# Executive Summary for decision makers

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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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# Content

# Preface

The National Institute of Ecology and Climate Change, with the support of the Mexico-Denmark Program on Energy and Climate Change, prepared the study "Roadmap of technology and mitigation potential of large-scale electricity storage in Mexico" to provide updated information about the role and the mitigation potential that energy storage technologies could have in the National Electricity System. These technologies could contribute to solve some flexibility or intermittence problems in the electrical system follow-on the increasing integration of renewals, that represents a potential contribution to the fulfillment of international commitments - National Determined Contributions (NDC) of México on climate change mitigation, goals that are also pointed out in the Mexican laws.

INECC presents the results of this work for the consideration of the interested public and the stakeholders involved. The study shows us that energy storage technologies can have a positive effect for the country, allowing fuel savings, increasing system reliability and reducing emissions. Likewise, the study shows us global trends on the subject, the barriers that hinder its deployment in the country, and the possible alternatives to carry out its implementation under current regulatory conditions. The final part shows the mitigation potential modeled for different scenarios.

The team members of the project want to thank the participation and contributions of public institutions, associations, companies and universities that supported the development of the study with their experience, knowledge and especially for their comments and discussions in the working groups that have enriched this study.

Mexico, October 2020

# Study request and objectives

The specific objective was to evaluate the mitigation potential of storage technologies in the Mexican power system as well as their costs, based on a well-established technology catalogue and energy systems analysis.

This study was oriented for compliance with the policy goal two of the National Strategy on Climate Change, focused on developing fiscal policies and economic and financial instruments with a climate focus, as defined in the line of action P2.10, which promotes the determination of energy tariffs according to a life cycle assessment analysis that considers externalities, including the associated cost of greenhouse gases emissions and with policy goal three of the Special Program on Climate Change, which sets the purpose of reducing greenhouse gas emissions in order to transition to a competitive economy and low emission development; particularly, according to the article 34.1 of the General Law on Climate Change. The Strategy 3.3, related to develop tools and instruments that facilitate the energy transition; and within this strategy and the line of action 3.3.2 that seeks to integrate environmental externalities in the valuation of electricity generation projects, integrating life cycle assessment criteria.

# Study context

In recent years the operations and configuration of the National Electricity System (SEN) has shifted, on the one hand there is a moderate increase in the participation of Variable Renewable Energy sources (VRE) in generation, an increase derived in part from the energy reform and long-term auctions that occurred in previous years, on the other hand, a notable increase in the use of natural gas in the generation matrix has also been observed in recent years, which has been replacing other fossil fuels within the matrix. In the regulatory field, the involved stakeholders are in a period of discussions that explore the role of VRE, ancillary services and the role of flexibility technologies (traditional and new) options within the system. Energy storage technologies are one option to provide the flexibility needed within the system due to change to a cleaner generation matrix or for provision of ancillary services needed for system reliability.

The study is carried out in a period of change within the National Electric System (SEN) conditions and the programmatic planning processes of the current administration in the energy and environment sectors. Likewise, this year the Nationally Determined Commitments of the country have been confirmed by the Inter-ministerial Commission on Climate Change, in which compliance with the commitments related to the reduction of emissions from the electricity generation sector is a fundamental. This study is carried out in order to identify the role and mitigation potential that energy storage technologies could have in this context. These technologies can provide electrical systems with the necessary flexibility to smooth the intermittent curves of the VRE, allowing a greater integration of VRE and also allow an increase in system reliability since they can provide various related services.

# Study scope

On January 2019, the Mexican Regulatory Commission of Energy, CRE, elaborates a project of agreement acknowledging certain services that electricity storage technologies could offer including, but not limited to: a) Energy, b) Capacity, c) Secondary reserves, d) Operating reserves, e) Non-spinning reserves, f) Operating reserves, g) Supplemental reserves, h) Reactive reserves, i) Reactive capacity, j) Black start, k) Isolated operation, and l) Services for the deferral of transmission and distribution investments. Furthermore, that agreement announced that, while keeping a neutral position towards electricity storage, CRE will regulate the products and services provided by storage technologies.

This study had the purpose of developing a Storage Technology Catalogue that should provide high quality estimates of key technical and economic data, from today and until 2050, on the most relevant storage technologies, based on existing information sources, with the aim to support the on-going discussion about electricity storage. Furthermore, the analysis was conceived to assess the potential contribution of utility-scale electricity storage in Mexico to achieve NDC goals.

In addition, technical, financial, market and regulatory barriers were identified along with recommendations to overcome them and highlighting the current enablers to electricity storage technologies in the Mexican power system. The study considers the estimation of the mitigation potential of storage technologies based on a system modeling approach, by identifying the affected technologies (e.g. mostly fossil fuels) as well as the induced ones (e.g. higher integration of variable renewable energy) when introducing storages in the energy system.

The main objective with the development of a catalogue for storage technologies was to have detailed and up-to-date data regarding the technical, economic and environmental characteristics of utility-scale electricity storage technologies, as well as their level of maturity in the national and international market, the prospects for development and the main barriers to their implementation. These data are of the utmost importance when estimating the mitigation potential of storage technologies.

# Report structure and outline

The Study was structured in five deliverables to cover the different aspects of the energy storage systems deployment at utility scale like global trends, feasible technologies for México, barriers for deployment, mitigation potential and case studies to look at the problems and requirements for this technology at regional level.

Deliverable D1: "Review of experiences and trends in electricity storage technologies in Mexico and globally", includes:

- The mapping of relevant stakeholders.
- Existing and Planned storage projects in Mexico.
- A review of global and regional trends on grid-scale electricity storage.

- Success criteria and drivers that enabled the deployment of utility-scale electricity storage projects.

Deliverable D2: “Technology Catalogue for energy storage”, includes:

- Design of a conceptual framework for developing the Technology Catalogue and the public consultation processes for selection of storage technologies.
- Storage technology catalogue, which includes description of technology selected and a table with the technical and financial data as well as the data projections and uncertainties for 2030 and 2050. The catalogue includes the results of feedback and comments.

Deliverable D3: “Barriers and enablers to the implementation of storage technologies in Mexico”, includes:

- Description of the regulatory and financial framework for electricity storage in Mexico.
- Identification of barriers and enablers for electricity storage.
- Set of measures to overcome barriers and best practices based on international experience
- Characterization of how different regulatory frameworks could impact the feasibility of the business case.

Deliverable “D4: “Potential of storage technologies in Mexico”, includes:

- A Mapping of geo-specific storage resources in Mexico: hydro reservoirs and caverns for CAES.
- Identification of five case studies of interest in Mexico.
- A common framework for the description of the five case studies of interest.
- Description of the five case studies.
- The specific storage requirements identified by the case studies and results of cost - benefits preliminary assessment of implementation of Energy Storage Systems (ESS) at regional level.

Deliverable D5: “Mitigation potential of selected storage technologies in Mexico”, includes:

- Review of the environmental impact assessment of storage technologies.
- Mitigation potential of storage technologies related to ancillary services.
- Mitigation potential of utility-scale electricity storage technologies using energy systems analysis.

The study was accompanied and supported by workshops for consultation with experts, progress presentation and dissemination of results.

# D1-summary

## Stakeholders

Figure 1 shows the seven groups of stakeholders identified.

1. Stakeholders who have a primary role in the development of public policy and regulation, with a great deal of influence in the decision-making process regarding the deployment of the electricity storage technologies: CENASE, CRE, SENER.
2. Stakeholders with a secondary role in the development of public policy and regulation in the environmental and public investment sectors: SEMARNAT, SHCP, INECC.
3. Stakeholders that provided electricity or other services in the Mexican power system, and who might have an interest in the development of electricity storage systems or in the impact electricity storage systems could have in their operations like CFE or Independent Energy Providers (PIEs).
4. Stakeholders that provide technology support to the government like public and private cooperation organizations like GIZ, the Danish Cooperation, etc.
5. Stakeholders involved in research, development and innovation related to electricity storage systems in Mexico.
6. Stakeholder that provides banking services and financial support at the international (WB, BID) and national level (NAFIN, BANOBRAS).
7. Private associations, think-tank's and non-governmental organizations supporting lobby activities or involved in the development of policy.

