4. Potential of storage technologies in Mexico

October, 2020

MEDIO AMBIENTE
SECRETARÍA DE MEDIO AMBIENTE Y RECURSOS NATURALES

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

Danish Energy Agency

Directory

María Amparo Martínez Arroyo, PhD

General Director, National Institute for Ecology and Climate Change

Elaboration, edition, review and supervision:

Claudia Octaviano Villasana, PhD

General Coordinator for Climate Change Mitigation

Eduardo Olivares Lechuga, Eng.

Director of Strategic Projects in Low Carbon Technologies

Roberto Ulises Ruiz Saucedo, Eng. Dr.

Deputy Director of Innovation and Technology Transfer

Loui Algren, M.Sc. (Global Cooperation)

Amalia Pizarro Alonso, PhD

Adviser, Mexico-Denmark Partnership Program for Energy and Climate Change

This report is part of the study:

Technology Roadmap and Mitigation Potential of Utility-scale Electricity Storage in Mexico

Drafted by:

Jorge Alejandro Monreal Cruz, M.Sc.

Juan José Vidal Amaro, PhD

Pawel Maurycy Swisterski, MSC. Econ.

Consultants, COWI, Mexico-Denmark Program for Energy and Climate Change

Commissioned by INECC with support of the Mexico-Denmark Program for Energy and Climate Change

D.R. © 2020 Instituto Nacional de Ecología y Cambio Climático

Blvd. Adolfo Ruíz Cortines 4209,

Jardines en la Montaña, Ciudad de México. C.P. 14210

http://www.gob.mx/inecc

Content

Content 5
Tables 7
Figures 8
Executive Summary 10
1. Mapping of geo-specific storage resources in Mexico 17
1.1 Pumped hydro storage geo-spatial resources 17
Global PHS resources 17
Pumped Hydro Energy Storage resources in Mexico 20
Existing dams in Mexico 23
1.2 Compressed Air Energy Storage geo-spatial resources 26
Global CAES resources 26
Geological underground resources for CAES in Mexico 28
2. Identification of five case studies of interest to Mexico. 36
2.1 Preliminary proposal of the case studies. 37
2.2 Evaluation criteria for case studies and preliminary proposal for the selection of five cases. 38
Mérida, Yucatán 38
Zimapán, Hidalgo 39
La Paz, BCS 39
Pesquería, Nuevo León 39
Villa de Reyes, SLP 39
Cuenca del Río Grijalva, Chiapas 40
2.3 Consultation and open discussion with the experts in a working group 40
3. Design a common framework for the description of the five case studies of interest 42
3.1 Locations 42
3.2 Approach 43
Technical component 43
Economical component 43
3.4 Data gathering 44
3.5 Economic Evaluation 46
Economic Externalities 47
Additional Assumptions 56

Key Assumptions and Model Limitations 56
3.6 Data sources 58
4. Case studies 61
4.4.1 Economic scenarios 61
4.4.2 Results 72
4.4.3 Conclusions and Takeaways 90
5. Study Cases technical summary 92
6. References 101

Tables

Table 1.1. Number of sites by energy storage, storage time and rank for Mexico and Central America. Self-elaboration with information from the Global summary spreadsheet available in (ANU, 2020).

Table 1.2. Overall storage capacity for Mexico and Central America. Self-elaboration with information from the Global summary spreadsheet available at (ANU, 2020).

Table 1.3. Compilation of information sources on geological formations in Mexico

Table 2.1. Preliminary proposal of the sites for the analysis of the case studies. Source: Own elaboration.

Table 2.2. Assessment criteria for case study sites. Source: Own elaboration.

Table 2.3. Regions of analysis for case studies. Source: Own elaboration.

Table 2.4. Selected case studies. Source: Own elaboration.

Table 3.1. Energy System Storage Sites. Source: Own elaboration.

Table 3.2. Environmental Impact Assessment (MIAs) projects data. Source: Own elaboration.

Table 3.3. Components of the PML and nodes. Source: Own elaboration.

Table 3.4. Capacity, generation and transmission capacity. Source: Own elaboration.

Table 3.5. Potential Positive Externalities of Energy Storage that at the time can be estimated.

Table 3.6. Quantification of Benefits Associated with Displaced Fossil Fuel Generation

Table 3.7. Quantification of Externalities Associated with Decreased Congestion

Table 3.8. "Conventional" Storage Earnings

Table 3.9. Parameters used in the CBM and data sources.

Table 4.1. Base Case and Sensitivity Scenarios.

Table 4.2. Base Case Assumptions and Parameters

Table 4.3. Sensitivity Scenarios

Table 4.4. Base Case Cost Benefit Analysis Outputs Over the Life of a Project, millions 2020$ MXN rounded to the nearest million.

Table 4.5. Sensitivity Analysis 2A, All Technologies replace fuel oil generation, millions 2020$ MXN rounded to the nearest million.

Table 4.6. Sensitivity Analysis 2B, All Technologies replace natural gas simple cycle generation, millions 2020$ MXN rounded to the nearest million.

Table 4.7. Results scenarios 4A.1 and 4A.2, described in in Table 43: The Displaced fuel and generation is varied.

Table 4.8. Results scenario 4B described in in Table 4.3: Specific investment and operating costs are varied

Table 4.9. Results scenario 4C described in Table 4.3: the CO_2 price varies.

Table 4.10. Results scenario 4D described in in Table 4.3: the social discount rate varies

Table 4.11. Results scenario 4E, described in in Table 4.19: the percentage % of storage charged with VRE is varied

Table 4.12. Results scenario 4F, described in Table 4.19: scenario 4A.1 is reset (the displaced fuel changes, all else remains the same) and CO2 price is varied.

Table 4.13. Results scenario 4G, described in Table 4.19: A matrix on the basis of scenarios 4E & 4F: Fuel Displaced by Storage is simple cycle and every price of CO_2/Tonne in scenario 4F is matched with each % of stored energy sourced from VRE in scenario 4F.

Table 5.1. Identified problems per study case.

Table 5.2. Identified problems, nodes, regional generation technology per study case.

Table 5.3. Identified problems, nodes, regional generation technology per study case.

Table 5.4. Identified regional energy storage requirements. Fuente: References: 3,4,5,6

Figures

Figure 1.1. Global potential SPHS projects and costs. (Hunt, et al., 2020).

Figure 1.2. Global pumped hydro Atlas. Potential 150 GWh and 18 h storage time PHS sites. Source: (ANU, 2020.).

Figure 1.3. Seasonal hydropower storage costs for Mexico. Adapted from (Hunt, et al., 2020).

Figure 1.4. Average land requirement for energy storage in different basins, extracted from (Hunt, et al., 2020).

Figure 1.5. Possible closed-loop Pumped Hydro Storage sites in Mexico and Central America classified by economic rank. Adapted from (Australian renewable energy agency, n.d.).

Figure 1.6. Location and water storage capacity range for the principal dams in México. Names of dams with water storage capacities over 1,000 hm3 are shown, names of dams over 4,000 hm3 of water storage capacity are shown in bold typeface (CONAGUA, 2018).

Figure 1.7. Cascade dams system in the Grijalva River. NAME: Maximum extraordinary reservoir capacity; NAMO: Operative reservoir capacity. Adapted from (CONAGUA, 2020).

Figure 1.8. Dam systems on the San Juan River in Queretaro and Tula River in Hidalgo, and their joint in the Zimapán dam (yellow dot). Adapted from (CONAGUA, 2020.).

Figure 1.9. Map of worldwide underground salt deposits (Sabine Donadei, 2016).

Figure 1.10. Global suitable locations for CAES. The stars represent the USA and Germany CAES plants (Aghahosseini & Breyer, 2018).

Figure 1.11. Map of the deep-water prospective regions in the Gulf of México. Source: (CNH, 2019a).

Figure 1.12. Location of the basins: a) Burro-Picachos, Sabinas and Burgos; b) Tampico – Misantla; c) Veracruz; and d) Sureste and Cinturón plegado de Chiapas. Adapted from the geological atlases available at (CNH, 2019b)

Figure 1.13. Hydrocarbon wells location in the basins represented by black dots. Basins:(a) Burro-Picachos, Sabinas and Burgos; (b) Tampico – Misantla; (c) Veracruz and (d) Sureste and Cinturón plegado de Chiapas. Adapted from the geological atlases available at (CNH, 2019b).

Figure 1.14. View of the online website for consulting the geological charts (SGM, 2020).

Figure 1.15. Vertical cuts in the E15-1-4 Coatzacoalcos mining geological chart (SGM, 2020).

Figure 1.16. Surface infrastructure of the underground CYDSA-PEMEX salt-cave based LP gas storage facility in Veracruz Mexico. Source: (CYDSA, 2020).

Figure 2.1. Process of identification and selection of case studies. Source: own elaboration.

Figure 4.1. NPV by components and regions. Source: own elaboration.

Figure 4.2. Technology Comparison, Displacing Fuel Oil Generation. North Region, Scenario 2A. Source: own elaboration.

Figure 4.3. Technology Comparison, Displacing Fuel Oil Generation. North Region, Scenario 2B. Source: own elaboration.

Figure 4.4. Fossil Fuel Displacement by Li-Ion Storage, Peninsular Region. By Fuel & Generation Type. Source: own elaboration.

Figure 4.5. Li-Ion Cost Scenarios, Peninsular Region. Scenario 4B. Source: own elaboration.

Figure 4.6. Li-Ion Storage Project NPV as a Function of CO2 Price. Peninsular Region. Source: own elaboration.

Figure 4.7. Li-Ion Storage Project NPV as a Function of Discount Rate. Peninsular Region. Source: own elaboration.

Figure 4.8. Li-Ion Storage Project NPV as a Function % Charged with VRE. Peninsular Region. Source: own elaboration.

Figure 4.9. Li-Ion Storage Project NPV as a Function of CO_2 Price. Replacing Simple Cycle Natural Gas Generation, Peninsular Region. Source: own elaboration.

Figure 4.10. Li-Ion Storage Project NPV as a Function of CO_2 Price & % Charged with VRE, replacing Simple Cycle Natural Gas Generation, Peninsular Region. Source: own elaboration.

Figure 5.1. Amount of ESS required

Executive 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 1. 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. – High share of renewable energies integration.	– Energy management – Renewable energy capacity firming

Control Region	Study Zone	Transmission region	Problems identified	Possible services from storage technologies
				– Ramping
Peninsular	Yucatán	Tabasco, Lerma, Mérida, Cancún Mayan Riviera	– Blackouts due to natural gas shortages. – Short circuit due to fire and high temperatures.	– Energy management – Ramping – Seasonal storage – back-up power
Western	Hidalgo – Querétaro (Zimapán)	Central, Querétaro, San Luis Potosí, Tamazunchale, Salamanca	– Congestion. – Non-ideal commercial conditions - Legacy contract (only to deliver energy). – Non-profitable generation machinery wastage (working synchronous capacitor).	– Frequency regulation, – Decongestion – Ramping – Transmission & distribution investment deferral.
Northeast	Coahuila - Nuevo León	Monterrey, Saltillo	– Congestion. – High share of renewable energies integration.	– Energy management – Renewable energy capacity firming – Ramping
South Baja California	La Paz	Villa Constitución, La Paz	– Supply Problems – Congestion – High share of renewable energies integration.	– Ramping. – Renewable energy capacity firming. – 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.

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

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 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 2. Base Case and Sensitivity Scenarios.

Base Case Scenario Locations: Control Region/Nodes	Sensitivity Analysis Scenarios
1: Western/ Zimapán – San José Iturbide	Base case outcome is reported without sensitivity analysis
2: North/ Moctezuma – Cereso Juárez	Outcomes are reported for all storage technologies Where: 2A North: The fuel oil generation is displaced 2B North: The simple cycle gas generation is displaced
3: Northeast/ Güémez-Saltillo	Base case outcome is reported without sensitivity analysis
4: Peninsular/ San Ignacio – Playa Mujeres	Base case outcome is reported, as well as outcomes where: 4A Peninsular: Displaced generation is varied 4B Peninsular: Specific investment and operating costs are varied 4C Peninsular: CO_2 price is varied 4D Peninsular: Social discount rate is varied 4E Peninsular: The % of storage charged with VRE is varied 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)/ 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.

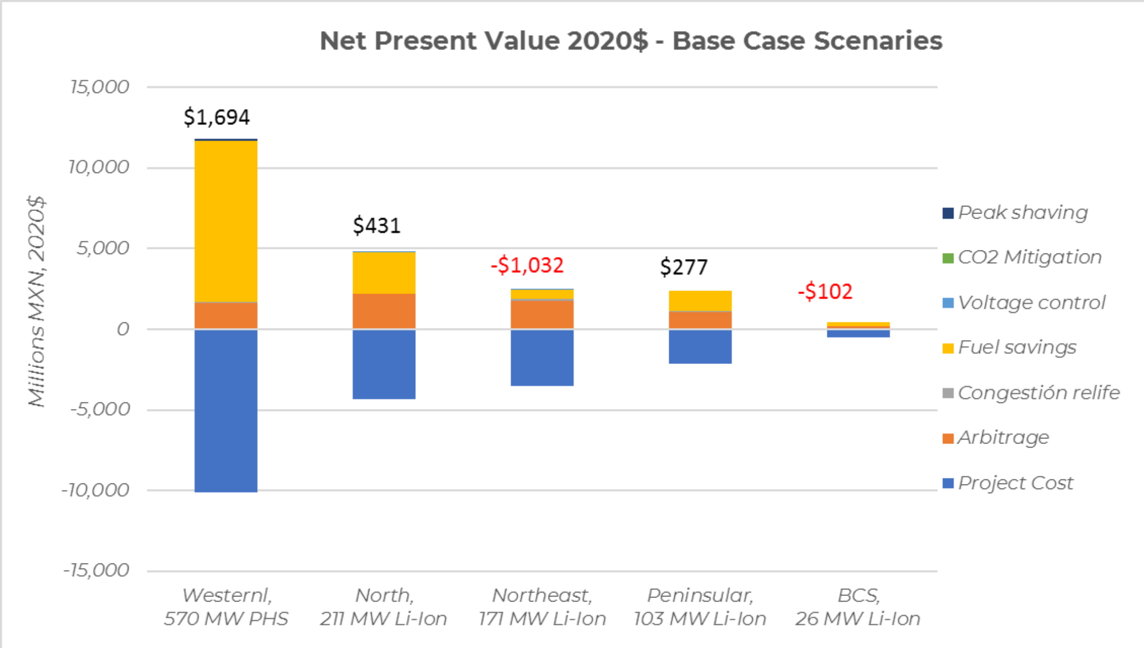


Figure 1. Net Present Value in MXN pesos for the 5 study cases – base case scenario.

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.

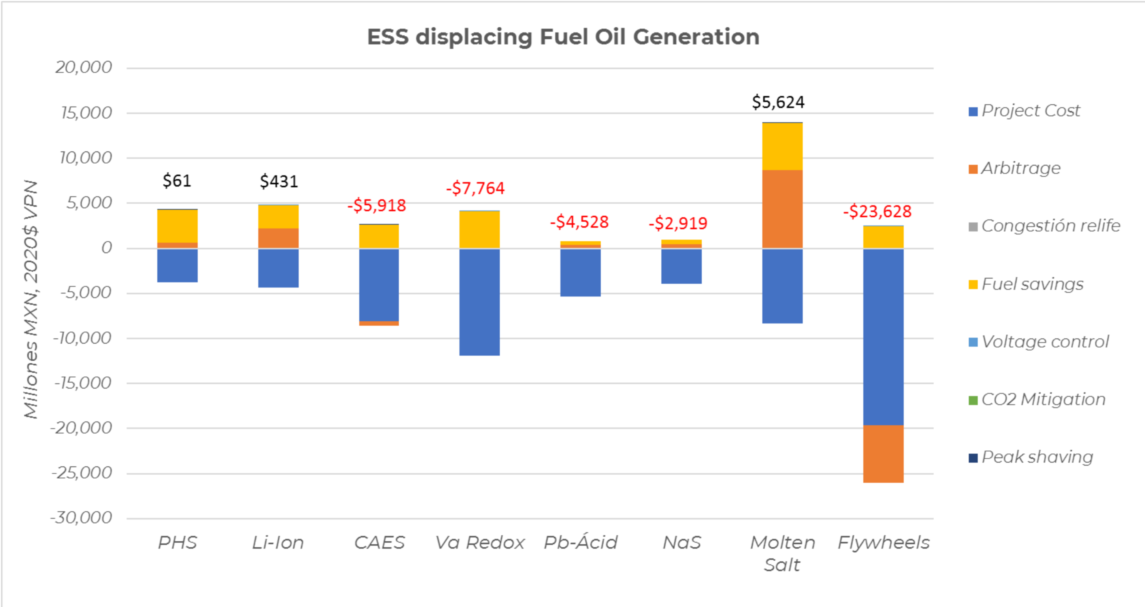


Figure 2. Net Present Value in MXN pesos for Scenario 2A - North control region, all technologies and fuel oil displacement.

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.

1. Mapping of geo-specific storage resources in Mexico

The deployment of pumped hydro energy storage (PHS) as well as compressed air energy storage (CAES) depends on the existence of specific geographical conditions, such as hydrology, orography, geology, etc. This section aims to show that there is a potential for developing utility-scale pumped hydro energy storage and compressed air energy storage projects in Mexico by identifying geo-specific storage resources in Mexico. It is not the scope of this section to make a thorough assessment of the specific potential of both technologies or to identify feasible sites, but to give a glimpse to the reader of potential sites of PHS and CAES in Mexico. In the section “Pumped hydro storage geo-spatial resources", studies on global PHS potential estimates are presented followed by a discussion on the Mexican resources that can be utilized for PHS. The section “Compressed air energy storage potential” studies on estimates of global potential for CAES are presented followed by a discussion on geological potentials for developing CAES projects in Mexico.

1.1 Pumped hydro storage geo-spatial resources

Global PHS resources

A brief description of the PHS resources around the world will be shown based on international reference. The findings on two sources of information regarding global general estimates on PHS resources are discussed, with a focus on Pumped Hydropower Storage through open-loop systems (seasonal PHS) and closed-loop systems

Open-loop systems. In the study “*Global resource potential of seasonal pumped hydropower storage for energy and water storage*” which assesses the World’s potential of Seasonal Pumped Hydropower Storage (SPHS) of water and energy, the global landscape was scanned with a 450 m grid resolution to identify mountainous regions alongside rivers with high hydraulic heads supporting cost-efficient SPHS system designs. SPHS plants are open-loop systems characterized by high-head variation reservoirs, with 150 m average height dams, built off-stream and connected through a tunnel to a major river. Water is pumped into the off-stream reservoir during periods of high-water availability or low energy demand and is discharged from the reservoir when it is scarce or when additional electricity capacity is required; water can be stored over annual or pluri-annual cycles. Energy storage costs and land use impacts for SPHS are lower than those for conventional hydropower plants, because the off-river reservoirs allow higher hydraulic head variations (Hunt, et al., 2020).

Hunt et al (2020) identify more than 5.1 million potential SPHS projects all over the globe with a fixed generation/pumping capacity of 1 GW, This study shows that SPHS costs vary from 0.007 to 0.2 US$/m of water stored, 1.8 to 50 US$/MWh of energy stored and 370 to 600 US$/kW of installed power generation. This potential is unevenly distributed with mountainous regions demonstrating significantly more potential. The estimated world energy storage capacity below a cost of 50 US$/MWh is 17.3 PWh, approximately 79% of the world electricity consumption in 2017.

To assess the global potential of SPHS, the methodology used integrates five critical components, which are: topography, river network and hydrology data, infrastructure cost estimation and project design optimization. SPHS project suitability mainly depends on the topography, distance to a river and water availability, which together determine the technical potential. Additional contextual factors, such as distance from energy demand and associated transmission infrastructure losses and associated costs, determine the economic feasibility. Since storage potential and infrastructure costs are highly dependent on the topography, this spatially explicit approach identifies numerous technically feasible candidate sites and provides estimates of costs.

The model goes through each grid cell location delineated at a 15" resolution, implementing a detailed siting assessment that accounts for topography and hydrology in the calculation of project-level costs. The model performs the stages as follows.

1. It looks for a river with reasonable flow rate up to 30 km away from a reservoir
2. It checks if a dam up to 250 m high can be built from the grid cell
3. It removes projects with competing dams.
4. It finds the flooded side of the dam and creates the reservoir.
5. It calculates the volume and flooded areas,
6. It compares the size of the storage site with the water available for storage
7. It estimates the costs of the dam, tunnel, turbine, generator, excavation and land,
8. It estimates water and energy storage costs

The study identifies, with the intention of eliminating competing projects and focusing on the best projects per region, the projects with the lowest costs for water storage (US$/m^3), long (US$/MWh) and short-term (US$/kW) energy storage, within a 1 arc degree resolution of the globe are presented. This consists of 1,457 water storage projects with water storage costs lower than 0.2 US$/m^3 and 1,092 energy storage projects with energy storage cost lower than 50 US$/MWh and water storage costs lower than 0.2 US$/m^3 (some of the water projects consist of the same energy projects). The analysis considers a deliberate high land-value of 41,000 US$/ha. In the mountainous regions where a cascade SPHS system can be developed, the energy storage costs are the lowest, those below 6.8 US$/MWh are more economically attractive than for example energy storage with natural gas (Figure 1.1).

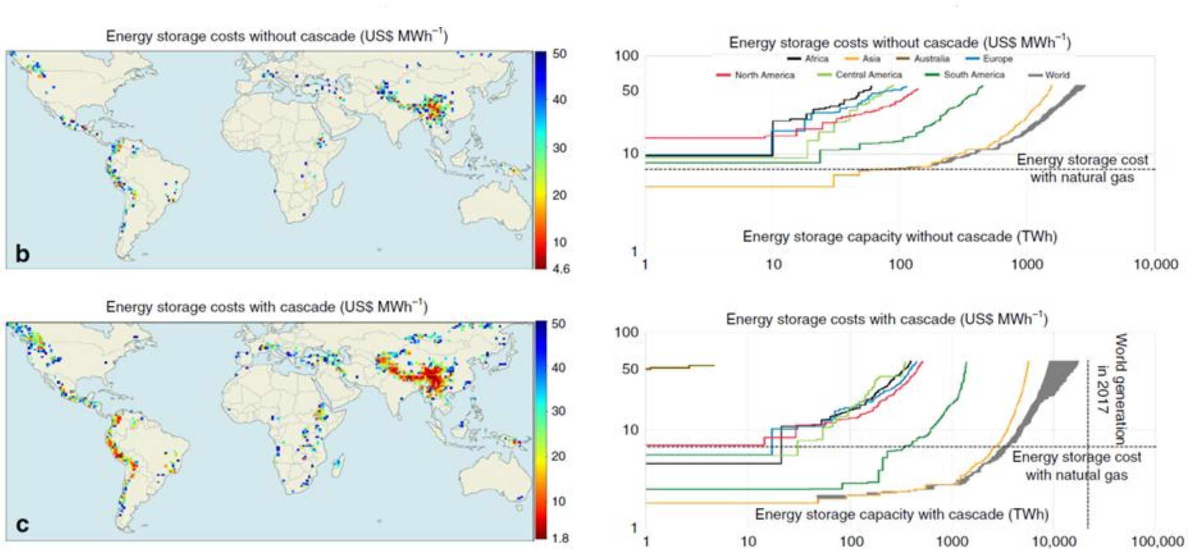


Figure 1.1. Global potential SPHS projects and costs. Extracted from: (Hunt, et al., 2020).

