas Nacional de Zonas con Alto Potencial de Energías Limpias* (AZEL) (SENER, 2017). As an example, the solar PV resource potential is displayed in Figure 4.1. A brief description of the main input data and sources, including demand prognosis, transmission capacity, generation and storage capacity, renewable resources potential, fuel prices and discount rate, can be found in Table 4.1. A more detailed description of input data and sources can be found in Appendix A.

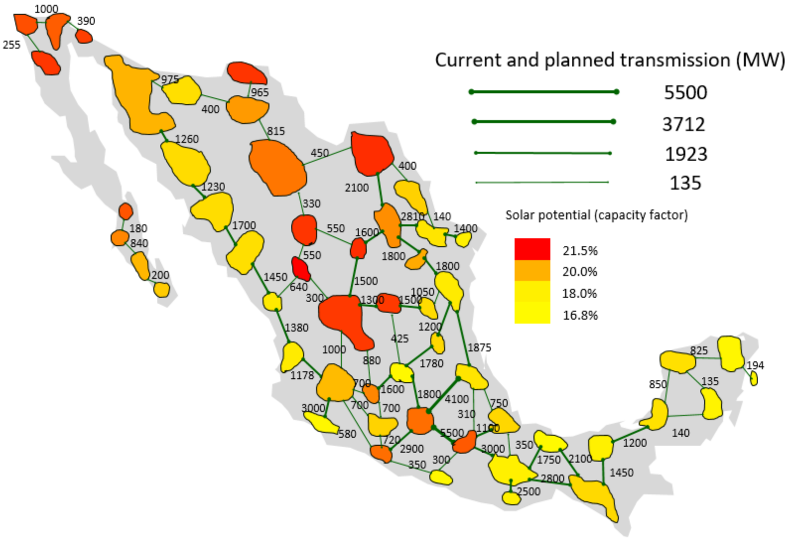

Figure 4.1. Representation of the 53 transmission regions, the current and planned transmission capacity between regions, and solar potential of each region (measured in capacity factor).

Table 4.1. Data and data sources used as input for Balmorel.

Parameter	Input data	Source
Demand prognosis	Regional electricity demand projections assuming a 2.9% average GDP growth per year in the period 2020-2031.	(SENER, 2018)
	Nationally, the electricity consumption is assumed to grow by 2.3% per year from 2020 to 2050.	
Power transmission capacity	Existing and planned transmission capacity	(SENER, 2019)
	Investments costs in new transmission capacity	(SENER, 2018)

Parameter	Input data	Source
Generation and storage capacity and techno-economical data	Existing	(SENER, 2018)
	Planned	(SENER, 2019)
	Technology catalogue for generation (efficiencies, operational and investment costs)	Appendix A
	Technology catalogue for storage (efficiencies, operational and investment costs)	Part 2 of this study Data Sheets
	Learning curve for solar PV technology	Appendix A
Availability of renewable resources	Solar and wind (hourly regional profiles)	(Renewable ninja, 2017) Appendix A
	Solar and wind capacity factor/full load hours	(SENER, 2017)
	Wind maximum installed capacity potential (< 20km from the transmission grid)	*Atlas Nacional de Zonas con Alto Potencial de Energías Limpias* (AZEL).
	Geothermal and biomass potentials	(SENER, CFE, 2018)
	Hydropower potential and seasonal profiles	(SENER, 2018)
Fuel prices	Price of natural gas, fuel oil, diesel, coal, uranium and biomass, further differentiated by regions per geographical availability and transport requirements. The price of natural gas follows the medium trajectory between 2019 and 2033, according to chapter VII in PRODESEN 2019-2033.	(SENER, 2019) Regional fuel costs can be found in Appendix A.
Discount rate	10%	(SHCP, 2014)

Natural gas prices are differentiated by regions and vary annually until 2032. After 2032, regional prices are assumed to remain constant due to the difficulties associated with making long-term prognosis. Figure 4.2 displays the regional variation in 2030.

As fuel oil is a by-product of refining and other utilizations, such as its use for shipping, might be limited (due to stricter regulations from the International Maritime Organization,), it is assumed that its consumption should be at least 200 PJ in all years, reflecting a situation where fuel oil cannot be minimized nor diverted from power generation plants.

The scenario in which the fuel oil consumption will not have any exogenous prescription within model will be examined, reflecting the situation in which the optimization seeks to optimize generation without considering a specific consumption.

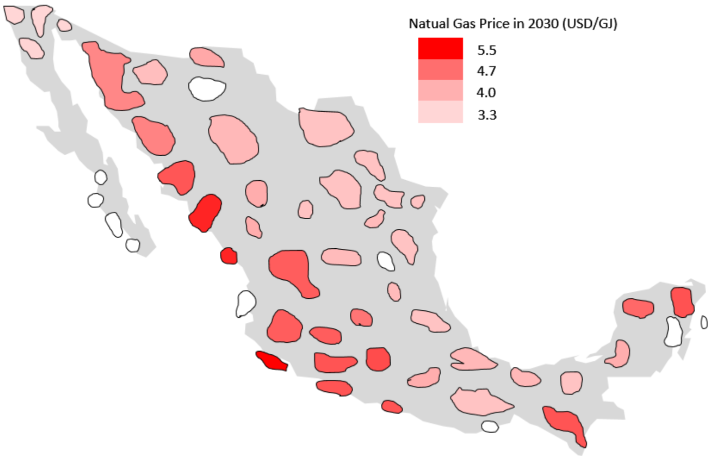

Figure 4.2. Natural gas price (USD/GJ) per region in 2030. Region in white does not have any natural gas infrastructure currently.

Regional electricity gross demand data is based on PRODESEN until 2031 (SENER, 2018). In the period 2032-2050, a uniform growth equal to the previous mean annual growth rate is assumed as shown in Figure 4.3.

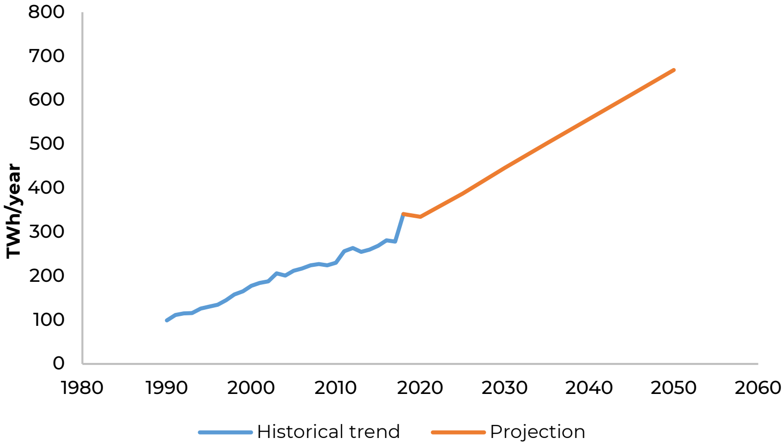

Figure 4.3. Historic and projected national electricity demand. In the Balmorel model, electricity demand is defined per region. This figure displays the sum of the 53 regions.

In order to have a detailed temporal representation of the dynamics of variable renewable energy generation and electricity storage, four individual full weeks (week 2, 10, 23 and 45) are modelled with hourly resolution, leading to a total of 672-time steps per year. Only the years 2020, 2030, 2040 and 2050 are modeled, as milestones years.

The main constraints induced in the model regarding the development of the electricity matrix are summarized below. Modeling is a simplification of the reality; hence there could be areas where a more detailed representation might be preferred depending on the specific question to be addressed.

- Exogenous decommissioned of power plants is defined according to the installation year and the technical lifetime associated to each technology. It is assumed that hydropower plants do not achieve their technical lifetime during the period of analysis.

- No endogenous decommissioning of plants has been assumed, due to the absence of foresight between years of optimization that could led to sub-optimal decisions in the long-term for actions taken in the short-term. Mothballing of plants could have been considered, given the myopic approach of the exercise, but it was leave out of the scope of the present analysis, as some of these plants could be useful to provide ancillary services, which are not modelled.
- Investments in nuclear power plants are allowed only in four regions, as identified by Sener (2018) as plausible locations for nuclear investments: Hermosillo, Huasteca, Veracruz and La Paz.
- Investments in hydropower plants are allowed according to the potential identified by Sener (2018). Re-powering of existing hydropower capacity has not been modeled.
- It is assumed that there are no further investments in coal power plants, including fluidized bed.
- It is exogenously fixed a restriction that enforces the consumption of 200 PJ of fuel oil in thermoelectric power plants; however, the impact of this restriction is assessed in a sensitivity analysis.
- It is possible to optimize investments in cogeneration plants, according to the potential defined in the PRODESEN 2018-2032 (SENER, 2018).

Model input and output

Figure 4.4 illustrates the flow of data in the model, where input data (technology data, electricity demand, renewable energy potential, fuel prices and policies and taxes) forms the necessary boundary conditions for the least-cost optimization. The output results are hourly dispatch, energy mix and investments, CO_2 emissions, system costs, etc.

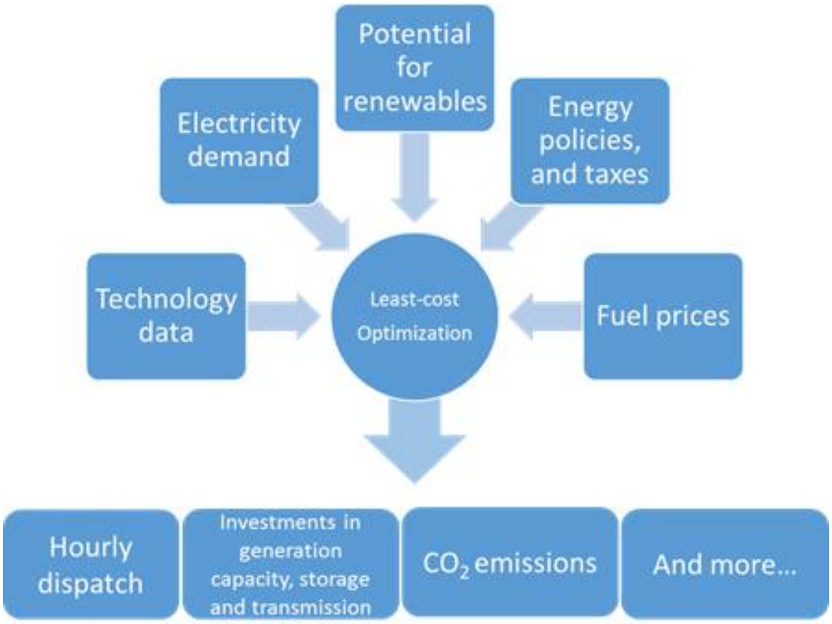

Figure 4.4. Illustration of input and output data of Balmorel Mexico.

Scenarios and methodology

In order to estimate the mitigation potential of storage, four scenarios from 2020 to 2050 are modeled, differing on two dimensions: storage availability and CO_2 price (as an environmental policy), as shown in Figure 4.5. The four main scenarios are:

- *Reference scenario.*
- *Reference scenario* with storage.
- *Climate scenario* (with CO_2 price).
- *Climate scenario* (with CO_2 price) with storage.

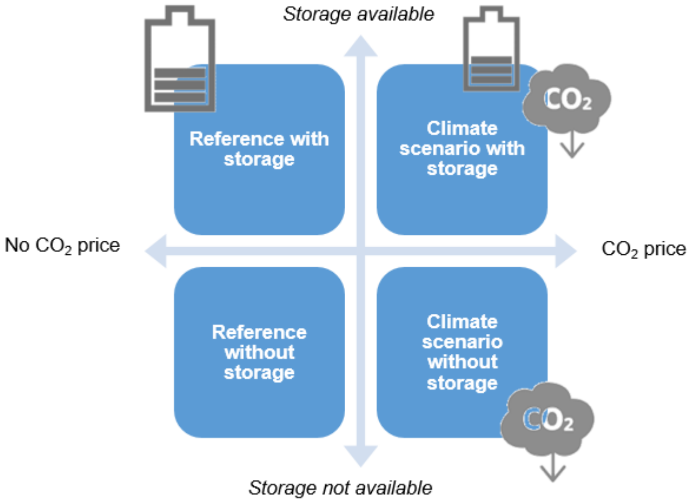

Figure 4.5. Main scenarios set-up.

Two of the four main scenarios involve the availability of storage technologies, using Li-ion batteries as a reference. The mitigation potential of pumped-hydro storage associated to hydro installations is analyzed in separate scenarios. Storage technologies are represented by key economic and technological data: lifetime, efficiency, operational costs and investment costs per energy volume (USD/MWh) and output capacity (USD/MW), and operational costs from the Storage Technology Catalogue. Storage volume and storage output capacity are optimized individually, which allows the model to find the optimal balance between volume and output power.

The *Climate scenarios* limit the electricity sector emissions in each year by applying a CO_2 price. The price is determined as the shadow value[5] of CO_2 emissions from a previous simulation, where CO_2 emissions are capped and reduced linearly from the current level to 75 $MtCO_2$ in 2050. This emission target aims to align with the Mexican Climate Change Mid-Century Strategy (SEMARNAT-INECC, 2016), which considers a goal of reducing emissions by 50% in 2050 compared to 2000-level: the 75 million ton limit implies a 35% emission reduction with respect to the level of emissions in the electricity sector in 2000 reported by the National Inventory on Greenhouse Gas Emissions. The modeling approach used in this report is not including neither demand-side interventions, such as energy-efficiency measures or demand electrification, nor fuel oil substitution (specifically assessed in a

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[5] A shadow value on CO_2 is the system cost of reducing the emission level by one extra ton.

sensitivity analysis). In addition, the decarbonization degree of other sectors is not being considered (e.g. transport, industry, agriculture, etc.). Hence, the level of emissions allocated to electricity generation of 75 $MtCO_2$ by 2050 could be considered moderate in order to reach the Mid-Century goals, and without the certainty that the level of the target allows to attain the overall mitigation goal. The *Climate* scenario should be seen as an exploratory scenario that seeks to assess what would happen in an electricity system with stringer GHG emissions thresholds.

The methodological approach used to assess the mitigation potential that could be allocated to storage technologies is depicted below (Figure 4.6). In a first step, a suitable carbon price that could allow achieving the desired level of decarbonization is calculated. The Balmorel model with the possibility to invest endogenously (as deemed optimal by the model) in storage technologies and constrained by annual greenhouse gas emissions (as shown in dark green in Figure 4.7) is run. The shadow value (also known as marginal or dual value) of the equation that limits annual greenhouse gas emissions represents the carbon price, i.e. the cost of emitting one unit less of CO_2, and it is shown in a dotted line in Figure 4.7. In a second step, the carbon price from the previous run is fixed and there is no limit to greenhouse gas emissions, which will be a result of the optimization considering the exogenously fixed carbon price. Two model runs are conducted: one run with the possibility to invest in storage technologies (to the level deemed optimal by the model), and another run without the possibility to invest in storage technologies. Both runs have the same carbon price, but they will have different level of emissions. This difference in emissions is caused by the effects of storage technologies as induced changes in the generation matrix, and in this report, it is defined as the mitigation potential that can be allocated to storage.

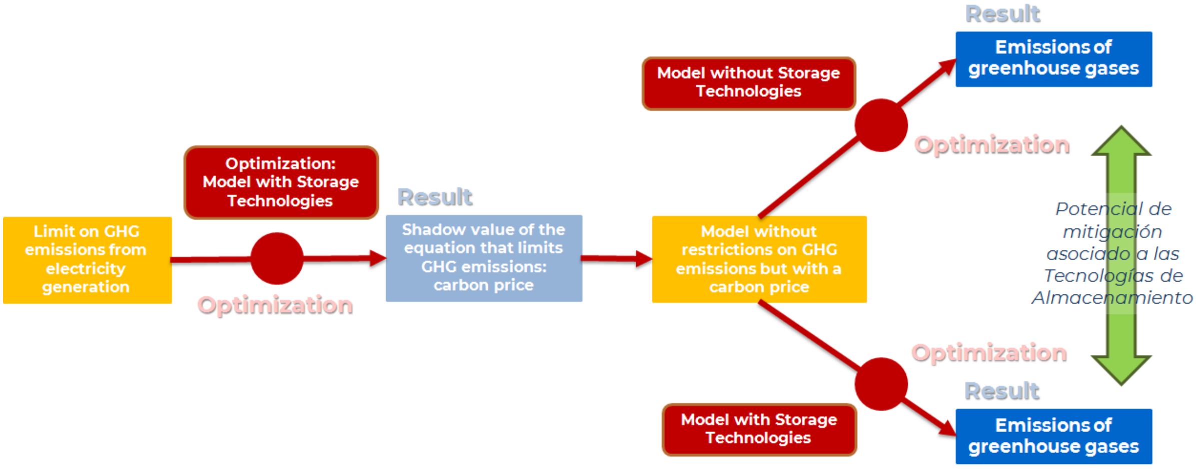

Figure 4.6. Modelling approach in Balmorel for the Climate scenarios.

Modeling results of the scenario with an emission cap give a carbon price of 6 USD/ton in 2030 which gradually rises up to 47 USD/ton in 2050. The relationship between the CO_2 cap and the resulting CO_2 price (as shadow value of the equation that limits greenhouse gas emissions) is displayed in Figure 4.7.