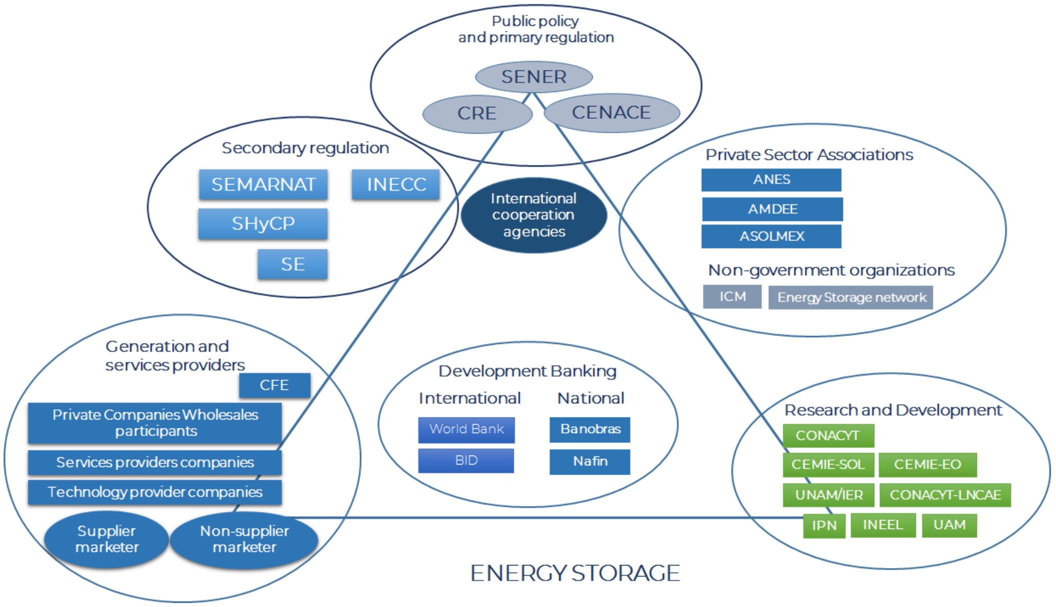

**Figure 1.** Stakeholders involved in the deployment of Energy Storage. Source: own elaboration.

# Technology trends

The national electricity system (SEN) is organized into ten control regions. Seven regions in the continental massif are interconnected building the National Interconnected System (SIN), which connects most of Mexico and shares resources and reserves of capacity. The 3 remaining regions of Baja California, Baja California Sur and Mulegé are completely isolated from the rest of the national electricity grid.

The increasing penetration of intermittent or variable renewal generation in the SEN represents challenges on frequency regulation, frequency quality, reduction of inertia of the system, primary regulation, reserve margins and on the useful life of conventional power plants due to the need for more frequent and steeper ramps.

The operation of the SEN will increasingly be faced with the influence of the following trends: the country's renewable energy goals -35% by 2024 and 50% by 2050, the new renewable-energy based projects resulting from the long-term energy auctions (derived from the reform of electric system), the trend to more natural gas power plants that already change the generation matrix, as well the sustained growth on distributed generation and the future requirements of transport transition.

Electricity storage technologies might have a growing role to address some of these challenges in a cost-efficient way while promoting the decarbonisation of the Mexican power sector. Energy storage technologies can support energy security and climate change goals by providing valuable services such as: improvement of energy system resource use efficiency; integration of higher levels of variable renewable resources and end-use sector electrification; supporting greater production of energy where it is consumed; increasing energy access; and improving electricity grid stability, flexibility, reliability and resilience. Moreover, they can provide associated products and related services that can contribute with the components of efficiency, quality, reliability, continuity, safety and sustainability of the network to which they are connected.

**On the global level** information available shows that total installed storage power capacity is currently dominated by pumped hydro storage (PHS), with 96% of the total of 176 gigawatts (GW) installed globally in mid-2017. The other electricity storage technologies in significant use around the world include thermal storage, with 3.3 GW (1.9%); electro-chemical batteries, with 1.9 GW (1.1%) and other mechanical storage with 1.6 GW (0.9%). In 2019 the total installed operational storage power capacity of electro-chemical (mainly batteries) raised up to with 2.8 GW (1.6%), and the capacity from other mechanical storage was 1.3 GW (0.8%). In terms of the number of installations, the applications of Energy Storage Systems (ESS) with batteries are the ones that top the list according to the DOE data and other technologies, such as thermal storage or flywheels, have a relevant representation in applications below 10 MW capacity (Figure 1).

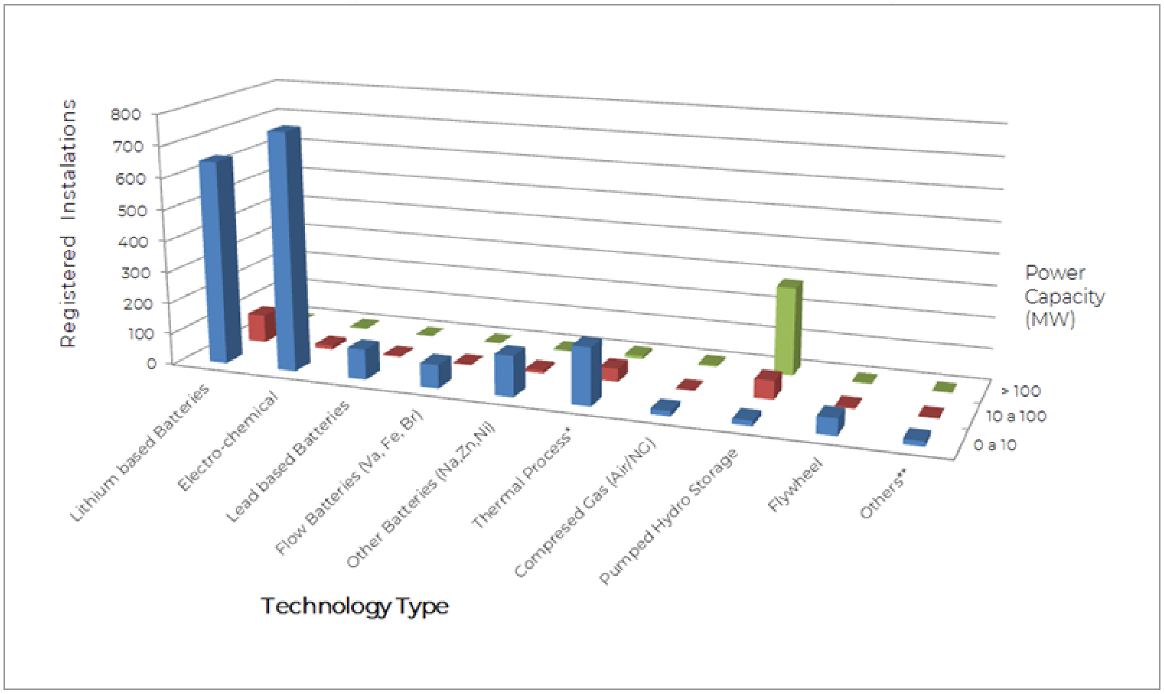

Figure 2. Global electricity storage number of projects by power capacity and technology. Source: own elaboration with data from (US-DOE, 2019).

Despite the lower levels of deployment of electro-chemical, electro-mechanical and thermal storage, the main services provided by them are more diverse than those of PHS plants. Thermal energy storage applications currently are applied on concentrate solar power (CSP), allowing them to store energy, in order to provide the flexibility to dispatch electricity outside of peak sunshine hours, e.g. into the evening or around the clock (IRENA, 2016). Molten salt is the dominant commercial technology applied with 86% of the total capacity deployed of thermal storage used for electrical applications (2.6 GW) (US DOE., 2019).

Electro-mechanical storage deployment has had a relatively small number of projects with a total operational installed capacity of 1.3 GW. It is dominated by the flywheel technology, with 0.9 GW (69% of the total electro-mechanical capacity). The total deployment of CAES has reached 0.4 GW of power, although it is concentrated in in-ground natural gas combustion compressed air, and the deployment of other types of storage with compressed air is 0.5% (US DOE., 2019). Although the installed operational power of electro-chemical storage is still relatively small, it is one of the most rapidly growing market segments. During the last 20 years, deployment of global installations of electrochemical storage grew exponentially (Figure 3), as rapidly decreasing costs and performance improvements are stimulating investments (IRENA, 2017).

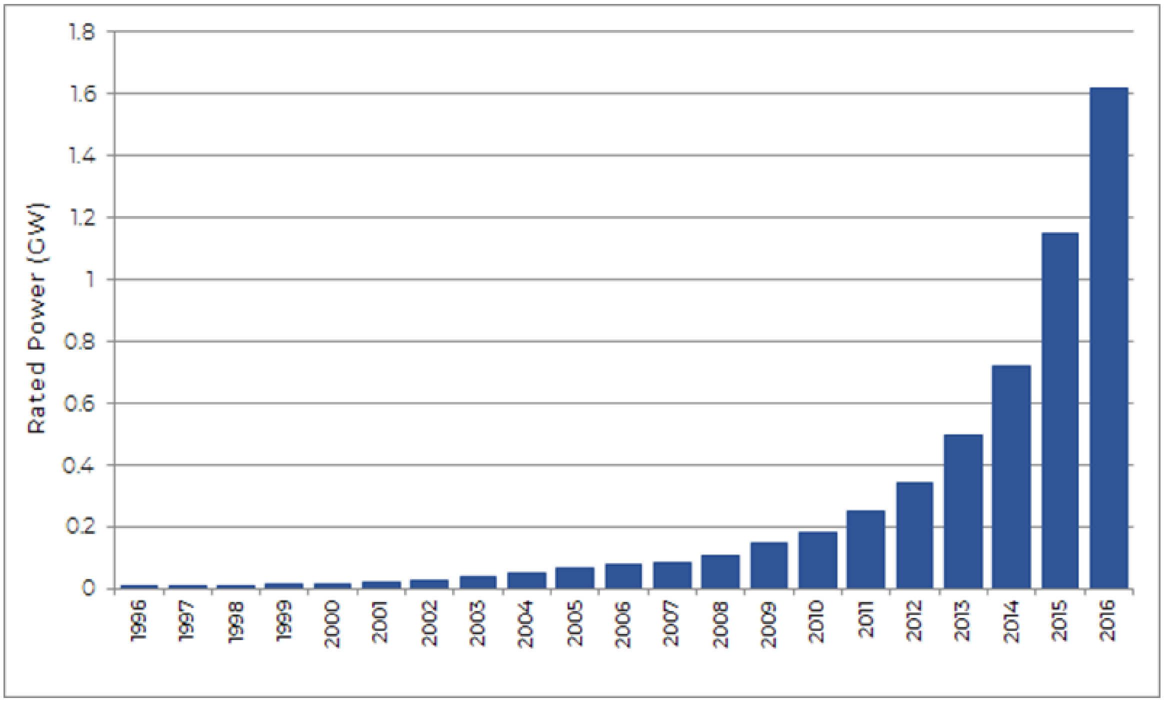

**Figure 3.** Global electro-chemical storage capacity for stationary purposes,1996-2016, Source: (IRENA, 2017).

In Mexico the Energy Regulatory Commission is beginning to recognize the value of storage and since 2018 has been working on developing a regulation for storage technologies. On January 2019, the CRE preliminarily defined the following products and services that energy storage may offer in Mexico: Energy; Capacity; Secondary reserves; Spinning reserves; Non-spinning reserves; Operating reserves; Supplemental reserves; Reactive reserves; Reactive capacity; Black start; Isolated operation; Services for the deferral of transmission and distribution investments. While energy storage in Mexico is not developed, some projects have been identified showing that there is a current interest on this area from the private and public sectors, as shown in the next Table 1.