Closed-loop systems. The Australian Renewable Energy Agency developed a geographic-information-system-based website for providing spatial information relevant to the renewable energy industry, the Australian Renewable Energy Mapping Infrastructure (AREMI) which hosts information regarding electricity infrastructure, environment, boundaries, topography, population, weather, communications and transport infrastructure and renewable energies for Australia (Australian renewable energy agency, n.d.).

The pumped hydro energy storage (PHS) module in the AREMI was developed by the 100% Renewable Energy Group (100REG) of the Australia National University and despite that was developed for the AREMI, it includes the only one global estimate information regarding potential sites for close-loop PHS. The identified sites correspond to locations that comprise an upper and lower pair of off-river reservoirs connected by a hypothetical tunnel. Each potential site is described by hydraulic head, slope, water volume, water area, rock volume, wall dam length and height, water/rock ratio, energy storage potential, storage time, approximate relative cost, latitude and longitude; however, none of the sites have been studied from a geological, hydrological, environmental, commercial, heritage or land ownership perspective nor any feasibility study has been conducted (AREA, 2020).

Based on the AREMI, the 100REG identified about 616,000 potential sites between the latitudes 56°S – 60°N for developing PHS projects all over the world with an overall storage potential of about 23,000 TWh as shown in Figure 1.2 (ANU, 2020). According to the authors, this resource is equivalent to 100 times the amount of energy storage required to support a 100% global renewable electricity system, and despite many of the sites may prove to be unsuitable, only about 1% of this potential is required to support a 100% global renewable electricity grid (Blakers, Stocks, Lu, Cheng, & Stocks, 2019). The global identified sites have an energy storage potential in the range of 2 - 150 GWh and a storage time of 5h to 25 h.

Figure 1.2. Global pumped hydro Atlas. Potential 150 GWh and 18 h storage time PHS sites. Source: (ANU, 2020.).

Note: Ranked A corresponds to more cost-effective sites; class A costs are approximately half of that of rank E by storage energy cost, class.

As shown in Figure 1.2, potential SPHS sites are spread unevenly over the world, mountainous regions from Asia as well as South America concentrate the larger number of identified sites; North America, especially in south and central México, the western border of the USA and Canada also possess significant potential sites. It is also clear that the regions with the most competitive energy-storage costs are the mountainous chains in South America and Asia.

Pumped Hydro Energy Storage resources in Mexico

A brief discussion on potential resources for developing open-loop and closed-loop pumped hydro energy storage systems in Mexico is shown based on international studies. Estimated energy storage costs, land use rates and geographic distribution for open-loop systems is presented. For closed-loop systems a total energy storage potential is identified as well as a number of possible PHS sites. The potentials presented are gross estimates and do not correspond to sites where any specific feasibility study has been conducted.

Open-loop SPHS. Hunt et al (2020) identify several sites for developing SPHS projects in Mexico, these sites correspond to open loop facilities that take water from a river with important seasonal water flow variation and store it into an upper reservoir or reservoirs when cascade arrangements are possible. The stored water helps to reduce the seasonal flow variations in the river.

Energy storage costs are estimated for these sites considering a flow variation index, water available for storage, water storage capacity, cost of the infrastructure construction and land cost. The costs range for the possible SPHS sites in Mexico is from 1.8 US$/MWh to 50 US$/MWh as illustrated in Figure 1.3. When cascade arrangements are considered, a few more sites result in an energy storage cost lower than 10 US$/MWh compared with the no-cascade scenario.

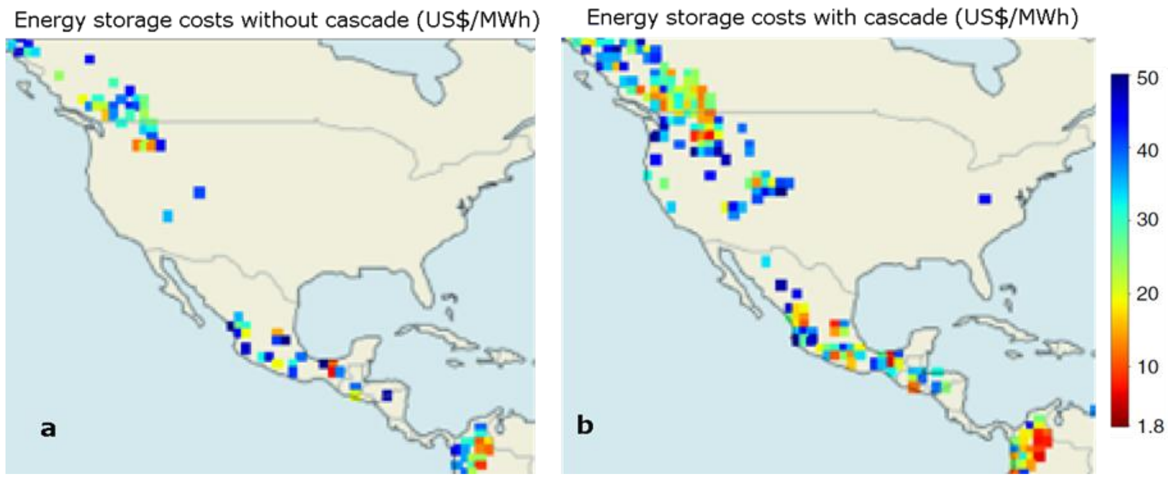


Figure 1.3. Seasonal hydropower storage costs for Mexico. Adapted from (Hunt, et al., 2020).

As seen in Figure 1.4, Mexico could develop SPHS systems especially in the central and southeast regions as well as in the mountains of the west coast. These sites correspond to locations in the mountain ranges of "Sierra madre occidental", "Sierra madre oriental" and "Sierra madre del Sur". Land requirement for the possible sites is relatively low (Figure 1.4), while the range in Mexico is from 0.8 km^2/TWh to 20 km^2/TWh as in other countries, most of the identified sites are located in areas where the land requirement is lower than 10 km^2/TWh. SPHS systems take advantage of the high-level variations that the off-river reservoirs allow, therefore these energy storage facilities are less land-intensive than conventional hydro power plants, which could have space impacts ten times higher than SHPS (Hunt, et al., 2020).

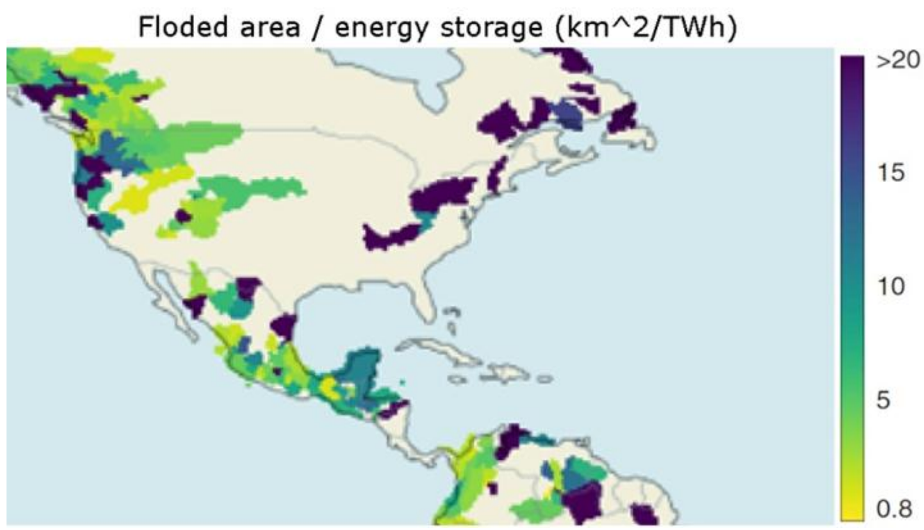


Figure 1.4. Average land requirement for energy storage in different basins, extracted from (Hunt, et al., 2020).

Closed-loop PHS. The AREMI system developed by the Australian Renewable Energy Agency allows identifying potential sites for close-loop PHS, PHS systems in which none of the two reservoirs are linked to a river, water is filled once in one of the reservoirs to begin cycle of pumping up when there is an excess of electricity and discharge when additional electricity is required.

The AREMI system shows several sites where closed-loop PHS systems could be developed in Mexico (Figure 1.5); it agrees with the Hunt et al. study in mapping the possible sites over the large Mexican mountain ranges (see Figure 1.3), however the number of locations identified by the AREMI system increases considerably due to the river-free characteristic of the closed-loop PHS.

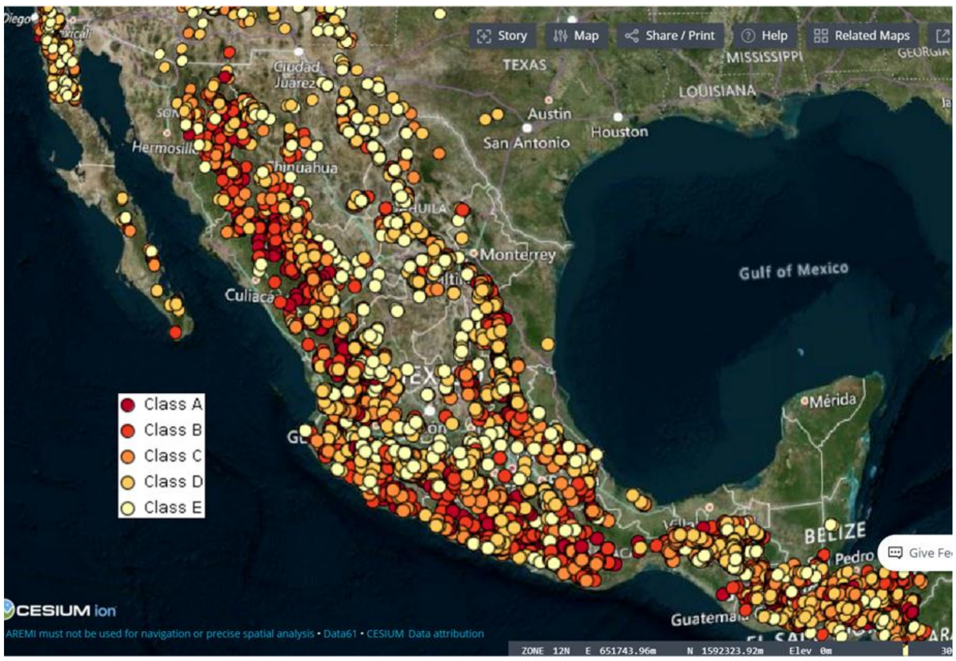


Figure 1.5. Possible closed-loop Pumped Hydro Storage sites in Mexico and Central America classified by economic rank. Adapted from (AREA, 2020).

According to the AREMI system, in the Central America region where Mexico is aggregated, there are more than 272,000 possible locations where a pair of off-river reservoirs can form a closed-loop PHS system with a total energy storage capacity of 4,200 TWh. The sites are classified by amount of energy storage paired with storage time and by energy storage cost, which is calculated taking into account water-rock-ratio (rock removed to build the dam), hydraulic head, slope between reservoirs and resulting power. These costs lead to a ranking from A, that corresponds to lowest cost facility, to E, that corresponds to the most expensive pair of reservoirs (AREA, 2020). Tables 1 and 2 shows the number of sites, capacity ranges, storage time and rank for the Central America region.

Table 1.1. Number of sites by energy storage, storage time and rank for Mexico and Central America. Self-elaboration with information from the Global summary spreadsheet available in (ANU, 2020).

Energy and storage time ranges per site	Power per site (GW)	Number of sites by rank					
		A	B	C	D	E	Sub total
2GWh_6h	0.3	51	1489	7599	15758	19404	44301
5GWh_6h	0.8	855	6291	14465	18604	17479	57694
5GWh_18h	0.3	2305	6503	11638	15596	14704	50746
15GWh_6h	2.5	491	4278	10252	12641	11818	39480
15GWh_18h	0.8	4864	8337	10676	10375	6705	40957
50GWh_6h	8.3	277	2380	4920	5644	4355	17576
50GWh_18h	2.8	2818	4512	4695	3853	2185	18063
150GWh_18h	8.3	1110	1112	834	549	280	3885
	Total	12771	34902	65079	83020	76930	272,702

Table 1.2. Overall storage capacity for Mexico and Central America. Self-elaboration with information from the Global summary spreadsheet available at (ANU, 2020).

Energy and storage time ranges per site	Power (GW) per site	Energy (TWh)					
		A	B	C	D	E	Subtotal
2GWh_6h	0.3	0.102	2.978	15.2	31.52	38.81	88.602
5GWh_6h	0.8	4.275	31.455	72.33	93.02	87.4	288.47
5GWh_18h	0.3	11.53	32.515	58.19	77.98	73.52	253.73
15GWh_6h	2.5	7.365	64.17	153.8	189.6	177.3	592.2
15GWh_18h	0.8	72.96	125.06	160.1	155.6	100.6	614.355
50GWh_6h	8.3	13.85	119	246	282.2	217.8	878.8
50GWh_18h	2.8	140.9	225.6	234.8	192.7	109.3	903.15
150GWh_18h	8.3	166.5	166.8	125.1	82.35	42	582.75
	Total	417.5	767.57	1065	1105	846.6	4,202

Existing dams in Mexico

A brief discussion on the Mexican dam infrastructure and its advantages for developing PHS projects is presented based on public information released by the Mexican governmental institution CONAGUA.

Mexico has an infrastructure of more than 5,000 dams with an approximate overall water storage capacity of 150,000 hm^3, this infrastructure is utilized for electricity generation, water supply, flood control, underground aquifers recharge, flow deviation and flow control; 180 dams concentrate 82% of the total water storage capacity (127,373 hm^3) (CONAGUA, 2018). Figure 1.6 shows the location of these 180 principal dams classified by water storage capacity.

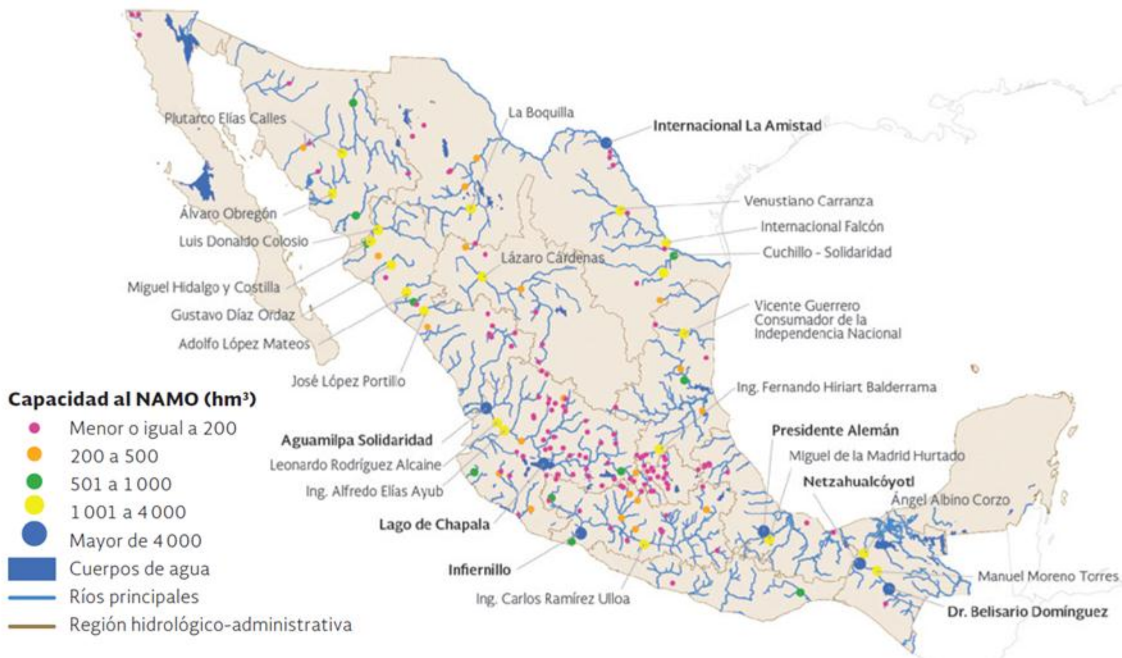


Figure 1.6. Location and water storage capacity range for the principal dams in México. Names of dams with water storage capacities over 1,000 hm^3 are shown, names of dams over 4,000 hm^3 of water storage capacity are shown in bold typeface. Source: CONAGUA, 2018).

Mexico's dam infrastructure naturally constitutes a potential resource for developing pumped hydro energy storage projects either by building open-loop systems with off-river reservoirs at a higher level linked to the main river or dam, as presented by Hunt et al (2020), or by installing a pump-back system when a cascade arrangement currently exists on a river.

The National Water Commission (CONAGUA by its acronym in Spanish), developed a GIS based online tool (Water National Information System, SINA by their acronym in Spanish) where the 180 principal Mexican dams can be identified along with the rivers in which they are constructed (CONAGUA, 2020). An example of a cascade dam system in Mexico exists in the Chiapas State, as seen in Figure 1.7, the Grijalva river is dam up in four places by the dams “La Angostura”, “Chicoasén”, “Mal paso” and “Peñitas”, the four dams are used for electricity generation and flooding control.

A careful exploration in the SINA allows identifying other cascade dam systems that could be suitable for pump-back energy storage. Figure 1.8 shows the Tula and San Juan rivers in the states of Queretaro and Hidalgo respectively in central Mexico, joining in the Zimapán dam; both rivers are dam up in several spots that are in cascade with the Zimapán dam too. However, despite the important number of dams in Mexico, there are neither public studies that help to assess the feasible PHS potential on the Mexican dam infrastructure nor feasibility studies on specific dams or cascade dam systems.

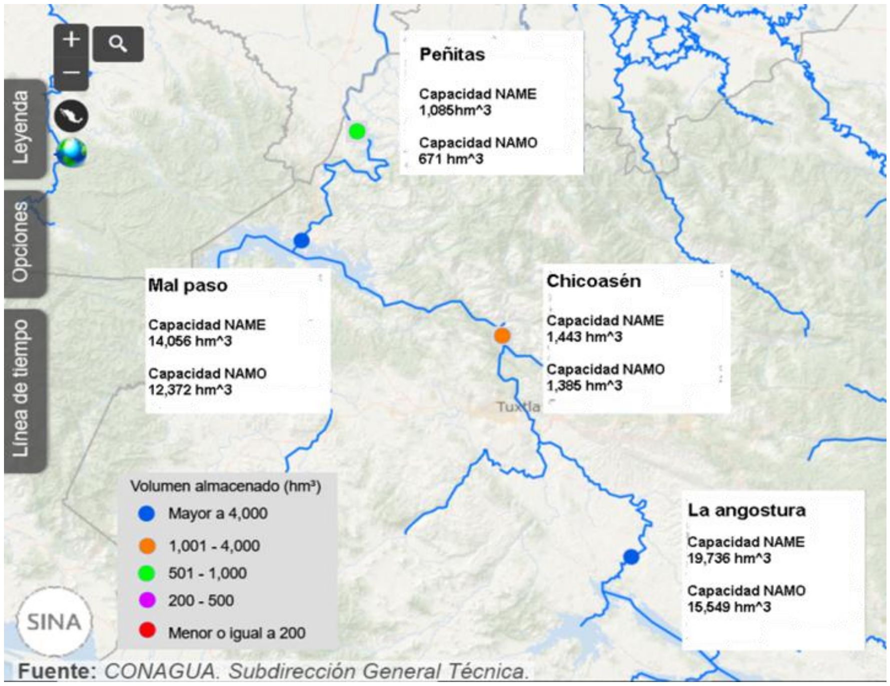


Figure 1.7. Cascade dams system in the Grijalva River. NAME: Maximum extraordinary reservoir capacity; NAMO: Operative reservoir capacity. Adapted from (CONAGUA, 2020).

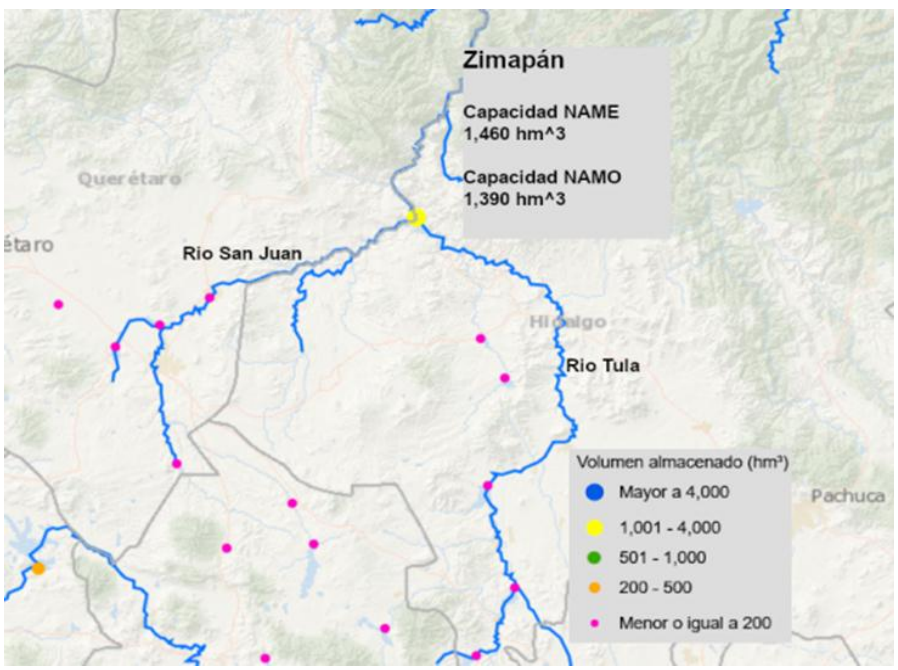


Figure 1.8. Dam systems on the San Juan River in Queretaro and Tula River in Hidalgo, and their joint in the Zimapán dam (yellow dot). Adapted from (CONAGUA, 2020.).

1.2 Compressed Air Energy Storage geo-spatial resources

Global CAES resources

Global underground geological resources for Compressed Air Energy Storage are shown based on international reference. The types of geological formations that can be suitable for CAES are described. Potential for CAES related to saline formations, hard rock and porous rock underground caverns and its distribution by country is presented.