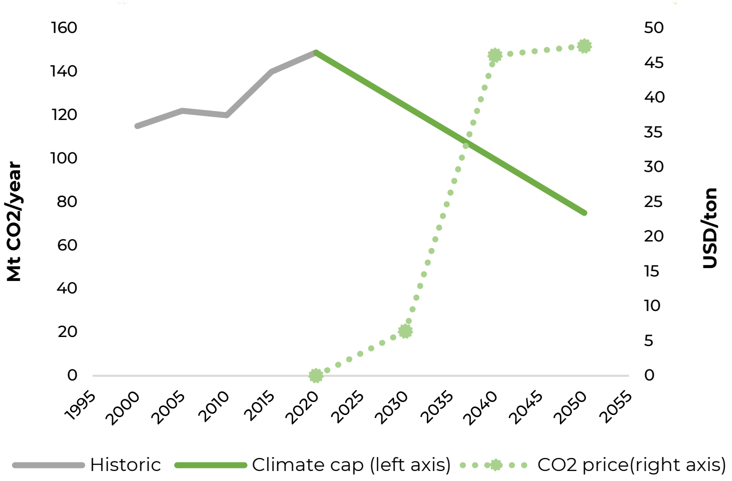

Figure 4.7. Limits to emissions and carbon price: assumed linear reduction of CO_2 emissions to 75 $MtCO_2$ by 2050 (left axis, *Climate* scenario with storage) and the resulting shadow value of CO_2 (right axis) applied in all the *Climate* scenarios.

By this method, the CO_2 price in the *Climate scenario* with storage of 47 USD/tCO_2 by 2050 would lead to an emission level of exactly 75 $MtCO_2$ by 2050. Applying the same carbon price levels to the *Climate scenarios* without storage would result in larger CO_2 emissions, because less renewable generation can be integrated in a cost-efficient way. The difference between these two *Climate scenarios* is regarded as *the mitigation potential of storage* (Chapter 5). Furthermore, it is evaluated the impact of having an enforcement of fuel oil consumption for electricity generation of 200 PJ, against a situation where there is no enforcement to fuel oil use for electricity, as fuel oil generation might be minimized or it might be diverted towards other utilizations.

Since the mitigation potential of storage effectively depends on the mitigation target, a set of alternative targets (50 and 100 million tons CO_2 in 2050) and the resulting mitigation potentials are analyzed in Chapter 6. Furthermore, the role that both Li-ion batteries and pumped hydro storage systems could play is also discussed in Chapter 6.

As documented in the analysis *Barriers and enablers to the implementation of storage technologies in Mexico* (Part 3 of this study) regulatory and financial barriers can hinder the deployment of storage technologies. To illustrate how such barriers would affect the system, three alternative scenarios (Double taxation, High Risk Environment and Restrictions on Battery Dimensions) are set-up in Chapter 7. These scenarios use the *Climate Scenario* with storage as baseline and add restrictions to the system.

To test the uncertainty of results towards the uncertainty in some key input parameters, a sensitivity analysis of the natural gas price, and solar PV and battery investment costs can be found in Chapter 8 and Appendix B.2. Table 4.2 sums up all the modelled scenarios.

Table 4.2. All scenarios with characteristics and reference chapter.

Group	Name	CO_2 pricing	Storage Tech.	Other Constraints	Chapter
Reference	Reference without storage	None	None	None	5
		None	None	No fuel oil constraint	5
	Reference with storage	None	Li-Ion	None	5
		None	Li-Ion	No fuel oil constraint	5
Climate	Climate without storage	Yes, medium	Li-Ion	None	5
	Climate with storage	Yes, medium	None	None	5
		Yes, medium	Li-Ion	No fuel oil constraint	5
Alternative GHG targets	Climate without storage	Yes, high	None	None	6
		Yes, low	None	None	6
	Climate with storage	Yes, high	Li-Ion	None	6
		Yes, low	Li-ion	None	6
		Yes, medium	PHS	None	6
Alternative storage technologies	Climate Scenario with storage	Yes, medium	PHS Li-Ion,	No Li-Ion available	6
		Yes, medium	PHS Li-Ion,	Max 2 hours Li-Ion	6
		Yes, medium	PHS Li-Ion,	Max 4 hours Li-Ion	6
		Yes, medium	PHS Li-Ion,	Li-Ion fully available	6
Restrictions	Climate Scenario with storage	Yes, medium	Li-Ion	Double tax	7
		Yes, medium	Li-Ion	High int. rate	7
		Yes, medium	Li-Ion	Min. 6 hours bat	7
Sensitivity	Climate Scenario with storage	Yes, medium	Li-Ion	None	8
		Yes, medium	Li-Ion	None	8
		Yes, medium	Li-Ion, high/low	None	8

5. Main scenarios and CO_2 mitigation potential

Summary: Renewable energy generation would grow substantially in all scenarios. Especially solar PV would lead the expansion and could increase the annual generation from 10 TWh in 2020 to 340 TWh in 2050, accounting for up to 50% of all electricity generation under the *Climate* scenario. To integrate such a large amount of variable renewable energy, grid scale storage could be efficiently deployed to balance fluctuations from day to night related to solar PV generation. If storage technologies are deployed in a cost-effective manner, they could mitigate up to 63 million tons of CO_2 as an effect of natural gas displacement and integration of more solar PV generation. Storage technologies would reduce CO_2 emissions through enabling a larger integration of variable renewable energy (VRE), while also decreasing total system costs of satisfying the electricity demand.

The modeling results are analyzed by comparing *Reference scenarios* with and without storage, and *Climate scenarios*, also with and without storage. The focus is on electricity capacity and generation, system costs, and CO_2 emissions. With respect to *Climate scenarios*, the CO_2 prices and hourly generation are also analyzed.

Reference scenarios

The *Reference scenarios* show how the power system might evolve in Mexico[6] with no climate ambitions, i.e. without pricing CO_2 emissions from electricity generation, and seeking to minimize the total cost of satisfying a growing electricity demand in the country. Nevertheless, in spite of the fact that there is no CO_2 pricing, renewable generation would grow in both scenarios (with and without storage), dominated by solar PV generation, as shown in Figure 5.1. This happens because the model finds it optimal to invest in VRE, as it becomes cost competitive compared to traditional fossil fuel technologies. The introduction of storage would enable a larger cost-efficient integration of solar PV, increasing its share in the electricity matrix: in 2030, solar PV generation would be 63% larger compared to the *Reference* scenario without storage and in 2050, solar PV generation would be 25% larger compared to the *Reference scenario* without storage (Figure 5.2).

This would correspond to a 23 GW capacity increase of solar PV due to storage technologies, ending at an optimal level of 111 GW in 2050.

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[6] The reference scenario was built upon the available data in 2017 and 2018, under assumptions of PRODESEN.

The total optimal storage capacity in 2030 would be of 16 GWh (volume)[7] and 5 GW (power),and it would rise up to 69 GWh (volume) and 23 GW (power) in 2050 (in the right graph of Figure 5.1, only the capacity associated to power is illustrated, and the storage volume is not included).

In terms of clean energy share (percentage of clean energy in total power generation), the *Reference scenario with storage* grows to 39% by 2030 and 50% by 2050. This is close to Mexico's National Strategy for Energy Transition and Sustainable Energy Use clean energy generation goals of 39.9% in 2033 and 50% in 2050 (SENER, 2020a).

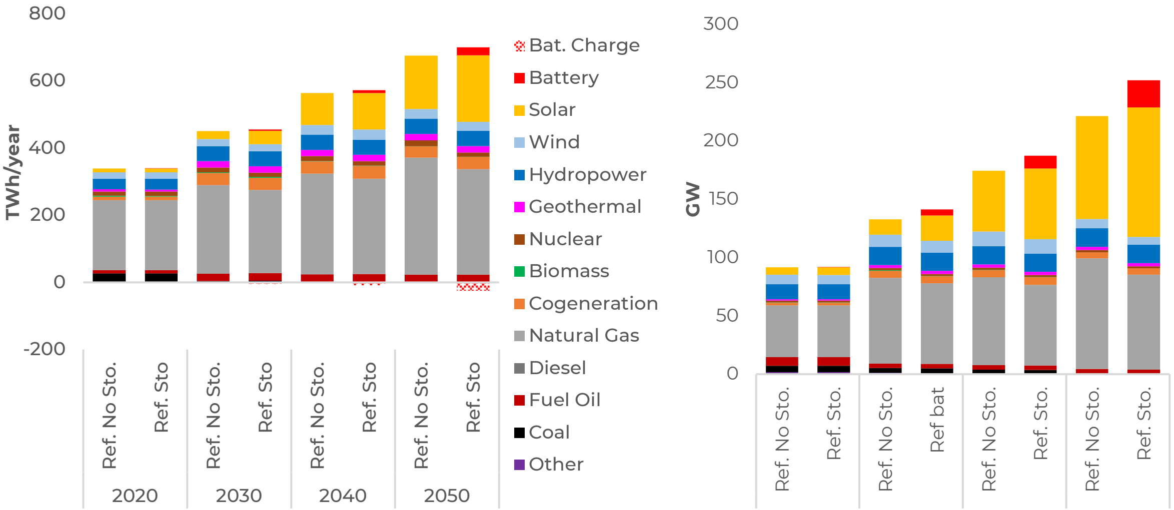

Figure 5.1. Annual electricity generation and capacity by source in the Reference scenarios.

From 2020 to 2050, natural gas-based generation would grow in both scenarios, but at a lower rate in the scenario where storage is allowed. Without storage technologies, a large integration of solar PV would not be possible because, among other aspects, they only generate during daytime; therefore, there is a technical barrier that would hinder high shares of solar PV.

Nevertheless, when storage is allowed, it would displace natural gas technologies, and act both as the so-called traditional base-load capacity (displacing combined cycle plants) and as backup capacity (displacing single cycle gas turbines) to compensate for variability in solar PV generation. Because of the large potential of solar technologies in Mexico and their expected cost decrease, generation from solar PV would be larger than from wind if there is no climate constraint in the modeled scenarios.

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[7] It should be noted that the capacity of storage systems in energy units is different than the annual generation by storage technologies illustrated in Figure 5.1, also in energy units. In 2030 in the Reference scenario with storage, the optimal capacity of it would be of 16 GWh, while the electricity sent to storage would be of 4.337 TWh and the electricity delivered by storage would be of 4.114 TWh, considering electricity losses during storage. This means that the storage system would have the equivalent of $\left(4.337\ \mathrm{TWh}\cdot\frac{1000\ \mathrm{GWh}}{1\ \mathrm{TWh}}\right)/16\ \mathrm{GWh} = 271$ full cycles per year, as of 2030.

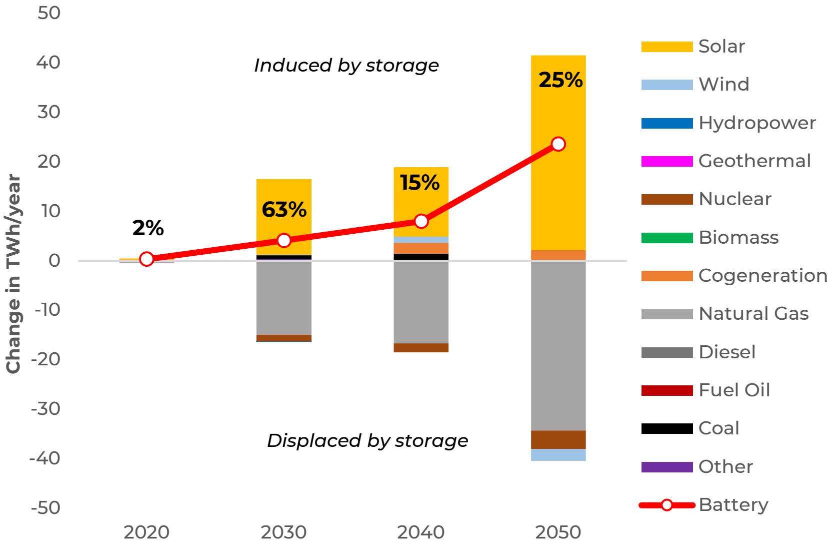

Figure 5.2. Change in annual electricity generation caused by storage technologies (Reference scenarios). Numbers in the yellow solar bar indicate relative change in solar PV generation compared to a scenario without storage.

Due to the large displacement of natural gas when higher shares of VRE can be integrated, emissions decrease in the *Reference scenario* with storage by around 6 million tons of CO_2 ($MtCO_2$) in 2030 and by around 15 $MtCO_2$ in 2050, compared to the same *Reference* situation without the possibility to invest in storage (Figure 5.3). This can be interpreted as the mitigation potential of storage under no climate policies.

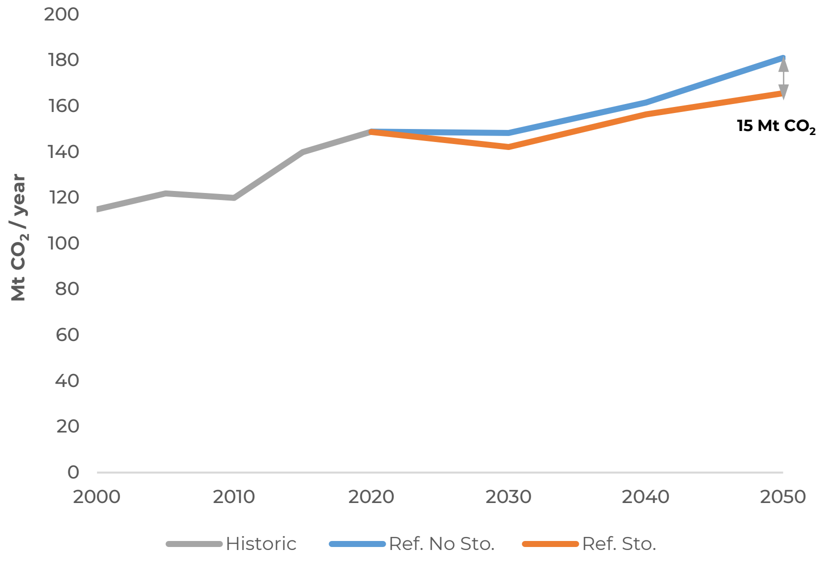

Figure 5.3. Annual CO_2 emissions in the Reference scenarios.

Key message #1: Even with no explicit climate ambition for the electricity sector, an optimal[8] electricity market for storage can increase the deployment of VRE energy, thereby contributing to CO_2 mitigation with up to 6 million tons of CO_2 by 2030 and 15 million tons of CO_2 in 2050.

The availability of storage technologies would decrease total fuel expenditures in the system, as the use of natural gas decreases; however, there would be an increase in capital expenditures (Figure 5.4). In total, the system costs would decrease by approximately 1% in the *Reference scenario* with storage by 2030 and around 3% by 2050.

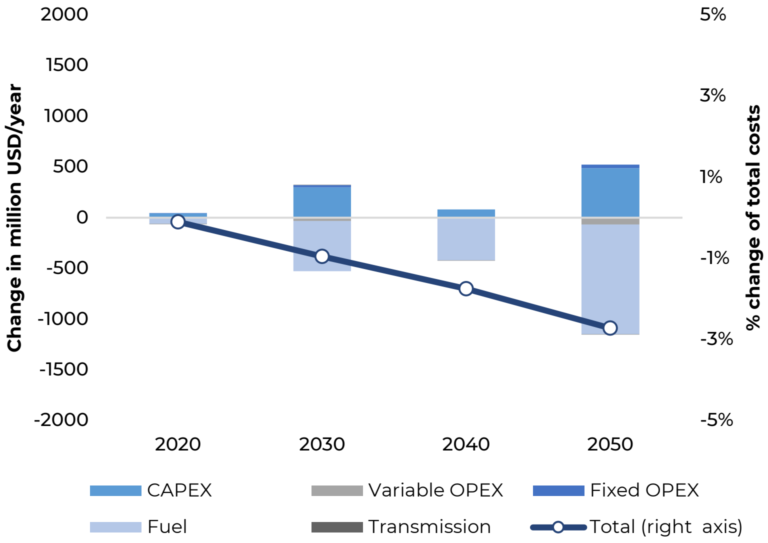

Figure 5.4. Change in system costs caused by storage technologies (Reference scenarios). The left axis shows the absolute numbers while the right axis shows the relative change in total system costs compared to a scenario without storage.

Climate scenarios

As described in the methodology section, the *Climate scenarios* limit annual electricity sector emissions by applying a CO_2 price, equivalent to the shadow value of CO_2 from a scenario where CO_2 is capped. A CO_2 price is a way to level the cost of different energy sources by incentivizing low-emission technologies. This approach can cost effectively reduce CO_2 emissions by internalizing some of the negative externalities of fossil fuels.

The only difference between the *Reference* and *Climate scenario* is the CO_2 price, which would encourage larger investments in low carbon technologies, mostly wind and solar, as

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[8] An electricity market that seeks to minimize the total cost of satisfying the electricity demand in the country; therefore, maximizing the welfare for the Mexican society; while considering that there are no barriers for storage technologies (see more in chapter 8).

fossil-based technologies would have a higher relative energy price, and the potential of hydropower and geothermal generation would already be fully utilized under no climate constraints/carbon pricing.