**Table 1.** Current projects in Mexico. Source Own elaboration.

| PROJECT | TECHNOLOGY | CAPACITY | LOCATION | PURPOSE | STATUS | NATURE |
|---|---|---|---|---|---|---|
| Aura Solar III | Lithium-ion batteries | 10.5 MW/7.0 MWh | La Paz, Baja California Sur | Stabilization of the grid. | Constructed | Private |
| Arroyo Power Energy | Chemical batteries | 12 MW/12 MWh | Monterrey, Nuevo León | Microgrid, Frequency Response, Spinning Reserve | Operating | Private |

| PROJECT | TECHNOLOGY | CAPACITY | LOCATION | PURPOSE | STATUS | NATURE |
|---|---|---|---|---|---|---|
| Mexico City Airport | Flywheel | 1,800 kVA | Mexico City | Back up | Operating | Private |
| Toluca City Airport | Flywheel | 600 kVA | Toluca, State of México | Back up | Operating | Private |
| San Juanico | Lead-acid | 2,450 Ah | Comondú, Baja California Sur | Supply | -- | Private |
| Zima-pán | Pumped Hydro | 570 MW | Zimapán, Hidalgo | Ancillary services | Planned | Public-CFE |

Also, a number of research projects related to energy storage have been launched in recent years financed by the CONACYT-SENER-Energy Sustainability Sector Fund through the National Council for Science and Technology (CONACYT) in various topics such as: hydrogen storage; material for efficiency improvement in capacitators; supercapacitors; regulatory, costs and economic energy storage feasibility studies; sodium-ion batteries; flow batteries; and fuel cells.

## Regulatory trends

The reform of the Mexican electricity sector adopted numerous structural and regulatory elements form the California electricity market. Since California is more advanced than Mexico in terms of electricity storage regulations, the similarities between the two markets allows Mexico to adopt many of California's storage regulations with relative ease.

In 2002, California signed into law a Renewable Portfolio Standard (RPS) calling for 20% of electric retail sales to come from renewable sources by 2020. The RPS increased progressively over the years to reach the current objective of 60% of electricity from renewable sources by 2030 and all generation to be carbon free by 2040 (California Senate, 2018).

As its portion of renewable generation increased, California faced intermittency and ramping challenges associated with wind and solar generation. To address those challenges, California regulation obligated its main utility companies to procure energy storage.

Since the deployment of energy storage was driven by regulation, in order to integrate storage into the market, the California Energy Commission, California Independent System Operator and the California Public Utilities Commission created a "California Roadmap and the Energy Storage and Distributed Energy Resources Initiative" (CAISO, 2014). The Roadmap identified a number of actions necessary to promote grid-scale energy storage, and grouped them under five headings: planning, procurement, rate treatment, interconnection, and market participation.

The Roadmap was replaced by the "Energy Storage and Distributed Energy Resources Initiative" composed of four phases. The first phase "enhanced the ability of grid-connected storage and distribution-connected resources to participate in the ISO market" (CAISO, 2019A). The second phase, among other things, defined the treatment of energy used for operating storage vs. energy used to charge storage (CAISO, 2018), and the third phase still has not been completed at the time of writing of this section. The goal of the third phase is to identify additional means for grid-connected storage to participate in the market. The fourth phase is expected to address the state of charge and market power of storage resources, and streamlining interconnection agreements.

In addition to the regulations and policies promoting storage, there are various initiatives on the State and the Federal levels meant to facilitate electricity storage through research, tax incentives, and Federal regulations.

Despite numerous similarities between Mexican and Californian regulatory frameworks, there are some important differences. The most important difference is that in California a storage system can offer frequency control on the day-ahead and real time markets for ancillary services while Mexico has no market for frequency control.

While California deployed storage through regulation, the UK took a market approach.

Both the UK and Mexico had centralized state-owned electricity systems prior to their respective energy reforms. The Mexican electricity sector reform, which took place 24 years after the one in the UK, left a significant portion of the generation capacity as well as transmission and distribution systems under the control of government-owned enterprises. On the other hand, the UK privatized all aspects of electricity sector and adopted a market approach to energy storage.

The UK's drive to decarbonize the electricity system, propelled by the "Climate Change Act" of 2008 (UK Parliament, 2008) detonated renewable generation investments. The portion of electricity sales from renewable sources increased from 7.2% in 2010, to 25.1% in 2017 (DUKES, 2018). Also, the Feed-In Tariffs (FiT) program encouraged distributed generation on a small scale, and in 2017 the program reached the capacity of 6.1 GW. Whereas in Mexico distributed generation applies to installations up to 0.5 MW, in the UK FiT program applies to projects up to 5 MW (UK Parliament, 2008).

The increased participation of intermittent generation in the UK electricity system has sparked interest in optimal ways to integrate electricity storage into the network. In 2015, the UK introduced an Enhanced Frequency Response, an ancillary service with a response time of one second or less. This particular service clearly favored storage technologies such as batteries, flywheels, and supercapacitors with a very fast response time.

In 2016, Carbon Trust and the Imperial Collage London published a report entitled "Can Storage Help Reduce the Cost of a Future UK Electricity System?". The report finds that storage could significantly reduce the cost of the UK system, even without emphasis on decarbonization. The report stated that the key solutions to overcoming barriers to storage deployment are policy related. Examples of solutions included monetizing system benefits including externalities, reducing policy uncertainty and defining storage performance standards.

In both UK and California, the energy storage regulations and policies are not finalized and like Mexico are striving to successfully integrate storage into the system. There are three principal ways governments can promote deployment of storage: through a regulatory obligation similar to California; through subsidies, such as various international programs focused on distributed generation, or storage producers such as German government's subsidies for battery producers; and through regulations which create a market for storage products, similar to the UK.

- Regardless of the path taken, a successful deployment of grid-scale energy storage requires at least three factors:
- Clear rules, definitions and classifications of storage services.
- Non-discriminatory regulation, which recognize storage physical and operational characteristics
- Security of revenues, either through a tariff structure similarly to California, or market conditions conducive to storage contracts similarly to the UK.

# D2-summary

The Technology Catalogue for Energy Storage is divided into three main sections: The first one is a guide to the structure and issues of the catalogue; where the basic concepts of energy storage are defined and described: technology and storage classification, technical characteristics for each of the technologies considered. It also shows a general framework of energy storage, the existing technologies, and the main applications or services that storage technologies can provide to the grid at utility scale. In this section an overview of the applications of energy storage around the world is included, identifying the application trends of different technologies, its main uses, the main components of each system, the technological maturity, the characteristics or conditions that restraint or enable its application, among other things.

The second section presents the energy storage options or technologies that are considered to have the potential to be implemented in the context of the Mexican national electricity system, their main characteristics, and the technical data that can be used to perform further analysis for each energy storage technology in a system.

The third part of the Technology Catalogue include the summary tables (Excel files) with the technical and financial data and the projections and uncertainties to 2030, the complete list of data sheets will be mentioned in the section "Web-only Materials".

The process of developing this catalogue was designed to enable the continual participation of stakeholders within this area of expertise. Therefore the stakeholder institutions within the academic, developer, and public administration sectors directly related to the subject were invited to an introductory workshop followed by the integration of a working group to discuss in detail the different aspects of the catalogue: the technology selection, the structure of the technology descriptions and the technical and financial data gathering as well as the best way to present projections and uncertainties.

The participative process consisted of the preparation and realization of three sessions with the working group where the interested parties were asked to review the documents of the catalogue and to provide feedback on the work in the different stages of realization of the project. As part of the preparation of the working group session, main files were shared. During the sessions, presentations were made regarding the different aspects of the technologies. The goal of this process was to keep the stakeholders inform about the progress and to get the most possible feedback from the participation of the greatest number of experts in the different areas.

In the case of this catalog of technologies, a working group was formed made up of experts from different sectors and institutions, which enriched this work with their support, review and valuable contributions throughout the development process. We thank the participants for their contributions and comments.