As mentioned in (Donadei, 2016) the use of compressed air to store energy is currently deployed in applications ranging from very small outputs up to installations with capacities of various megawatt. However, the aim of this analysis is to identify utility-scale CAES resources, for this reason the focus of this section is on underground caverns that could be suitable for energy storage at grid scale, comparable to pumped hydro power plants.

There are several options for underground grid-scale CAES in geological formations such as natural porous storages, i.e. depleted oil and gas fields and aquifer formations, artificially constructed cavities such as salt and rock caverns, and depleted mines.

Although the deployment of intermittent renewable energy generation plants has reawakened interest in this type of energy storage, there are only two CAES utility-scale plants operating in the world. The underground CAES power plant constructed in Huntorf (Germany) in the middle 1970s was constructed to assist non-flexible coal and nuclear power plants, during low periods of demand, the energy is stored in the CAES facility and is feed back into the grid during periods of high demand; the CAES plant also provides cold-start capacity services, frequency regulation and phase shift assistance (Garvey, 2016). The second CAES power plant was constructed in McIntosh, Alabama (United States) in 1991. Technical details about these two facilities are shown in the technology catalogue.

According to (Garvey, 2016), "Underground CAES generally has a number of advantages over surface storage tanks:

- High storage capacity as a result of large volumes and high operating pressure capacities of up to 200 atm.
- Considerable protection against external influences since the only surface devices are the connection valves.
- Very low footprint compared with surface pressure tanks.
- Low specific storage capacity costs".

When storing compressed air in underground geological formations, the following aspects become relevant (Garvey, 2016):

- "The high reactivity of oxygen in compressed air, for example, forming compounds with the mineral constituents of the storage rock, and thus leading to oxygen depletion.
- Suitability/dimensioning of the storage for frequent, rapid operation cycles, and high injection and withdrawal rates, because CAES power plants are typically operated in an extremely fluctuating mode.
- Possibility of operating the storage for a short period of time at atmospheric pressure, for example, during repairs and maintenance measures".

When building a CAES facility, having a one large open-space and inert cavity provides many advantages; hence salt caverns become the best alternative due to low specific costs, high level of imperviousness and large realizable volumes, which allows flexibility regarding injection and withdrawal cycles (Donadei, 2016). On the other hand, depleted oil and gas fields, or aquifers, which consist of a large number of microscopic interconnected pore spaces, result less favorable regarding injection and withdrawal flexibility because air must counteract the resistance of a pore matrix to the flow of gases, nevertheless these type of formations are also recognized as alternatives for developing CAES facilities especially when salt formations are not an available resource. Advantages and disadvantages of each type of formation for CAES can be consulted in (Garvey, 2016).

Existing CAES power plants in Germany and the United States use salt caverns as the storage vessel. "Salt caverns are artificial cavities in underground salt formations, which are created by the controlled dissolution of rock salt by injection of water during the mining process" (Donadei, 2016). Today there are more than 2,000 salt caverns in North America and over 300 salt caverns in Germany used to store energy carriers such as natural gas, oil and oil derivatives, hydrogen, compressed air and LP gas (Garvey, 2016)

The distribution of salt deposits worldwide tends to favor some countries while others have low or no resources at all. As seen in Figure 1.9, northern European countries, Canada and the USA in America, a large coastal area below the Guinea gulf, the north of Africa, some Middle East countries and Russia, concentrate most of the salt deposits (Donadei, 2016).

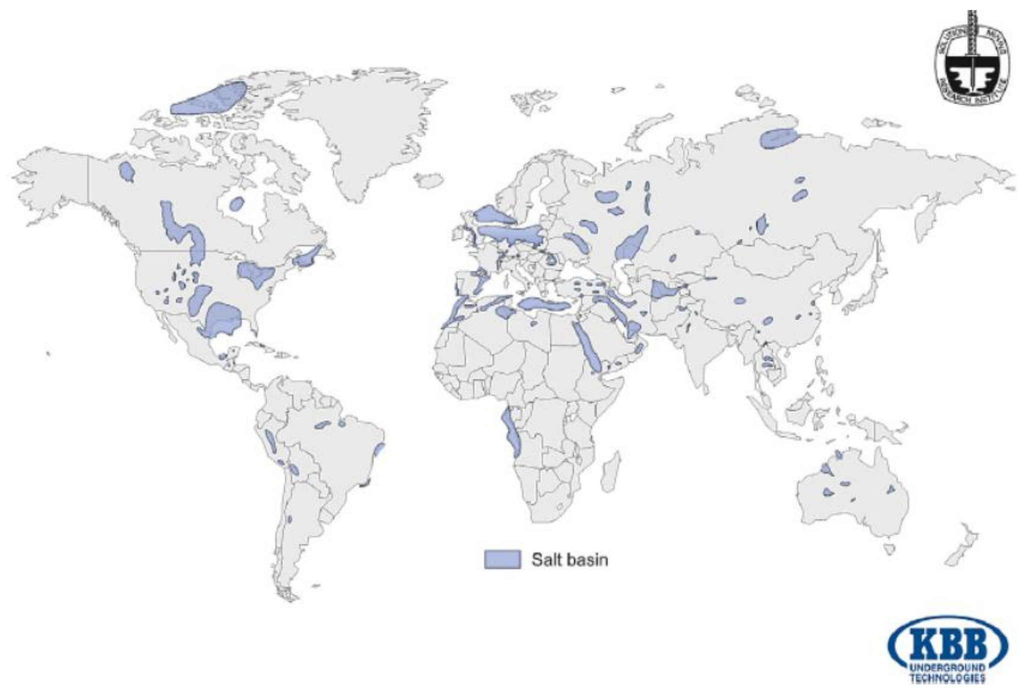


Figure 1.9. Map of worldwide underground salt deposits (Donadei, 2016).

Using as a reference the technical parameters from the two operating CAES plants in the world, the McIntosh and Huntorf plants drilled for 230 m and 150 m depth, (Aghahosseini & Breyer, 2018) analyzed the geological resources of salt, hard rock[2], and porous rock cavities for estimating a global CAES potential. Three scenarios were constructed including different

[2] Hard rock in the study corresponds to igneous and metamorphic rocks such as granite, gneiss, basalt and schist.

constraints, resulting in 1%, 5% and 10% CAES-suitable total area of the global scanned surface. In the most conservative scenario, the North America region possesses the most CAES-suitable geological resource, with 0.26% of total area analyzed, followed by Sub Saharan Africa and South America with 0.20% and 0.19% respectively. Furthermore, most of the countries possess some CAES-suitable geological resources (Figure 1.10).

The total energy that can be stored in the global geological resources is estimated at 6,574 TWh (Aghahosseini & Breyer, 2018) according to the authors, between 70% to 80% of this stored energy would be sufficient for supporting a 100% global renewable energy system using only one full charge-discharge CAES cycle, hence, there cannot be a major constraint in the global geological resource for supporting a global 100% renewable energy scenario. The study concludes that the global geological CAES potential can be used as a bulk energy storage option when balancing electricity demand and supply is needed, helping to solve the intermittency of renewables towards a 100% renewable energy system.

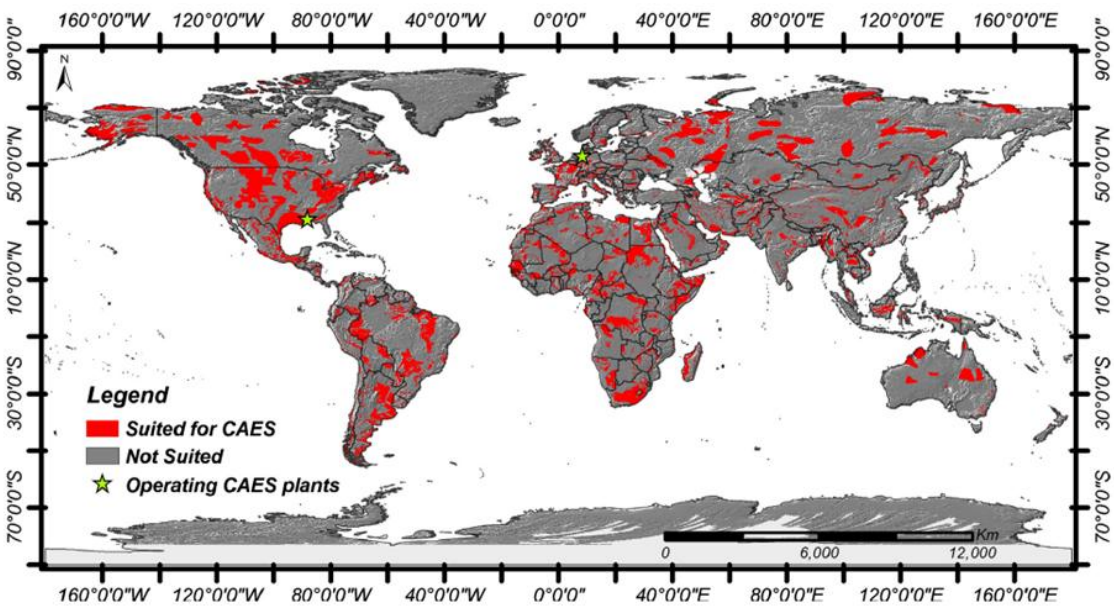


Figure 1.10. Global suitable locations for CAES. The stars represent the USA and Germany CAES plants (Aghahosseini & Breyer, 2018)

Geological underground resources for CAES in Mexico

Information on regions of Mexico where underground geological formations suitable for CAES are located is shown based on international studies as well as on national references including one saline-dome study, national hydrocarbon perspectives and geological atlases. Also, information on a private underground salt-cavern-based facility for providing LP gas storage services to PEMEX is presented.

As shown in Figure 1.10, the extension of hard rock, porous rock and saline underground formations in México lead to an important possibly suitable CAES resource. With the exception of Sinaloa, Durango and Nayarit and the Yucatán peninsula, most of the States in Mexico could develop CAES projects taking advantage of the different underground geological resources aforementioned and analyzed in (Aghahosseini & Breyer, 2018) (Figure 4.10). Many oil and gas deposits are related to certain geological salt and Sulphur structures, therefore, studies and explorations on salt are directly related to activities on hydrocarbon exploration and extraction, likewise, given this association, salt structures are conceived as means for locating oil fields.

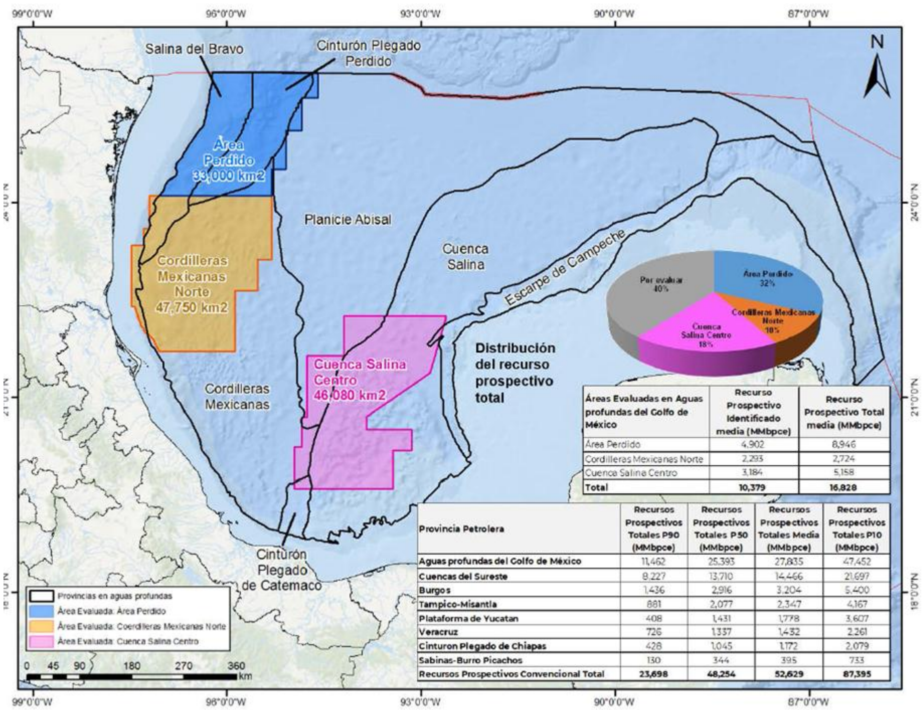
The existence of saline deposits is well known in various parts of Mexico; in (Donadei, 2016) large areas in the States of Chihuahua Nuevo Leon and Tamaulipas in north Mexico as well as coastal and undersea formations in Veracruz, Tabasco and Campeche in the Gulf of Mexico are identified as saline deposits that could be suitable for CAES (Figure 4.9). In (Benavides García, 1983) the States of Chihuahua, Nuevo Leon, Veracruz, Tabasco, Oaxaca and Chiapas are recognized by possessing saline deposits.

In the Southeast Mexico there are numerous oil fields associated with salt structures, some of them, such as those of Jaltipan, San Cristobal, Soledad, Tecuanapa and Concepcion, discovered in the Gulf of Mexico in the first years of oil exploration at the beginning of the 20th century, are depleted and currently abandoned, others remain productive..

Benavides Garcia (1983) highlights the importance of saline domes beyond the scope of oil production, as a source of raw materials for industrial use or for human consumption, but also as possible storage sites, under certain conditions, for important resources such as hydrocarbons (Benavides García, 1983). Domes such as those to the west of the Salina basin located to the south and southeast of Coatzacoalcos Veracruz, are closer to the surface than those found in the States of Tabasco and Chiapas; the shallower salt wells represent the most suitable sites to be used as reservoirs for energy carriers (Benavides García, 1983).

Information on salt formations (SGM, 2020), is available in the online platform of the Mexican Geological Service (SGM by its acronym in Spanish) however, it does not represent the location of saline caverns directly suitable for CAES.

The National Hydrocarbon Commission (CNH by its acronym in Spanish) has, amongst other attributions, to update the Mexican hydrocarbon resources. Due to the natural association with hydrocarbon, saline formations can be identified in documents such as the *Prospective Resources of Mexico: Perdido Area, Mexican Cordilleras and Saline Basin, deep waters of the Gulf of Mexico* (CNH, 2019a) which presents the results of the analysis on three regions in the Gulf of Mexico; saline formations are shown in Figure 1.11, nevertheless, by their distant location and high deep, it is unlikely that these saline basins could be useful for developing CAES projects as these must be close to the electricity infrastructure to prevent from large connection investments.



Áreas Evaluadas en Aguas profundas del Golfo de México	Recurso Prospectivo Identificado media (MMbpce)	Recurso Prospectivo Total media (MMbpce)
Área Perdido	4,902	8,946
Cordilleras Mexicanes Norte	2,293	2,724
Cuenca Salina Centro	3,184	5,158
Total	**10,379**	**16,828**

Provincia Petrolera	Recursos Prospectivos Totales P90 (MMbpce)	Recursos Prospectivos Totales P50 (MMbpce)	Recursos Prospectivos Totales Media (MMbpce)	Recursos Prospectivos Totales P10 (MMbpce)
Aguas profundas del Golfo de México	11,462	25,393	27,835	47,452
Cuencas del Sureste	8,227	13,710	14,466	21,697
Burgos	1,436	2,916	3,204	5,400
Tampico-Misantla	881	2,077	2,347	4,167
Plataforma de Yucatan	408	1,431	1,778	3,607
Veracruz	726	1,337	1,432	2,261
Cinturon Plegado de Chiapas	428	1,045	1,172	2,079
Sabinas-Burro Picachos	130	344	395	733
Recursos Prospectivos Convencional Total	**23,698**	**48,254**	**52,629**	**87,395**

Figure 1.11. Map of the deep-water prospective regions in the Gulf of México. Source: (CNH, 2019a).

The CNH also provides a few geological atlases where it can be identified, amongst other, information related to the number of closed hydrocarbon wells which could be studied later for the development of CAES facilities (CNH, 2019b).

For example, in following basins (CNH, 2019b) a great deal of closed well were reported: Tampico Misantla (2,371); Veracruz (215); Provincias del Sureste and Cinturón Plegado de Chiapas (1,090) and Burros – Sabinas – Burgos (454).

The suitability of these wells for CAES applications requires specific evaluations that should consider at least: the location and the geological characteristics. Figure 1.12 shows the geographic location of the basins and Figure 1.13 shows a detail of the hydrocarbon wells in the aforementioned basins, some of which correspond to the reported closed wells.

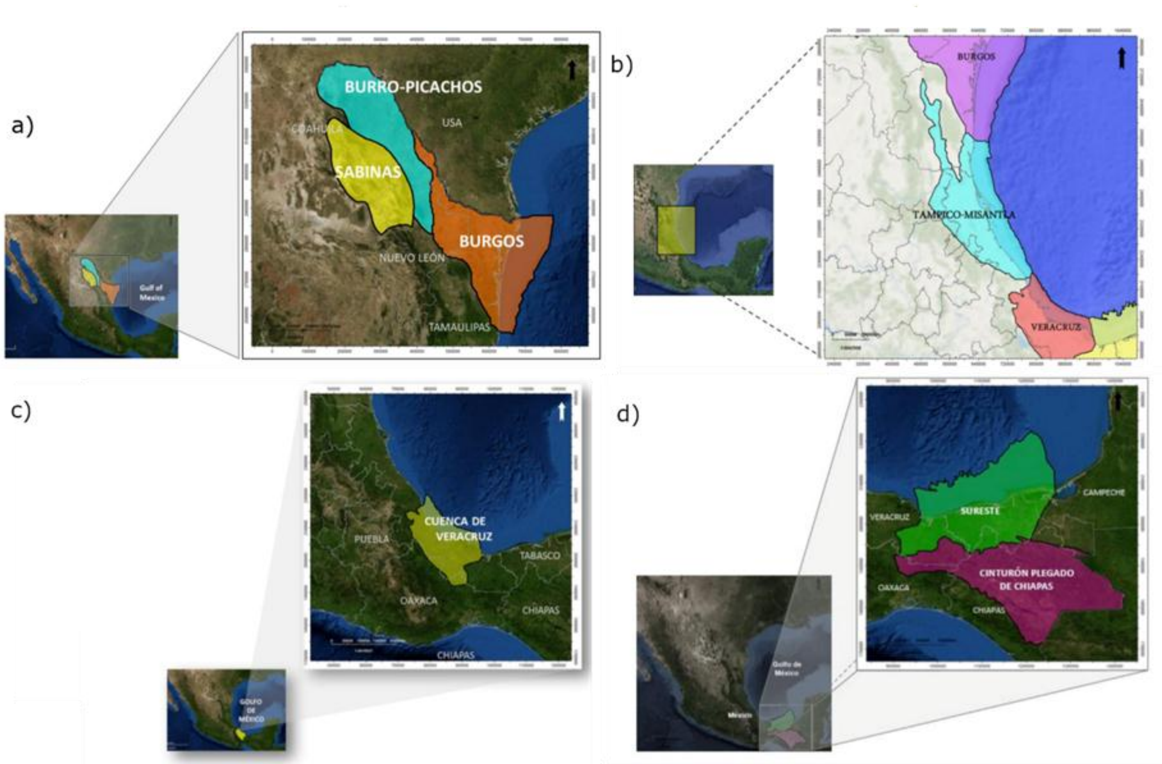
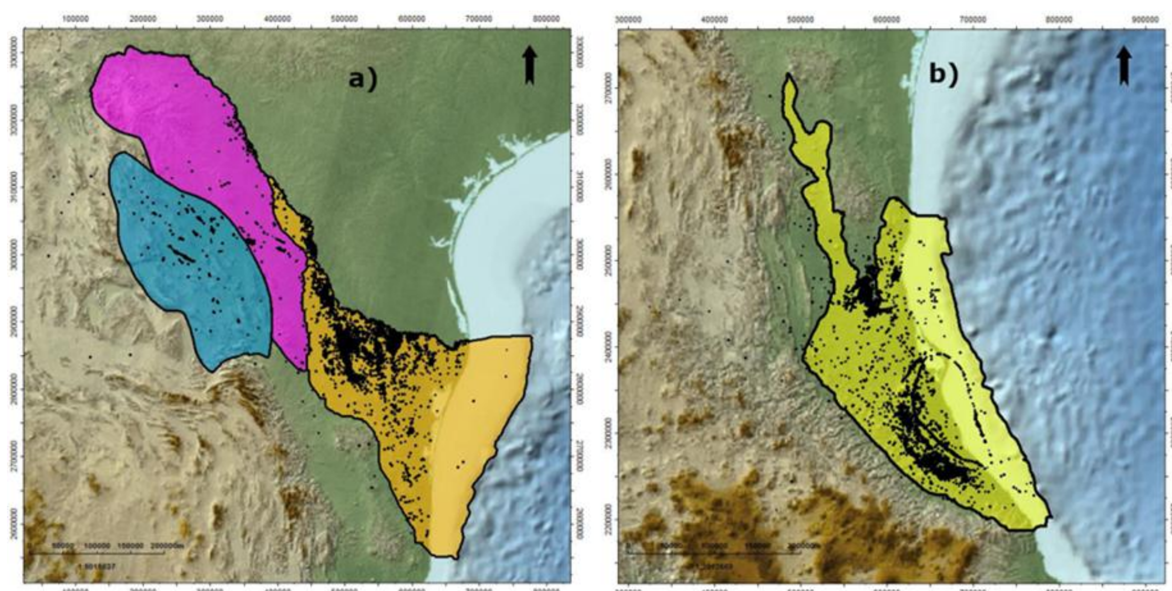


Figure 1.12. Location of the basins: a) Burro-Picachos, Sabinas and Burgos; b) Tampico – Misantla; c) Veracruz; and d) Sureste and Cinturón plegado de Chiapas. Adapted from the geological atlases available at (CNH, 2019b)



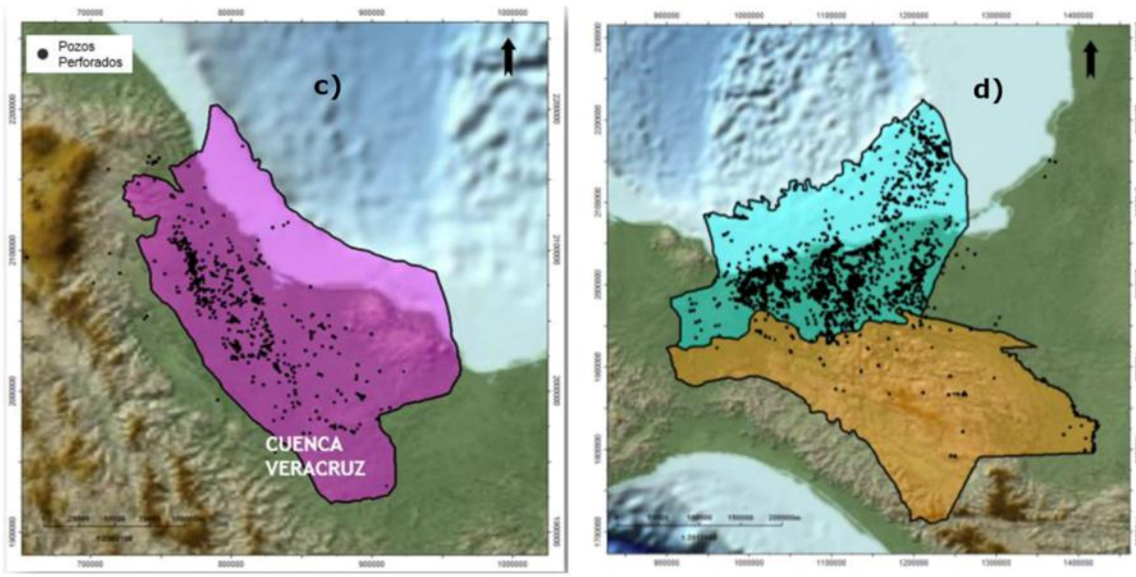


Figure 1.13. Hydrocarbon wells location in the basins represented by black dots. Basins:(a) Burro-Picachos, Sabinas and Burgos; (b) Tampico – Misantla; (c) Veracruz and (d) Sureste and Cinturón plegado de Chiapas. Adapted from the geological atlases available at (CNH, 2019b).