In the *Climate scenario*, a large deployment of clean technologies is due regardless of availability of storage, as shown in Figure 5.5. In order to achieve the desired levels of decarbonization, there are a few options available with regard to technology (apart from measures that would minimize or shift demand): renewable technologies, where the potential for hydropower and geothermal upscaling is more limited (e.g. it is not possible to build new large dams and exploration of new geothermal fields has a lot of uncertainties on its success), nuclear power plants, and carbon capture and storage (CCS) power plants. CCS technologies are not part of this assessment due to their uncertainty and current high cost prognosis. Under the defined scenario with CO_2 price, a high integration of VRE, even without storage, is more cost efficient than of nuclear. Nevertheless, if the CO_2 price is raised, nuclear might enter into the power system when there is no storage, as solar and wind technologies might face technical limitations regarding availability at very high integration shares

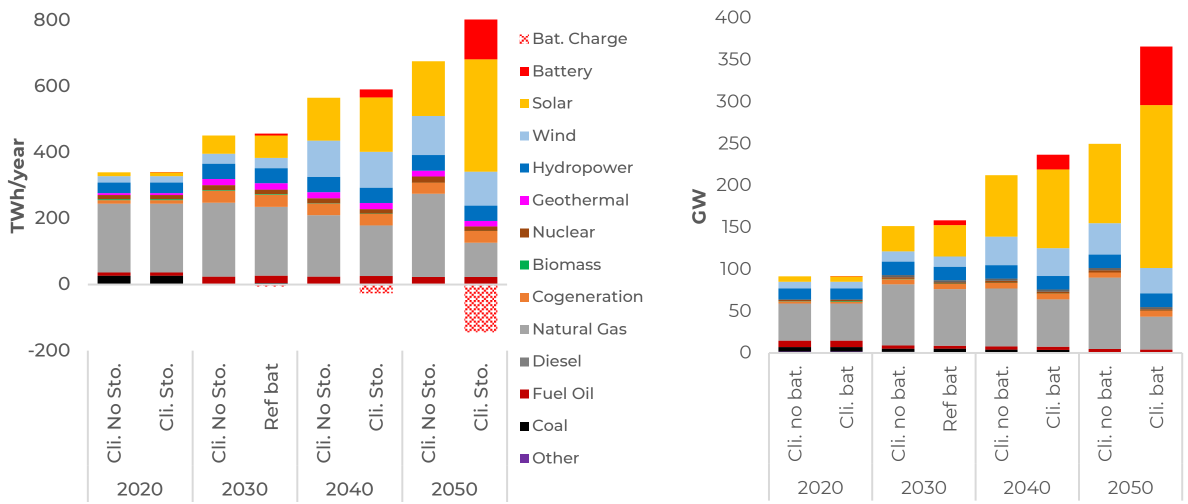

Figure 5.5. Annual electricity generation and capacity by source in the Climate scenarios (same CO_2 price in both scenarios).

Introducing storage, coupled with CO_2 pricing, would enable a larger cost-efficient integration of renewables, especially solar PV technologies.

Solar generation would be 23%, 28% and 105% higher than in the Climate scenario with no batteries, by 2030, by 2040 and by 2050 respectively (Figure 5.5). This corresponds to a 99 GW capacity increase of solar PV due to storage technologies, ending at an optimal level of 194 GW installed solar PV capacity in 2050, i.e. the solar PV capacity that can be cost-effectively integrated would more than double with storage technologies. The total optimal storage capacity would be 410 GWh (volume) and 70 MW (power) in 2050 (in the right graph of Figure 5.5, only the capacity associated to power is illustrated, and the storage volume is not included).

However, by 2030, the total optimal storage capacity would already be of 19 GWh (volume) and 6 GW (power), which shows that already in the short to medium term storage technologies could play a relevant role.

This would lead to a large displacement of natural gas generation, which would be substantially reduced, as solar PV coupled with storage would compete with natural gas generation (Figure 5.6).

In the *Climate scenarios* with storage, natural gas generation is reduced by 50% from 2020 to 2050. In comparison, in the *Reference scenario* and in the *Climate scenario* with no storage, natural gas generation from 2020 to 2050 is expanded by 68% and 21%, respectively.

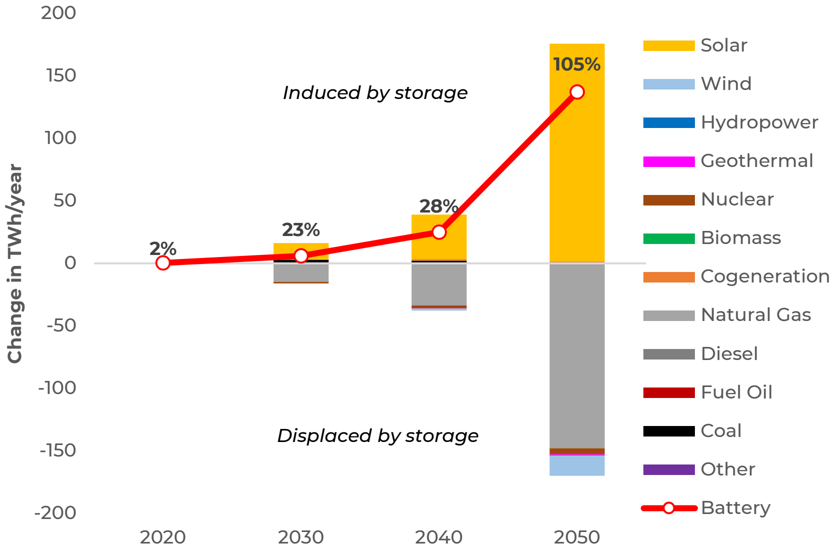

Figure 5.6. Change in yearly electricity generation caused by storage technologies (Climate scenarios). Numbers in the solar bar indicate the relative change in solar PV generation compared to the scenario without storage.

Key message #2: VRE in combination with energy storage mainly displaces technologies such as natural gas combined cycle and single cycle gas turbines. Climate targets reflected in carbon pricing would make solar PV and storage cheaper than fossil-based generation plus the carbon price associated to fuel burning.

In terms of clean energy share (percentage of clean energy in total power generation), the Climate scenario with storage shows that Clean Energy participation could grow to 48% by 2030 and 81% by 2050 (Figure 5.5).

This is exceeding the Mexico's "National Strategy for Energy Transition and Sustainable Energy Use" that shows clean energy generation goals of 40% in 2033 and 50% in 2050 (SENER, 2020a).

The results reflect the need to carefully plan for the use of natural gas in the transition towards decarbonization to avoid either technological lock-ins or stranded assets. The role of gas in the system changes from providing the so-called traditional base load nowadays, being the main source of power generation in the grid, towards back-up, providing flexibility and enabling the integration of high shares of renewable energy. The energy independence benefits of depending less on natural gas are also considerable, since import dependency has increased significantly during this century in Mexico, as can be observed in Figure 5.7. The increase in import dependency is both a result of increased consumption and declining domestic production.

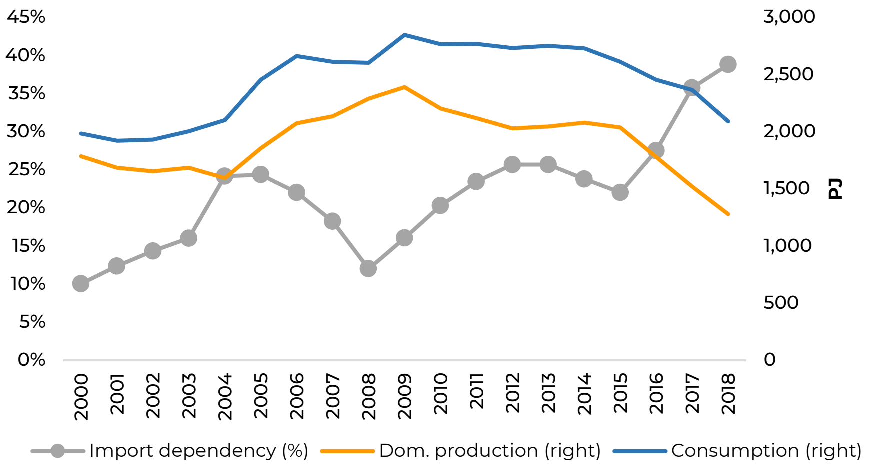

Figure 5.7. Natural gas imports (difference in demand and domestic production) as share of total demand. Source: SENER (2020).

The possibility of investing in storage technologies, would make solar PV and wind to "compete" against each other, making solar technologies more cost-efficient than they would be without storage, as they can overcome the barrier that they only generate during day-time. Solar PV systems+storage could potentially "rival" with wind, promoting a cost-efficient competition among renewable energy technologies to achieve the desired decarbonization goals of the country. Figure 5.8 illustrates that renewable technologies would dominate the growth in electricity generation from 2020 to 2050. Wind, for example, would grow by 83 TWh by 2050 from 2020, which is the equivalent to a five-fold increase. In the same period solar PV generation grows by 329 GWh.

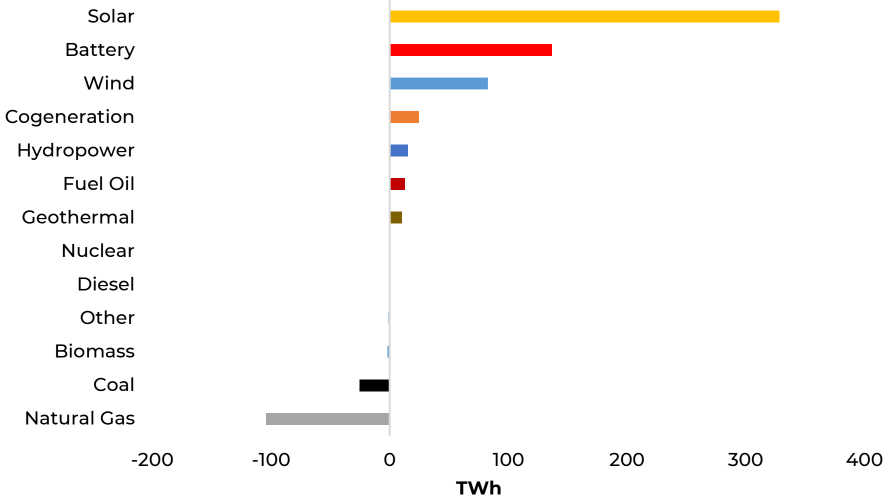

Figure 5.8. Electricity generation change from 2020 to 2050 in the Climate scenario with batteries.

Key message #3: Both wind and solar technologies would expand from 2020 to 2050 under a *Climate* scenario, while the availability of storage would make solar PV more cost-efficient. Wind would increase by 83 GWh and solar PV by 329 GWh in the *Climate scenario* including storage from 2020 to 2050.

System costs, not considering the changes in the payments from carbon pricing, vary little (by less than 1%) across *Climate scenarios;* however, its composition would shift from fuel costs to capital expenditures (Figure 5.9). If payments from carbon pricing are included, the total system cost decreases by 10%, when allowing for storage.

The lower observed costs for 2030 and 2040 (excluding carbon pricing) reflect the fact that relatively moderate investments in storage would allow the replacement of more expensive generation, which would not be possible without storage. However, by 2050, carbon pricing would play a key role in shifting from the more expensive generation to renewable energy plus storage. A carbon price high enough would cause that capital costs increase and fossil fuel savings themselves would not be enough to compensate for the high capital costs, but a combination of both fossil fuel savings and reduced carbon expenditures.

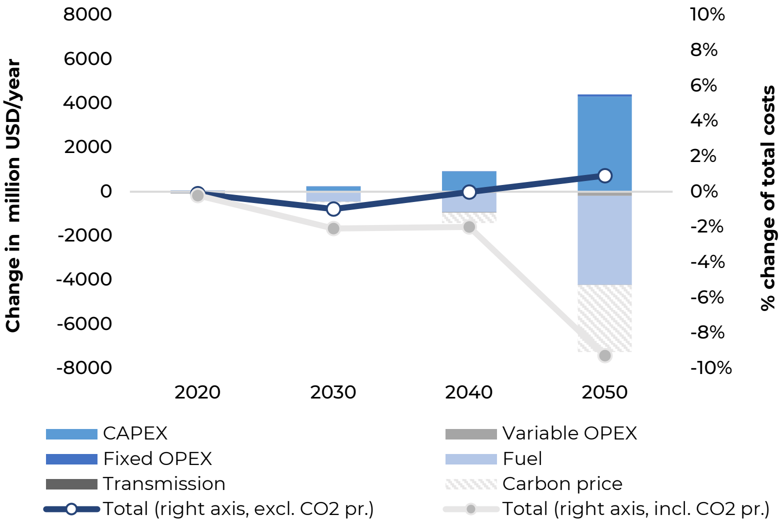

Figure 5.9. Change in system costs caused by storage technologies in the *Climate* scenario. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices) compared to a scenario without storage.

Key message #4 In the Climate scenario with storage, fuel savings from decreased natural gas consumption level out increased capital investments in solar PV and battery capacity, being both components similar.

Under equal carbon pricing, emissions in the *Storage scenario* decrease linearly down to 75 $MtCO_2$ in 2050, while emissions would grow from 112 $MtCO_2$ in 2040 to 138 $MtCO_2$ in 2050 if storage is not available in spite of the carbon pricing. This happens because the “low hanging fruits” for decarbonzation in the *Climate scenarios* without storage would have already been used in 2040, whereafter it would become increasingly costly to integrate more renewable. If solar PV cannot be paired with batteries or other storage devices, it would drastically limit its cost-effective integration, which would lead to larger consumptions of fossil fuels.

The emission gap of 4 million tons of CO_2 in 2030 and 63 million tons of CO_2 in 2050, between the climate scenario with storage and the scenario without storage (Figure 5.10), is assumed to be the mitigation potential allocated to electricity storage technologies.

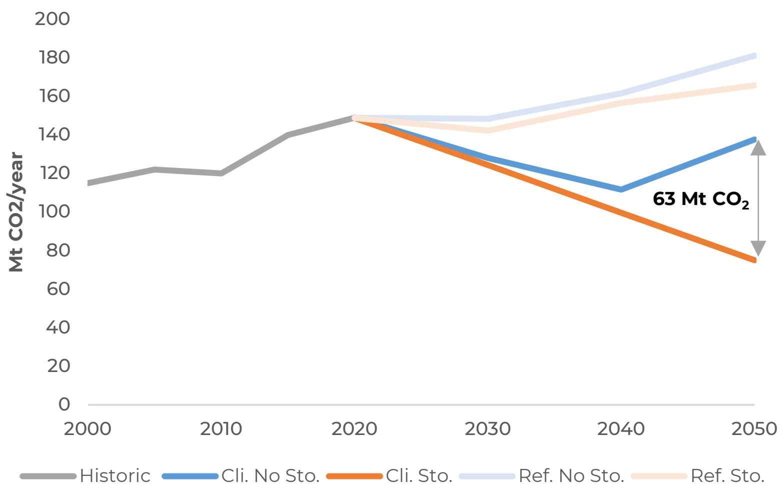

Figure 5.10. Annual CO_2 emissions in the Climate scenarios.

Comparing this potential to the *Reference scenario,* the mitigation potential increases from 15 $MtCO_2$ to 63 $MtCO_2$ as a result of imposing a price of carbon at 47 USD/tCO_2[9] in 2050.

Key message #5: If Mexico pursues GHG mitigation policies by means of carbon pricing, the mitigation potential of storage (comparing the climate scenario with and without storage) could be up to 63 $MtCO_2$ in 2050, equivalent to a 45% reduction of the emissions in the electricity sector compared to a scenario without electricity storage.

Generation profile, regional breakdown and battery dimension

Analyzing the hourly generation profile for representative weeks in winter and summer in 2050 (Figure 5.11 and Figure 5.12), variable solar PV would be expanded in the Storage scenario thanks to its coupling with batteries –and displacement of back-up technologies like natural gas-based power plants. During daytime, electricity production, largely consisting of solar power, is far higher than the actual electricity demand. The excess production is used to charge batteries (negative values in shaded red below), which can be consumed during nighttime, when there is no solar PV production.

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[9] The price of carbon of 47 USD /tCO2 is the shadow value associated to a cap of 75 $MtCO_2$ by 2050, where emitting one unit less of CO_2 would cost 47 USD /tCO_2.

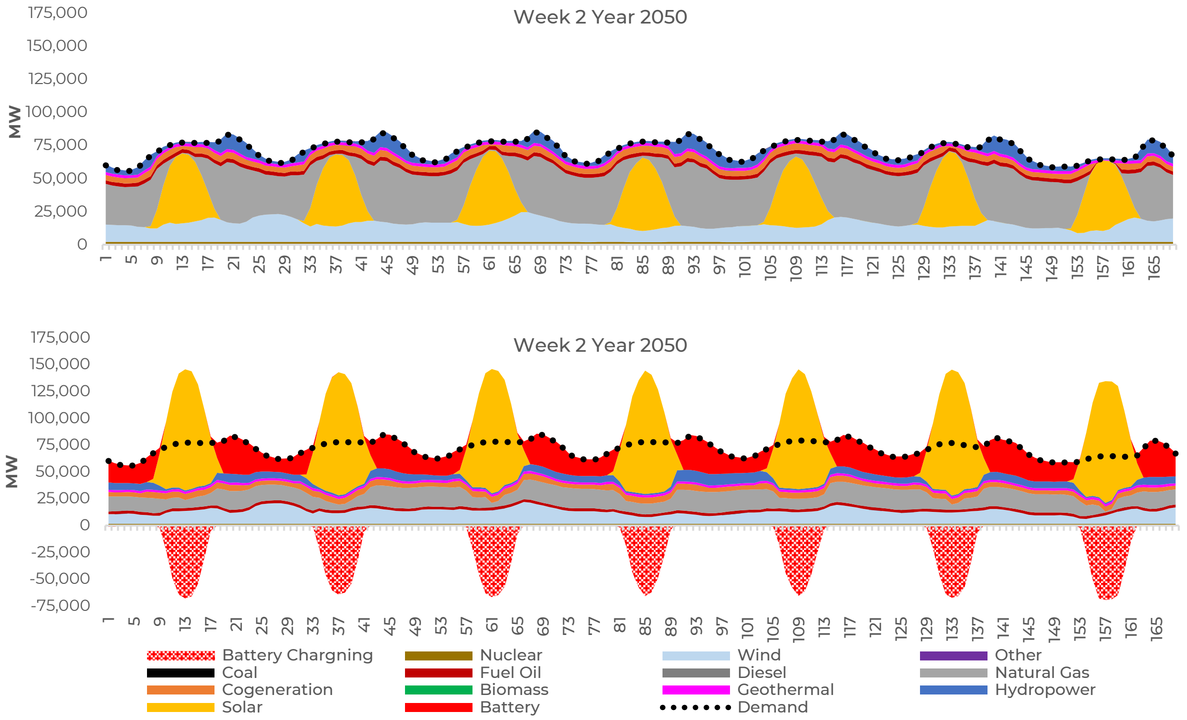

Figure 5.11. Hourly generation in January 2050 (week 2) in the Climate scenarios; no storage available (above) and storage available (below).