# D3-summary

The deployment of energy storage systems can potentially offer an array of benefits. If the value of those benefits (market, environmental, socioeconomic, technical, etc.) surpasses concomitant costs, then it might be worthwhile to consider implementation of storage in the electric system. While this section does not compare benefits to costs, it does identify the barriers and enablers to storage implementation -should implementation be desirable-, which presently exist in Mexico. Since no enablers were identified, the discussion is focused on barriers found in the electricity sector's regulatory framework.

The key barriers identified by the working group participants from the public and private sectors were:

- Lack of a market for fast frequency response, the principal way for storage systems to participate in energy markets around the world, even though frequency control provided by reserves is remunerated.
- The absence of a formal procedure for procurement of ancillary services not included in the wholesale market excludes storage systems from offering those services.
- Lack of long-term contractual framework for services offered by storage, which could reduce risk of long-term-investment.

Additional regulatory shortcomings worth mentioning:

- Classifying storage as generation presents various challenges, such as:
  - Paying transmission tariff twice. As a generator, storage pays transmission tariff for injecting the energy into the grid, which is meant to cover 30% of transmission costs. Storage is also required to pay a transmission tariff when it is charging, a tariff paid by the load, which is meant to cover 70% of the cost of transmission.
  - Classifying storage as generation forces storage technologies to compete on equal footing with conventional generation, which it cannot do for numerous services because of the limited time energy can be released.
- Lack of technical norms and standards, as well as environmental regulations related to storage.
- Lack of fiscal incentives akin to those afforded to renewable generation.
- More stringent requirements than conventional generation to receive availability payments in capacity market. Whereas storage is required to provide electricity for 6 hours at full capacity, the conventional generation is required to provide it for only 3 hours.

- Long-term generation capacity auctions do not recognize energy supply limitations faced by storage. Consequently, although storage is classified as generation, it cannot compete with conventional generation.

In response to the aforementioned barriers, the participants of electricity storage workgroups suggested solutions, which were generally the inverse of the stated barriers. For example, if an identified barrier was "undefined process for provision of ancillary services", the proposed mitigant was "defining a process for provision of ancillary services", etc. Another fragment of responses suggested monetizing benefits to the grid, investigating in more detail potential benefits of storage through pilot projects, promoting storage education at universities, etc.

Potential removal of barriers to storage participation could permit four prototype modalities for storage to participate in the electrical system. Although all storage technologies potentially offer positive externalities, such as mitigation of greenhouse gases, increased energy independence, decrease in peak electricity prices, etc., each modality of participation in the electrical system presents a different set of costs and benefits to both storage investors and society as a whole. Whereas the chapter lists numerous costs and benefits associated with each mode of market participation, here only key costs and benefits are presented for each modality.

Table 2. Implementing option under current regulations- advantages and disadvantages.

| Option | Benefits/ Disadvantages | Investors (CFE & IPPs) | Society |
|---|---|---|---|
| Market-Driven Standalone Storage | Benefits | Investor controls and administers the asset as she sees fit (if it is under 20 MW capacity). | Decline in GHG emissions and decline in power prices due to peak shaving and decreased congestion. |
| | Disadvantages | Investor pays double transmission tariff. | Possible environmental impacts, conditional on the type and the use of storage technology. |
| Market-Driven Associated Storage | Benefits | Investor pays only generator's transmission tariff | Decline in GHG emissions and decline in power prices due to peak shaving and decreased congestion. |
| | Disadvantages | Significant long-term capital investment without security of a long-term contract | Possible environmental impacts, conditional on the type and the use of storage technology. |

| Option | Benefits/ Disadvantages | Investors (CFE & IPPs) | Society |
|---|---|---|---|
| Standalone Storage, Classified as Transmission & Controlled by CENACE | Benefits | Security of a long-term contract and no market risk | Previously mentioned benefits to society can be optimized, because decisions are not market-based |
| | Disadvantages | Investor operates, but doesn't control the asset | Long-term contract might make it difficult for CENACE to take advantage of the latest technology |
| Associated Storage, Controlled by CENACE | Benefits | Security of a long-term contract and no market risk | Previously mentioned benefits to society can be optimized, because decisions are not market-based |
| | Disadvantages | There might be a conflict between the operation of the plant and the operation of storage, since both interconnected on the same premises. | Long-term contract might make it difficult for CENACE to take advantage of the latest technology |

Note. IPP: Independent Power Producer

Arguably, there might also be certain drawbacks associated with a contractual storage arrangement. For example, a long-term contract might make it difficult for CENACE to take advantage of latest storage technologies which enter the market, and which might be cheaper and more efficient.

It is also worthwhile mentioning that in some markets around the world, such as in Denmark, storage is classified as storage and not as generation. Creating a new market participant category eliminates numerous challenges associated with classifying storage as generation. The rest of Europe is reviewing the Danish treatment of storage, and is likely to follow suit.

# D4-summary

**Section 4.1 shows the findings on global and Mexican Pumped Hydro Energy Storage (PHS) and (Compressed Air energy Storage (CAES) gross-potential estimates.** On Pumped Hydro

Energy Storage (PHS), international studies regarding open-loop and closed-loop seasonal energy storage are presented while at national level, information on the Mexican dam infrastructure is discussed in addition to the international benchmark, to bring up an idea of the geo-specific hydro and orographic potential for developing PHS projects.

Seasonal pumped hydro energy storage (SPHS) potential sites identified for developing SHPS facilities with a fixed generation/pumping capacity of 1GW amount to more than 5.1 million around the globe. SPHS costs vary from 0.007 to 0.2 US$/m$^3$ for water storage, 1.8 to 50 US$/MWh for energy storage and 370 to 600 US$/kW of installed capacity. 1902 sites could be developed with energy storage capacity costs lower than 50 US$/MWh accounting for a total storage capacity of 17.3 TWh, approximately 79% of the world electricity consumption in 2017. In Mexico, SPHS projects could be developed specially in the mountain ranges where cascade arrangements are possible, some projects could be developed with energy storage costs lower than 10 US$/MWh. Most of the identified sites are located in areas where the land requirement is lower than 10 km$^2$/TWh.

Closed-loop PHS are systems formed by an upper and a lower reservoirs connected through a tunnel, however, none of the reservoirs are linked to any river, reservoir is filled with water once from an external source in one of the reservoirs to begin the pump up. The discharge cycle between them and the amount of water loss has to be restored periodically. There are more than 616,000 potential sites for developing PHS projects all over the world with an overall gross storage potential of about 23,000 TWh. The estimated energy storage capacity required for supporting a 100% renewable energy system is of about 200 TWh, hence, there is no limitation on the global PHS potential for providing storage services for a global renewable-based energy system. In Mexico, more than 272,000 possible locations could be suitable for developing closed-loop PHS systems with a total energy storage capacity of 4,200 TWh.

On the other hand, Mexico has an infrastructure of more than 5,000 dams with an approximate overall water storage capacity of 150,000 hm$^3$; 82% of the total water storage capacity is concentrated in 180 dams. This infrastructure constitutes a potential resource for developing pumped hydro energy storage projects either by building an off-river reservoir at a higher level, or by installing pump-back systems when a cascade arrangement currently exists on a river. Examples of cascade arrangement exist on the Grijalva river where four dams are on cascade or in the Tula and San Juan rivers in the states of Querétaro and Hidalgo respectively, both of which has dam-cascade systems and join in the Zimapán dam creating a further cascade arrangement.

For Compressed Air Energy Storage (CAES), a discussion on international reference regarding global geological resources suitable for developing underground CAES facilities including a global gross CAES potential is presented. In the Mexican context, information on geological resources that can be used for developing CAES projects is discussed based on geological atlases and geological charts provided by the National Hydrocarbons Commission (CNH by its acronym in Spanish) and the Mexican Geological Survey (SGM by its acronym in Spanish), as well as, on international references.

CAES systems take advantage of underground caverns either natural or artificially created to be used as storage vessels. Therefore, the assessment of geo-spatial resources for estimating an underground CAES potential turns into the assessment of geological resources that could lead to underground cavities. The estimated global gross CAES capacity including salt, porous rock and hard rock formations is 6,574 TWh, therefore, the gross global CAES potential looks enough for supporting a 100% renewable energy system too.

In Mexico, salt formations are located along the Gulf of Mexico where the States of Tamaulipas, Veracruz, Tabasco and Campeche shows salt formations that could be directly studied for CAES development purposes, other States such as Nuevo León, Chihuahua, Oaxaca and Chiapas possess salt resources too. The geological charts provided by the Mexican Geological Service (SGM) are a very powerful tool for identifying possible CAES-suitable sites as they include information regarding the extension and sometimes the structure of the salt and other underground formations. In Veracruz, the only underground storage facility in Mexico started operations in 2017. Using a salt cavern, the private facility provides LP gas storage services for Petróleos Mexicanos with a storage capacity of 1.8 million barrels and a transfer capacity of up to 120,000 barrels of gas per day.

While the gross potential in Mexico for PHS and CAES seems to be large, it is also evident that its necessary to conduct further research to assess the global potential for these two technologies al national level in order to facilitate feasibility studies at specifics sites to identify the projects that could be developed in the short, mid and long terms.

Section 4.2 discusses the most relevant issues of the study cases, the site selection process, the scope of the data gathering, and of the analysis that was conducted. Study cases where selected after a consultation and participation process with stakeholders.