The SGM hosts a website where several geological charts can be consulted, they include georeferenced information on physiography, lithostratigraphy, structural alteration and mineral deposits. The charts are the result of the collection, integration, and reinterpretation of the existing geological information, followed by the interpretation of satellite images in digital form and a period of research and fieldwork, (SGM, 2020). The specific information varies from one chart to another by virtue of availability of studies for each region. However, these charts are available for the entire surface of the national territory and can be consulted in two ways: searching by chart name or code or by navigating through an interactive map (Figure 1.14).

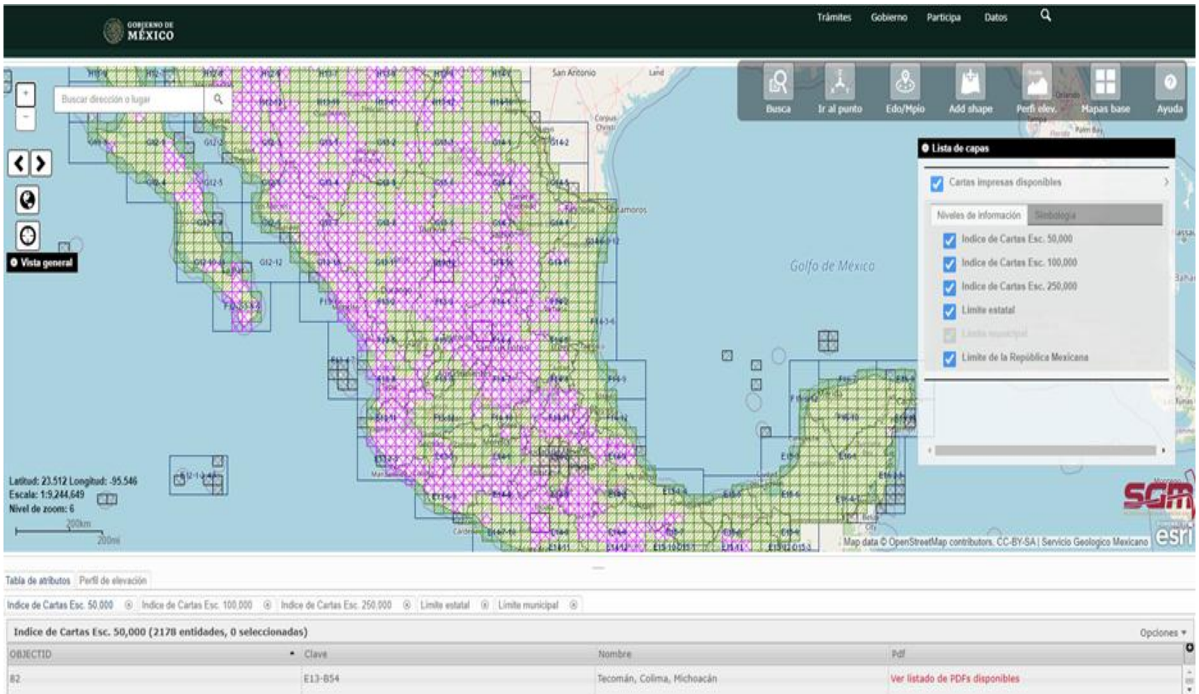


Figure 1.14. View of the online website for consulting the geological charts (SGM, 2020).

The very detailed information available through the geological charts allows making an idea of the most feasible sites for developing a CAES projects; it can be obtained the specific location of salt domes as well as some detail about their physical structure. As an example, in the Coatzacoalcos E15-1-4 mining geological chart, it is possible to visualize a vertical cut in a salt dome structure (Figure 1.15).

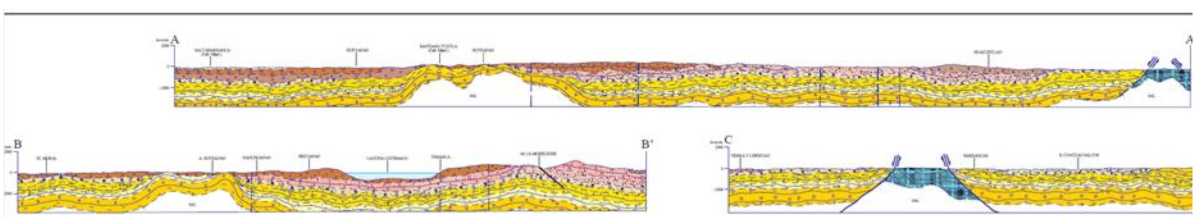


Figure 1.15. Vertical cuts in the E15-1-4 Coatzacoalcos mining geological chart (SGM, 2020).

Despite all this information that allows recognizing a high potential for the development of caves and their possible uses for CAES in Mexico, the reality and the literature consulted shows that the near future of the development of this type of storage projects will be guided by the use of the caverns already made by other uses such as the extraction of hydrocarbons, sulfur or salt.

While salt exploitation by dissolution and extraction as brine is an industrial process thoroughly developed and widely implemented, and could seem logical that such works could operate in common agreement with developing a storage project, it is not necessarily an straight way for creating underground artificial stores for energy carriers; i.e. the industrial exploitation of salt may require a slower rhythm than the required to create storage caves, while the creation of salt caverns with the single purpose of developing an storage facility might not find economic justification. Typical capital cost for developing a salt cavity for CAES by solution mining is of 2,000 USD/MWh (Aghahosseini & Breyer, 2018), cost that results i.e. 40 times higher than the seasonal PHS energy cost range of 1.8 to 50 US/MWh reported by (Hunt, et al., 2020), see Figure 4.3. Hence it is inferred that wells already open in depleted salt mines are the most attractive options for the storage of compressed air or gas.

The only case of underground storage in Mexico is in the State of Veracruz where the company CYDSA developed an LP gas storage facility in a salt cavern (see Figure 1.16) which was first exploited to obtain brine. The pioneer project in Mexico was built specifically to provide storage services for Petróleos Mexicanos (PEMEX) and is located in the Ixhuatlan - Nanchital state road near the "Pajaritos" hydrocarbon maritime PEMEX terminal. The facility has a storage capacity of 1.8 million barrels of LP gas and can transfer up to 120,000 barrels per day. The salt brine exploitation began in 2012, in November 2014 CYDSA and PEMEX formalized the contract and at the end of November 2017, CYDSA successfully managed to supply LP gas storage services (CYDSA, 2020).

Figure 1.16. Surface infrastructure of the underground CYDSA-PEMEX salt-cave based LP gas storage facility in Veracruz Mexico. Source: (CYDSA, 2020).

It is clear that there is an important potential for developing CAES projects in Mexico taking advantage of the large number and variety of underground geological formations that are spread across the country, it is also clear that further investigation is required for evaluating the CAES suitability of specific geologies. Table 3 shows a compilation of the sources of information that are currently available regarding geological formations in Mexico and can be the starting point for performing such studies.

Table 1.3. Compilation of information sources on geological formations in Mexico

Information	Available at
Geological atlases - Main hydrocarbon exploitation zones in Mexico	https://www.hidrocarburos.gob.mx/cnih/informaci%C3%B3n-digital/atlas-geol%C3%B3gicos/
Prospective resources of Mexico: Lost area, Mexican cordilleras and Salina basin, deep waters of the Gulf of Mexico	https://www.gob.mx/cms/uploads/attachment/file/517230/Libro_de_Recursos_Prospectivos-Perdido-Cordilleras-Salina.pdf
Sistema Nacional de Información del Agua (SINA)	http://sina.conagua.gob.mx/sina/
Geological charts edited by the Mexican geological service:	
By interactive map	https://www.sgm.gob.mx/CartasDisponibles/
By name or letter key	https://www.sgm.gob.mx/CartasPdf/Inicio.jsp

2. Identification of five case studies of interest to Mexico.

For the selection of the analysis sites for case studies, different activities were carried out that led to their selection under criteria and specific interests to the objectives of the study, but also with the addition of a process of consultation with experts from the sector that allowed a useful selection and proactive to promote energy storage in Mexico.

The process consists of 3 main stages:

- The proposal of sites of natural interest or prior identification based on the knowledge and interest of the INECC and on the feedback of the participants of the study presentation workshop.
- The definition of the evaluation criteria for the case studies and a preliminary proposal for the selection of 5 cases.
- Consultation and open discussion with the experts of the working group formed for the analysis of the case studies, and the definition of the 5 cases.

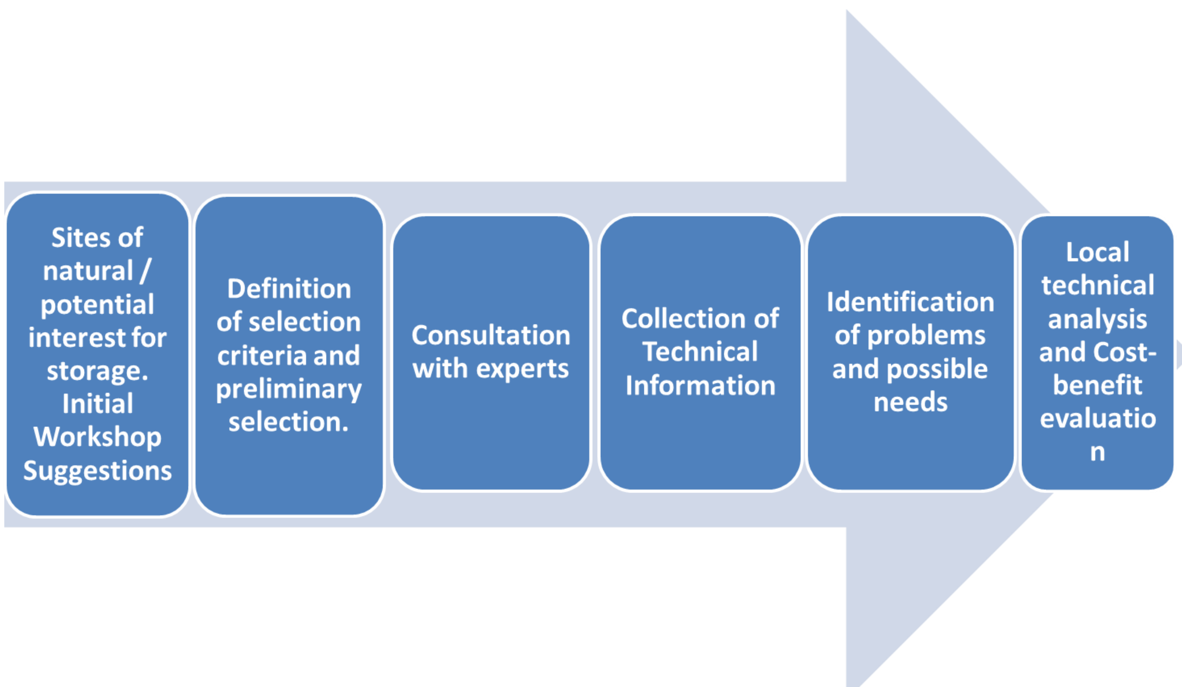


Figure 2.1. Process of identification and selection of case studies. Source: own elaboration.

2.1 Preliminary proposal of the case studies.

In the initial proposal for the case studies, the interest of INECC was considered to show a wide range of options that could cover the analysis of different conditions for the studies, such as regions with a lack of large power transmission capacity, regions without access to natural gas, regions with high potential for variable resources, regions with hydro-pumping potential, etc., for which the following sites were initially proposed:

Table 2.1. Preliminary proposal of the sites for the analysis of the case studies. Source: Own elaboration.

Where?	Why?
Yucatan Peninsula	Peak shaving, Infrastructure Deferral, Arbitrage, System Reliability, in relation to natural gas supply and history of blackouts.
Baja California Sur	Peak Shaving, System Reliability, Curtailments, Arbitrage, in addition to presenting the particularity of an isolated system with supply problems
Isolated Communities (Pueblo Nuevo, Durango), National Parks & Protected Areas (Cascada de Bassaseachic, Chihuahua)	Infrastructure Deferral/Avoidance, Minimum Infrastructure Footprint, operating conditions.
A Hydrogeneration Plant: Yesca or Aguamilpa or Malpaso or Chicoasén or Zimapán	Pumped Hydro Storage could result in Reduced cost of voltage control, Arbitrage, System Stability, Infrastructure Deferral.
Wind Farms: Ventosa, Oaxaca or Rumorosa, Baja California	Primary Regulation, Congestion Relief, Accurate forecasting, Arbitrage, Specific case associated with a type of generation from renewable sources.
Nuevo Laredo, Reynosa, Saltillo, Monterrey	Congestion Relief, Arbitrage, Wind Farm Investment, sustained growth in demand and generation projects through renewable energy sources
Suggestions?	Depleted salt caverns offer an opportunity to utilize Compressed Air Energy Storage (CAES)

During the study presentation workshop, the topic was opened to the suggestions of the participants, receiving valuable feedback and suggestions that allowed reaffirming some proposals (Yucatan Peninsula, Baja California Sur), and delimiting others (Zimapán, Monterrey), as well as exploring various suggestions (Baja California, Bacalar, The Grijalva River basin) for the definition of the analysis sites.

2.2 Evaluation criteria for case studies and preliminary proposal for the selection of five cases.

Based on the preliminary proposals and the feedback received in the first exchange with researchers and experts in the sector, it was possible to identify what type of information would be necessary and useful, which is why the exploration of the available information began and this allowed to define more precision the level at which the case studies could be addressed. From the identification of the availability of information, it was defined what the evaluation criteria should be according to the availability of information and the scope of the study:

Table 2.2. Assessment criteria for case study sites. Source: Own elaboration.

CRITERIA	INFORMATION TYPE
Physical characteristics of the site	- Location, the most accurate available. - Installed capacity in MW and / or generation GWh / a - Description of the associated installation (number of wind turbines, solar panels or modules). - Node (s) with which the installation is probably associated.
Local Marginal Price Analysis	- Congestion - Losses. - Electricity prices
Characteristics of electricity generation and demand in the region.	- Regional generation (CE, RE) and how it is contemplated to 2020 according to PRODESEN. - Local demand on the selected associated nodes. - Transmission and distribution infrastructure.
Identification of the problem that the storage can solve.	- Characteristics and projections of electricity generation and demand in the region. - Identification of on-site network operating conditions that can be solved or improved with energy storage

Based on these criteria, a new proposal for the case studies was made based on the information consulted and the previous feedback from the first workshop, this preliminary proposal being the following:

Mérida, Yucatán

- RE projects around Mérida (406 MW-WE, 421 MW-PVE; auction results)

- Electric congestion and high MPL
- Possible decrease in the use of fossil fuel plants with storage implementation
- Average electricity prices 30% higher than the average for the rest of the country[1] and forecast to continue increasing due to a lack of access to natural gas.
- The Cancun-Mérida link presents losses to the transmission of electricity of more than 3 USD / MWh[3]

Zimapán, Hidalgo

- Pre-existing feasibility study.
- Required frequency and voltage control services.
- Operation of the Zimapán Hydroelectric Power Plant as a synchronous condenser and not as a turbine.
- Use of the flow to locate a lower reservoir and store.
- 500 MW pumping capacity.

La Paz, BCS

- High MPL.
- Possible replacement of fuel oil and diesel plants. (427 MW effective capacity) Isolated region of the SIN, with high potential of renewable energy sources. (intelligent networks)[2]
- Aura Solar III PV Plant (32 MW) with storage (10.5 MW).
- Average prices doubled those of the SEN average[1]

Pesquería, Nuevo León

- High electrical congestion[4]
- Growth in demand and sustained industry.
- RE infrastructure in operation (705 MW-WE)[5].
- RE projects in the area (2877 MW-WE)[2]

Villa de Reyes, SLP

- RE projects in the area (1,207 MW projected 2019)[2]

---

[3] Outlook for the electricity sector, 2018

[4] Outlook for the electricity sector, 2018

[5] PRODESEN 2019-2033

- The Tepic-San Luis Potosí, Aguascalientes-Tepic links present considerable losses to electricity transmission[1].
- Sustained industrial growth zone.
- Possible decrease in fossil fuels (conventional fuel oil-based thermoelectric, 700 MW) with storage implementation[2]

Cuenca del Río Grijalva, Chiapas

- Wind power plants in nearby regions (Oaxaca).
- The Grijalva hydroelectric system supports the electricity grid in its operation.
- Inefficient use of generating equipment.
- 4 cascading reservoirs that could be connected to each other for re-pumping.

2.3 Consultation and open discussion with the experts in a working group

From the definition of the evaluation criteria, it was tried to limit the selection to the regions that allow its analysis and in which, based on the information consulted, it could identify the solution of problems and obtain benefits from the implementation of a storage system of Energy.

Thus, seeking to contain a range of diverse cases, the 5 study regions, their problems, related services, and possible technology for the storage system were selected:

Table 2.3. Regions of analysis for case studies. Source: Own elaboration.

Region	Problems identified	Related services	Possible Applicable Technology
North	Congestion RE integration	Energy management, RE capacity firming, ramping.	Batteries Molten Salts
Peninsular	Blackouts due to natural gas shortages. Short circuit due to fire and high temperatures.	Energy management, Ramping, seasonal storage, back-up power	CAES Batteries
Western	Congestion. Non-ideal commercial conditions-Legacy contract (only to deliver energy). Non-profitable generation	Frequency regulation, decongestion, ramping, T & D deferral.	PHS

Region	Problems identified	Related services	Possible Applicable Technology
	machinery wastage (working synchronous capacitor).		
Northeast	Congestion RE integration	Energy management, RE capacity firming, ramping.	Batteries
South Baja California	Supply Problems Congestion RE integration	Ramping. RE capacity firming. T-D deferral	Batteries
Baja California	Power deficit. Lack of reliability.	Energy management, Seasonal storage, back-up power	Batteries Molten Salts

With this proposal open to discussion in the working group that decided to participate in this topic, it was possible to define the analysis sites with greater precision:

Table 2.4. Selected case studies. Source: Own elaboration.

Regional Control Region	Study Zone	Transmissions region
North	Chihuahua - Ciudad Juárez	Juarez, Moctezuma, Chihuahua
Northeast	Coahuila - Nuevo León	Monterrey, Saltillo
Peninsular	Yucatán	Tabasco, Lerma, Mérida, Cancun
Western	Hidalgo – Querétaro (Zimapán)	Central, Querétaro, San Luis Potosí, Tamazunchale, Salamanca
South Baja California	La Paz	Villa Constitution, La Paz

3. Design a common framework for the description of the five case studies of interest

3.1 Locations

Except for Zimapán, a CFE hydroelectric power plant, the locations were selected according to a number of technological or environmental problems that could be solved with energy storage systems. The Zimapán location was selected not only due to problems that energy storage could solve, but also because it is one of the principal candidates selected by CFE for a pump hydro storage. The following table lists the case study sites, the presumed possible problems that could be solved by energy storage before the analysis and the reference to appendix with the full description of the study cases.

Table 3.1. Energy System Storage Sites. Source: Own elaboration.

The Site Location	Previously identified site problems that storage could solve	Full description
Peninsular, Yucatán	High technical losses, congestion, blackouts, Diesel Generation	Appendix D.4.1
South Baja California, La Paz	Low operating reserves, Diesel generation, curtailment of renewable generation	Appendix D.4.2
North, Juárez, Chihuahua	High Congestion	Appendix D.4.3
Northeast, Saltillo – Monterrey	High Congestion	Appendix D.4.4
Western, Hidalgo – Querétaro (Zimapán)	Congestion	Appendix D.4.5

In the **Appendixes 4.1 to 4.5** the full and detailed information of the study sites resulting from the information compilation carried out to identify the problem at the local or regional level is shown. The information and data gathering were carried out according to the approach described below.

3.2 Approach

Technical component

- Gathering of the data in the same manner for all the 5 study cases.
  - Congestion and loses problems
  - Possible future increase of VRE in the region.
  - Actual capacities and generation
  - Planed generation and transmission expansion
  - Fossil fuel consumption
  - Transmission capacity
- Identification of problems for example: transmission, supply, frequency control, voltage control problems.
- Technologies of possible application according to the needs and requirements of identified services.
- Proposal of the size and location of possible storage facilities on the basis of gathered information.

Economical component

- The cost-benefit analysis of the electricity storage system adopts a uniform approach for all case studies.
- The methodologies, assumptions, and scenarios used in the cost-benefit analysis were principally determined by data availability.
- The initial approach to evaluating storage considered the following aspects:
  - Environmental: e.g. reduction of GHG (greenhouse gases) by displacing generation by the plants supplying electricity during peak demand and which are usually expensive to operate (thus are dispatched only during peak hours), or spinning reserves which consume fossil fuels without injecting electricity into the grid.
  - Socioeconomic: e.g. decrease in electricity prices, decrease in investment in transmission infrastructure, increase in energy independence, potential creation of an economic energy storage sector, decreased congestion.
  - Market participants: e.g. compliance with the Network Code frequency control requirements (VRE generators), the possibility of profits from ancillary services, arbitrage, decrease in transmission costs for the load.
  - The National Electric System: decrease in Ohmic losses due to decreased congestion, decrease in losses, increase in system reliability.
- Conduct a cost-benefit analysis of the above-mentioned aspects for each case study.

3.4 Data gathering

In the tables 3.2 to 3.4 will be pointed out the information that should be gathered for every site in order to describe the situation and problems at regional level.