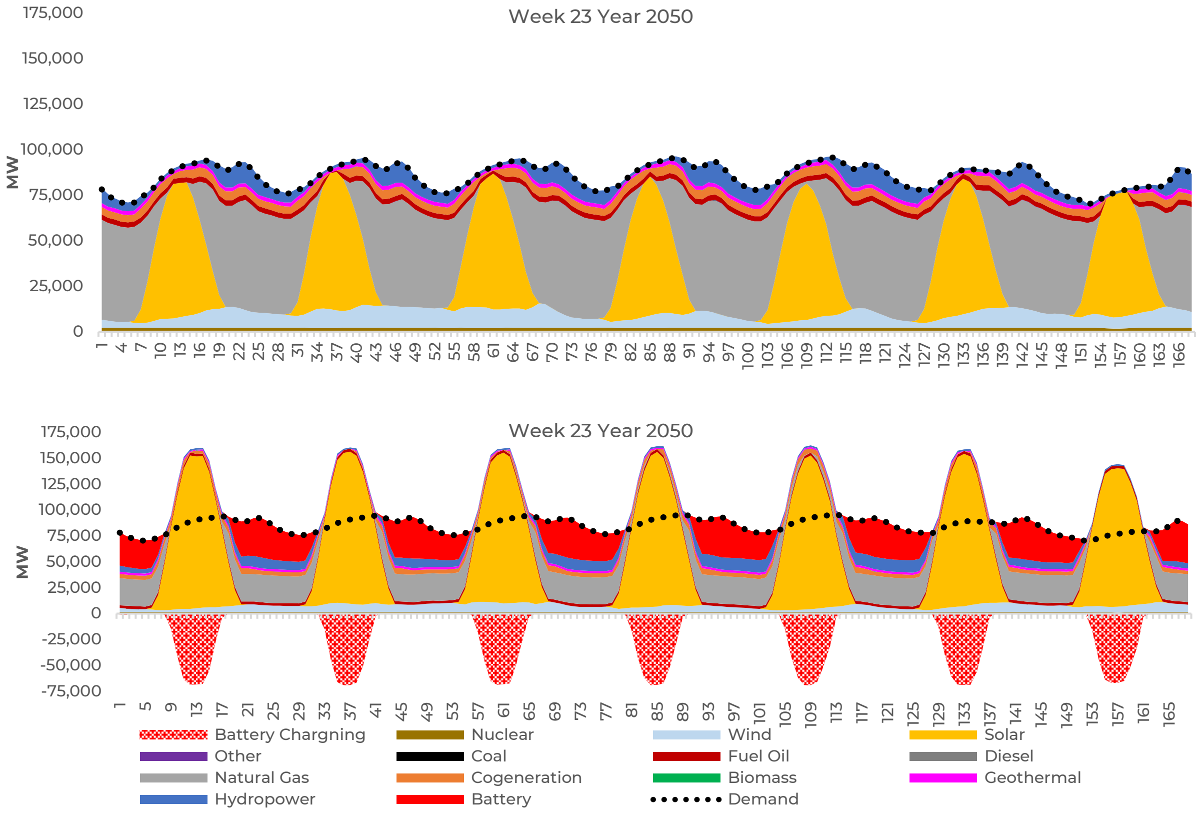

Figure 5.12. Hourly generation in June 2050 (week 23) in the Climate scenarios; no storage available (above) and storage available (below)

It is likely that wind power might be coupled with transmission capacity in such a way that investments in transmission capacity might lead to larger expansion of wind power. However, within the scope of this study, this has not been analyzed further and the topic should instead be explored in subsequent studies. Disaggregating the cumulative installed capacity of solar PV and storage to the regional level reveals large solar PV capacity investments in the transmissions regions: Central, Aguascalientes, Queretaro and Salamanca (El Bajío), and Monterrey (Figure 5.13).

This figure also illustrates that solar PV investments would match with investments in storage capacity at a regional level, i.e. storage technologies would relate mostly with solar PV technologies. Storage technologies would not be linked so strongly with wind, as wind availability profile has a different pattern, often with high generation during peak time at dusk; however, in areas with large investments in wind capacity, storage can be deployed to balance large fluctuations while minimizing curtailment and potential investments in transmission.

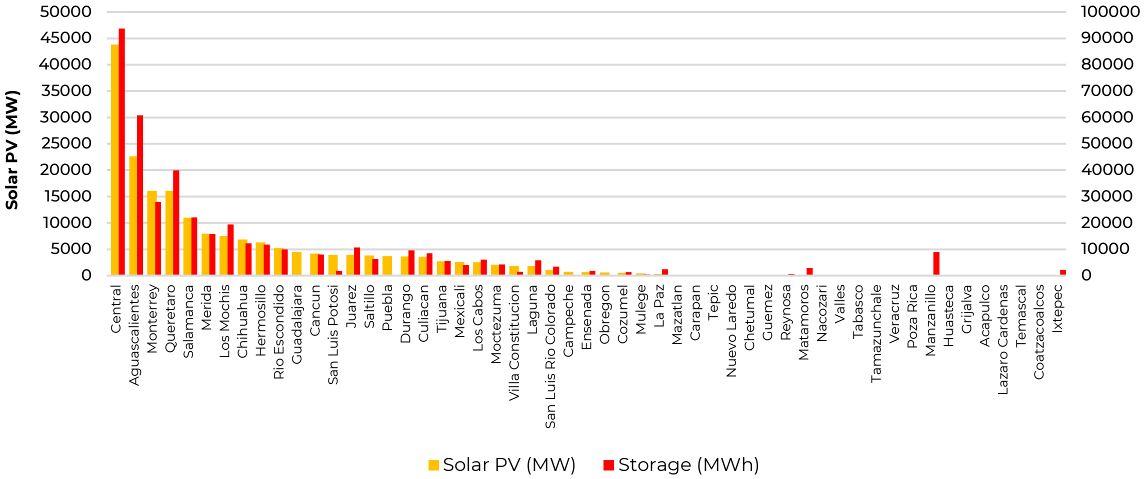

Figure 5.13. Regional expansion of solar PV capacity (left axis) and storage capacity (right axis) in the accumulated period 2020-2050.

The model does not have an exogenous limitation to the installed capacity of solar PV and storage in a given region, i.e. there is no constraint regarding maximum potential of solar PV technologies. However, it was checked that the endogenous investment in solar PV in every region was smaller than the potential indicated in the Scenario 2 of the Clean Energy Atlas (AZEL), which considers those areas that are not more than 10km far away from the grid.

Large investments on solar PV capacity would depend on the availability of alternative cheaper resources, such as nuclear or hydroelectric generation, areas with high capacity factor of wind (results show that in those regions with capacity factors higher than 35%, wind might be preferred in spite of the possibility to have solar PV and storage-to some extent) or access to cheap natural gas, as well as the electricity demand of the region (for instance, large solar PV investments happen in regions with a high and growing electricity demand). For this reason, regions with growing electricity demand and far away from nuclear or hydropower-based generation and with relatively smaller wind capacity factors or potential, would have a larger solar PV capacity installed in the *Climate* scenario.

In 2050, for every 1 MW of solar PV investment, it is cost-optimal to invest in approximately 2 MWh of storage capacity (Figure 5.14). In the 2040, solar PV is less dependent of storage, and only 0.6 MWh are needed per 1 MW of additional solar PV.

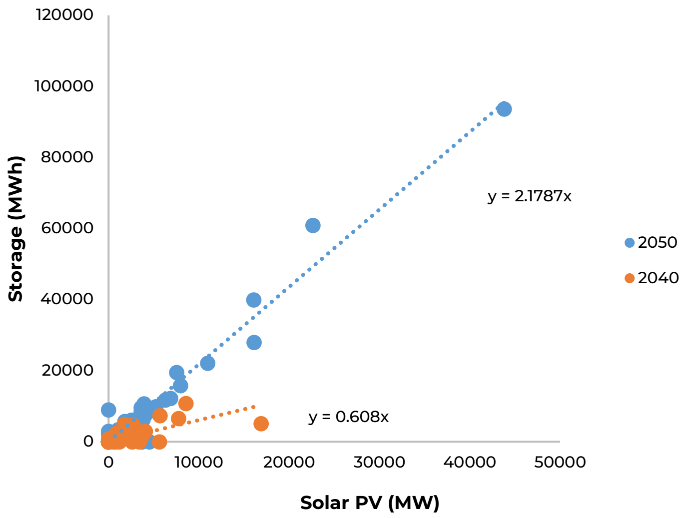

Figure 5.14. Cumulative regional investments in storage capacity and solar PV in the period 2020-2050.

Impact of fuel oil availability in the mitigation potential of storage technologies

The previous model runs assumed that the amount of fuel oil that had to be used by the electricity sector remained constant from nowadays level. The goal of this enforced restriction aimed to represent the fact that fuel oil is produced during the oil refining, and it could be used for different purposes, such as shipping or the industrial sector; however, the optimal allocation of fuel oil among different uses, or the potential decrease in fuel oil production through cokers in refineries, are outside the boundaries of this optimization. In order to assess the impact of this assumption in the results, the Reference and Climate scenarios are also run without fuel oil consumption enforcement, which could represent e.g. a decrease in fuel oil production, or a major use of fuel oil for other purposes rather than electricity generation.

Modelling results of the Reference and Climate scenarios with and without storage when there is no restriction to fuel oil consumption are shown in Figure 5.15. When comparing these results with Figure 5.2 and Figure 5.5, it can be noted that the dark red bar associated to fuel oil-based electricity generation is significantly reduced. As fuel oil prices are high, already in a Reference scenario with no restrictions regarding emissions, fuel oil-based generation decreases, as there could be cheaper ways to satisfy the electricity demand. These runs are deterministic, i.e. they do not consider the impact of uncertainties, such as disturbances in the natural gas supply, which might be covered by e.g. fuel oil.

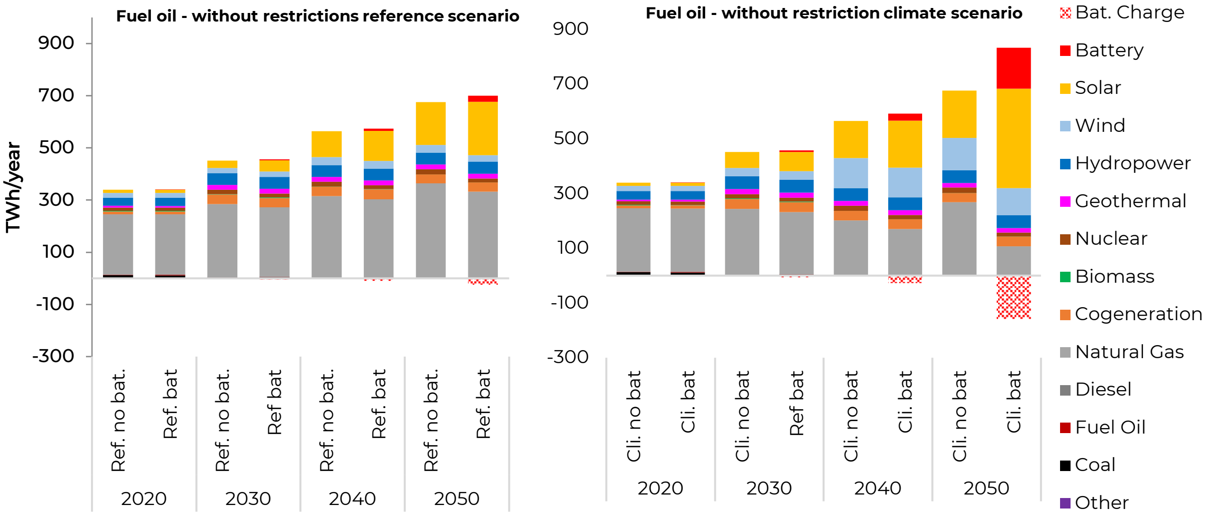

Figure 5.15. Annual generation reference and climate scenarios with and without storage and without any fuel oil restriction in the period 2020-2050.

Therefore, the emissions associated to the electricity sector would decrease even in the Reference scenario, and they will be approximately 9 $MtCO_2$ lower by 2050 than in a situation where the consumption of fuel oil for electricity generation remains constant compared to the current level.

The impact of electricity storage technologies in the Reference scenario is similar with or without use of fuel oil for electricity generation, as shown in the Figure above,

The Climate scenario is run assuming the carbon price level estimated previously: 6 USD/tCO_2 by 2030 and 47 USD/tCO_2 by 2050. Under this carbon price, the GHG emissions of the Climate scenario with storage technologies and no restrictions regarding fuel oil consumption are 60 $MtCO_2$ by 2050, considerably lower than the 75 $MtCO_2$ in the scenario that enforces fuel oil consumption. This lower level of GHG emissions by 2050 under the same carbon pricing is due to twofold reasons: fuel oil substitution by less emitting technologies, and a 10% increase in storage capacity that also increases renewable energy generation. The possibility to have storage technologies changes how the electricity that was supplied by fuel oil plants is satisfied by other plants. If there is no storage, approximately 72% of it would be supplied by natural gas power plants by 2050; however, if there are storage technologies, only 13% of the original electricity supplied by fuel oil would now be supplied by natural gas, and most of the electricity would be supplied by solar PV and storage, thus increasing the storage capacity compared to a scenario that enforces fuel oil consumption and increasing the mitigation potential allocated to storage technologies. For all the above mentioned, the mitigation potential allocated to storage by 2050 in a Climate scenario with no restrictions to fuel oil used would 69 $MtCO_2$ under a carbon price of 47 USD/tCO_2.

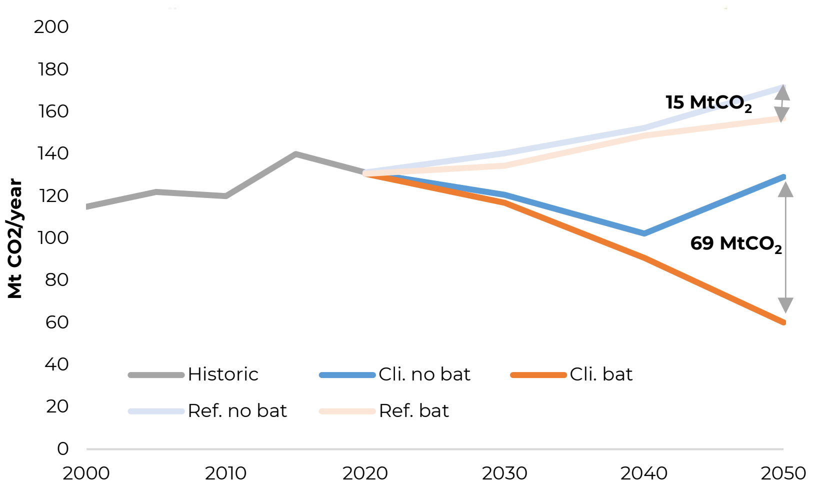

Figure 5.16. Annual CO_2 emissions in the Reference and Climate scenarios and without any fuel oil restriction in the period 2020-2050.

Key message #6: The modelling approach in this study cannot optimize fuel oil production and usage, as only the electricity sector is represented. When the consumption of fuel oil in the power system is not enforced, it represents a scenario where its production could be minimized or there could be more optimal usages in other sectors. Under a same carbon pricing and no restriction to fuel oil used for electricity generation, the mitigation potential allocated to storage would increase, as the combination of renewable energy + storage would be more cost-efficient than natural gas power plants in order to cover the previous fuel oil-based electricity supply. The mitigation potential allocated to storage would be 69 $MtCO_2$ by 2050 if there are no restrictions to fuel oil use for electricity generation.

6. Mitigation potential of alternative CO_2 targets and other technologies

Summary: Since the CO_2 price is derived from the climate target, alternative CO_2 targets could change the mitigation potential of storage, as an effect of changing CO_2 prices. If this climate target is strengthened from 75 down to 50 $MtCO_2$ in 2050, the mitigation potential of storage would decrease from 63 to 38 $MtCO_2$. If the climate target loosens up from 75 to 100 $MtCO_2$, the mitigation potential of storage would also decrease from 63 to 55 $MtCO_2$.

The mitigation potential of an alternative storage technology, pumped hydro storage, would be similar to Li-Ion batteries in 2040 while it would be lower in 2050. However, pumped hydro storage could contribute considerably to lowering emissions and has mitigation potential of 46 $MtCO_2$ in 2050.

The level of carbon pricing changes the dynamics of the system, thereby also changing the mitigation potential that could be allocated to storage technologies.

A very high carbon price would make clean energy cost-efficient compared to fossil-based generation, with a relatively smaller impact from storage technologies, but still highly significant and playing a role to achieve decarbonization.

At moderate carbon prices, the possibility to invest in storage systems would allow to achieve large levels of decarbonization, increasing the cost-efficiency of solar PV, wind and storage systems.

Alternative GHG targets

Since the mitigation potential that could be allocated to storage technologies depends on the carbon price, and therefore, in the desired level of greenhouse gas emissions, an additional assessment that evaluates the impact of different GHG goals is conducted, as described in Table 6.1 (Table 6.1 derives from Table 4.2).

Table 6.1. Scenarios for alternative CO_2 targets with and without storage technologies

Group	Name	CO_2 pricing	Storage Technology	Other Constraints
Alternative GHG targets	Climate Scenario without storage	Yes, high	None	None
		Yes, low	None	None
	Climate Scenario with storage	Yes, high	Li-Ion	None
		Yes, low	Li-Ion	None

The carbon prices in Balmorel are calculated as the shadow price of the equation that represents the GHG emissions constraint, also known as dual or marginal values. The carbon price reflects the total cost for the system when emitting one unit less of GHG, i.e. how much it would cost to reduce 1 tCO_2 the emissions in the electricity sector. Therefore, if the climate ambition is to achieve 75 $MtCO_2$ by 2050, the cost associated to emitting 1 tCO_2 less would be 47 USD (Climate Scenario with storage) in that year, thus the carbon price is defined as 47 USD/tCO_2.