The initial selection of sites took into consideration: (a.) site physical characteristics, local marginal electricity nodal price, electricity generation and demand by region and regional technical grid problems, (b.) the assumption that the selection should take into consideration services that energy storage could provide and (c.) that those services could contribute to problem alleviation or renewable energy integration.

The high-demand isolated Baja California Sur electricity system, the sustained growing renewable capacity in the Coahuila – Nuevo León electric region or the use of an important PHS potential in the Zimapán dam in Hidalgo are examples of the diversity of conditions that exist in the Mexican Electricity System and that constitute interesting cases for evaluating the effect of energy storage technologies. The five study cases are summarized in the following chart.

Table 3. Case studies: summary of identified problems (not exhaustive). Source: own elaboration based on data from SENER and CENASE.

| Control Region | Study Zone | Transmission region | Problems identified | Possible services from storage technologies |
|---|---|---|---|---|
| North | Chihuahua - Ciudad Juárez | Juarez, Moctezuma, Chihuahua | - Congestion.<br>- High share of renewable energies integration. | - Energy management<br>- Renewable energy capacity firming<br>- Ramping |
| Peninsular | Yucatán | Tabasco, Lerma, Mérida, Cancún Mayan Riviera | - Blackouts due to natural gas shortages.<br>- Short circuit due to fire and high temperatures. | - Energy management<br>- Ramping<br>- Seasonal storage<br>- back-up power |

| Control Region | Study Zone | Transmission region | Problems identified | Possible services from storage technologies |
|---|---|---|---|---|
| Western | Hidalgo – Querétaro (Zimapán) | Central, Querétaro, San Luis Potosí, Tamazunchale, Salamanca | – Congestion.<br>– Non-ideal commercial conditions - Legacy contract (only to deliver energy).<br>– Non-profitable generation machinery wastage (working synchronous capacitor). | – Frequency regulation,<br>– Decongestion<br>– Ramping<br>– Transmission & distribution investment deferral. |
| Northeast | Coahuila - Nuevo León | Monterrey, Saltillo | – Congestion.<br>– High share of renewable energies integration. | – Energy management<br>– Renewable energy capacity firming<br>– Ramping |
| South Baja California | La Paz | Villa Constitución, La Paz | – Supply Problems<br>– Congestion<br>– High share of renewable energies integration. | – Ramping.<br>– Renewable energy capacity firming.<br>– Transmission & distribution investment deferral |

Section 4.3 offers a common framework for the economic evaluation of the five case studies. The case study locations were chosen according to the grid and environmental problems storage could alleviate[1]. This section present public information from CENACE, SENER, SEMARNAT, INECC among others, gathered for every site, the information includes e.g. environmental impact assessments VRE projects, Local Marginal Prices, regional generation and demand.

The technical description also includes: (a) technical data such as congestion and losses problems, possible future increase of variable renewable energies in the region, current capacities and generation, planned generation and transmission expansion, fossil fuel consumption and transmission capacity; (b) Identification of problems in transmission, supply, frequency control and voltage control; and (c) technologies of possible application according to the needs and requirements of identified services. This section presents a proposal of the size and location of possible storage facilities based on gathered information.

The description of the economic evaluation framework from a social perspective begins with the identification of positive economic externalities which are benefits not included in the price of storage transactions, and which positively affect society. The positive

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[1] With the exception was Zimapán, where CFE expressed interest in pumped-hydro storage

externalities were grouped under three headings: Intangible; Tangible, but without enough information to be estimated; and Tangible and estimated by the cost benefit model.

An example of a tangible externality estimated by the model is the fossil fuel savings derived from displacement of conventional generation by storage, which can lead to an increase in energy independence derived from reduced reliance on fossil fuel imports.

There are also tangible externalities which were not evaluated, either because they would require too many debatable assumptions, or simply because relevant data were not available. Mitigated ohmic electricity losses due to high congestion are an example of a tangible externality that was not estimated because of the lack of reliable data.

No negative tangible externalities associated with storage system were considered. Arguably, there is not enough information to estimate tangible impacts of negative externalities, such as reclamation beyond the costs considered in the investment decision for example, or the negative impact of communities downstream of PHS systems, that were not considered by the government agencies issuing relevant permits. Section 4.3 also lists the equations used to quantify the Net Present Value (NPV) of the benefits in terms of displaced fossil fuel generation, congestion relief, cleaner environment, and decreased cost of electricity.

Specifically, he following benefits were estimated over the technical lifetime of each storage system technology using at 10% social discount rate: (1.) Peak shaving; (2.) Value of mitigated $CO_2$ emissions; (3.) Fossil fuel cost savings from displaced conventional generation; (4.) Value of decreased congestion; (5.) Voltage control and (6.) Arbitrage. The cost-benefit model (CBM) evaluated the NPV of each storage system by summing the benefits (1-6) and Capital and operating costs.

The section concludes with the discussion of key assumptions and model limitations. The principal challenge of conducting a cost-benefit analysis was the lack of data. The assumptions in the cost-benefit model fall on the conservative side and underestimates the value of energy storage.

The section 4.4 starts with the assumption that all storage technologies reviewed in the catalogue are technically feasible, and that one of the key purposes of this investigation is to assess whether or not their implementation makes economic sense for each case study.

To that end, a set of common base case assumptions is established for all storage technologies, such as the social discount rate, the prices of fuels used in conventional generation and their carbon content, the heat rates of each conventional generation, the demand growth, the percentage of storage charged with VRE, etc. Also, a set of base case assumptions is established for each technology and each region. For example, a base case for each technology defines the round-trip efficiency, the monthly amount of MWh released from storage, the technical lifespan, capital and operating costs (fixed and variable), etc. On the other hand, base case assumptions specific to each region include the required size of storage capacity, the nodes at which congestion is evaluated, and the fuel/generation type that storage would displace. The NPV of base case scenarios is estimated using evaluation methodologies described in section 4.3.

Table 4. Base Case and Sensitivity Scenarios.

| Base Case Scenario Locations: Control Region/Nodes | Sensitivity Analysis Scenarios |
|---|---|
| 1: Western/<br>Zimapán – San José Iturbide | Base case outcome is reported without sensitivity analysis |
| 2: North/<br>Moctezuma – Cereso Juárez | Outcomes are reported for all storage technologies<br>Where:<br>2A North: The fuel oil generation is displaced<br>2B North: The simple cycle gas generation is displaced |
| 3: Northeast/<br>Güémez-Saltillo | Base case outcome is reported without sensitivity analysis |
| 4: Peninsular/<br>San Ignacio – Playa Mujeres | Base case outcome is reported, as well as outcomes where:<br>4A Peninsular: Displaced generation is varied<br>4B Peninsular: Specific investment and operating costs are varied<br>4C Peninsular: $CO_2$ price is varied<br>4D Peninsular: Social discount rate is varied<br>4E Peninsular: The % of storage charged with VRE is varied<br>4F Peninsular: the scenario 4A1 is reset (the displaced fuel changes, all else remains the same) and $CO_2$ price is varied |
| 5: Baja California Sur (BCS)/<br>Olas Altas – Insurgentes | Base case outcome reported without sensitivity analysis |

The initial expectations of storage benefits were centered on peak shaving and congestion relief. The model results, however, suggest that from the social perspective the most significant contribution of energy storage for all technologies lies in fossil fuel savings by displacing fuel oil generation. This also suggests that CFE could potentially realize significant benefits from adopting storage technologies, since an important fraction of generation still uses fuel oil.

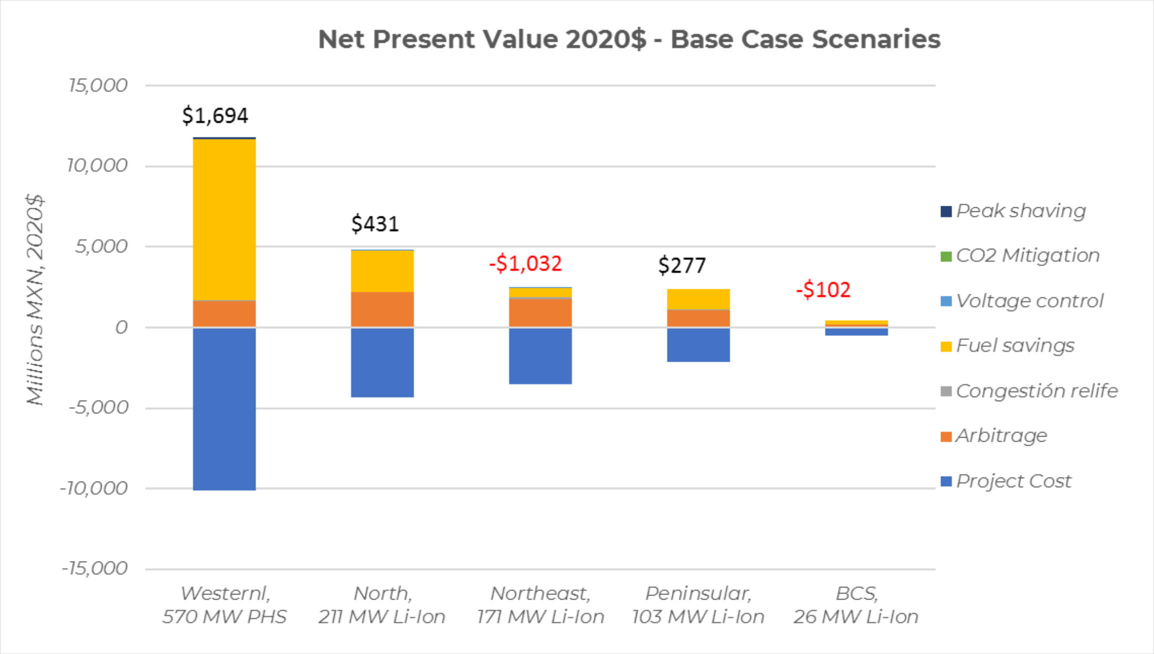

**Figure 4.** Net Present Value in MXN pesos for the 5 study cases – base case scenario.

There are two types of sensitivity analysis performed on base case scenarios. The first type compares the NPV of costs and benefits of storage technologies with one another in the North region, maintaining the reference nodes and regional storage capacity requirement constant for all technologies.