Environmental Impact Assessment (MIAs) projects

Table 3.2. Environmental Impact Assessment (MIAs) projects data. Source: Own elaboration.

<table>
<tr><th>Data</th><th>Source</th><th>What for</th></tr>
<tr><td colspan="3">MIAs projects</td></tr>
<tr><td>Location, the most accurate available (State, Municipality, Address, coordinates).</td><td rowspan="6">SEMARNAT
EIA 2017-2019
(SEMARNAT, 2019)

SENER
PRODESEN 2017-2019
(SENER, 2019)
(SENER, 2018)
(SENER, 2017)

CENACE
PNARNTyRGD, 2019
(CENASE, 2019a)
Public data of wholesales market
(CENASE, 2019b)</td><td rowspan="5">To include in geo-database and identification of future VRE generation capacity in the region</td></tr>
<tr><td>Area occupied by the project and the area occupied by the facilities (in hectares), the difference is possibly the space available to install storage.</td></tr>
<tr><td>Investment costs</td></tr>
<tr><td>Description of the installation (number of wind turbines, solar panels or modules)</td></tr>
<tr><td>Capacity and generation</td></tr>
<tr><td>Transmission line and substation to which it is connected.</td><td>Node identification</td></tr>
</table>

Local Marginal Price

Analysis of the components of the Local Marginal Price (energy, congestion and losses) at the site and surrounding nodes to evaluate congestion and losses.

Table 3.3. Components of the PML and nodes. Source: Own elaboration.

Data of selected Nodes	Sources	What for
Congestion	CENACE (CENASE, 2019a) (CENASE, 2019b)	Identification of congestion and Loses problems in the transmission's regions
Loses		
Electricity prices (Energy Component)		
Volatility of PML components		
Evolution (1 year)		

Regional generation

Description of the main characteristics of electricity generation and demand in the region.

Table 3.4. Capacity, generation and transmission capacity. Source: Own elaboration.

Data	Sources	What for
Regional capacity in MW and generation in GWh (Conventional, Renewal).	SENER (SENER, 2019)	Identification actual and planned capacity and infrastructure.
Installed capacity. and/or generation in possible per technology type	CENACE (CENASE, 2019a)	Identification of drivers and problems in the regions
Demand (regional) actual and projections		
Fossil fuels consumption	INEGyCEI, 2017 (INECC, 2017)	
Transmission capacity Transmission projects	Nonpublic Data (INECC, 2019)	
System and Network problems as identified by CENACE	INEGI CONAPO	
Node(s) with which the installation is probably associated.	CENACE (CENASE, 2019b)	Node identification Energy cost, Congestion and Loses

Identified regional problems

- Description of the problem that storage can solve, supported by the description of the main characteristics, and projections of the generation and demand for electricity in the region

Characterization of required ancillary services

- Requirements of frequency control
- Requirements of voltage control
- Requirements of backup

3.5 Economic Evaluation

Whereas Report D3 reviewed the prevailing regulatory framework and suggested regulatory changes that could make the utility-scale electricity storage feasible in Mexico, this section 3.5 proposes a framework for evaluating costs and benefits of electricity storage at the five case studies of interest.

The economic evaluation is principally based on the data from:

- The technology catalogue, which provides an estimate of capital, installation, operation costs, as well as the lifespan and efficiency of each storage technology.
- The efficiency of generation likely used for charging storage and the efficiency of generation potentially replaced by storage, as well as the associated fuels.
- Other input sources include the nodal prices published by CENACE, social discount rate published by the Federal Treasury department, and own assumptions. Section 3.6 shows the full list of data sources used in the assessment.

It is not the purpose of the case studies to make a business case for electricity storage. Rather, it is to examine from a social perspective whether the benefits of storage surpass its costs. Consequently, the cost-benefit analysis (CBA) will consider various externalities that a business case would not consider, externalities not included in the price of storage services such as decreased greenhouse gas emissions, for example. On the other hand, the CBA will not consider factors a business case would consider, such as a hurdle rate, risk appetite, financing costs, etc. In addition to comparing the cost of storage to externalities, the income a storage system can expect to earn in course of its operations is also considered.

The outcome of an economic evaluation depends on how a storage system is used. The description of each case study specifies the type of generation used for charging storage and the type of generation replaced by storage, as well as operating times. This section also specifies which benefits associated with energy storage are remunerated, and the concomitant assumptions.

Keeping in mind that the principal function of storage systems is delivery of electricity, the preliminary step to economic evaluation involved comparing the levelized cost of electricity (LCOE) of each storage technology with the cost of electricity not delivered. The LCOE can be thought of as an average cost of each MWh released from storage over the lifetime of the storage system. Clearly, the LCOE not only depends on capital and operating costs, but also on the use patterns of storage technology: the more MWh released from storage, the cheaper the cost per MWh.

In 2017, SENER estimated the cost of electricity not delivered to be USD$2,600/MWh (SENER, 2017a), or around $50,000 MXN depending on the exchange rate assumptions. If LCOE were to surpass that amount, the value of economic externalities would determine whether the cost of a solution offered by storage would exceed the cost of a problem. Opportunely, LCOE associated with each storage technology was far below the estimated cost of electricity not delivered.

Economic Externalities

This section considers three types of economic externalities[6]. There are externalities that arguably are not very tangible, and which – while difficult to quantify – are important to recognize. There are also externalities that theoretically could be quantified but are not due to the lack of readily available information. The third type of externalities is composed of benefits that are deemed tangible and quantifiable.

The first type of benefits will not be quantified in the CBA, but all the same they are important to mention. Those potential benefits include:

- Increased national energy independence. The savings derived from decreased fossil fuel imports, attributable to displaced thermal generation can be measured. The benefits in addition to those savings are more difficult to measure, such as increased strategic self-sufficiency.

- Robustness of the overall electrical system. The most recent PRODESEN, 2019-2033 (SENER, 2019a), puts emphasis on grid's reliability, especially in the context of new network projects. One of the ways to measure the value of reliability, i.e. a functioning network, is by evaluating the consequences of it not functioning, the so-called value of the electricity not delivered. However, it is harder to assign a monetary value to different degrees of reliability in terms of probabilities of network failure, or the level of network robustness. It is important to recognize that storage can contribute to network robustness and that this additional robustness has value.

- Economic development associated with growth of the national electric storage industry. It is difficult to quantify the GDP effect of developing a storage industry in Mexico without making assumptions which most certainly could be debatable. Nevertheless, in 2013, International Work Organization published a study which evaluates potential employment growth in "green" industries in Mexico, which could arguably be extended to energy storage systems. The study suggests that diverting demand towards green industries would decrease "conventional" GDP by 0.04%, on one hand, but would increase national employment by 2%, on the other hand (OIT, 2013). By conjecture, it is reasonable to assume that the net economic effect of developing a national energy storage value chain would be positive.

[6] Externalities refer to costs or benefits not included in the price of a transaction, which are experienced by a third party not included in that transaction. The originator of an externality is not affected by it, in a sense that he/she neither pays the cost of it (in case of a negative externality), nor receives a remuneration for it (in case of a positive externality).

- **Health benefits derived from a cleaner environment, net of the CO_2 price**. An argument could be made that the price of CO_2 emissions reflects in a quantitative manner the harmful effects of CO_2. However, fossil fuel emissions also include SO_2 and NO_X compounds which are harmful to the environment as well as the population at large, and which do not have a market per se. Consequently, displacing fossil fuel generation with e.g. wind and solar power produces health benefits in addition to reduction in CO_2 emissions.

- **Reducing cold starts**. A study conducted by EnerAB, which lists some of the benefits associated with battery energy storage indicates that an average cost of a cold start of General Electric's LMS 100 turbine costs over four thousand US dollars. Using batteries can help avoid that cost. The number of cold starts avoided is difficult to estimate, consequently it is not quantified, but recognized as a benefit (EnerAB, 2016).

- **Lower Market Heat Rate**[7]. Using storage systems makes electricity generation more efficient by lowering overall market heat rate. When storage systems are used for frequency control, it liberates approximately 1.5% of conventional plant capacity reserved for secondary regulation (i.e. frequency control). This liberated capacity decreases the dispatch of units with a higher heat rate. (EnerAB)

In addition to the above-mentioned benefits of storage which are difficult to quantify, there are benefits that could be quantified if we had enough relevant information. For example:

- **Speed and Accuracy of Frequency Control**. The frequency control refers to injection of active energy into the grid. Frequency control is executed faster and more accurately using storage systems than conventional generation and is the principal manner in which batteries participate in electricity markets around the world. In Mexico there is no market for frequency response, and therefore there is no market price (or a regulated price for that matter) which would suggest the value of those services. Also, considering that frequency control refers to injection of active (as opposed to reactive) power, it is important to recognize that frequency control cannot be provided independently of marketing activities described below under peak-shaving and arbitrage headings. Put differently, frequency control is provided when electricity is sold and injected into the grid, in the same manner that any generator provides frequency when injecting electricity into the system. Consequently, although frequency control is a service that energy storage systems can offer, in Mexican context the model focuses on marketing activities, which are potentially mutually exclusive with frequency control. Although energy storage has a potential of replacing spinning reserves to provide frequency control and precipitate significant fuel savings. That potential depends on the fuel used to generate electricity intended for storage, and the frequency of charging and discharging for frequency control purposes.

- **Capacity Market Revenues.** The potential earnings from the capacity market revenues are not considered in the **Cost Benefit Model (CBM),** because for most storage systems that would require making assumptions about both price and quantity. Specifically, for storage systems that can offer energy for less than six consecutive hours, it's necessary to estimate the number of hours of operation that coincide with the 100 critical hours. Also, regardless of the size of the storage system, there is not enough information to make a reliable

[7] A heat rate is a measure of efficiency of generation and is defined as the amount of fuel required to produce 1 MWh of electricity. A lower heat rate is more efficient than higher heat rate. A market heat rate is calculated by dividing the price of electricity by the current price of natural gas (assuming gas units are the marginal generators).

prediction of what the per MW price of storage might be. The load is required to acquire capacity that meets its needs. That capacity is procured on a bilateral basis and there is no capacity market that signals per MW price in real time. If load's maximum employed capacity exceeded the contracted capacity, then it is required to pay a capacity price established by CENACE in February of the following year, and only if the contracted capacity was exceeded during the 100 critical hours. For the Mexican Interconnected System (SIN, for its acronym in Spanish[8]), the capacity market price was little over US$60/kW-year in 2017, US$37/kW-year in 2018 and little over US$6 in 2019 (NERA, 2020). Arguably, the prices are not stable enough to forecast capacity market earnings over the life of a project.

- Mitigated Electricity Losses. One of the components of a nodal price is a naturally occurring loss of electricity in transmission lines, principally in the form of heat associated with resistance (ohmic losses). Losses depend on a number of factors, such as environment temperature, length of a transmission line, voltage, etc. Clearly storage cannot eliminate losses. Nevertheless, in cases of high thermal losses due to high congestion, storage could relieve congestion and therefore decrease losses. Practically, the CBM model is not able to differentiate between high losses due to congestion or due to the length of the transmission line or line voltage, for example. Put differently, under certain circumstances storage has a potential to decrease losses, but the CBM is not sophisticated enough to recognize or model those circumstances. Consequently, the CBM does not estimate potential decline in technical losses. It is important to mention that loss mitigation could be significant and was one of the reasons for making storage mandatory in California see Assembly Bill No. 2514 (California Legislative, 2010).

- Black Start. Energy storage is very well suited to re-energize the network, or provide the black start service. The Market Basis 6.2.1, lists black start as one of the ancillary services that CENACE is required to procure, but it doesn't specify the capacity to be procured. This leaves CENACE room to negotiate with CFE the desired capacity[9], and it makes it difficult to quantify. Also, energy storage might find it difficult to compete on the cost basis with conventional generation capable of providing black-start service, unless technical norms are established that put emphasis on speed, for example. The first step in quantifying the benefit associated with storage providing the Black Start service, is articulating the capacity to be procured by CENACE. The second would require articulation of the process by which the Black Start service could be offered to CENACE.

Finally, there are benefits evaluated in this study. Those benefits can be classified into benefits that result in either a decreased cost of providing electricity, or a cleaner environment. As Table 3.5 shows, those benefits can be broadly grouped under the headings of congestion or displacement of conventional generation.

[8] Sistema Inerconectado Nacional encompasses all of Mexico with the exception of Baja California, where Baja California Norte, Baja California Sur, and Mulegé systems are found.

[9] Until a formal process for contracting black start capacity is formulated, CENACE is likely to rely on CFE for that service.

Table 3.5. Potential Positive Externalities of Energy Storage that at the time can be estimated.

	Decreased Cost of Providing Electricity	Cleaner Environment
Displaced Fossil Fuel Generation	• Charging storage during low electricity prices and releasing it during peak prices potentially displaces generation by expensive peaker plants.	• Displacing peaker plants, which usually burn least-efficient fossil fuels, has a potential of decreasing greenhouse gas emissions and pollutants such as sulfur oxides (SO_x) and nitrogen oxides (NO_x), especially if the storage plants were charged with energy from renewable sources.
Congestion	• Nodal power prices are composed of the price of congestion, the price of technical losses, and the price of electricity. Since congestion is one of the components of a nodal power price, if congestion is decreased using storage, the nodal price will also decrease.	N/A
	• If storage can decrease congestion, it has a potential of eliminating or postponing transmission infrastructure investments necessary to relieve the said congestion. Consequently, storage has a potential of decreasing cost of transmission reflected in transmission tariffs.	N/A
	• A percentage of technical losses, which along with congestion and energy price comprise the nodal price, are produced by excessive congestion[10]. Decreasing congestion has a potential of decreasing technical losses, and thus the electric bill. To the extent storage can decrease technical losses caused by congestion, it can decrease the electric bill as well.	N/A

[10] "Ohmic Losses increase proportionally with the square of the power flow" (Parsons, 2017)

The methodologies for quantifying select storage benefits are summarized in **Tables 3.6, 3.7 and 3.8**, respectively, and explained in more detail in Appendix 4.1. Those tables also summarize key associated assumptions.

Table 3.6. Quantification of Benefits Associated with Displaced Fossil Fuel Generation

Benefits	Estimation	Assumptions
Decreased Cost of Electricity Due to Peak Shaving	$PS^v = \frac{E^s}{E^m} * P^P * E^s$ Where: PS^V – Value of peak shaving, MXN E^S – Monthly energy released from storage, MWh E^M – Monthly SIN energy consumption, MWh P^P – Peak electricity prices, MXN/MWh	• The decline in peak prices is inversely proportional to energy released from storage as a share of total energy consumed in the system (explained in more detail in **Appendix A** "Arbitrage and Peak Shaving"). • Electricity demand is inelastic.
Mitigated CO2 Emissions	$VM = (CC^y * E^s - CC^z * E^c * (1 - CG)) * P^{CO2}$ Where: VM – Value of CO2 mitigation, MXN CC^Y – Carbon content (metric tonnes) per MWh of "y" generation displaced by energy released from storage[11] E^s – Monthly energy (MWh) released from storage	• Plants are dispatched from least expensive to most expensive. • It is assumed that the energy released from storage will replace peaker plants.

[11] Calculated by multiplying the carbon content per MMBtu of the fuel used by the displaced technology and the heat rate (MMBTu/MWh) of that technology.

Benefits	Estimation	Assumptions
	CC^{z} – Carbon content (metric tonnes) per MWh of "c" generation used to charge storage[12] E^{C} – Energy used to charge storage, MWh CG – A percentage of storage that is charged with renewable (i.e. CO_2 free) generation (%) P^{CO2} – Price of CO_2 emissions (MXN) per metric tonne	
Fossil Fuels Cost Savings	$$F^{S} = F^{Y} * E^{S} * P^{Y} - F^{Z} * E^{C} * P^{Z} * (1 - CG)$$ Where: F^{S} – Value of fossil fuel savings, MXN F^{Y} – Amount of fuel required to generate 1MWh using displaced generation E^{S} – Monthly energy (released from storage, MWh P^{Y} – Price of fuel used by displaced generation, MXN F^{Z} – Fuel required to generate 1MWh by "z" generation used to charge storage P^{Z} – Price of fuel used to charge storage, CG – A percentage of storage that is charged with renewable (i.e. CO_2 free) generation (%)	• Generation with the cheapest fuels is dispatched first.

[12] Calculated by multiplying the carbon content per MMBtu of the fuel used by the technology used for charging storage and the heat rate (MMBTu/MWh) of that technology.

Table 3.7. Quantification of Externalities Associated with Decreased Congestion

Benefits due to Decreased Congestion	Estimation	Assumptions
Decreased Nodal Price of Electricity	$$C^v = [max(A,B) \; - min(A,B)\,] * E^S * x$$ Where: C^v – Value of decreased congestion ($MXN), A, B – Nodes for which average monthly congestion prices are compared ($MXN/MWh), E^S – Monthly energy released from storage, MWh x – absolute value of the rate of change of congestion price with respect to decrease in congestion constraint, $0 < x \leq 1$	• Storage can reduce congestion price differential between two nodes to zero. • The price of congestion is conversely and linearly related to energy released from storage.

In addition to benefits provided by positive externalities associated with storage which are not included in the price of services, there are benefits which do have a price, and which form a storage income base. Those include income from selling electricity (arbitrage), and potential income from ancillary services. Capacity is not included for reasons mentioned above.

Table 3.8. "Conventional" Storage Earnings

Earnings Associated With:	Calculation	Assumptions
Arbitrage	$$R^A = \left(P^P - \left(\frac{E^S}{E^M} * P^P\right)\right) * E^S - P^B * \left(\frac{E^C + E^M}{E^M}\right) * E^C$$ Where: R^A – Revenue from arbitrage, MXN E^S – Energy released from storage, MWh E^M – Monthly SIN energy consumption, MWh, P^P – Peak electricity prices, MXN P^B – Bottom electricity prices, MXN E^C – Energy used to charge storage, MWh	• Energy is stored when prices are low and is released when prices are high. • The high and low prices coincide with high and low demand, respectively, and it is assumed that prices reflect changes in supply and demand. • Electricity demand is inelastic. • Ceteris paribus, an increase in supply of electricity decreases electricity prices. Likewise, an increase in demand, increases prices. • The decline in peak prices is inversely proportional to energy released from storage as a share of total energy consumed in the system (explained in more detail in Appendix D4.1 "Arbitrage and Peak Shaving"). • The high and low prices coincide with high and low demand, respectively. • Costs (EPC, fixed and variable O&M) as well as losses are considered in the overall cost-benefit analysis for each storage system.

Earnings Associated With:	Calculation	Assumptions
Voltage Control	$$VC = E^S * y * V^T$$ Where: VC – Revenue from voltage control E^S – Energy released from storage V^T – Voltage control regulated tariff y – Remunerated reactive power defined as a % of active power released from storage	• A storage system can provide ancillary services which can be independent from discharging energy.

Additional Assumptions

Key Assumptions and Model Limitations

Assumptions

Storage systems shall be classified as Transmission. As such, storage does not pay double transmission tariff (as a load when it charges, and as a generator when it discharges).

The CENACE will operate storage systems under long-term contracts and will maximize social benefit. To avoid a possible conflict of interest, all energy shall have a price, including energy from renewable sources stored to avoid curtailment, which shall be priced at lowest market rates. This does not apply to Molten Salts storage technology which is charged with concentrated solar power. The opportunity cost of concentrated solar power is deemed to be zero.

Energy from renewable sources in this study (principally wind and solar) produces no CO_2. For the purposes of this study biomass generation is not considered significant enough to be relevant.

The Engineering Procurement and Construction (EPC) costs are deemed to be overnight costs, thus financing expenses are not considered and are distributed evenly between months it takes to construct the storage system. Thereafter only fixed and variable O&M costs are applied during storage operation period.

Reclamation and decommissioning costs are not considered at the end of a storage system's useful life, and neither is its salvage value.

The electricity prices and supply both move in a linear fashion.

The regulated tariff for voltage control in 2020 shall be $5.6 MXN/MWh, in line with "Acuerdo A/039/2019" which states regulated tariffs for 2020.

The price of CO_2 emissions is exogenous to the CBM.

It is assumed that all energy released from storage displaces conventional thermal generation, which could be fueled by natural gas, fuel oil, or diesel. It is assumed that all displaced conventional generation creates fossil fuel savings proportional to the corresponding not generated energy.

The useful life of storage technologies in the Technology Catalogue is defined both in years and charge-discharge cycles, whichever comes first. The CBM sets the number of hours of daily discharge such that the storage technology completes its useful life defined in years. Consequently, the net present value of benefits is not inflated by accruing benefits at the beginning of the project's life and reducing storage lifetime in years.

A charge-discharge cycle is defined as charging and discharging a storage system.

Model Limitations

The cost-benefit analysis aggregates the net present value of seven factors for each technology: capital and operating costs, fossil fuel savings, CO_2 emissions, congestion relief, peak shaving, and arbitrage. The most significant model limitation deals with the lack of data used for arbitrage, congestion, and peak shaving calculations. The hourly nodal (energy, congestion, technical losses) prices were not accompanied by the consumption/supply data and therefore strong assumptions had to be made about the relationship between electricity and congestion prices vis a vis the corresponding electricity volume. Based on the available annual 2018 system data, a monthly consumption in MWh could be calculated. However, without information about the peak consumption patterns, the arbitrage, and peak shaving calculations had to be based on system volumes. Specifically, a one-to-one percentual trade-off is assumed between peak monthly prices and volumes. For example, suppose that $75/MWh represents a peak monthly price and 1000 MWh represents total monthly demand. Imagine a cartesian plane with electricity prices on the Y axis and electricity volumes on the X axis. Imagine a vertical demand curve at 1000 MWh, and the upward sloping supply curve which crosses the origin on one end and the vertical demand curve at $75/MWh.

The one-to-one percentual trade-off between peak prices and monthly volumes implies that if in the above example 200 MWh is released from storage, thus shifting the supply curve to the right, the price decreases 20% from $75/MWh to $60/MWh (i.e. on one end the shifted supply curve crosses the X axis at 200 MWh instead of the origin, and crosses the vertical demand curve at $60/MWh). The demand is assumed to be inelastic and does not react to price changes.

This assumed relationship between the electricity prices and volumes is used to estimate arbitrage, congestion, and peak shaving values. One of the limitations of this assumption, for example, is a potentially significant underestimation of peak shaving value. The estimation of peak shaving should consider the volume of electricity released from storage in proportion to peak consumption volumes, not monthly consumption volumes. Since the electricity supply curve is convex and not linear, a relatively small increase in supply during peak hours can have a very significant impact on price. Without consumption data associated with hourly prices, however, a simplistic set of assumptions had to be adopted.

Following the example above to the limit, releasing 1000 MWh from storage would shift the supply curve to the right such that it would cross the demand curve at 1000 MWh, and $0/MWh.