In the following, the same analysis and methodology as above is carried out with two additional climate targets in 2050: the **most ambitious scenario** of 50 $MtCO_2$ and a **less ambitious scenario** of 100 $MtCO_2$ (Figure 6.1). When setting the 100, 75 and 50 $MtCO_2$ targets in Balmorel, while allowing investments in electricity storage systems, the carbon price associated to the scenarios would be 30, 47 and 106 USD/tCO_2, respectively.

The different carbon prices illustrate that it becomes increasingly difficult, i.e. expensive, a larger decarbonization. This is due to the fact that the "low-hanging fruits", the cheapest alternatives, are used in the beginning. Examples are the closure/refurbishment of inefficient fossil fuel plants, or the integration of relatively small shares of variable renewable energy in areas with high potential.

However, as the CO_2 emissions reduction becomes more stringent and the "cheapest" options are already being exploited, it would be increasingly expensive to decarbonize, and major changes to the electricity matrix would be needed, increasing substantially the carbon price, i.e. the cost associated to emitting one unit less of CO_2. Going from 75 $MtCO_2$ to 50 $MtCO_2$ by 2050 would be more expensive because the cheapest solar potential and the most attractive wind sites would be almost fully utilized, and less cost-efficient locations and more expensive technologies would have to be used. As solar PV technologies generate during daytime, without storage, it becomes increasingly difficult to decarbonize the demand peak around 8-10 pm (when the sun is not shining), and major technological changes might be required, which would increase costs.

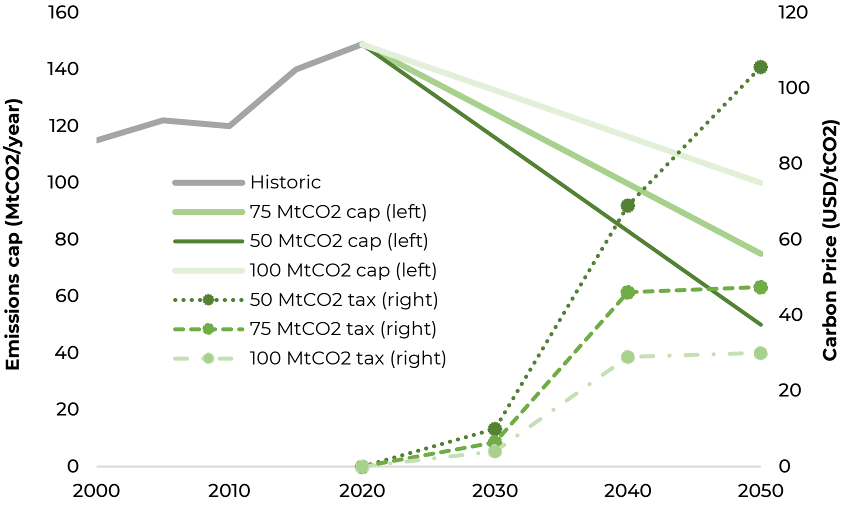

Figure 6.1. Alternative CO_2 targets in 2050 in the electricity sector (left axis) and the resulting shadow value of CO_2 (right axis) when under least-cost optimization including storage.

It should also be noted that the carbon prices shown in Figure 6.1 derive from scenarios that assume a constant annual consumption of 200 PJ of fuel oil for electricity generation, which would emit 15.5 $MtCO_2$, and it is considered that this fuel consumption cannot be reduced (as it is exogenously fixed), which virtually tightens even more the decarbonization targets, and causes a very high carbon price.

The role of nuclear technologies, would increase slightly whit stricter climate goals and without storage technologies (Figure 6.2), finding optimal to invest up to near 1 GW during the period 2030-2050, in the scenario 50 $MtCO_2$ – No Storage; however, other technologies would achieve higher shares.

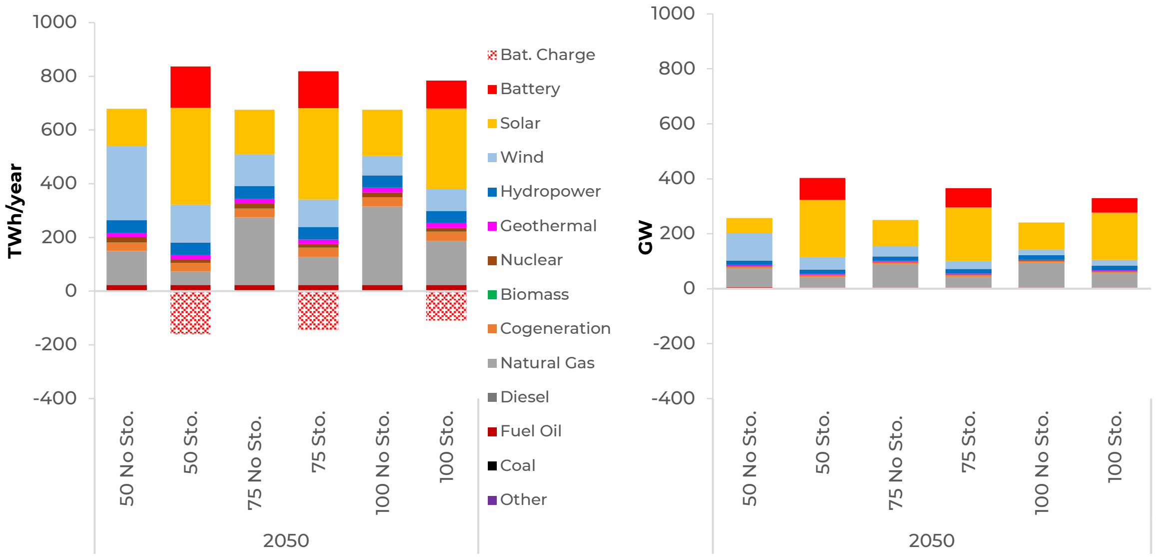

Figure 6.2. Electricity generation and generation capacity in the "Climate scenarios" under different emission CO_2 targets by 2050.

It is worth noting in Figure 6.2, that the share of solar PV decreases (in scenarios without storage), when increasing carbon price, which might seem contra intuitive. This could be an effect of decreased natural gas generation (caused by a high CO_2 price) which per haves cannot act as backup capacity for solar.

Furthermore, as solar PV technologies generate during daytime, without storage, it becomes increasingly difficult to decarbonize the demand peak around 8-10 pm (when the sun is not shining), and major technological changes might be required, which would increase costs.

Figure 6.2 and Figure 6.3 illustrate the annual electricity generation under different greenhouse gas emissions reduction targets and the impact that storage technologies could have on the matrix by 2050.

Very ambitious climate targets (see 75 and 50 $MtCO_2$ targets in Figure 6.2) would imply low levels of CO_2 emissions in comparation to Reference Scenarios (Se Figure 6.4), and this would require substantial decreases in the use of natural gas (See Figure 6.3). The reduction of natural gas generation becomes expensive if there are no storage technologies.

When storage technologies can be deployed, not only natural gas-based generation would be avoided, but also less efficient wind plants, as shown in Figure 6.3. In 2050.

Comparatively, the role of storage technologies seems smaller in the moderately ambitious scenario than in the most ambitious one (see red bar in Figure 6.2); although crucial however, they would be key to achieve deep decarbonizations in a cheaper cheap way.

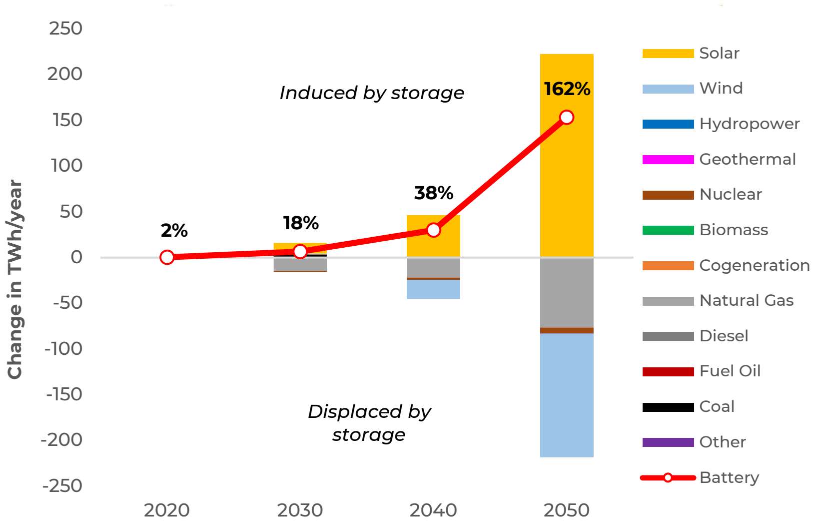

Figure 6.3. Change in yearly electricity generation caused by storage technologies (50 $MtCO_2$ target) Numbers in the solar bar indicates the relative change in solar PV generation compared to the scenario without storage.

Under the **most ambitous climate** target (50 $MtCO_2$ in 2050), the mitigation potential of storage technologies would be smaller in 2050, from 63 $MtCO_2$ to 38 $MtCO_2$ (left and middle of Figure 6.4). Likewise, under a **less ambitous scenario** with a target of 100 $MtCO_2$ in 2050, the mitigation potential is also smaller (55 $MtCO_2$) than in the **central or moderately ambitious scenario** of 75 $MtCO_2$, but still larger than in the most ambitious scenario (middle and right in Figure 6.4) This illustrates that altough storage technologies have a considerable mitigation potential under all scenarios, highly ambitious climate policies do not necessarily imply a larger mitigation potential of storage technologies.

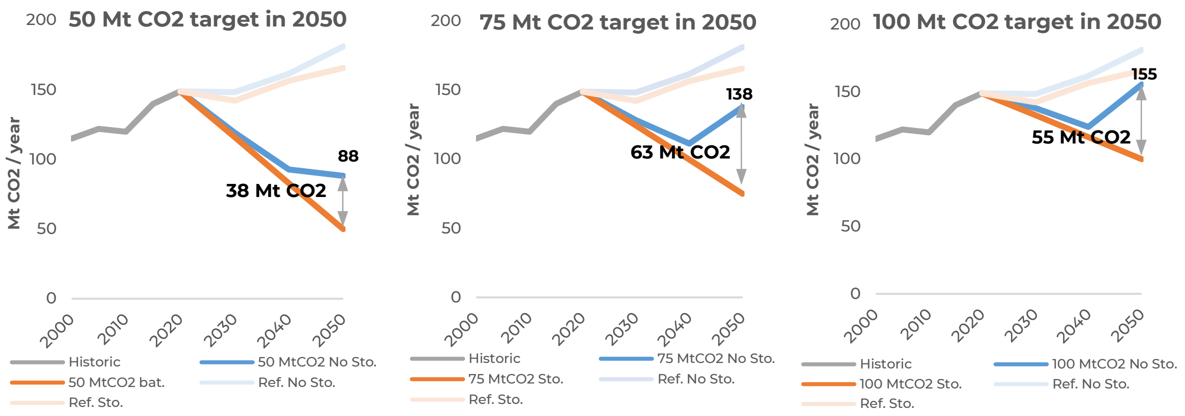

Figure 6.4. Annual CO_2 emissions under different targets and CO_2 price levels, both with and without storage technologies.

The emission shadow values increase in the **most ambitious scenario** of 50 $MtCO_2$ with a carbon price of 106 USD/tCO_2, which would promote by it-self large investments in low-carbon technologies, as fossil-based generation is greatly penalized.

The mitigation potential that could be allocated to storage technologies in 2050 in **the most ambitious scenario** would be of 38 $MtCO_2$ [88 $MtCO_2$ (no storage)-50 $MtCO_2$ (storage)].

If storage cannot be used, in the **most ambitious scenario**, the GHG emissions associated to that carbon price would be 88 $MtCO_2$ in 2050 (see left, Figure 6.4). while e.g. in the medium scenario with a carbon price of 47 USD/tCO_2, emissions would be 138 $MtCO_2$ without storage technologies in 2050 (see middle, Figure 6.4).

When applying medium and high carbon prices (**most and moderately ambitious scenarios**), the difference in total emissions if storage technologies are deployed is of 25 $MtCO_2$ (63 $MtCO_2$ (no storage)-38 $MtCO_2$ (storage)) less emitted. When no storage technologies are allowed the difference is 50 $MtCO_2$ (138 $MtCO_2$ (no storage)-88 $MtCO_2$ (storage)).

This potential is smaller than in the **moderately ambitious scenario** (see middle, Figures 6.4) as with high carbon prices. In the **most ambitious scenario,** the use of fossil fuels is already greatly minimized, even without the flexibility induced by storage systems, and wind farms with lower capacity factors would be integrated.

The **less ambitious scenario** with an emission level of 100 $MtCO_2$ by 2050 (see right, Figure 6.4) would have a carbon price associated of 30 USD/tCO_2 in 2050 when there are investments in storage systems. However, if storage cannot be deployed, the emissions would be up to 155 $MtCO_2$ by 2050 if the carbon price remains as 30 USD/tCO_2 (see Figure 6.3 and 6.4). Therefore, the mitigation potential that could be allocated to storage technologies would be of 55 $MtCO_2$. This mitigation potential is smaller than in the moderately ambitious scenario, as due to the fact that at lower carbon prices **solar PV plus storage systems** are a little less advantageous than in that moderate scenario in comparison with fossil fuel generation.

After 2040, the **climate scenarios without storage** deviate greatly from the **scenarios with storage** under the same carbon pricing. For the 75 and 100 $MtCO_2$ target, these emissions would increase after 2040. **This discontinuity observed in 2040 in the scenarios without storage** (blue lines in the Figure 6.4) can be explained a. o. by a combination of a growing electricity demand and less cost-efficient renewable energy. Since solar PV cannot be paired with storage, it drastically limits the cost-effective integration of solar PV, which leads to larger consumptions of fossil fuels to satisfy a growing electricity demand.

In the **most ambitious scenario,** the total cost associated to electricity generation in the country would be 8% smaller with storage technologies than without, when excluding the impact of the carbon price by 2050, and it would be 16% smaller when also including the impact of the carbon price. These numbers can be compared to -1% and 10% total cost reduction, respectively by 2050, in the **moderately ambitious scenario** (see Chapter 5). In the **less ambitious scenario**, by 2050, the total cost would be -1% cheaper (i.e. more expensive) with storage technologies than without if the impact of the carbon price is excluded, but it would be 6% cheaper when the carbon price effect is included.

Key message #7: The level of carbon pricing associated to different emission targets would change the dynamics of the power system, thereby also changing the mitigation potential that could be allocated to storage. A very high carbon price would make clean energy cost-efficient compared to fossil-based generation without storage. There would be a relatively smaller impact from storage technologies in terms of mitigation, but highly significant in terms of cost, as clean energy generation would become cheaper. At moderate carbon prices, the possibility to invest in storage systems would allow to achieve larger levels of decarbonization, increasing the cost-efficiency of solar PV and storage systems compared to fossil-based generation. At low-moderate carbon prices, storage would mostly displace fossil-based generation, while at high carbon prices, storage would also displace more expensive clean energy sources.

Alternative storage technologies: Pumped Hydro Storage

In order to avoid increasing the complexity of the model and the interpretation of results, and given the uncertainties still associated to storage technologies development and cost prognosis, the main scenarios are run only with the option to invest in Li-ion batteries, which would represent any storage system that could achieve similar costs and efficiencies, as the ones forecasted for Li-ion technologies. Pumped-hydro storage (PHS) is currently the most deployed storage technology worldwide, and it is considered the most mature; however, due to this maturity level, it is not expected it will have the future technological improvements of e.g. Li-ion batteries. Figure 6.5 compares the investment costs (adjusted for round trip efficiency) of PHS with Li-Ion batteries at two different storage dimensions (3 and 6 hours refers to a storage unit which can provide full power during 3 and 6 hours, respectively). The graph shows that both dimensions of Li-ion batteries have lower investment costs from 2030 and onwards if compared to 3-hour PHS. Comparing the 6-hour alternative, Li-ion battery investment costs only become lower than PHS after 2030. These numbers do not consider fixed and operational costs, and lifetime; therefore, it does not show the most optimal technology in a full system perspective, but only a comparison with regard to investment cost. Furthermore, it should be considered that the cost of a PHS will largely depend on the specific project, such as orography, geology, open system vs. closed system, etc.

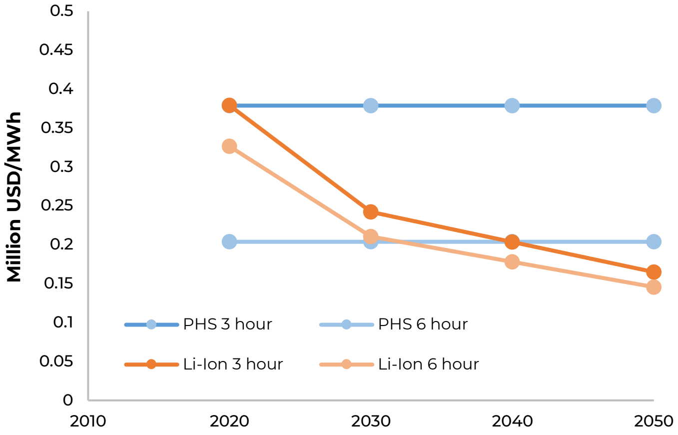

Figure 6.5. Investment costs (adjusted for round trip efficiency) per storage volume at stated storage dimensions. Source: Technology Catalogue (2020).

The role of PHS in the future energy system is analyzed, by modeling the *Climate Scenario* with pumped hydro storage systems instead of Li-ion batteries. From 2040 and onwards batteries are most cost-efficient (including 6-hours storage) than PHS, so a least-cost optimization model, such as Balmorel, might preferentially chose batteries over PHS, other things being equal. However, there are some aspects relevant to PHS that have not been integrated in this model set-up, and could make more attractive one technology over the other under specific circumstances:

- PHS could store electricity inter-seasonally, i.e. from one period of the year to another, e.g. from the wet season to the dry season.
- PHS could store electricity inter-annually, i.e. across years, which would strengthen the power system against climate variability, such as dry years.