In scenario 2A, all technologies are charged 15% with VRE, and 85% natural gas combined cycle generation (with the exception of molten salts which is charged with concentrated solar power), where all technologies are displacing fuel oil generation. The technologies vary by cost, technical lifespan, round-trip efficiencies, and the amount of MWh released per month. In the scenario 2B, all is the same as in the scenario 2A, except instead of displacing fuel oil, storage displaces simple cycle natural gas generation. In scenario 2A, only molten salts, Lithium-Ion, and PHS had a positive NPV. In scenario 2B only molten salts technology maintained a positive NPV.

It is important to point out that in both scenarios 2A and 2B the $CO_2$ price is $0/tonne, and all energy used to charge storage has a market price, including the energy from renewable sources that would otherwise be curtailed. The cost-benefit analysis is performed under the assumption that storage is classified as transmission, a mode of participation in the electrical system described in chapter 3. This particular classification is specifically tailored to Mexican regulatory framework and is not meant as a general example to be followed.

If the displaced generation is simple cycle fueled by natural gas, then the fossil fuel savings are significantly smaller, principally due to the currently low price of natural gas, by historical standards. Also, the analysis 2B only varies the type of generation that is being displaced, while there are numerous factors which determine the NPV of a storage project.

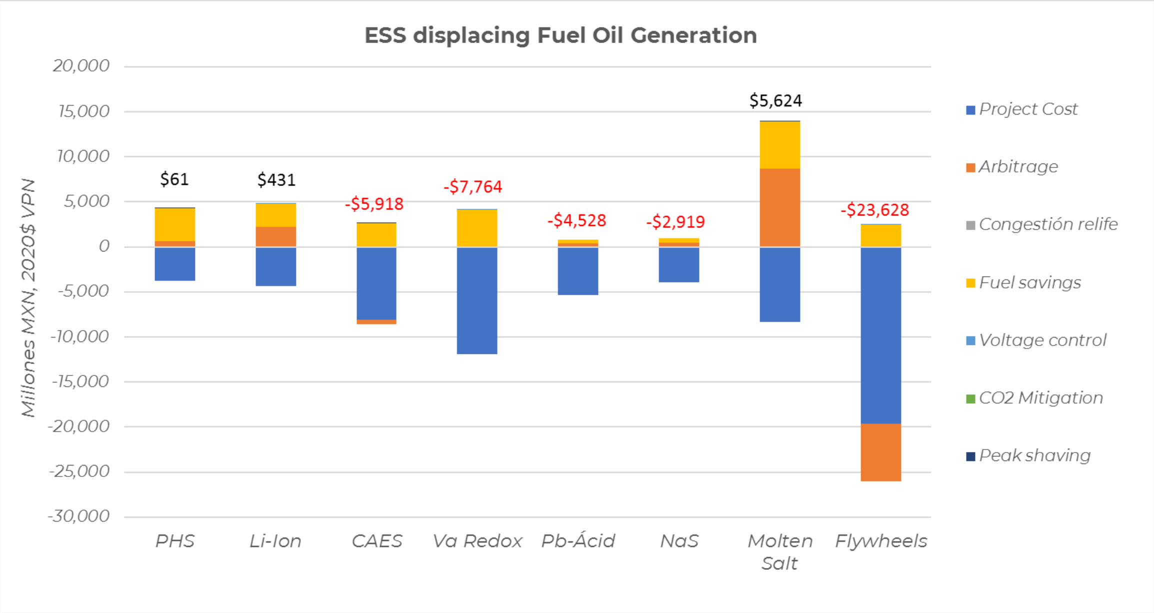

**Figure 5.** Net Present Value in MXN pesos for Scenario 2A - North control region, all technologies and fuel oil displacement.

The second type of sensitivity analysis compared the performance of a one technology to itself under varying scenarios. Specifically, the cost-benefit model examined how the NPV of Lithium-Ion batteries in the Peninsular region changed under different scenarios of $CO_2$ prices, the percentage of storage charged with VRE, the type of conventional generation and fuel displaced by storage, the increase/decrease in social discount rate, and the change in project costs.

The cost-benefit analysis suggests that Lithium-Ion storage in Peninsular region can yield a sizable NPV displacing simple cycle natural gas generation, not just fuel oil, under a number of assumptions such as: the $CO_2$ is priced comparably to other world markets, at least half of the electricity used for charging storage comes from renewable resources, the price of natural gas reverts from its current historically low levels, and the cost of Lithium-Ion batteries decreases by an additional 10%. As mentioned in the Technology Catalogue section describing the Lithium-Ion batteries, the cost of the technology declined by more than 20% in 2015 and 2016, by approximately 15% in 2017, and is expected to decrease further by approximately 70% over the next decade. In the case of molten salt storage systems, on the other hand, a large NPV can be realized without carbon pricing or more normalized natural gas price levels.

The principal takeaway from the cost-benefit analysis is that from a social perspective, a select few energy storage technologies make sense, and could provide a significant net present value both to CFE and to society. Those technologies can also provide benefits not captured by the positive NPV, such as increased national energy independence, facilitation of renewable energy to meet international commitments, strengthening the grid reliability, promoting access to energy in marginalized communities, and possibly creating a new energy storage value-added economic sector in Mexico.

# D5-summary

## Environmental impacts

The report identifies the possible impacts of energy storage systems associated with the manufacture, use and final disposal of the equipment that constitutes said storage technologies. For Pumping Hydroelectric Storage (PHS), the main impacts were those related to the reservoir that is created, the loss of soil due to the flooding, changes in river flows and GHG emissions associated with the reservoir. Batteries can affect the environment during their manufacture, use, storage, treatment, final disposal, confinement and recycling. Its production requires a large amount of metals and non-metals, which has different environmental and public health impacts due to mining issues. Certain metals and non-metals from which batteries are made can have adverse effects on human health through various forms of exposure. In general, the environmental impacts during its operation are relatively low, appearing again in the final phase of the life cycle. In the case of batteries, the different technologies present differentiated environmental impacts in the recycling stage, probably due to the level of development of the production chains, showing that technologies such as lead batteries present lesser emissions than batteries that are still in periods in which the productive chains are not well developed. As an indicator of the total useful life of the system, the Energy Stored On Invested (ESOI) was identified, which is the relationship between the electrical energy stored during the useful life of a storage device and the amount of primary energy incorporated required to build the device. Given that batteries present most of their life cycle impacts during the manufacturing and disposal phases, including primary energy use, the key indicators proposed to assess environmental performance are geared towards indirect emissions. The table below shows possible emissions and typical EOSI values for different battery types.

In general terms, it can be pointed out that the environmental impacts in terms of emissions from storage systems due to their infrastructure are greater in electrochemical storage (e.g. Lead-Acid and Lithium Ion batteries) than in bulk technologies such as PHS or CAES and that the emissions in the use phase of all the technologies are relative similar depending on the configuration and application.

**Table 5.** Specific effect per kg and per MJ of battery production and typical ESOI values for battery storage technologies. Source: own elaboration with data from (Dehghani-Sanij et al., 2019) (Kourkoumpas et al., 2018).

| Battery type | Climate impact ($CO_2$ kg/kg) | GHG emissions ($\text{kgCO}_{2eq}$/MJ) | ESOI |
|---|---|---|---|
| Pb-Acid | 0.9 | 5–7 | 5 |
| Li-ion (NMP solvent) | 12.5 | 17–27 | 32 |
| Li-ion (water solvent) | 4.4 | - | |
| Vanadium redox battery | | | 10 |
| Ni-Cd | 2.1 | 10–15 | |

| Battery type | Climate impact ($CO_2$ kg/kg) | GHG emissions (kg$CO_{2eq}$/MJ) | ESOI |
|---|---|---|---|
| Ni-MH | 5.3 | 16–20 | |
| Na-S | 1.2 | 2 | 20 |
| Zinc bromide battery | | | 9 |

Nota. NMP Solvent: Solvent of N-Methyl-2-pyrrolidone

## Energy Storage Systems for Ancillary services

This study analyses the introduction of storage into the electricity network operation, both by providing balance services on a large scale, as has been done until now or by using it as a tool for improving the quality of service (resolving network contingencies). It provides the system with anciliary services (inertial response, primary reserves, "spinning" reserve). Numerous applications are identified in electrical networks, grouped into five categories according to the system in which they perform their function (generation, transmission, distribution, demand or auxiliary services). This study refers only to the latter.