Similarly, an assumption about the relationship between congestion prices and energy released from storage had to be used for calculating congestion benefits. It is assumed that the energy released from storage can relieve congestion between the two nodes to the point where their congestion prices are equivalent. To see why this is a very conservative approach which likely significantly underestimate the potential congestion relief, consider a case of two nodes with nearly identical, but very high congestion prices. Because the model considers only the difference between those two nodes, the calculated value of congestion relief virtually be zero, whereas in a model which considers multiple nodal interconnections, the calculated value of congestion relief could be much higher.

The relationship between prices and volume is described in more detail in Appendix 3A.

A relationship between power prices and demand also needed to be assumed, but the assumption that power demand is inelastic, i.e. independent of prices, is much less contentious in the short-run, especially when prices are not visible to consumers in real time. Disputably, the demand could respond to power prices in the long run.

Arguably, another significant limitation of the model is that it deterministic and not stochastic. The model inputs are not based on relevant probabilities but on the value judgement of the model's user. Also, the model calculations are based on only one year of data, which might not be representative of the Mexican electricity market that arguably is still in transition.

3.6 Data sources

Table 3.9. Parameters used in the CBM and data sources.

Parameters used in equations	Source	Tab in CBM
E^S – Energy released from storage	Calculated based on user inputs	Arbitrage
P^P – Peak Prices	Calculated based on CENACE nodal prices	Charge & Discharge Prices
E^M – Monthly energy consumption	Calculated based on user inputs	Energy Consumption
PS^V – Value of Peak Shaving	Calculated based on user inputs	Peak Shaving
VM – Value of CO_2 mitigation	Calculated based on user inputs	Fuel Savings & CO_2 Mitigation
CC^Y – Carbon content per MWh of displaced generation	Calculated based on the generation type to be displaced	Fuel Savings & CO_2 Mitigation
CC^z – Carbon content per MWh of generation used to charge storage	Calculated based on the generation type to be used to charge storage	Fuel Savings & CO_2 Mitigation
E^C – Energy used to charge storage, MWh	Calculated based on the efficiency of the generation type used to charge storage	Fuel Savings & CO_2 Mitigation
CG – A percentage of storage charged with renewable generation	This is an input determined by the user	Summary of Inputs & Outputs
P^{CO2} – Price of CO2 emissions (MXN) per metric tonne	This is an input determined by the user	Summary of Inputs & Outputs
F^S – Value of fossil fuel savings, MXN	Calculated based on user inputs	Summary of Inputs & Outputs
F^Y – Amount of Fuel required to generate 1MWh using displaced generation	Calculated based on the type of fuel to be displaced, determined by user input	Summary of Inputs & Outputs
P^Y – Price of fuel used by displaced generation, MXN P^Z – Price of fuel used to charge storage,	Fuel prices are input by a user	Summary of Inputs & Outputs
F^Z – Amount of fuel required to generate 1MWh used to charge storage	Calculated based on the type of fuel to be used to charge storage, determined by user input	Summary of Inputs & Outputs
C^v – Value of decreased congestion	Calculated based on the nodes chosen by the user	Congestion
A, B – Nodes for which average monthly congestion prices are compared	Nodes are chosen by the user	Summary of Inputs & Outputs

Parameters used in equations	Source	Tab in CBM
x – absolute value of the rate of change of congestion price with respect to decrease in congestion constraint	This is an input determined by the user	Summary of Inputs & Outputs
R^A – Revenue from arbitrage	Calculated based on user inputs	Arbitrage
• Storage technology to be considered • Daily dispatch (hrs) • Generation type displaced by storage • Generation type used to charge storage • % of storage charged by renewables • CO2 Price (2020$ MXN/Metric Tonne) • Real discount rate (%) • Mexican Inflation Rate • Exchange rate (MXN/USD) • Rate of decline in congestion price due to congestion relief • Fuel Prices: coal, Diesel, natural gas, fuel oil (2020$) • Voltage control tariff (MXN/MWh) • Mvar/h provided as % of each MW/h of energy released • Nodes to be compared	User Input	Summary of Inputs and Outputs
Carbon content by fuel & generation technology Heat content by fuel Heat Rates by Generation Technology	Energy Information Administration https://www.eia.gov/electricity/annual/html/epa_08_01.html https://www.eia.gov/energyexplained/units-and-calculators/british-thermal-units.php https://www.eia.gov/electricity/annual/html/epa_08_02.html	Inputs
Hourly Local Marginal Prices	CENACE (CENSASE, 2020)	Nodal Prices Chihuahua Nodal Prices Zimapan Nodal Prices Yucatan Nodal Prices Coahuila

Parameters used in equations	Source	Tab in CBM
		Nodal Prices Baja California S
Energy consumption Monthly distribution of annual consumption Expected consumption growth	PRODESEN 2019-2033 (SENER, 2019)	Inputs
Historic Mexican Inflation	INEGI: https://www.eia.gov/electricity/annual/html/epa_08_02.htm	Inputs
Capital cost, Fixed O&M, Variable O&M, Charge times, Discharge rate, Construction time	Technology Catalogue	CAES Flywheels Molten Salt PHS Li-ion PB Acid VRB NaS

4. Case studies

4.4.1 Economic scenarios

All the energy storage technologies reviewed in this paper are technically feasible. Whether or not they should be pursued, however, is determined by their economic feasibility. The purpose of this section is to explain the data and scenarios applied and how that feasibility was estimated.

At the outset, Table 4.1 provides an overview of locations for each case study in terms of the control region, the relevant nodes used to evaluate the impact of energy storage as the "Base case scenario", and the changes to base case assumptions used for sensitivity scenarios. The second column of Table 4.1 lists the sensitivity analysis scenarios for the Northeast region and the changes to the base case assumptions in the Peninsular region.

The "base case scenario" for the 5 study sites can be described through a set of data and assumptions common to the 5 cases or study sites. For example, for these 5 cases the same social discount rate will be applied, or the percentage of renewable generation that is applied to charge the energy storage systems will be the same. At 4 study sites the applied storage technology is Lithium Ion Batteries (North, Northeast, Peninsular and Baja California Sur), and in the Western study site (Zimapán) the storage technology is pumped hydro storage (PHS). The principal reason why PHS was chosen for the Western region was CFE's interest in possible installation of PHS technology at the Zimapán hydroelectric plant. In the other regions the Lithium-Ion batteries were suggested because of the response speed, favorable cost and efficiency as well as certain security that comes from selecting one of the most popular battery storage technologies. In summary, the key assumptions and inputs underlying the base case cost benefit model (CBM) outputs are basically the same for all 5 "base case scenarios"

Table 4.1. Base Case and Sensitivity Scenarios.

Base Case Scenario Locations: Control Region/Nodes	Sensitivity Analysis Scenarios
1: Western/ Zimapán – San José Iturbide	Base case outcome is reported without sensitivity analysis
2: North/ Moctezuma – Cereso Juarez	Outcomes are reported for all storage technologies Where: 2A North: The fuel oil generation is displaced 2B North: The simple cycle gas generation is displaced
3: Northeast/ Guemez-Saltillo	Base case outcome is reported without sensitivity analysis
4: Peninsular/	Base case outcome is reported, as well as outcomes where:

Base Case Scenario Locations: Control Region/Nodes	Sensitivity Analysis Scenarios
San Ignacio – Playa Mujeres	4A Peninsular: Displaced generation is varied 4B Peninsular: Specific investment and operating costs are varied 4C Peninsular: CO_2 price is varied 4D Peninsular: Social discount rate is varied 4E Peninsular: The % of storage charged with VRE is varied 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)/ Olas Altas – Insurgentes	Base case outcome reported without sensitivity analysis

The **Table 4.2** below lists "base case scenario" assumptions and parameters in more detail. The first section of the table lists those assumptions which are independent of storage technology or its location. The second section lists those variables that do change according to technology and location.

Table 4.2. Base Case Assumptions and Parameters

	Base Case Assumptions and Parameters
Same for All 8 Storage Technologies and 5 Case Study Locations	● MXN/USD 2020 = 23.17 MXN 2020$ ● MXN/USD 2021 = 22.12 MXN 2020$ ● MXN/USD 2022+ = 20.0 MXN 2020$ ● Year over Year Demand growth rate for SIN and BCS: 3% ● CO_2 Price (MXN/Tonne) = $0 ● Coal US$/Tonne = US$48 ● Diesel US$/Gal = US$1.24 ● Natural Gas US$/MMBtu = US$1.70 ● Fuel Oil US$/BBL = US$36.53 ● Voltage Control $MXN/Mvar/hr = MXN$5.6/MWh (all prices are constant in 2020$ currencies) ● 15% of stored energy comes from VRE sources, 85% from conventional generation (natural gas, combined cycle plants).* ● VRE energy used for charging storage has a market price (including stored energy that would otherwise be curtailed).*

<table>
<tr><td></td><td>Base Case Assumptions and Parameters</td></tr>
<tr><td></td><td>
All costs and benefits are calculated in constant 2020$ MXN
Discount Rate: 10% as per the Mexican Treasury Department guidelines
Mvar/hr as % of MW/hr released: 5%
Decline in Revenue from Decline in Congestion Price: 50%
Lifespan of storage technologies is defined in charge-discharge cycles and in years. For all storage technologies the number of cycles is adjusted to ensure lifespan in years
The average electricity price for SIN is $1,633.25/MWh (MXN 2020$)
The average electricity price for BCS is $3,044.79/MWh (MXN 2020$)
</td></tr>
<tr><td>Specific to Case Study Location and/or Base Case Technology</td><td>
Prices of Nodal Congestion and Losses
Nodes by region used for congestion relief calculations:

Western: Zimapán – San José Iturbide
North: Moctezuma – Cereso Juarez
Northeast: Guemez - Saltillo
Peninsular: San Ignacio – Playa Mujeres
BCS: Olas Altas - Insurgentes

Storage Capacity to be Installed:

Western: 570 MW
North: 211 MW
Northeast: 171 MW
Peninsular: 103 MW
BCS: 26 MW

Base Case Storage Technology, Western Region: PHS

Lifespan: 60 yrs
Capacity: 8,500 MWh
Daily Discharge: 10 hrs
Discharge Rate: 1,060 MW/hr
Round-trip Efficiency: 78%
Fixed Operation & Maintenance: US2020$ 5.1/MW/yr
Variable Operation & Maintenance: US2020$ 0.24/MWh
Specific Investment: US2020$ 128,000/MWh

</td></tr>
</table>

	Base Case Assumptions and Parameters
	● Base Case Storage Technology for All Other Regions: Li-Ion o Lifespan: 20 yrs o Capacity: 6 MWh o Daily Discharge: 4 hrs o Discharge Rate: 3 MW/hr o Round-trip Efficiency: 92% o Fixed Operation & Maintenance: US2020$ 540/MWh/yr o Variable Operation & Maintenance: US2020$ 2.22/MWh o Specific Investment: US2020$ 410,000/MWh ● Generation Displaced by Storage, by Region: fuel/technology o Western: fuel oil, simple cycle o North: fuel oil, simple cycle o Northeast: coal, simple cycle o Peninsular: fuel oil, simple cycle o BCS: Diesel, simple cycle ● Fuel and Generation Technology Used to Charge Storage, by Region: fuel/technology (85% net of 15% charged with VRE)*: o Western: natural gas, combined cycle o North: natural gas, combined cycle o Northeast: natural gas, combined cycle o Peninsular: natural gas, combined cycle o BCS: fuel oil, simple cycle

* The Molten Salts technology is an exception, since it's charged with concentrated solar power.

The base case parameters and assumptions come from various sources which could be categorized under three headings: The Technology Catalogue, Public Institutions, and own assumptions and calculations.

Technology Catalogue

The principal source of the technical base case parameters in Table 3.9 is the Technology Catalogue:

Storage Technology/Lifespan: The type of storage technology determines most of the remaining inputs and assumptions in the model, including storage lifespan. The model results are reported over the technical lifespan of the storage system.

Efficiency: The round-trip efficiency takes into account energy lost during charging, storage, and discharging. Specifically, the CBM considers the CO_2 and fuel cost implications of the "extra" energy that will be lost.

Daily Discharge: The daily discharge refers to the number of hours spent releasing energy from storage, rounded to the nearest hour. The amount of energy released per hour depends on each technology's output parameters defined in the Technology Catalogue. The number of hours dedicated to energy discharge is a judgement call derived from a combination of a typical storage period associated with each storage technology reported in the Technology Catalogue, and the maximum daily charge and discharge hours that would permit a storage technology to reach its technical lifespan.

Technology-Specific Costs and Sizing (fixed and variable operation and maintenance costs, specific investment costs) listed in the Technology Catalogue as well as size of a reference technology based on internal research.

The Table 5.4 identified regional storage needs to address frequency control, voltage control, ancillary services, and support for growing PV and EO generation. It is important to recognize that those evaluations were conducted considering only the issue at hand (for example, the amount of MW required for frequency control did not consider voltage control, even if storage capacity could address the two problems simultaneously). Considering the overlap between the identified storage requirements, the storage capacity for each region – with the exception of the Western region – was defined as the sum of storage required for frequency control and ancillary services associated with photovoltaic driven generation. For the Western region the storage capacity was guided by CFE's desire for 570 MW in the Zimapán area.

The Technology Catalogue considers most common storage sizes by technology, which are different than storage needs identified in Table 5.4. This is not problematic. The regional storage needs can be satisfied with capacity distributed among various locations. For example, the need for 103 MW of storage in the Peninsular region is arguably better addressed by 34 Li-Ion storage units at multiple locations, than one large storage unit at one location. That is because some services that storage can provide, such as congestion relief or voltage control, are confined to limited areas. Spreading storage capacity in the region can address more local problems and optimize grid reliability.

Assuming that the nodal prices within a region are very similar, as suggested by the data used by the model, it is reasonable to extrapolate model outcomes based on storage sizes specified in the Technology Catalogue, to the storage sizes specified identified in Figure 5.1 or Table 5.4. In case of the Western region, the PHS reference case specified in the Technology Catalogue must be scaled downwards.

Public Institutions

Most of the remaining base case scenario parameters come from Mexican public institutions, such as CENACE, the Banco de Mexico, the Treasury Department, the Mexican Department of Energy, and CFE are also important sources of information for the base case scenarios.

Nodal Prices: The CBM and the analysis of costs and benefits associated with storage is based on components of nodal prices (energy, congestion, losses) obtained from the CENACE website. The average price of electricity faced by each project (2020$ MXN/MWh), reported in the tables below, represent the average of annual hourly SIN and BCS energy (as opposed to nodal) prices from 2018, in 2020$ pesos.

Exchange Rate, MXN/USD: The historical exchange rate is taken from the Banco de Mexico website, whereas the future exchange rate is own elaboration. Both investment and fuel costs used for generation (natural gas, coal, etc.) are quoted in USD, consequently the exchange rate plays an important part in determining the results of the cost benefit analysis which is reported in MXN 2020$.

The Discount Rate of for social projects was decreased from 12% to 10% at the beginning of 2014 b the Mexican Treasury Department.

Annual Demand Growth: Energy consumption is expected to increase over time, and Mexican's Department of Energy expectation is 3% per year for both SIN and BCS, according to PRODESEN 2019-2033.

Displaced Generation/Generation Used for Charging was based on information received from CFE and the information contained in PRODESEN 2019-2033. The type of generation displaced by storage, and the type of generation used to charge storage determines fuel savings as well as CO_2 mitigation values.

The fuel prices were taken directly from the market, specifically from the Chicago Mercantile Exchange (CME). Since all fuels used in the analysis are traded internationally, and CME is arguably one of the largest international commodity markets, the quotes used here are considered transparent and not bias.

Own assumptions and calculations

Finally, numerous parameters were decided on internally:

15% of Stored Energy Comes from VRE Sources: The potential fossil fuel savings and the CO_2 mitigation is amplified if storage is charged with energy which comes from VRE, as opposed to conventional generation. While it is not unusual for the stored energy to come from renewable sources (especially if that energy would otherwise be curtailed), the model DOES NOT consider such energy to be free. Even energy that would otherwise be curtailed is valued at (low) market prices for charging purposes. The percentage of stored energy which comes from renewable generation impacts fuel savings and CO_2 mitigation.

CO_2 Price: The value of CO_2 mitigation is a function of CO_2 price. The current CO_2 price in Mexico is approximately US$2/Tonne and does not apply to natural gas generation. Consequently, the base case scenario assumes that the price of CO_2 is zero; an assumption which will be revisited in the sensitivity analysis table.

Mvar/hr as % of MW/hr Released: Most storage technologies are capable of voltage control, and can even act as a synchronous condenser. In Mexico, certain level of voltage control is considered auxiliary service not included in the market and remunerated through a regulated tariff. Storage can provide active and reactive power simultaneously. It is assumed that storage provides 5% of reactive power for which it is remunerated, for each MWh of active power released.

Sensitivity Analysis

The Table 4.3 below, proposes changes to base case assumptions in Table 4.2 and quantifies the specific changes to the "base case scenario" assumptions behind sensitivity scenarios listed in Table 4.1.

The sensitivity analysis is performed in two regions, the North and the Peninsular. In order to compare the costs and benefits of the 8 different technologies considered in the technology catalogue in one study site a case study location had to be chosen where potentially all types of storage could be applied. Out of the five control regions, the Western and the North regions were considered most favorable for pumped hydro storage due to existing hydro generation facilities in those zones. The North region was chosen as the point of reference to compare base case performance scenarios among technologies, first displacing fuel oil generation, and then displacing simple cycle natural gas generation. The sensitivity analysis performed in the Peninsular region is not focused on comparing storage performance between different technologies, but on the performance of the same technology (lithium ion batteries) under varied assumptions.

Recall that Table 4.2 which listed base case scenarios was divided into two sections. The first section listed assumptions that were the same for all 8 technologies and 5 regions. Those assumptions still apply to sensitivity analysis 2A and 2B (described in Table 4.1). In fact, the only tangible difference between the base case scenario for the North region and scenarios 2A and 2B, is that the base case scenario only examines the performance of Li-Ion technology, whereas scenarios 2A and 2B consider the performance of all 8 technologies in the region. In Scenario 2A all technologies replace fuel oil generation, and in Scenario 2B all technologies replace simple cycle gas generation. The second section of Table 4.3 also deals with sensitivity analysis 4A through 4G in the Peninsular region where the performance of Li-Ion storage is evaluated once various base assumptions are altered.

Table 4.3. Sensitivity Scenarios

	Assumptions and Parameters used in Sensitivity Scenarios
Sensitivity analysis Case Study: North	● All Table 4.15 assumptions hold[13]. In addition to Li-Ion technology described in base case scenario for North region, additional technologies are added to the region, with following characteristics: ● PHS o Lifespan: 60 yrs o Capacity: 8,500 MWh o Daily Discharge: 10 hrs o Discharge Rate: 1,060 MW/hr o Round-trip Efficiency: 78% o Fixed Operation & Maintenance: US2020$ 5.1/MW/yr o Variable Operation & Maintenance: US2020$ 0.24/MWh o Specific Investment: US2020$ 128,000/MWh ● Compressed Air Energy Storage (CAES) o Lifespan: 40 yrs o Capacity: 8,500 MWh o Daily Discharge: 8 hrs o Discharge Rate: 1,060 MW/hr o Round-trip Efficiency: 64% o Fixed Operation & Maintenance: US2020$ 2,730/MW/yr

[13] The only exception is Molten Salt, which uses 100% of sunlight to charge storage.

	Assumptions and Parameters used in Sensitivity Scenarios
	o Variable Operation & Maintenance: US2020$ 2.73/MWh o Specific Investment: US2020$ 238,000/MWh ● Flywheels o Lifespan: 22 yrs o Capacity: 6.7 MWh o Daily Discharge: 6 hrs o Discharge Rate: 5 MW/hr o Round-trip Efficiency: 85% (+53%/day of energy losses during storage) o Fixed Operation & Maintenance: US2020$ 5,800/MW/yr o Variable Operation & Maintenance: US2020$ 2.20/MWh o Specific Investment: US2020$ 3,800,000/MW ● Molten Salt o Lifespan: 30 yrs o Capacity: 1,362 MWh o Daily Discharge: 8 hrs o Discharge Rate: 150 MW/hr o Round-trip Efficiency: 95% o Fixed Operation & Maintenance: US2020$ 18,100/MW/yr o Variable Operation & Maintenance: US2020$ 0.78/MWh o Specific Investment: US2020$ 410,000/MWh ● Lead Acid Battery o Lifespan: 13 yrs o Capacity: 30 MWh o Daily Discharge: 1 hrs o Discharge Rate: 15 MW/hr o Round-trip Efficiency: 82% o Fixed Operation & Maintenance: US2020$ 3,770/MW/yr o Variable Operation & Maintenance: US2020$ 0.41/MWh o Specific Investment: US2020$ 554,000/MWh ● Vanadium Redox Battery (VRB) o Lifespan: 14 yrs o Capacity: 6.65 MWh o Daily Discharge: 10 hrs o Discharge Rate: 1.66 MW/hr o Round-trip Efficiency: 73% o Fixed Operation & Maintenance: US2020$ 9,440/MW/yr o Variable Operation & Maintenance: US2020$ 1.0/MWh o Specific Investment: US2020$ 602,000/MWh ● Sodium Sulfur: o Lifespan: 19 yrs o Capacity: 30 MWh o Daily Discharge: 1 hrs o Discharge Rate: 15 MW/hr

	Assumptions and Parameters used in Sensitivity Scenarios
	o Round-trip Efficiency: 91% o Fixed Operation & Maintenance: US2020$ 4,000/MWh/yr o Variable Operation & Maintenance: US2020$ 2.0/MWh o Specific Investment: US2020$ 380,000/MWh ● Scenario 2A: All technologies displace fuel oil generation ● Scenario 2B: All technologies displace natural gas simple cycle generation
Sensitivity analysis Peninsular Case Study	● All assumptions and parameters remain the same as in the base case (Table 4.15), except for the changes associated with each scenario, below. ● Scenario 4A: Fuel Displaced by Storage changes from fuel oil, simple cycle to: Scenario 4A1: o Natural Gas, Single Cycle Scenario 4A2: o Diesel, Combined Cycle ● Scenario 4B: Storage Capex and Opex Change: o Lower Uncertainty Level from Technology catalogue – Fixed Operation & Maintenance: US2020$ 450/MWh/yr – Variable Operation & Maintenance: US2020$ 0.44/MWh – Specific Investment: US2020$ 320,000/MWh o 10% decrease in costs – Fixed Operation & Maintenance: US2020$ 486/MWh/yr – Variable Operation & Maintenance: US2020$ 2.00/MWh – Specific Investment: US2020$ 369,000/MWh o Upper Uncertainty Level from Technology catalogue – Fixed Operation & Maintenance: US2020$ 540/MWh/yr – Variable Operation & Maintenance: US2020$ 6.22/MWh – Specific Investment: US2020$ 550,000/MWh ● Scenario 4C: CO_2 changes from $0/Tonne to: o US$10/Tonne o US$15/Tonne o US$20/Tonne o US$30/Tonne o US$50/Tonne ● Scenario 4D: Social Discount Rate changes from 10% to: o 6%

	Assumptions and Parameters used in Sensitivity Scenarios
	o 8% o 12% • Scenario 4E: The % of stored energy sourced from VRE changes from 15% to: o 30% o 50% o 70% o 100% • Scenario 4F: On the basis of scenario 4A.1: Fuel Displaced by Storage changes from fuel oil, simple cycle to Natural Gas, simple cycle and CO_2 changes from $0/Tonne to: o US$10/Tonne o US$15/Tonne o US$20/Tonne o US$30/Tonne o US$50/Tonne • Scenario 4G: A matrix on the basis of scenario 4E & scenario 4F: Fuel Displaced by Storage is simple cycle and every price of CO_2/Tonne in scenario 4F is matched with each % of stored energy sourced from VRE in scenario 4F.