- The use of some mineral resources, such as lithium, might be limited, where PHS might be preferred over Li-ion batteries under relatively similar conditions and constrained availability of sustainable mineral resources. On the other hand, land use for PHS in regions usually owned by communities could also be a limiting factor, as well as potential environmental impacts.

Figure 6.6 and Figure 6.8 compare the energy mix with Li-ion batteries vs. PHS in the *Climate* scenario (only one type of storage is allowed per model run). While results regarding the deployment of storage systems and integration of renewable energy are relatively similar for both technological scenarios from 2020 to 2040, as the technologies would have similar costs; more Li-ion batteries would be coupled with solar PV by 2050, as it is expected that the technology would become more cost-efficient, especially at lower ratios of storage capacities.

The electricity sent to storage systems by 2050 would be approx. 20% higher with the possibility to have Li-ion batteries; although due to the higher round-trip efficiency of the batteries, the electricity provided from storage by batteries would be larger. Therefore, due to the uncertainties associated to the technological development of batteries and the aforementioned benefits or restraints of PHS, which are not captured endogenously in the current version of the model, results show that both technologies could have a very important impact in enabling higher integrations of renewable energy and a larger cost-efficient mitigation of carbon emissions. The possibility to have cheap batteries (other things being equal) would allow achieving even higher integration of renewable energy.

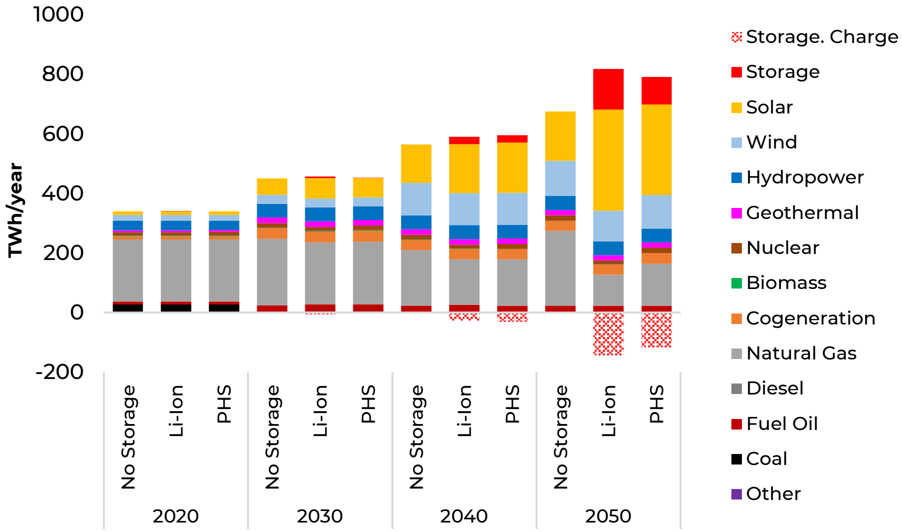

Figure 6.6. Annual electricity generation by source in the *Climate* scenarios without storage, with Li-ion batteries and pumped hydro storage.

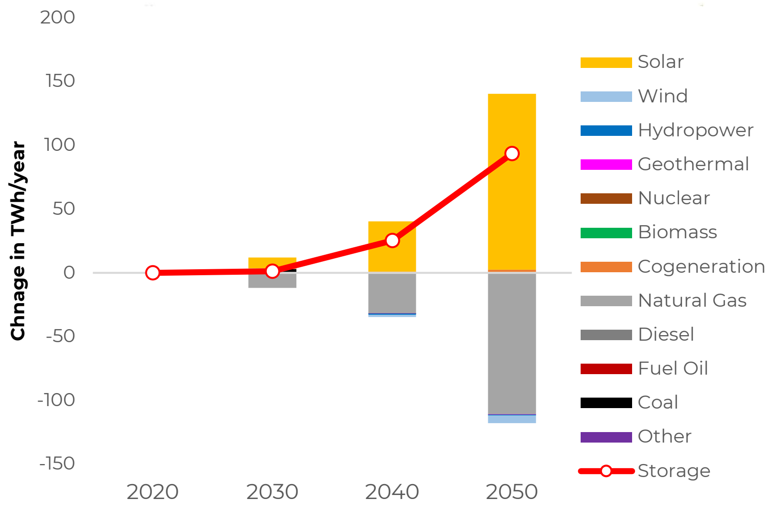

Figure 6.7. Change in annual electricity generation when comparing scenario with PHS and the scenario without storage. Numbers in the solar bar indicates relative change in solar PV generation.

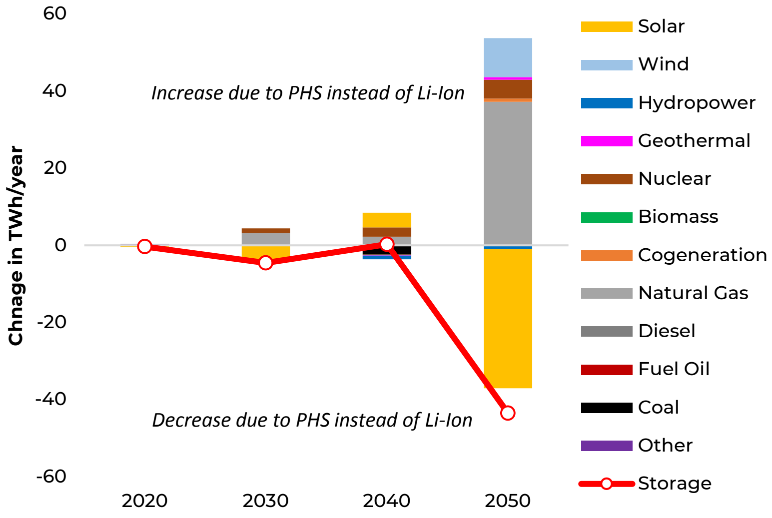

Figure 6.8. Change in annual electricity generation when comparing PHS with Li-Ion batteries. Numbers in the solar bar indicates relative change in solar PV generation.

Because PHS is a mature technology with no expected significants declines in investment cost in the future, total system costs would rise by almost 3% in 2040 and almost 2% in 2050 if no Li-ion batteries could be deployed (Figure 6.9).

In 2040, costs would mainly rise due to increased capital expenditures, driven by more expensive storage technologies and larger deployment of solar PV. In 2050, system costs would mainly rise due to increased fuel costs expenditures (caused by a larger penetration of natural gas) partly offset by falling capital investments in solar PV and batteries.

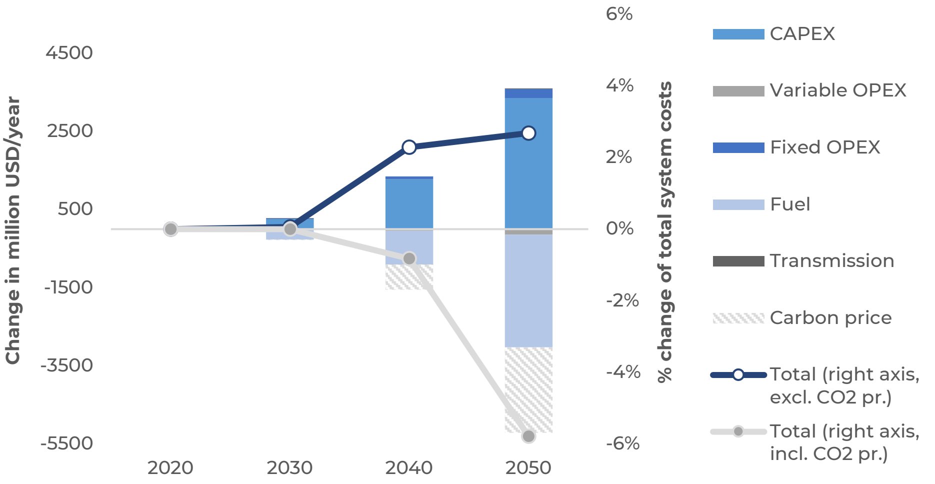

Figure 6.9. Change in system costs applying PHS instead of a scenario without storage. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices).

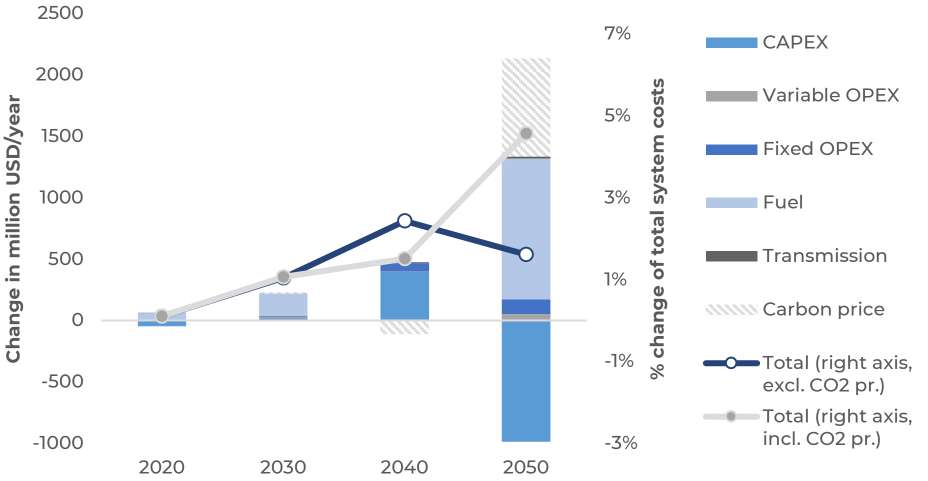

Figure 6.10. Change in system costs applying PHS instead of Li-Ion batteries. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices).

The scenario with PHS is modelled under a carbon price of 47 USD/tCO_2 by 2050, i.e. the moderate Climate scenario. The total emissions of the power system when having this carbon price and the possibility to deploy pumped hydro storage systems would be 92 MtCO_2 by 2050 (Figure 6.11), i.e. the emissions would be larger than in a scenario where Li-ion batteries are deployed (75 MtCO_2), as the possibility to invest in cheap Li-ion batteries would increase the amount of efficient clean energy that can be integrated. Nevertheless, the mitigation potential of PHS until 2040 (inclusive) would be similar to the one of Li-ion batteries, and by 2050, PHS would enable an additional mitigation of 46 MtCO_2 compared to a scenario where no storage is deployed.

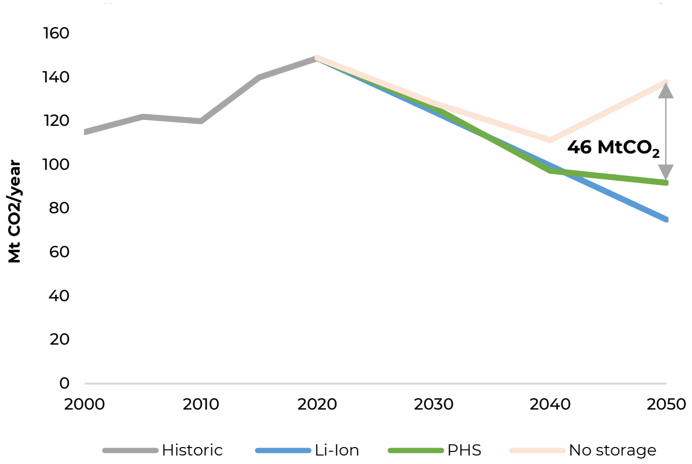

Figure 6.11. Annual CO_2 emissions in the Climate scenarios with Li-Ion batteries and PHS

Key message #8: The deployment of Pumped Hydro Storage systems would promote the efficient integration of VRE compared to a scenario without storage and would have a mitigation potential of 46 $MtCO_2$ in 2050. Nevertheless, due to the expected large cost-reduction of Li-ion batteries in the mid term, the mitigation potential associated to only pumped hydro storage is lower than the one associated with only Li-ion batteries after 2040, and the deployment of both technologies might be the preferred solution, combining the advantages of PHS (inter-seasonal and inter-annual storage, and a lower use/import of mineral resources) and Li-ion batteries (lower costs, higher round-trip efficiencies and fast response for ancillary services).

The integration of Li-Ion batteries and Pumped Hydro Storage (PHS)

In order to capture the differences between PHS and Li-ion batteries within the dynamics of the future electricity supply, the impact of potential limitations to the storage capacity of Li-ion batteries is assessed through a sensitivity analysis, as described in Table 6.2, for the Climate scenario, using a moderate carbon price of 47 USD/tCO_2 by 2050. The results of the scenario where no Li-ion battery is available and PHS is available have been introduced previously, and these further analyses explore the role that both technologies could play simultaneously in the future electricity system subject to some limits to Li-ion batteries sizing. Therefore, it is modeled a scenario where the energy to power ratio is restricted to a maximum of 2 hours, a scenario where it is restricted to a maximum of 4 hours, and a scenario where there is no restriction regarding storage volume for Li-ion batteries. PHS is fully available in all the scenarios.

Table 6.2. Scenarios for Medium CO_2 target with storage PHS and Li-Ion technologies

Group	Name	CO_2 pricing	Storage	Restrictions
Alternative Storage technologies	Climate Scenario with storage	Yes, medium	PHS and Li-Ion	No Li-Ion available
				Max 2 hours Li-Ion
				Max 4 hours Li-Ion
				Li-Ion fully available

The results of the aforementioned scenarios are summarized in Table 6.3. They show that in a scenario where both technologies could be deployed, by 2050 there would be approximately 5 GW of PHS and 66 GW of Li-ion batteries, finding the model optimal to invest in both technologies. If the size of Li-ion batteries is restricted to a maximum of 2 or 4[10] hours, a combination of both PHS and Li-ion technologies would be optimal, increasing the share of PHS system when there are tougher restrictions to Li-ion battery volume. These results might e.g. represent a situation where batteries could provide frequency control[11] and store energy during a few hours, while PHS would store energy during larger periods of time, as shown in Figure 6.12.

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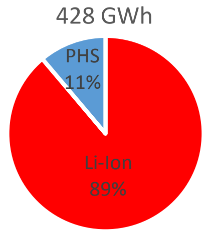
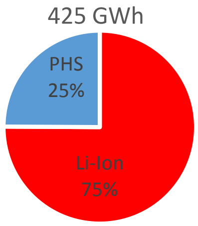
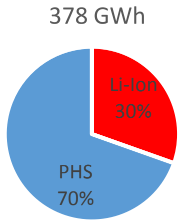
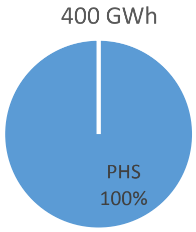
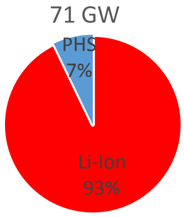
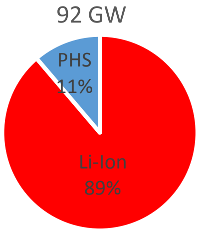
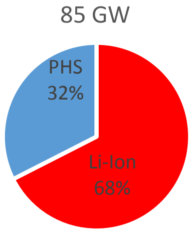
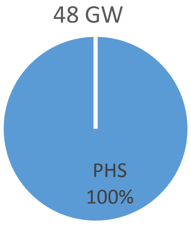
[10] Currently, the largest Li-ion batteries in the world are in Qinghai province (China) with a 202.8MW/MWh battery (https://www.pv-magazine.com/2020/10/01/worlds-largest-solar-plant-goes-online-in-china/) and in the Hornsdale Power Reserve in Jamestown (South Australia) with a 100 MW/129 MWh battery, which is being upgraded to 150 MW/194 MWh (https://hornsdalepowerreserve.com.au/), thus within 1-1.29 hours of storage. However, the Gateway project in San Diego County in California is expecting to have soon a 250 MW battery with four hours of storage (https://reneweconomy.com.au/australias-tesla-big-battery-is-no-longer-biggest-battery-in-the-world-30125/), and in Antofagasta (Chile), the largest battery system in Latin America of 112 MW/560 MWh (5 hours) is also planned (https://www.energy-storage.news/news/aes-begins-work-on-560mwh-largest-battery-system-in-latin-america-for-solar). Nowadays, it is not common to see large-scale storage outside of the four-to-six duration range (https://www.pv-magazine.com/2020/08/20/worlds-largest-battery-storage-system-now-operational/).

[11] The Balmorel model used in this study has an hourly representation, so intra-hour variations are not represented, which would allow identifying optimal technologies for frequency response. Hence, this statement is based in current literature of existing projects in the field.

Table 6.3. Results for the scenarios with PHS and Li-ion batteries using a medium CO_2 target.

Role of Li-Ion		Grid-scale storage ◄			► Ancillary services
Scenario		Li-Ion fully available PHS available	Max 4 hours Li-ion PHS available	Max 2 hours Li-ion PHS available	Li-Ion not available PHS available
Total storage capacity and share in 2050	Volume (Generation)				
	Power (Capacity)				
Mitigation potential (Mton CO_2)	2030	4	4	4	2
	2040	11	11	9	14
	2050	63	62	50	46

The mitigation potential when both PHS and Li-ion batteries are deployed would be of 4 $MtCO_2$ by 2030, and considering that the NDC goal for the electricity sector is approx. 58 $MtCO_2$ mitigation by 2030, it could represent 7% of the mitigation effort in the electricity sector. The scenario with limitations of batteries of 2 and 4 hours would imply investments of approximately 5.0 GW and 5.3 GW, respectively, of Li-ion batteries and 1.2 GW of pumped hydro storage (both cases) by 2030, i.e. already in the short to medium term it would be optimal to deploy storage technologies in order to achieve cost-efficient greenhouse gas emission reductions in the electricity sector.