This study estimates the size of ancillary services and the $CO_2$ mitigation potential of utility-scale storage in Mexico through the two fundamental actions that are taken into account to offer a quality electric service: (i) frequency regulation; and (ii) voltage regulation. It presents results and an assessment of such actions in the Mexican interconnected system (SIN), composed of 158 generators, 2,022 buses[2], and 3,025 lines as well as in the isolated system of Baja California Sur.

Studies are carried out to assess the frequency behavior, in the different control areas of the Mexican interconnected system (SIN), under sudden load increments. Likewise, the possible reactive power compensations in areas of paramount interest for the system are quantified to solve low voltage profile problems, which were detected in previous studies carried out by national authorities. This is done to assess its behavior and propose the embedding elements to help improve it.

Based on reserve values required by the National Energy Control Centre (CENACE)[3], it is proposed to provide them through energy storage technologies. The reduction in $CO_2$ and polluting emissions is quantified, assuming that the generation technologies that are displaced are conventional technologies that are out of operation.

From the generators viewpoint, the spinning reserve is a problem for several reasons, among them the fact that it forces the generators to work in non-optimal points or under deviation from the nominal operation. The use of storage allows generators to operate at full power, thus, in case of an increase in power, storage supplies that services. In this way, storage systems and their associated converters can take over the spinning reserve, allowing conventional machines to work at their nominal or maximum power. Thus, the

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[2] https://www.cenace.gob.mx/CENACE.aspx

operation of the transmission and distribution network also benefits from storage facilities. Various forms of energy storage contribution to the maintenance of the system frequency have been described in the document. The high speed of response, characteristic in batteries, allows them to collaborate effectively in primary frequency control.

This study shows in the first and second sections an understandable review of ancillary services especially frequency and voltage control. In sections three and four, the context of these services within the concept of flexibility for the integration of Variable Renewable Energies (VRE) in electrical systems and Energy Storage Systems (ESS) are also presented. In section five, the study system is described as well as the results of the frequency and voltage studies. Section six and seven explain the role of power electronics in the VRE integration and an approach on how to estimate the mitigation potential of ESS. Sections 8 and 9 show the results of an analysis to determine the location of ESS based on the reactive compensation degree of single buses and the size of ESS requirements, based on ancillary services and backup needs. Finally, in section 10 some conclusions are outlined as well as a comparison of the possible emissions mitigation potential comparing the approach presented in section seven with the IPCC 2006 guidelines and the estimation based on the national inventory emissions factors.

The results show for the different control areas in the Mexican Interconnected System that ESS could be employed to provide ancillary services. In these cases, ESS allows deviations in frequency and voltage signals within technically acceptable limits. The speed of response of such ESS technologies is critical to the success of the support they provide, especially concerning frequency. ESS could support the integration of VRE on those regions with ancillary services and backup requirements. Yet ESS makes sense only if regulations are in place to ensure ESS will be used with clean or exclusively renewal energy.

For 2018 the capacity requirement for Fast Frequency Control (FCC) was estimated on approximately 37 MW, these data represent a minimum installation to help improve the operation of the network, this requirement could be supplied with storage technologies. By 2033 these capacity requirements for FFC are estimated to be 121 MW

This contribution of ESS for frequency control is significant in small systems (for instance, the Baja California Sur system), where asynchronous technologies may displace a considerable part of the synchronous machine-based generation. In more extensive networks, storage technologies used in the appropriate locations may achieve significant results for frequency and voltage control. The high speed of response, characteristic of batteries, allows them to collaborate effectively in primary frequency control. But at the present high-speed frequency control is not a recognised ancillary service and will not remunerated.

Flexibility is another relevant factor at the stage of grid planning before the integration of renewables and storage technologies. The use of storage technologies allows providing flexibility services to the system and contributing to improving the quality of the service provided by the utility within the process of VRE integration.

Regarding the location of ESS, it seems results show a distribution along with the network, associated with the generation facilities near areas of high consumption since it would mean that the storage devices are close to the points that require a higher input of reactive power. Some geographical regions become exceptional cases, such as the areas around León, Querétaro, Chihuahua, Riviera Maya, Saltillo, the isolated BCS system. There, due to low voltage levels, it would be convenient to use reactive resources to help support them. The potential mitigation of ESS for ancillary services could lie between 2.2 and 2.5 kt $CO_2$, under the assumptions made in this study, if we only consider only carbon dioxide, The mitigation potential profoundly depends on the energy mix used to load an ESS.

# Modeling mitigation potential of ESS

## 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.

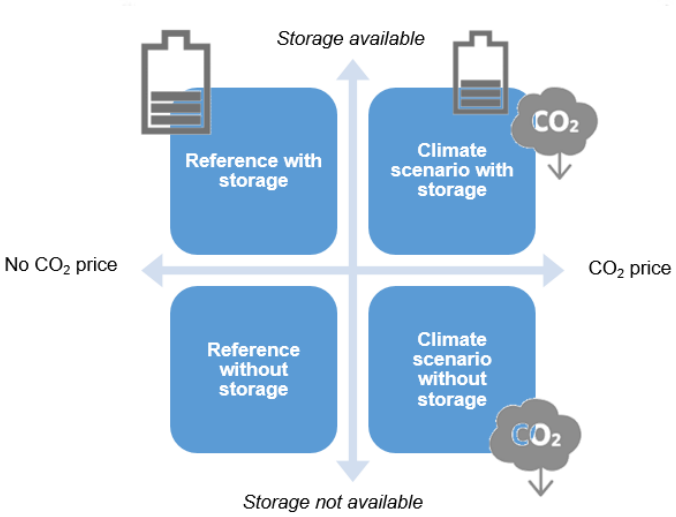

**Figure 1.** Main scenario set-up.

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.

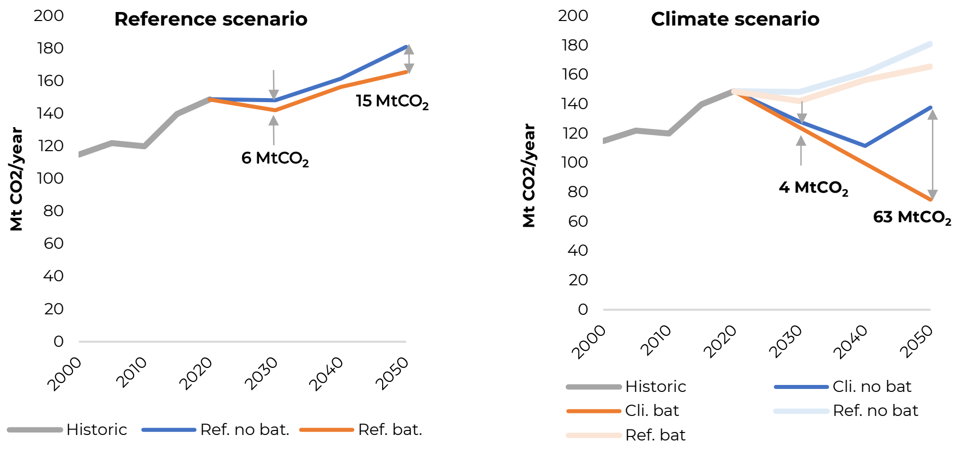

**Figure 2.** Annual $CO_2$ emissions and $CO_2$ mitigation potential (arrow) in the Reference and Climate scenario

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.

# Key findings and recommendations

## D1 Global trends

- Energy storage regulations and policies are still not finalized even in advanced markets like California or the UK.
- The success of integrating energy storage into the electric system operations would require:
  - Both regulatory and commercial incentives.
  - The development of energy storage driven by regulation alone or market alone is not optimal.
  - Coordination between CENACE, CRE, SENER, the private sector as well as other stakeholders in identifying and eliminating barriers to deployment of energy storage.
  - Quantification of benefits energy storage can provide at an energy storage developer level, as well as at a social level (i.e. quantification of externalities).
  - Definition of storage and of the products that energy storage can provide to the grid, and a methodology that would permit valuating those products.
  - Predictable and transparent regulatory framework.

## D2 Technology catalogue

- The technology catalogue provides technical and economic data for preliminary evaluation of storage in a single database.
- The development of storage technologies can substantially change the information contained in the catalog and it will always be necessary to update it regularly to add. new technologies and other applications.
- The costs of storage technologies will be falling in the coming years.
- The global trend is towards larger storage facilities.
- Storage technologies are versatile in their characteristics and can provide different types of services and in different applications.

## D3 Barriers

The key barriers identified were:

- Lack of a market for fast frequency response, the principal manner for storage systems to participate in energy markets around the world, even though frequency control provided by reserves is remunerated.
- Absence of a formal procedure for procurement of ancillary services not included in the wholesale market excludes storage systems from offering those services.
- Lack of long-term contractual framework for services offered by storage, which could reduce risk of long-term-investment.
- Classifying storage as generation presents various challenges, such as:
    - Paying transmission tariff twice. As a generator, storage pays a transmission tariff for injecting the energy into the grid which is meant to cover 30% of transmission costs. Storage is also required to pay a transmission tariff when it is charging, a tariff paid by the load, which is meant to cover 70% of the cost of transmission.
    - Classifying storage as generation forces storage technologies to compete on equal footing with conventional generation, which it cannot do for numerous services because of the limited time energy can be released.
    - Lack of technical norms and standards, as well as environmental regulations related to storage.
    - Lack of fiscal incentives akin to those afforded to renewable generation.
    - More stringent requirements than conventional generation to receive availability payments in capacity market. Whereas storage is required to provide electricity for 6 hours at full capacity, the conventional generation is required to provide it for only 3 hours.
    - Long-term generation capacity auctions do not recognize energy supply limitations faced by storage. Consequently, although storage is classified as generation, it cannot compete with conventional generation.