Economic estimations

To evaluate the costs and benefits associated with each project, the CBM sums the net present value of seven model outputs:

1. Costs (storage capital and operating costs over the life of the project).

2. Arbitrage (revenue obtained from charging storage during low prices and selling during high prices).

3. Congestion relief (decrease in congestion between the nodes considered, associated with energy released from storage).

4. Fossil fuel savings (the difference in cost of fuel used for generation displaced by storage, and the cost of fuel used to charge storage).

5. Income from ancillary services, specifically voltage control, which has a regulated tariff.

6. Value of CO_2 mitigation, determined by the price of CO_2, the heat rate of displaced generation, and the heat rate of generation used to charge storage.

7. Peak shaving, the estimated impact in decreasing prices due to increased supply of energy during peak periods.

The Table 4.4 presents the CBM outputs based on Table 4.3 "base case scenario" assumptions and data. Some of the key assumptions from Table 4.3 are reproduced in Table 4.4 as previously mentioned, the results obtained using reference storage sizes described in the Technology Catalogue are extrapolated to meet storage needs identified in each region.

4.4.2 Results

Table 4.4. Base Case Cost Benefit Analysis Outputs Over the Life of a Project, millions 2020$ MXN rounded to the nearest million.

Case Study	Storage Requirements	Storage Type	Lifespan	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
	(MW)		(years)	(M2020$)							
Western	570	PHS	60	*-10,141*	1,627	49	10,016	3	0	140	1,694
North	211	Li – Ion	20	*-4,321*	2,207	1	2,544	1	0	0	431
Northeast	171	Li – Ion	20	*-3,502*	1,788	93	589	1	0	0	-1,032
Peninsular	103	Li – Ion	20	*-2,109*	1,077	67	1,242	0	0	0	277
BCS	26	Li – Ion	20	*-532*	159	0	271	0	0	0	-102

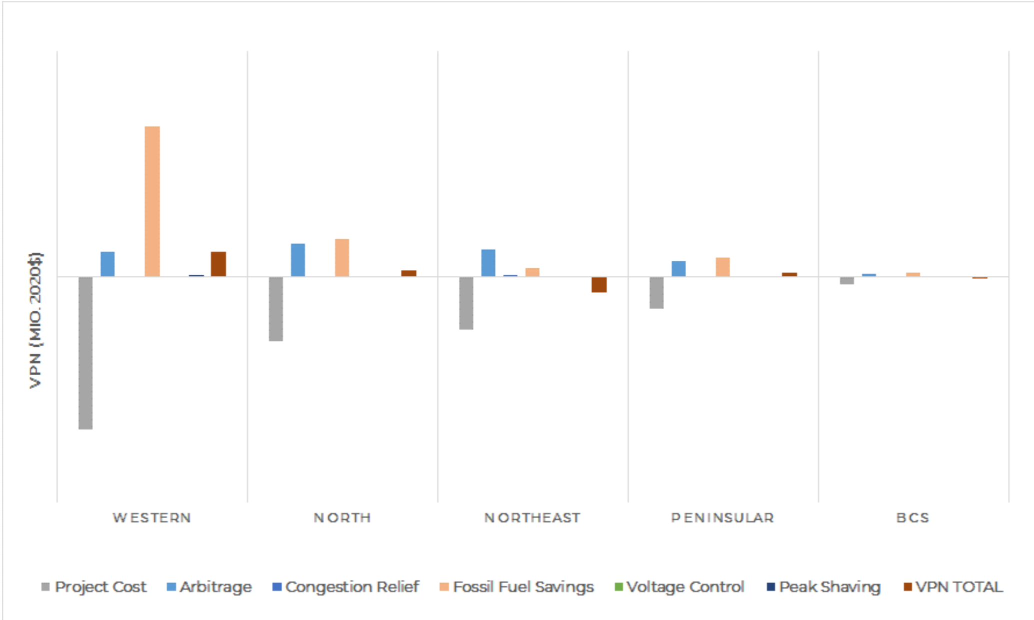


Figure 4.1. NPV by components and regions. Source: own elaboration.

The graph shows a number of salient points which are less obvious looking at the table. For example, the difference between regions in terms of respective NPV components is determined by the size of the regional storage requirements. Whereas the Western region's storage requirement is 570 MW, Baja California Sur's requirement is 26 MW. The graph's key point is that for all regions the most important determinant of the cost benefit analysis outcomes seems to be fossil fuel savings associated with displaced generation, not arbitrage, not peak shaving. This is contrary to initial expectations listed in Table 2.1, where arbitrage and peak shaving are reoccurring justifications for energy storage.

The positive peak shaving effect of energy storage is underestimated in the model, as discussed in section 3.5 where some of the model limitations are reviewed. Arguably, the positive arbitrage effect is also marginally muted by the model assumption that storage is classified as Transmission and therefore always has to pay for electricity used for charging, including for electricity that would otherwise be curtailed. The arbitrage figure could be significantly greater if the cost-benefit analysis were made from a private sector VRE generator point of view, especially in Baja California Sur where electricity prices are approximately double those of SIN, and where VRE is curtailed more often than in SIN. The high cost of generation in BCS mute both arbitrage and fossil fuel savings. The graph above indicates that the fossil fuel savings are the dominant benefit of storage for all regions except the Northeast. That is because in the Northeast region storage replaces coal generation, as opposed to fuel oil which is replaced in all other regions. It is important to note that fossil fuel savings associated with displacing fuel oil generation is considered a benefit principally from a social, and not private sector perspective. In addition to benefits from the social perspective include the CO_2 mitigation which is not captured on the graph because in a base case scenario the price of CO_2 is zero.

Table 4.5. Sensitivity Analysis 2A, All Technologies replace fuel oil generation, millions 2020$ MXN rounded to the nearest million.

Case Study	Storage technology	Lifespan	Roundtrip Efficiency	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		(years)	(%)	(M2020$)							
North Storage Required 211 MW	PHS	60	78%	*-3,754*	602	2	3,708	1	0	52	611
	Lithium – Ion	20	92%	*-4,321*	2,207	1	2,544	1	0	0	431
	CAES	40	64%	*-8,091*	*-522*	1	2,663	1	0	28	-5,918
	Vanadium Redox	14	73%	*-11,912*	34	2	4,111	1	0	0	-7,764
	Lead Acid	13	82%	*-5,353*	387	0	437	0	0	0	-4,528
	Sodium Sulfur	19	91%	*-3,921*	465	0	536	0	0	0	-2,919
	Moten Salt	30	95%	*-8,293*	8,689	2	5,217	1	0	8	5,624
	Flywheels	22	45%*	-19,646	-6,413	2	2,429	1	0	0	-23,628

*The round-trip efficiency is 85%, but the daily energy losses are 47%, thus 85%*53% = 45% of energy released from storage. The round-trip efficiency inflates the project costs.

Table 4.6. Sensitivity Analysis 2B, All Technologies replace natural gas simple cycle generation, millions 2020$ MXN rounded to the nearest million.

Case Study	Storage technology	Lifespan	Roundtrip Efficiency	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		(years)	(%)	(M2020$)							
North Storage Required 211 MW	PHS	60	78%	-3,754	602	2	286	1	0	52	-2,811
	Lithium – Ion	20	92%	-4,321	2,207	1	328	1	0	0	-1,784
	CAES	40	64%	-8,091	-522	1	17	1	0	28	-8,565
	Vanadium Redox	14	73%	-11,912	34	2	231	1	0	0	-11,644
	Lead Acid	13	82%	-5,353	387	0	40	0	0	0	-4,925
	Sodium Sulfur	19	91%	-3,921	465	0	47	0	0	0	-3,408
	Moten Salt	30	95%	-8,293	8,689	2	1,564	1	0	8	1,971
	Flywheels	22	45%	-19,646	-6,413	2	-804	1	0	0	-26,860

*The round-trip efficiency is 85%, but the daily energy losses are 47%, thus 85%*53% = 45% of energy released from storage

The purpose of the sensitivity analysis 2A is to compare the efficiency of various storage technologies under similar circumstances in terms of storage requirements, the fuel being replaced, and the nodal congestion prices. The time to charge and discharge, however, is specific to each technology according to its base case scenario.

Based on the base case assumptions, only three storage technologies have a positive NPV: PHS, Lithium-Ion, and Molten salt. Out of those three, the Molten Salt technology represents by far the highest NPV, driven by arbitrage and fuel savings. Whereas all other technologies have to pay for electricity and losses associated with charging, Molten Salt storage is charged for free with concentrated solar radiation.

The base case scenario assumes that the price of CO_2 is zero. If the price of CO_2 were US$20/tonne, the NPV of Molten Salts storage would be over seven billion MXN. Again, whereas carbon emissions for other storage technologies are measured as the net difference between CO_2 displaced by storage and the.CO_2 emitted by generation used to charge storage, the energy used to charge Molten Salts does not emit CO_2.

Another key takeaway from this scenario is that from the social perspective, fossil fuel savings is one of the principal considerations for implementing energy storage. Currently, fuel oil still represents an important fraction of generation in Mexico.

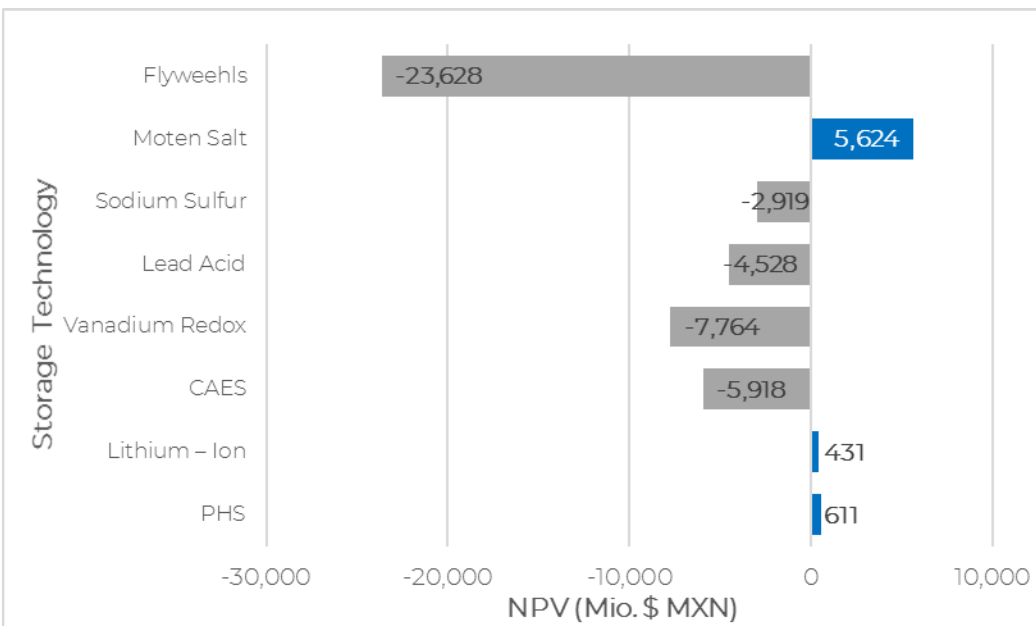


Figure 4.2. Technology Comparison, Displacing Fuel Oil Generation. North Region, Scenario 2A. Source: own elaboration.

The only difference between sensitivity analysis 2A and 2B, is that in the former the fuel oil generation is replaced by storage and in the latter its simple cycle natural gas. The Molten Salts storage systems are the only ones with the positive NPV for the reasons described in scenario 2A.

The Table 4.6 and the associated graph make it clear that in order for storage technologies to displace single cycle natural gas generation, the CO_2 needs to be priced, and the renewable generation needs to be more widespread to maximize the percentage of storage charged with VRE. Those two factors combined with a declining cost of storage will determine are likely to foster displacement of fossil fuel generation in the future.

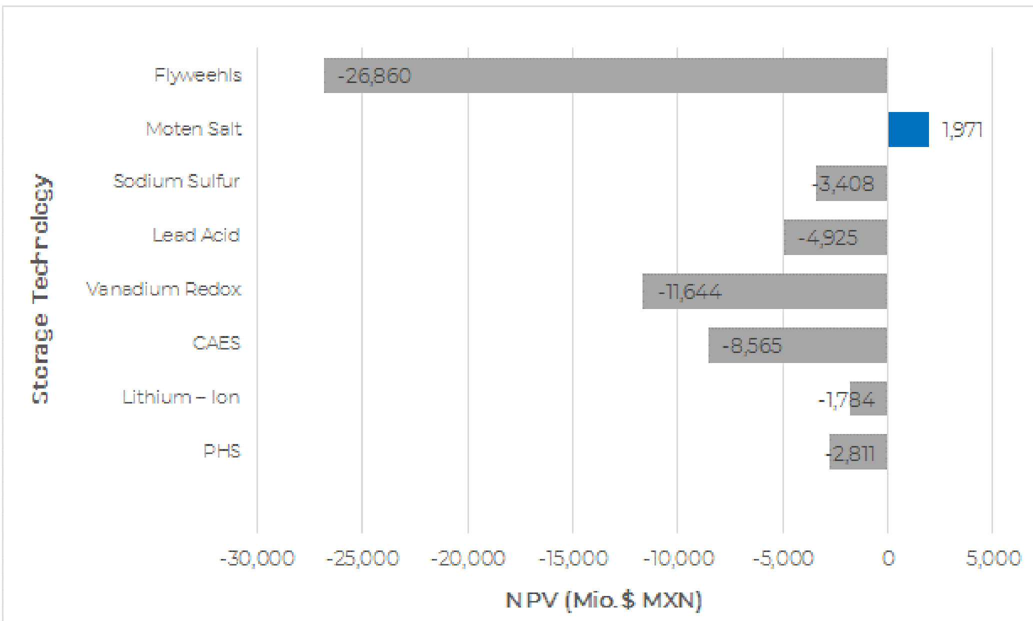


Figure 4.3. Technology Comparison, Displacing Fuel Oil Generation. North Region, Scenario 2B. Source: own elaboration.

Table 4.7. Results scenarios 4A.1 and 4A.2, described in in Table 4.3: The Displaced fuel and generation is varied.

Case Study	Scenario	Fuel Replaced	Generation Replaced	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
				(M2020$)							
Storage Required 103 MW	BASE CASE	Fuel Oil	Simple Cycle	-2,109	1,077	67	1,242	0	0	0	277
	Scenario 4A.1	Natural Gas	Simple Cycle	-2,109	1,077	67	160	0	0	0	-804
	Scenario 4A.2	Diesel	Combined Cycle	-2,109	1,077	67	1,987	0	0	0	1,022

The scenarios 4A1 and 4A2 focus on the performance of Lithium-Ion storage under different assumptions and circumstances in the Peninsular region. The graph below reiterates the point that from a social perspective the NPV of a storage project is principally determined by the type of generation it can replace.

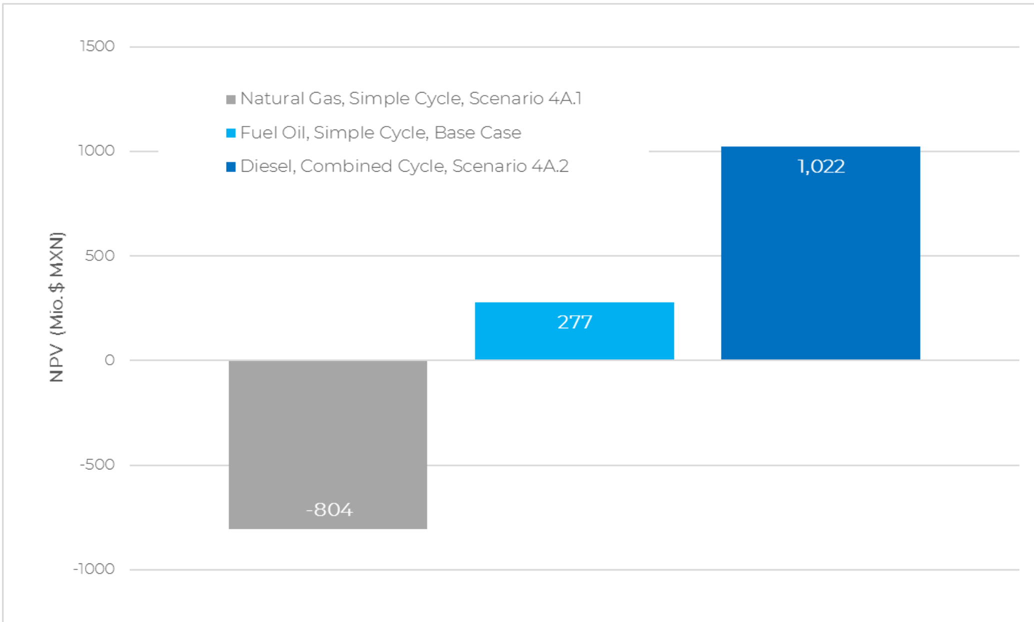


Figure 4.4. Fossil Fuel Displacement by Li-Ion Storage, Peninsular Region. By Fuel & Generation Type. Source: own elaboration.

Table 4.8. Results scenario 4B described in in Table 4.3: Specific investment and operating costs are varied

Case Study	Scenario	Specific Invest.	Fixed O&M	Variable O&M	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		USDM 2020$/MWh	USD/MW/yr 2020$	USD/MWh 2020$	(M2020$)							
Storage Required 103 MW	Upper Uncertainty	.550	540	6.22	*-2,914*	1,077	67	1,242	0	0	0	-527
	BASE CASE	0.410	540	2.22	*-2,109*	1,077	67	1,242	0	0	0	277
	10% Cost Decrease	0.369	486	2.00	*-1,899*	1,077	67	1,242	0	0	0	488
	Lower Uncertainty	0.320	450	0.44	*-1,613*	1,077	67	1,242	0	0	0	774

The costs of storage technologies are critical in determining the NPV of the project. In the case of Lithium Ion, the storage costs have been declining over the last few years and as the graph below shows, the cost uncertainty is not symmetrical: the low uncertainty, i.e. the uncertainty that costs will be lower, are more favorable than the upper uncertainty of costs increasing.

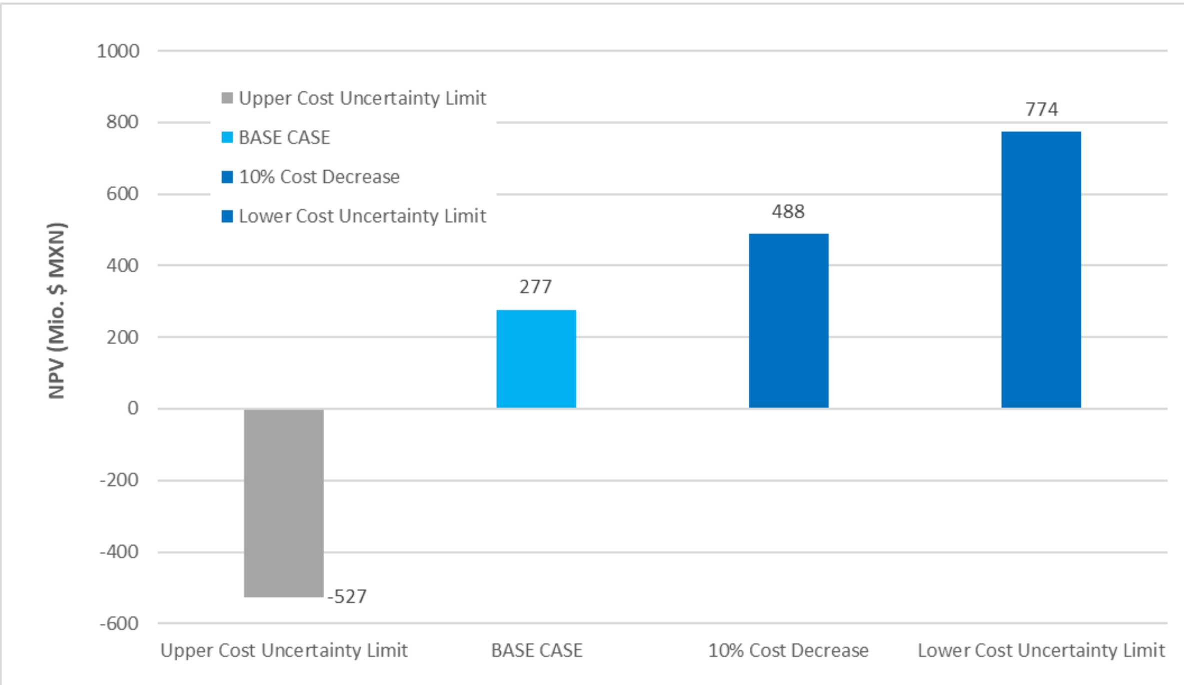


Figure 4.5. Li-Ion Cost Scenarios, Peninsular Region. Scenario 4B. Source: own elaboration.

Table 4.9. Results scenario 4C described in Table 4.3: the CO_2 price varies.

Case Study	Scenario	CO_2 price	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		USD/Ton CO_2	(M2020$)							
Storage Required 103 MW	BASE CASE	$0	-2,109	1,077	67	1,242	0	0	0	277
	Scenario 4C.1	$10	-2,109	1,077	67	1,242	0	118	0	395
	Scenario 4C.2	$15	-2,109	1,077	67	1,242	0	177	0	455
	Scenario 4C.3	$20	-2,109	1,077	67	1,242	0	237	0	514
	Scenario 4C.4	$30	-2,109	1,077	67	1,242	0	355	0	632
	Scenario 4C.5	$50	-2,109	1,077	67	1,242	0	591	0	864

Table 4.10. Results scenario 4D described in in Table 4.3: the social discount rate varies

Case Study	Scenario	Social Discount Rate	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		%	(M2020$)							
Storage Required 103 MW	BASE CASE	10	*-2,109*	1,077	67	1,242	0	0	0	277
	Scenario 4D.1	6	*-2,130*	1,436	90	1,650	0	0	0	1,047
	Scenario 4D.2	8	*-2,118*	1,237	77	1,423	0	0	0	619
	Scenario 4D.3	12	*-2,102*	949	59	1,096	0	0	0	2

The **Table 4.9** shows how the NPV of Lithium Ion storage changes with an increasing CO_2 price, ceteris paribus.