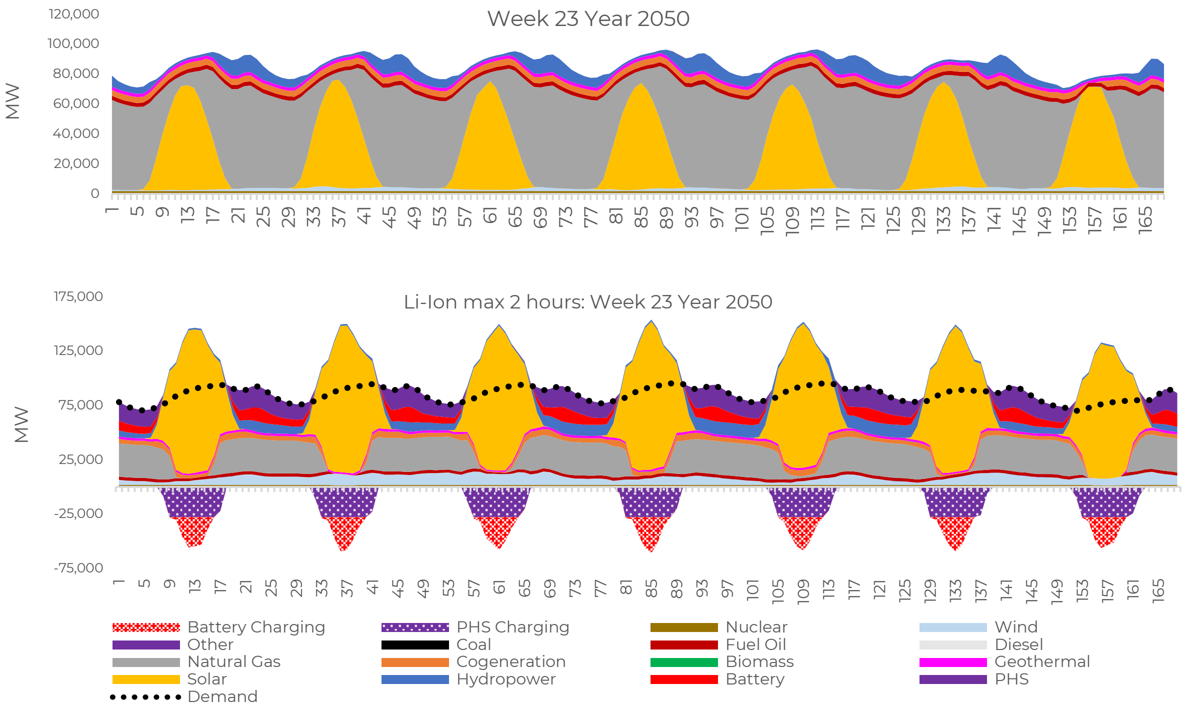


Figure 6.12. Hourly generation in June 2050 (week 23) in the Climate scenarios; without (above) and storage available (below) with Li-Ion batteries and PHS

For further details on the comparative cost see Appendix B.1.

Key message #9: Scenarios that consider simultaneous investments in Li-ion batteries and pumped hydro storage systems show that investments in both technologies would be optimal, where PHS would store energy during larger periods of time.

If there are limitations to the Li-ion battery volumen (MWh), the role of PHS could increase but the role of storage technologies would be in an overall way smaller. Scenarios with Li-ion limits of two-to-four hours duration range, would already imply optimal investments of 1.2 GW of PHS by 2030 and 5.0-5.3 GW of Li-ion batteries, which would increase substantially towards 2050.

7. Regulatory and financial barriers

Summary: Regulatory and financial barriers can influence the effective deployment of storage technologies, affecting the level of VRE integration. This chapter shows that some schemes for electricity transmission to and from storage sources could decrease solar PV generation by 3% to 5%, resulting in 3 $MtCO_2$ of additional emissions in 2050. Further, if the regulation hinders the participation of storage devices with a volume/capacity ratio below 6 hours, emissions could increase by up to 4% in 2040 and 10% in 2050, equivalent to an 8 $MtCO_2$ increase. Lastly, if investors have a higher risk perception of storage technologies, emissions could likewise increase.

Table 7.1. Scenarios for restrictions: double taxation, social discount rate, capacity time with storage

Group	Name	CO_2 pricing	Storage	Restrictions	Chapter
Restrictions	Climate Scenario with storage	Yes, medium	Li-Ion	Double tax	7
		Yes, medium	Li-Ion	High int. rate	7
		Yes, medium	Li-Ion	Min. 6 hours bat	7

As describe in Part 3 of this study, some regulatory and financial barriers might hinder a cost-effective deployment of storage technologies. This section aims to assess quantitatively how some of the current identified barriers for storage could impact its deployment, by integrating them in the optimization model Balmorel:

- The scheme of transmission electricity fees, where storage would pay as a load and as a generator, is integrated by increasing the variable operating cost associated to storage technologies.
- The restriction to storage from fully participating in the capacity market if it has less than 6 hours of storage (i.e. it is only paid for the electricity generated) is modeled as a constraint to only allow for 6 hours battery investments or above, —which would be an extreme situation.
- To illustrate how uncertainty could result in investors assessing storage technologies with a higher risk, storage technologies are modeled with a higher discount rate (12%) than other technologies (10%).

The *Climate scenario* from Chapter 5 is used as a base to which the barriers are compared to.

Key message #10: Storage technologies would be economically attractive even under existing barriers. However, changes in regulation could facilitate a faster and larger integration, thereby reducing the cost of storage, which would result in a decrease of the overall cost of satisfying the electricity demand in Mexico and fulfilling the climate obligations.

Current transmission tariff

Regulation requiring batteries and other storage technologies to pay transmission tariff both when charging and discharging may entail effects on the competitiveness and financial viability of storage. To assess this potential impact, a “double-tariff scheme” is modelled by increasing variable costs of storage technologies by 3.5 USD/MWh, effectively increasing variable costs from 2 USD/MWh to 5.5 USD/MWh (+175%) (CRE, 2015).

Figure 7.1 and Figure 7.2 show the possible setback of solar PV generation, which could fall by 3% in 2050, compared to a single tariff scheme. In absolute numbers, solar PV would fall by 12 TWh/year and storage by 10 TWh/year. In parallel, natural gas and wind power become more attractive and grow by 3 TWh/year and 6 TWh/year respectively.

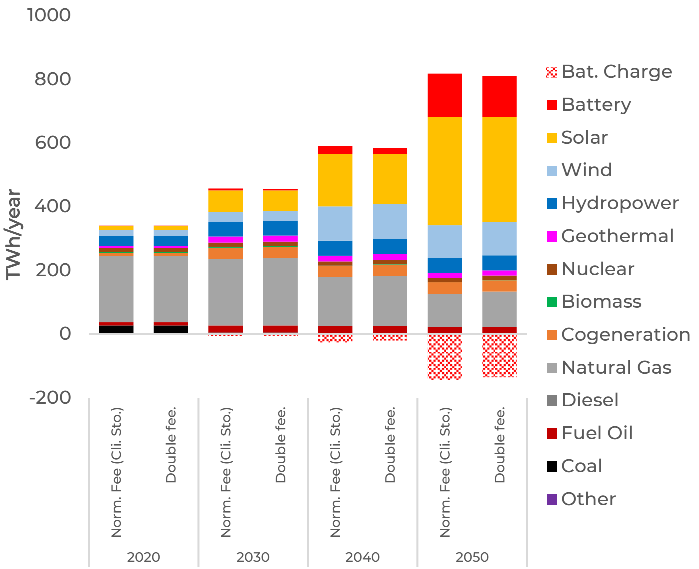


Figure 7.1. Annual electricity generation by source with a single tariff scheme (Clim. Sto) and double tariff scheme for storage.

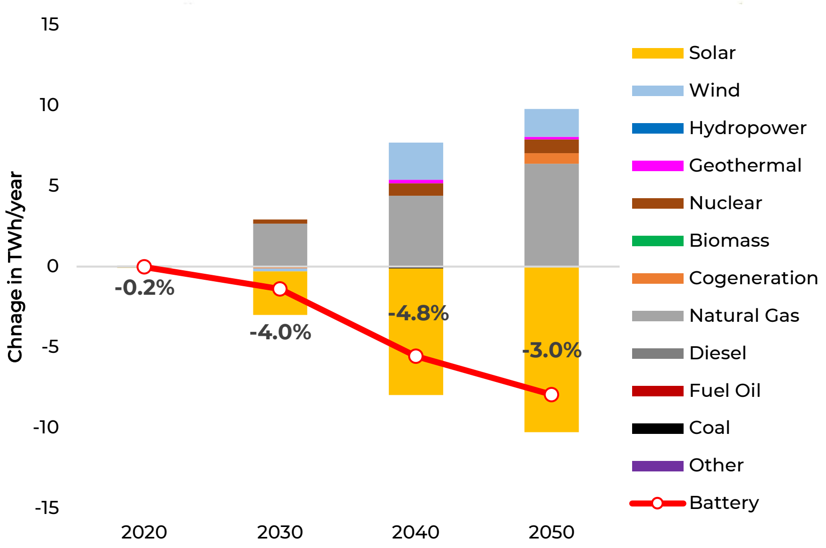


Figure 7.2. Change in annual electricity generation when applying a double tariff scheme compared to a single tariff scheme. Numbers in the solar bar indicates relative change in solar PV generation.

System costs (not including the increased expenditure of transmission tariff) largely remain unchanged with only ± 0.2% changes observed (Figure 7.3).

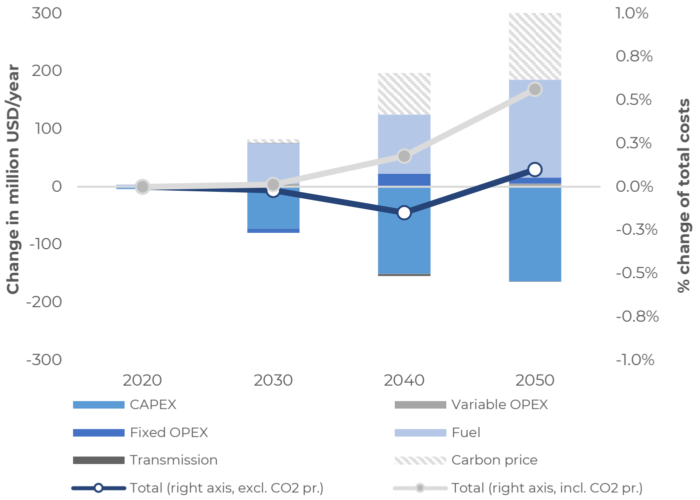


Figure 7.3. Change in system costs when applying a double tariff scheme. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices).

Emissions increase by approximately 3 $MtCO_2$ in 2050 (Figure 7.4). Even though the effects are small, it should not be concluded that the regulation is not hindering the development of storage projects. In general, costs are not very much increased by this loading and unloading tariff. Most importantly, storage deployment does not fall substantially, meaning that even with less favorable conditions, it would still be beneficial to invest in the technology although the optimal level of deployment of the technology would be smaller.

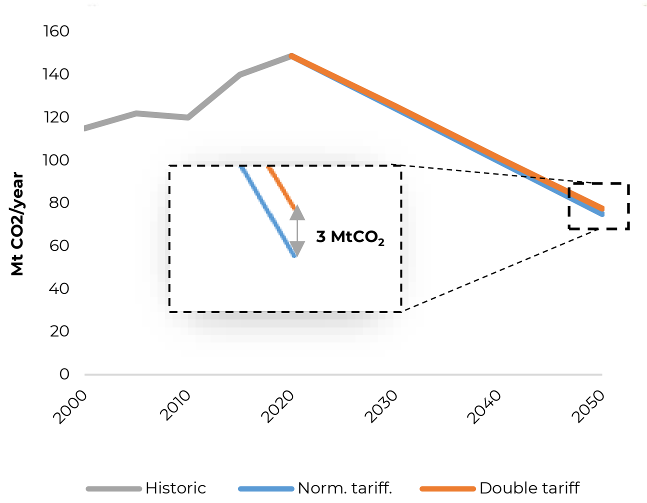


Figure 7.4. Annual CO_2 emissions in the Climate scenarios with a normal tariff scheme and double tariff scheme for storage.

Key message #11: Under the current transmission tariff where storage technologies are levied both when charging and discharging, the mitigation potential would decrease by a small, but non-negligible amount of 3 $MtCO_2$ by 2050.

Restrictions on battery dimensions

The analysis of regulatory and financial barriers shows that storage facilities will be remunerated in the capacity market for their capacity if they are dimensioned to deliver electricity at minimum 6 consecutive hours at full capacity; otherwise, they would be remunerated for the electricity they provide during the 100 most critical hours (Part 3 of this study). As a simplified example of how such a barrier could affect the deployment of storage, this section demonstrates a scenario where batteries are required to have a dimension of at least 6 hours. Acknowledging that this is more restrictive than the current regulation, the goal is to assess how constraints related to the sizing of storage plants could affect the power system, rather than making a full detail analysis of the exact impact of the current regulation.

Analyzing the results of previous scenarios, the optimal dimension of batteries is less than 6 hours for the period of 2020 to 2040. Figure 7.5 shows the model-optimized dimensioning of batteries at regional level in different model years. It is evident that the optimal deployment of batteries changes over time: in 2030, most dimensions are approximately 1-3 hours; in 2040, most dimensions are 4-5 hours; while in 2050, the most common dimension in the optimized system is 6 hours.

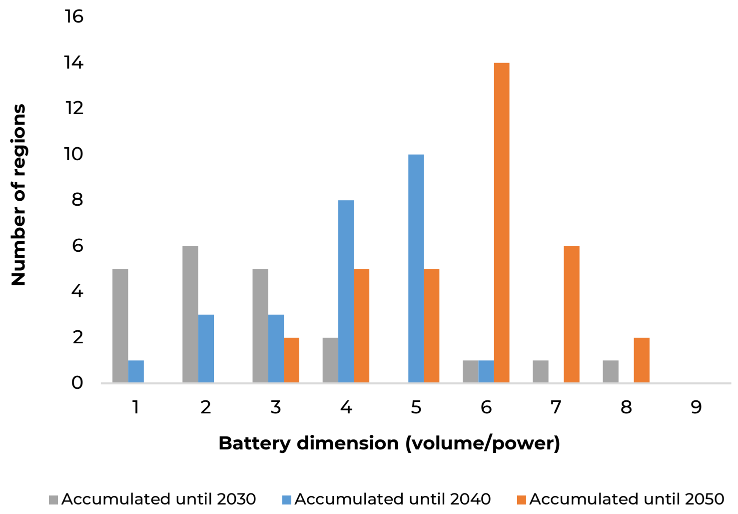


Figure 7.5. Distribution of battery dimensions at the regional level (transmission region) in different model years in the Climate scenario. Battery dimension numbers are rounded to nearest integer for easier grouping and the division volume/power is equivalent to hours.

This means that a regulation that demands storage devices to have a dimension of at least 6 hours, will constrain the model, make storage technologies less competitive, and result in less storage deployment and less CO_2 mitigation. This is demonstrated in Figure 7.6 and Figure 7.7, which show the results of such restrictions: solar PV generation is reduced by 10-15 TWh/year in the years 2030 to 2050, and replaced with natural gas generation.

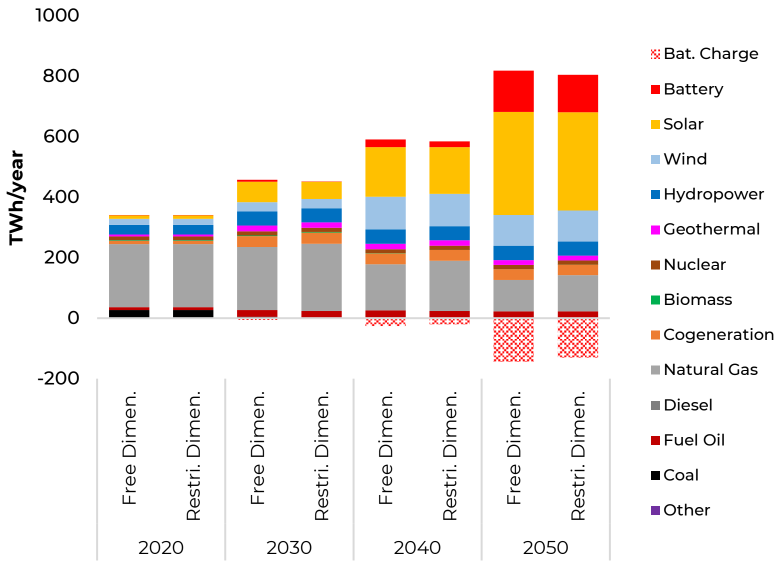


Figure 7.6. Annual electricity generation by source under free dimensioning (Climate scenario) and restricted dimensioning (≥6 hours).

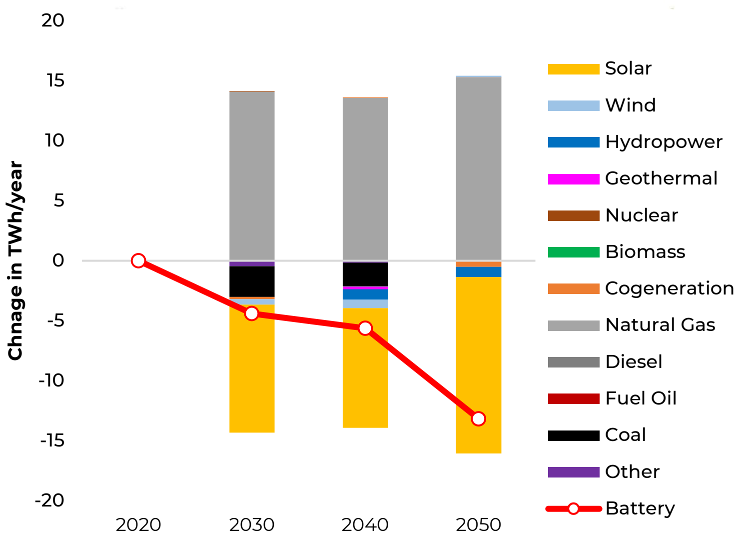


Figure 7.7. Change in annual electricity generation when restricting battery dimensioning to ≥6 hours. Numbers in the solar bar indicate relative change in solar PV generation.