- The CFE has limited incentives to implement pumped hydro storage under existing vesting contracts:
    - Vested contracts have a fixed rate of return, and CFE would not be able to take advantage of market fluctuations.
    - In order for CFE to build a pumped-hydro storage system, it would also have to build a new hydrogeneration plant, since all existing hydro plants are under vested contracts.
    - If additional investment is made linked to the plant under a vested contract, that investment falls under the vested contract as well. Without renegotiating the contract, CFE has no incentive to make an investment that it would not be able to control.
    - In short, CFE competes in the electricity market with private sector participants, and it acts like a for-profit private sector participant itself. Consequently, in order for CFE to make an investment, it needs a return on that investment which it considers acceptable. However, limitations placed on

CFE through vesting contracts can make earning the desired level of return on investment difficult.

- 4 possible ways to integrate energy storage technologies under current regulation were identified:
  - Market-Driven Standalone Storage
  - Market-Driven Associated Storage
  - Standalone Storage, Classified as Transmission & Controlled by CENACE
  - Associated Storage, Controlled by CENACE

- Some aspects should be considered regarding the CENASE controlled assets:
  - Fuel savings, GHG emissions reductions and decline in power prices due to peak shaving and decreased congestion are some of the benefits to society that can be optimized, because decisions are not market-based.
  - Security of a long-term contract and no market risk.
  - Long-term contract might make it difficult for CENACE to take advantage of the latest technology.
  - Investor operates but doesn't control the asset.

- In the long term it could be better to define a new asset class called "electricity storage". The principal benefit of creating a new asset class is a recognition of distinct characteristics associated with storage.

# D4 Potential of storage technologies in Mexico

- In Mexico, PHS projects could be developed specially in the mountain ranges where cascade arrangements are possible, some projects could be developed with energy storage costs lower than 10 US$/MWh. Most of the identified sites are located in areas where the land requirement is lower than 10 km$^2$/TWh.
- In Mexico, more than 272,000 possible locations could be suitable for developing closed-loop PHS systems with a total energy storage capacity of 4,200 TWh.
- Mexico has an infrastructure of more than 5,000 dams with an approximate overall water storage capacity of 150,000 hm$^3$; 82% of the total water storage capacity is concentrated in 180 dams. This infrastructure constitutes a potential resource for developing pumped hydro energy storage projects either by building an off-river reservoir at a higher level, or by installing pump-back systems when a cascade arrangement currently exists on a river.

- In Mexico, salt formations are located along the Gulf of Mexico where the States of Tamaulipas, Veracruz, Tabasco and Campeche shows salt formations that could be directly studied for CAES development purposes.
- While the gross potential in Mexico for PHS and CAES seems to be large, it is also evident that its necessary to conduct further research to assess the global potential for these two technologies at the national level in order to facilitate feasibility studies at specifics sites to identify the projects that could be developed in the short, mid- and long terms.

Study cases

- In Mexico, a variety of problems are identified that could be alleviated through the implementation of storage technologies, which could help the integration of renewable energies and lead to a mitigation of GHG emissions in the SEN.
- Access to information is currently limited, which makes a timely analysis of SEN operating problems difficult (at local level). Therefore, carrying out specific projects requires the close cooperation of CENACE and the actors involved.
- The five regions studied present different problems depending on a. o. their transmission capacity, the conventional and renewable generation, the demand, the regional generation matrix and in the future of the possible interconnection of new VRE. The problems identified on regional level are were:

  Peninsular
    - Curtailment
    - Frequency control problems.
    - Lack of supply of Natural Gas
    - Demand exceeded transmission
    - Demand exceeded supply
    - Some transmission lines reached their transmission limits

  Baja California Sur
    - Some conventional centrals are at the end of its useful life
    - Derating of centrals
    - Increase in residential and tourist demand
    - Transmission network underdeveloped
    - Load saturation in transformation banks
    - Voltage control problems

  North
    - Some centrals show derating
    - Saturation of transmission lines and voltages outside the permissible limits.
    - Non-supplied energy associated with saturation problems in the Northeast-North and North-Northwest connections.

  - Ciudad Juárez region will have an increase in peak demand
  - Increased load in autotransformers

Northeast

  - Transmission lines shows congestion like those in central and north direction.
  - Voltage variations
  - Increase in peak demand in the Monterrey area
  - Some plants show derating.
  - Participation of conventional technologies in generation is high.
  - Increase in the participation of VRE in the generation

Western

  - Increases in residential, commercial and industrial consumption
  - Low voltage profiles and regulation problems in some areas
  - Reduction in the transmission capacity of the region and saturation in some transmission lines.
  - Increase in the participation of ERV in the generation

- The delimitation of the storage projects must start from the identification of the main problems to be solved, the location and the physical characteristics of the network at the local level. The selection of type and size of energy storage technologies should be oriented to the anker problems to be solved at regional or local level.
- Energy storage technologies could displace different kinds of generation, depending of regional generation matrix and that will have a great influence on benefits.

## Cost benefit assessment

- The main conclusion of the cost-benefit analysis is that, from a social perspective, a few energy storage technologies (Batteries, PHS, Molten salts) make sense and could provide a significant net present value for both CFE and the company. society.
- There are many factors that determine the NPV, storage projects can have a positive NPV with very reasonable assumptions, an example where Li-Ion technology has a positive NPV is the scenario where the simple cycle generation of natural gas is displaced and when:
  - Storage is loaded 50% from renewable sources
  - $CO_2$ price is at least 15 US $ / ton
  - Natural gas price rises (for example, from US $ 1.70 to US $ 3.75 / MMBtu)
  - 10% reduction in current prices for LI-Ion systems (in recent years prices have dropped more than 10% / year).

- These technologies can also provide benefits not captured by the positive NPV, such as:
    - greater national energy independence,
    - facilitating the integration of renewable energy to meet international commitments,
    - strengthening the reliability of the network,
    - promoting access to energy in marginalized communities and
    - possibly creation of a new economic sector with added value in Mexico such as energy storage.

# D5 Mitigation potential of selected storage technologies in Mexico

## 5.1 Environmental impacts

- In general terms, it can be pointed out that emissions from storage systems due to their infrastructure (manufacture) are greater in electrochemical storage (e.g. Lead-Acid and Lithium Ion batteries) than in bulk technologies such as PHS or CAES.
- In the use phase emissions depends on the specific configuration (size) and application.

## 5.2 Ancillary services

- Some geographic regions or zones require special attention, such as: Bajío, Chihuahua, Riviera Maya, Saltillo and the isolated BCS system.
- In 2018 the capacity requirement for (fast) frequency control estimated is 37 MW, these data represent a minimum installation to help improve the operation of the network, this requirement could be supplied with storage technologies. By 2033 these capacity requirements are estimated to be 121 MW
- The reduction in emissions may be greater if storage technologies provide not only frequency regulation but also other related services, for example participating in energy reserves (e.g. ramping) and temporary transfer of energy.
- The technologies that will be mostly displaced will be: Combined Cycles, Coal, Turbogas, and Thermoelectric, in that order.
- The results show that Storage Technologies could be used positively to provide auxiliary services in the SIN, support the integration of renewables and deepen the reduction of emissions if clean energy or exclusively renewable energy will be used with higher percentages and this at a reasonable cost.

### 5.3 Modelling mitigation potential of ESS

- Even with no explicit climate ambition for the electricity sector, an optimal electricity market for storage can increase the deployment of Variable Renewal Energies (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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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.
- 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).

- 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 volume (MWh), the role of PHS could increase but the role of storage technologies would be in an overall way be 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.
- 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.
- 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 $MtCO_2$.
- 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.

# Appendices

D1: "Review of experiences and trends in electricity storage technologies in Mexico and globally"

No appendix

D2: "Technology Catalogue for energy storage",

2. Appendix A

2. Appendix B

D3: "Barriers and enablers to the implementation of storage technologies in Mexico"

3. Appendix A

3. Appendix B

D4: "Potential of storage technologies in Mexico"

4. Appendix A

Appendix 4.1, Peninsular

Appendix 4.2, Baja California Sur

Appendix 4.3, North: Juarez-Chihuahua

Appendix 4.4, Northeast: Saltillo-Monterrey

Appendix 4.5, Western: Hidalgo–Querétaro

D5: "Mitigation potential of selected storage technologies in Mexico"

5.1 Review of the environmental impact assessment of storage technologies.

No appendix

5.2. Use of storage technologies for ancillary services provision and its potential for climate change mitigation.

Appendix A, Generation Control

Appendix B, Methodology for calculating the Regulatory Reserve Requirement

Appendix C, Short circuit capacity and PV-curves

Appendix D, Energy Storage Calculation

Appendix E, Tables of emissions reduction by control area

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

D5.3 Appendix A

D5.3 Appendix B

# Web-Only Materials

From D2 Technology Catalogue for energy storage (data sheets)

D2 PHS.xlsx

D2 Li-ion.xlsx

D2 Lead Acid.xlsx

D2 VRB.xlsx

D2 NaS.xlsx

D2 Molten Salt.xlsx

D2 Flywheels.xlsx