Key message #12: Barriers restricting the capacity requirements, here exemplified by imposing a 6-hour minimum requirement on storage, could lead to a reduced participation of renewable energy and storage technologies, resulting in an increased of CO_2 emission due to the larger use of natural gas.

Total system costs are mostly affected in 2030 if excluding carbon prices, when they are raised by 0.7 % (Figure 7.8). This number declines towards 2050, ending at a cost increase of 0.3%. Emissions will grow by 3% in 2030, 4% in 2040 and 10% in 2050, equivalent to an 8 $MtCO_2$ increase with respect to the original *Climate* scenario (Figure 7.9).

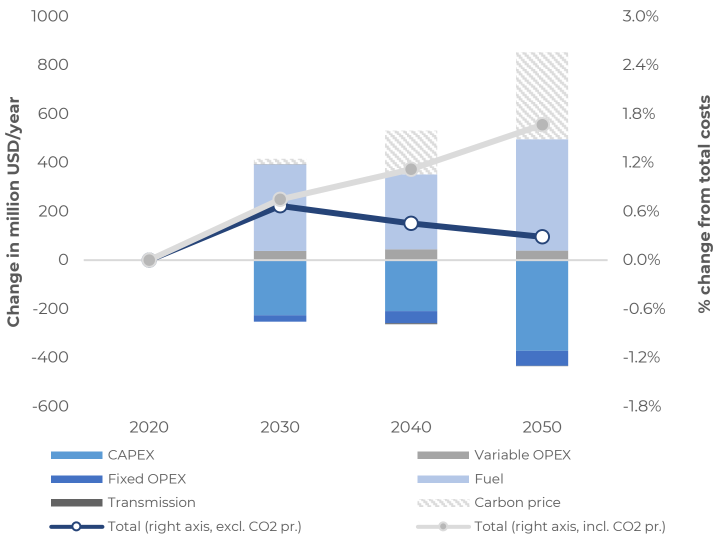


Figure 7.8. Change in system costs when restricting battery dimensioning to ≥6 hours. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices).

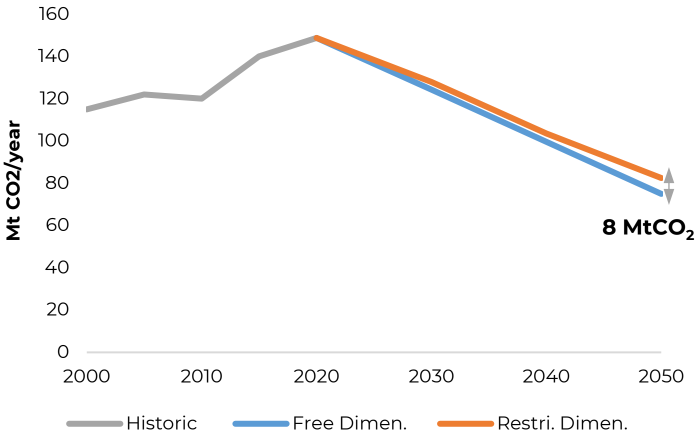


Figure 7.9. Yearly CO$_2$ emissions in the Climate scenarios with free and restricted battery dimensioning.

Higher perceived risk towards storage investments

Another barrier comprises the investor confidence and a perception of high risk. To model this issue, the discount rate for storage technologies is raised from 10% originally, to 12%, to reflect more intertemporal trade-offs of investing in storage.

This scenario shows a significant drop in generation by solar technologies (-9%) and storage by 2050 (Figure 7.10 and Figure 7.11). Solar PV generation is replaced by natural gas, which results in an increase in emissions of 10 MtCO$_2$ (Figure 7.12).

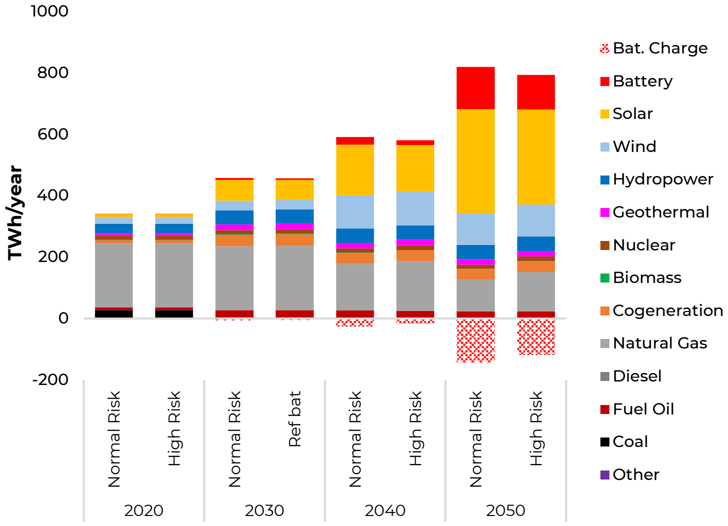


Figure 7.10. Annual electricity generation by source under a normal and high risk (discount rate at 12%) for storage technologies.

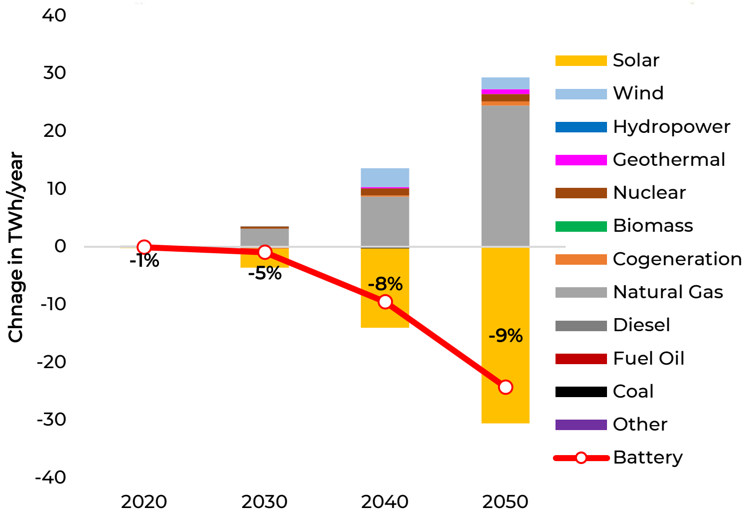


Figure 7.11. Change in annual electricity generation when applying a high discount rate (12%) for storage. Numbers in the solar bar indicates relative change in solar PV generation.

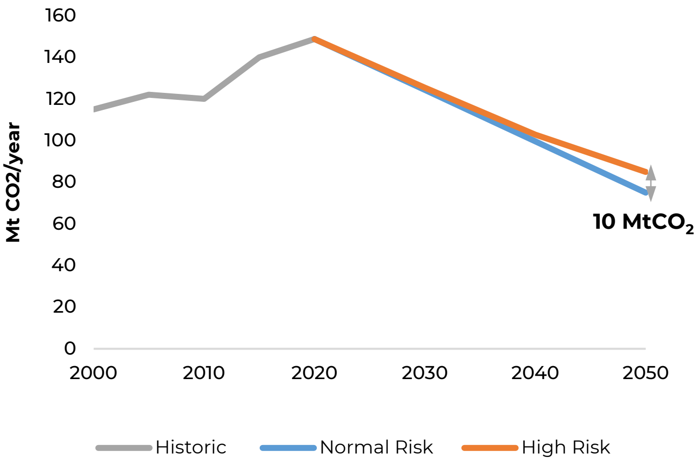


Figure 7.12. Annual CO_2 emissions in the Climate scenarios with a normal and a high perceived risk for storage.

Total system costs are changed by less than 1% (Figure 7.13). The exercise shows that perceived risk can impact the development of storage and its potential level of decarbonization. When natural gas consumption grows, this is likely to result in higher import dependece and a scenario of undersupply could cause dynamics in the direction of higher emissions due to congestion and use of other fossil fuels at the local level.

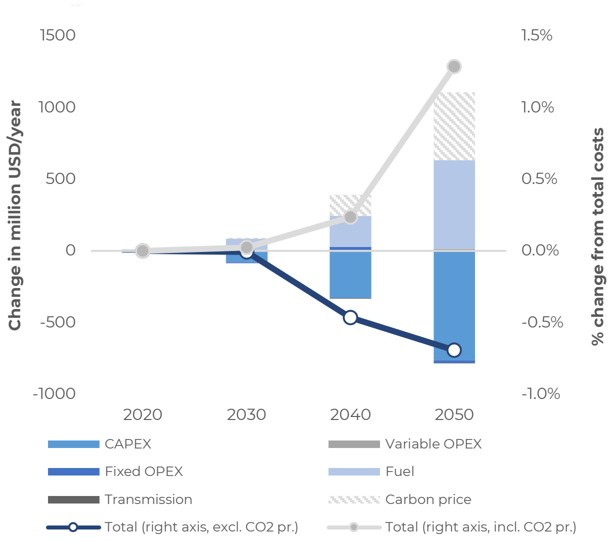


Figure 7.13. Change in system costs when applying a high discount rate (12%) for storage. The left axis shows the absolute numbers while the right axis shows the relative change in total system costs (the blue line excludes CO_2 prices while the grey line includes CO_2 prices).

8. Sensitivity Analysis

Summary: Emissions are very sensitive to variations in the natural gas price in the whole period, while changing the assumptions for solar PV investment cost only has a large influence in 2030. Changes in expectations towards battery investment costs has a high impact on the CO_2 mitigation potential: If batteries remain at high prices the mitigation potential is close to zero, i.e. the technology would not be optimally deployed, while a low price development of batteries could boost the migration potential from 63 $MtCO_2$ to 72 $MtCO_2$.

Table 8.1. Scenarios for sensitivity: gas price, solar PV investment cost, Lithium Ion storage cost.

Group	Name		CO_2 pricing	Storage	Restrictions
Sensitivity	Climate Scenario with storage	High/low gas prices	Yes	Li-Ion	None
		High/low solar investment costs	Yes	Li-Ion	None
		High/low Li-Ion investment costs	Yes	Li-Ion, high/low	None

The robustness of the emission levels and the mitigation potential is analyzed by running scenarios with alternative gas prices, solar PV investment cost and battery investment cost.

- The gas scenarios contain a high (+ 2 USD/GJ) and a low (-1 USD/GJ) profile of gas prices.
- The solar PV scenarios contain alternative investments costs (±10 % of the main scenarios estimate in 2030 and ±20 % of the main scenarios estimate in 2050).
- The variation on battery investment costs are based on the storage technology catalogue uncertainties (Part 2 of this study): in 2030 +88%/-29% per MWh and +167%/-17% per MW; in 2050[12] +125%/-42% per MWh and +273%/-27% pr. MW.

The effect on the mitigation potential is displayed in Figure 8.1.

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[12] The Technology Catalogue does not display uncertainty values for 2050. Here it is assumed that the high and low cost vary with the same absolute change in 2030 to 2050 as the central estimate.

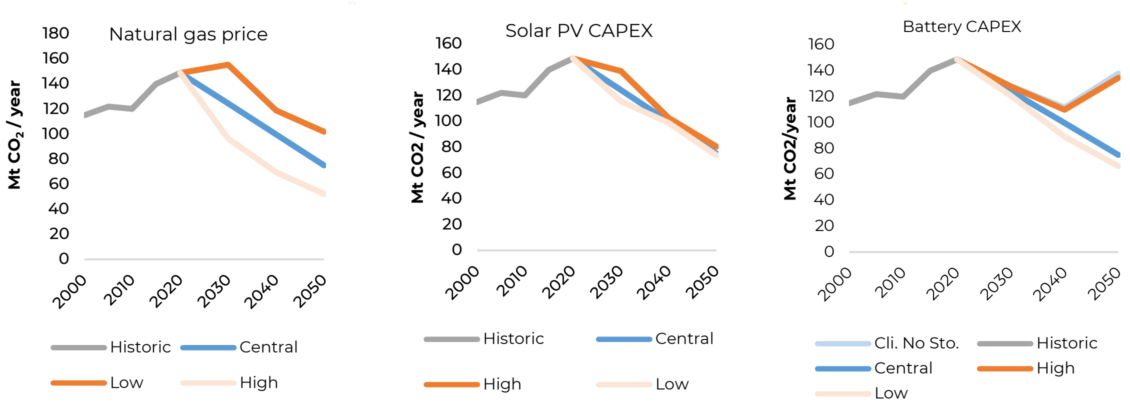

Figure 8.1. Annual CO_2 emissions under sensitivity analysis.

Emissions are very sensitive to variations in the natural gas price in the whole period, while changing the assumptions for solar PV investment cost only has a large influence in 2030. Changes in the development of the battery investment costs have a high impact on the CO_2 mitigation potential. If batteries remain at high prices, the emission pathway closely follows the one of the *Climate scenario* without storage, which means that almost no batteries are being deployed and the mitigation potential is close to zero. If batteries become cheaper than the central estimate, the mitigation potential grows from 63 $MtCO_2$ to approximately 72 $MtCO_2$. A more detailed description of the sensitivity analysis can be found in Appendix B.

9. Conclusions

This study shows that storage technologies can facilitate the integration of VRE in a cost-efficiently way; therefore, a considerable CO_2 mitigation potential could be allocated to storage. These are key advantages in the context of climate change mitigation and the green transition in Mexico. Together with the technology catalogue and the parallel publications, this study provides knowledge-based inputs to support Mexican decision-makers. The inputs are summarized in the following 12 key messages:

Key message #1: Even with no explicit climate ambition for the electricity sector, an optimal[13] electricity market for storage can increase the deployment of VRE energy, thereby contributing to CO_2 mitigation with up to 6 million tons of CO_2 by 2030 and 15 million tons of CO_2 in 2050.

Key message #2: VRE in combination with energy storage mainly displaces technologies such as natural gas combined cycle and single cycle gas turbines. Climate targets reflected in carbon pricing would make solar PV and storage cheaper than fossil-based generation plus the carbon price associated to fuel burning.

Key message #3: Both wind and solar technologies would expand from 2020 to 2050 under a *Climate* scenario, while the availability of storage would make solar PV more cost-efficient. Wind would increase by 83 GWh and solar PV by 329 GWh in the *Climate scenario* including storage from 2020 to 2050.

Key message #4 In the Climate scenario with storage, fuel savings from decreased natural gas consumption level out increased capital investments in solar PV and battery capacity, being both components similar.

Key message #5: If Mexico pursues GHG mitigation policies by means of carbon pricing, the mitigation potential of storage (comparing the climate scenario with and without storage) could be up to 63 $MtCO_2$ in 2050, equivalent to a 45% reduction of the emissions in the electricity sector compared to a scenario without electricity storage.

Key message #6: The modelling approach in this study cannot optimize fuel oil production

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[13] An electricity market that seeks to minimize the total cost of satisfying the electricity demand in the country; therefore, maximizing the welfare for the Mexican society; while considering that there are no barriers for storage technologies (see more in chapter 8)

and usage, as only the electricity sector is represented. When the consumption of fuel oil in the power system is not enforced, it represents a scenario where its production could be minimized or there could be more optimal usages in other sectors. Under a same carbon pricing and no restriction to fuel oil used for electricity generation, the mitigation potential allocated to storage would increase, as the combination of renewable energy + storage would be more cost-efficient than natural gas power plants in order to cover the previous fuel oil-based electricity supply. The mitigation potential allocated to storage would be 69 $MtCO_2$ by 2050, if there are no restrictions to fuel oil use for electricity generation.

Key message #7: The level of carbon pricing associated to different emission targets would change the dynamics of the power system, thereby also changing the mitigation potential that could be allocated to storage. A very high carbon price would make clean energy cost-efficient compared to fossil-based generation without storage. There would be a relatively smaller impact from storage technologies in terms of mitigation, but highly significant in terms of cost, as clean energy generation would become cheaper. At moderate carbon prices, the possibility to invest in storage systems would allow to achieve larger levels of decarbonization, increasing the cost-efficiency of solar PV and storage systems compared to fossil-based generation. At low-moderate carbon prices, storage would mostly displace fossil-based generation, while at high carbon prices, storage would also displace more expensive clean energy sources.

Key message #8: The deployment of Pumped Hydro Storage systems would promote the efficient integration of VRE compared to a scenario without storage and would have a mitigation potential of 46 $MtCO_2$ in 2050. Nevertheless, due to the expected large cost-reduction of Li-ion batteries in the mid-term, the mitigation potential associated to only pumped hydro storage is lower than the one associated with only Li-ion batteries after 2040, and the deployment of both technologies might be the preferred solution, combining the advantages of PHS (inter-seasonal and inter-annual storage, and a lower use/import of mineral resources) and Li-ion batteries (lower costs, higher round-trip efficiencies and fast response for ancillary services).

Key message #9: Scenarios that consider simultaneous investments in Li-ion batteries and pumped hydro storage systems show that investments in both technologies would be optimal, where PHS would store energy during larger periods of time.

If there are limitations to the Li-ion battery volumen (MWh), the role of PHS could increase but the role of storage technologies would be in an overall way smaller. Scenarios with Li-ion limits of two-to-four hours duration range, would already imply optimal investments of 1.2 GW of PHS by 2030 and 5.0-5.3 GW of Li-ion batteries, which would increase substantially towards 2050.

Key message #10: Storage technologies would be economically attractive even under existing barriers. However, changes in regulation could facilitate a faster and larger integration, thereby reducing the cost of storage, which would result in a decrease of the overall cost of satisfying the electricity demand in Mexico and fulfilling the climate obligations.

Key message #11: Under the current transmission tariff where storage technologies are levied both when charging and discharging, the mitigation potential would decrease by a small, but non-negligible amount of 3 $MtCO_2$ by 2050.

Key message #12: Barriers restricting the capacity requirements, here exemplified by imposing a 6-hour minimum requirement on storage, could lead to a reduced participation of renewable energy and storage technologies, resulting in an increased of CO_2 emission due to the larger use of natural gas.

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