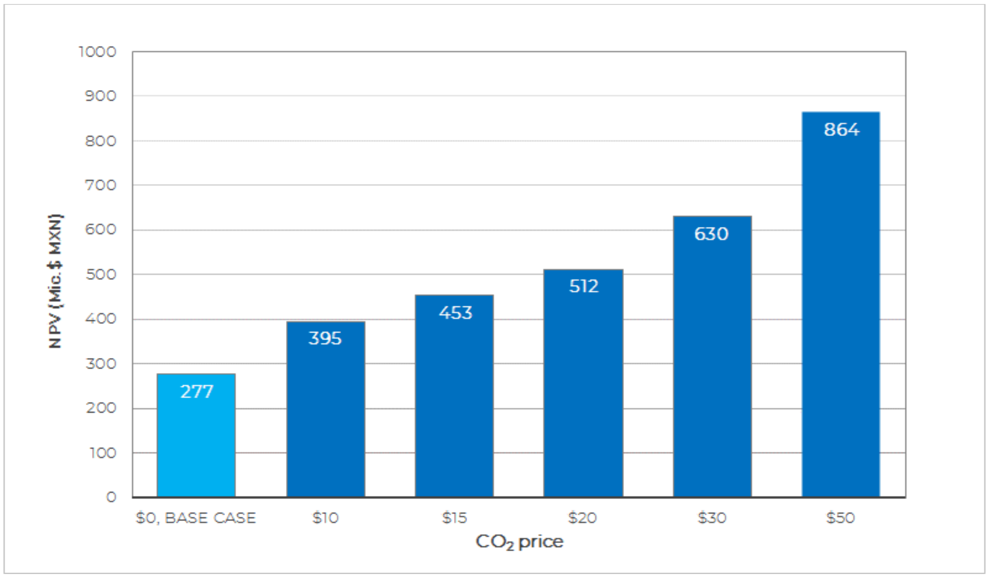


Figure 4.6. Li-Ion Storage Project NPV as a Function of CO2 Price. Peninsular Region. Source: own elaboration.

The Table 4.10 shows how the NPV of Lithium-Ion storage changes with a varying social discount rate, all other things being equal.

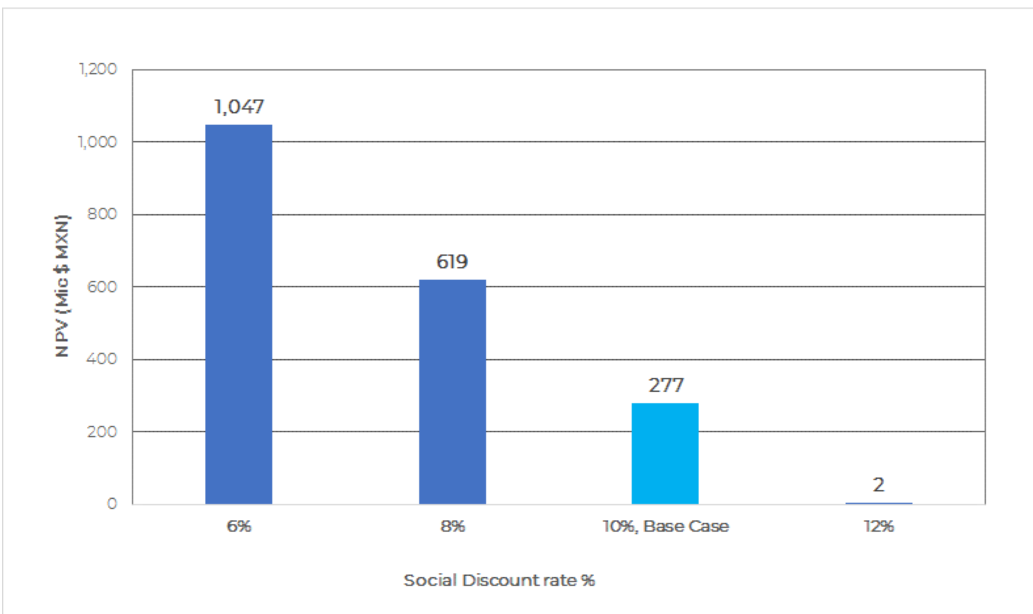


Figure 4.7 Li-Ion Storage Project NPV as a Function of Discount Rate. Peninsular Region. Source: own elaboration.

Table 4.11. Results scenario 4E, described in in Table 4.3: the percentage % of storage charged with VRE is varied

Case Study	Scenario	% of VRE Stored	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
		%	(M2020$)							
Storage Required 103 MW	BASE CASE	15	-2,109	1,077	67	1,242	0	0	0	277
	Scenario 4E.1	30	-2,109	1,077	67	1,295	0	0	0	331
	Scenario 4E.2	50	-2,109	1,077	67	1,367	0	0	0	402
	Scenario 4E.3	70	-2,109	1,077	67	1,438	0	0	0	473
	Scenario 4E.4	100	-2,109	1,077	67	1,545	0	0	0	580

Table 4.12. Results of scenario 4F, described in Table 4.3. scenario 4A.1 is reset (the displaced fuel changes, all else remains the same) and CO_2 price is varied.

Case Study	Scenario	CO_2 price	Project Cost	Arbitrage	Congestion Relief	Fossil Fuel Savings	Voltage Control	CO_2 Mitigation	Peak Shaving	TOTAL NPV
Storage Required 103 MW		USD/Ton CO_2	(M2020$)							
	RESET BASE CASE	$0	-2,109	1,077	67	160	0	0	0	-804
	Scenario 4F.1	$10	-2,109	1,077	67	160	0	50	0	-754
	Scenario 4F.2	$15	-2,109	1,077	67	160	0	75	0	-729
	Scenario 4F.3	$20	-2,109	1,077	67	160	0	100	0	-704
	Scenario 4F.4	$30	-2,109	1,077	67	160	0	150	0	-654
	Scenario 4F.5	$50	*-2,109*	1,077	67	160	0	250	0	-554
	Scenario 4F.6	$100	*-2,109*	1,077	67	160	0	500	0	-304

The Table 4.12 shows how the NPV of Lithium Ion storage changes when it is charged with increasing proportion of electricity which comes from renewable sources, ceteris paribus.

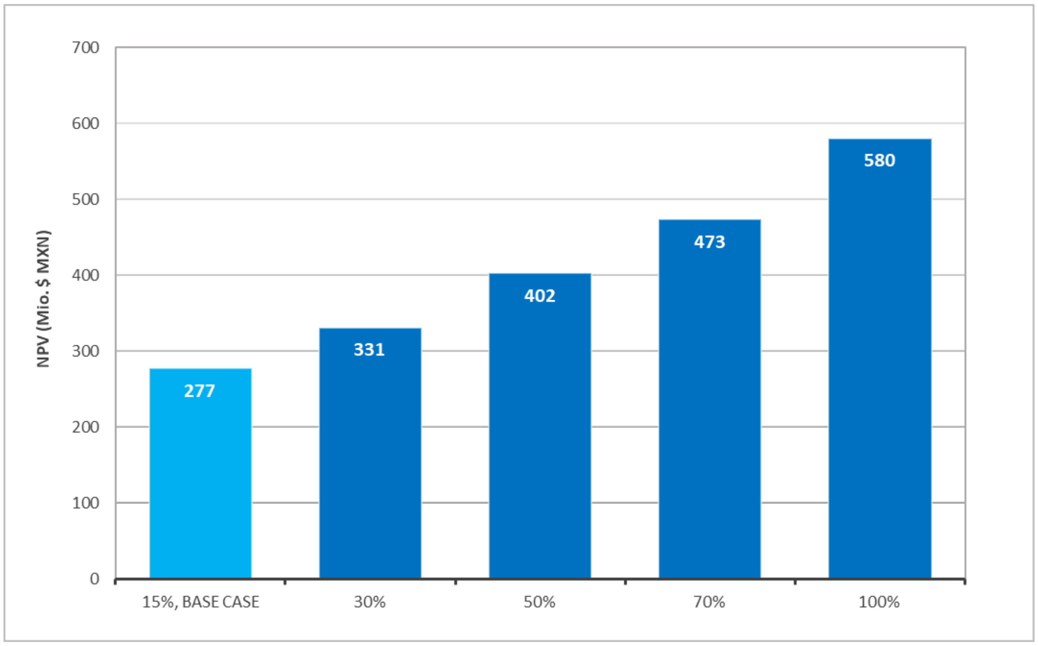


Figure 4.8. Li-Ion Storage Project NPV as a Function % Charged with VRE. Peninsular Region. Source: own elaboration.

The Table 4.13 shows that if energy storage is to displace a simple cycle natural gas generation, introduction of carbon pricing is not enough to make storage a competitive choice.

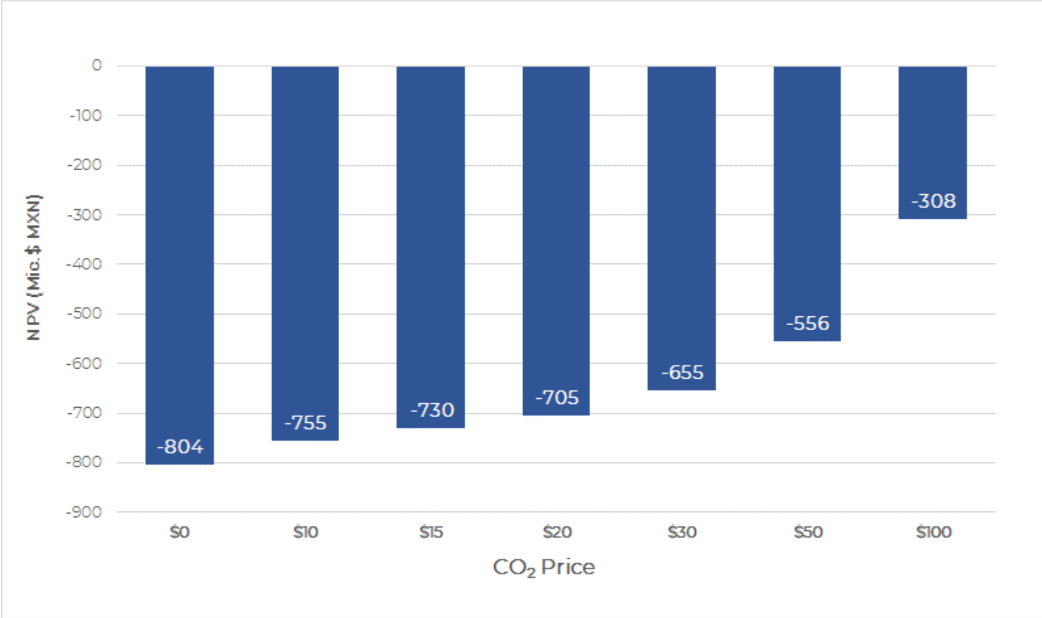


Figure 4.9. Li-Ion Storage Project NPV as a Function of CO_2 Price. Replacing Simple Cycle Natural Gas Generation, Peninsular Region. Source: own elaboration.

Table 4.13. Results scenario 4G, described in Table 4.3: A matrix on the basis of scenarios 4E & 4F: Fuel Displaced by Storage is a simple cycle and every price of CO_2/Tonne in scenario 4F is matched with each % of stored energy sourced from VRE in scenario 4F.

Case Study 4G	Total NPV (M 2020$)					
	CO_2 price	% of Storage Charged with VRE				
		15%	30%	50%	70%	100%
Storage Required 103 MW	$10	-754	-684	-591	-497	-357
	$15	-729	-651	-546	-442	-285
	$20	-704	-618	-502	-386	-213
	$30	-654	-551	-413	-275	-68
	$50	-554	-418	-235	-53	221
	$100	-304	-84	210	503	944

There are numerous factors which determine the NPV of a storage project. Unlike the previous scenarios where the impact on NPV of changing one factor was examined, this table examines a simultaneous impact of two factors, namely the price of carbon and the percentage of storage charged with VRE. The base case assumption is storage charged with natural gas combined cycle (85%) and VRE (15%), displacing natural gas simple cycle generation.

The table restates the gargantuan impact of the type of fuel that is displaced on storage NPV. If the displaced generation uses relatively expensive fuels, such as Diesel or fuel oil, the fossil fuel savings drive the NPV up, compared to using much less expensive natural gas. Consequently, in order for the NPV to be positive when replacing single cycle generation, when the price of CO_2 is US$50/tonne, at least 76% of storage needs to be charged with VRE.

Since fossil fuel savings were identified as the most important factor, it is critical to recognize that the current cost of fossil fuels is very low. For example, the price of natural gas used in the model is US$1.70/MMBtu, which is very low by historical standards. If the price of natural gas were US$4.50/MMBtu[14], for example, and 76% of storage were charged with VRE, the price of CO_2 per tonne could be zero, and the NPV would still be a positive $35 million MXN.

The discussion of the Case Study 4.G begun with an observation that numerous factors determine the NPV of a storage project, in this case Lithium-Ion batteries in the Peninsular region. Let us consider another factor, the cost.

The cost of Lithium-Ion batteries has been decreasing substantially over the last few years. If the cost of Lithium-Ion batteries falls by just 10% from its current level, the price of CO_2 is US$15/tonne, the price of natural gas is US$3.75/MMBtu, and 50% of stored energy comes from VRE, at the 10% social discount rate the NPV of the project would be a positive $8 million MXN.

The current economic downturn aside, arguably a long-term price of natural gas of US$3.75/MMBtu in real terms is quite rational. Likewise, the CO_2 price of $15/tonne is also conservative. Charging 50% of storage capacity with VRE is reasonable, especially with the growth of renewable generation. The point is, it is not difficult to see that under reasonable scenarios, even with underestimating peak shaving contribution to the NPV, certain technologies could replace not only inefficient generation which uses expensive fuels, but also simple cycle natural gas plants.

[14] The average closing Henry Hub natural gas price over the last 15 years (2005-2019) was US$4.55/MMBtu.

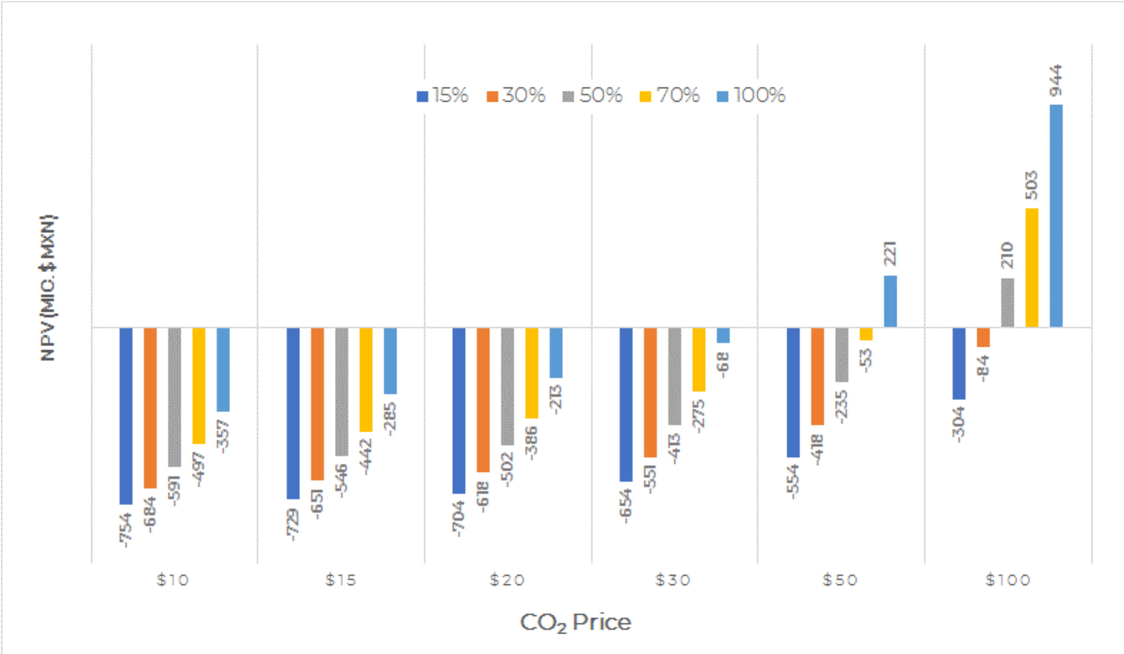


Figure 4.10. Li-Ion Storage Project NPV as a Function of CO_2 Price & % Charged with VRE, replacing Simple Cycle Natural Gas Generation, Peninsular Region. Source: own elaboration.

4.4.3 Conclusions and Takeaways

The preliminary proposal for the case studies supposed that the principal benefits associated with storage will be related to peak shaving, arbitrage, and congestion relief. The cost-benefit analysis revealed that the most important driver behind the value of storage is associated with fossil fuel savings from displacing fuel oil generation.

Currently, the fraction of electricity generated in Mexico using fuel oil is larger than the amount of electricity that storage capacity considered in this study could provide. This suggests that if CFE were to implement storage, it could substantially reduce its operating costs.

Generation using fuel oil has been declining in Mexico for some time. In the future energy storage could also replace natural gas single cycle generation, if CO_2 were priced similarly to other markets such as California, if storage were charged with VRE, and if the price of natural gas recovered from its historically low levels.

Out of the eight storage technologies considered, only the PHS, Lithium-Ion, and Molten Salts had a positive NPV under the base case assumptions. The Molten Salts system had the optimum NPV, principally because of the negligible costs of charging storage. Also, since a Molten Salts system is charged with concentrated solar power (as opposed to conventional generation), it presented the most favorable CO_2 mitigation potential.

The principal challenge of conducting a cost-benefit analysis was the lack of data. Certain benefits, such as peak shaving, congestion relief and arbitrage were calculated combining hourly nodal price data with assumptions as to how that price data relates to power supply. Other benefits could not be calculated at all, such as the value of possible deferral of transmission infrastructure projects, decrease of ohmic losses due decreased congestion, or capacity market revenues, to name a few. Calculating those benefits would arguably require too many assumptions. The key message is that the cost-benefit model errs on the conservative side and underestimates the value of energy storage.

The section D3 suggested four prototype ways for storage to participate in the electrical system. The cost-benefit analysis evaluated standalone storage classified as Transmission & controlled by CENACE. On one hand, classifying storage as Transmission increases the net present value (NPV) of a storage system by eliminating transmission costs. On the other hand, to avoid conflict of interest, all stored energy is assumed to be bought on the market (even energy that would otherwise be curtailed), which decreased the NPV.

The principal takeaway from the cost-benefit analysis is that from a social perspective, a select few energy storage technologies make sense even under conservative assumptions, and can provide significant net present value 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.

5. Study Cases technical summary

From the compilation and analysis of the information, it has been possible to define the main characteristics of the case studies:

Table 5.1 Identified problems per study case.

<table>
<tr><th>Region/ Study case</th><th>Identified problems (1)</th><th>Reserve required</th><th>Percentage reserve reduction per control area (2)</th><th>Amount of ESS required for Frequency control (MW) in the case of 1 % failure (3) Interval 0.03 Hz to 0.04 Hz</th><th>ESS Capacity for voltage control (MVAr or MW) (4)</th><th>ESS Capacity for Ancillary services (MW) (5)</th><th>ESS Power Capacity for % of VRE (6) (2020) (7)</th></tr>
<tr><td>Western / Zimapán</td><td>ERV increases participation between 24-29%
High consumption of gas and fuel oil in power generation
Increase electricity consumption in the residential, commercial and industrial sector
Voltage regulation problems
Low voltaje profiles
Reduction of transmission capacity
Saturation transmission networks
Expansion of Las Delicias-Querétaro transmission network or failing this there will be congestion</td><td>Frequency and voltage regulation</td><td>According to the scenarios (SC):<table><tr><th>SC</th><th>(%)</th></tr><tr><td>1</td><td>0.06</td></tr><tr><td>2</td><td>0.16</td></tr><tr><td>3</td><td>0.32</td></tr></table></td><td>2.53 - 2.46</td><td>400 MVAR</td><td>289.13</td><td><table><tr><th>Characteristic</th><th>ESS (MW)</th></tr><tr><td>PV-dominated</td><td>86-193.5</td></tr><tr><td>EO-dominated</td><td>21.5-43</td></tr></table></td></tr>
</table>

<table>
<tr><th>Region/ Study case</th><th>Identified problems (1)</th><th>Reserve required</th><th>Percentage reserve reduction per control area (2)</th><th>Amount of ESS required for Frequency control (MW) in the case of 1 % failure (3) Interval 0.03 Hz to 0.04 Hz</th><th>ESS Capacity for voltage control (MVAr or MW) (4)</th><th>ESS Capacity for Ancillary services (MW) (5)</th><th>ESS Power Capacity for % of VRE (6) (2020) (7)</th></tr>
<tr><td>North / Juarez-Chihuahua</td><td>Increase peak demand in Juárez City for the year 2023
Transmission line overload and voltages outside operating allowable limits
Increase in the load of auto-transforme,
lack of infrastructure and servicing
Electric units present derating
Saturated transmission lines
Energy not supplied associated with saturation problems in the Northeast-North and North-Northwest connections.</td><td>Frequency and voltage regulation</td><td>According to the scenarios (SC):<table><tr><th>SC</th><th>(%)</th></tr><tr><td>1</td><td>0.03</td></tr><tr><td>2</td><td>0.08</td></tr><tr><td>3</td><td>0.16</td></tr></table></td><td>6.99 -6.80</td><td>148 MVAR</td><td>139.73</td><td><table><tr><th>Characteristic</th><th>ESS (MW)</th></tr><tr><td>PV-dominated</td><td>126-283</td></tr><tr><td>EO-dominated</td><td>31.5-63</td></tr></table></td></tr>
<tr><td>Northeast/ Saltillo-Monterrey</td><td>ERV increase participation in generation
High capacity in transmission lines and congestion in the south direction and in the North-GCR valve gate
High power generation with fossil fuels
Voltage variations and high level of short circuits in SE</td><td>Frequency and voltage regulation</td><td>According to the scenarios (SC):<table><tr><th>SC</th><th>(%)</th></tr><tr><td>1</td><td>0.09</td></tr><tr><td>2</td><td>0.23</td></tr><tr><td>3</td><td>0.47</td></tr></table></td><td>5.16 -5.02</td><td>365 MVAR</td><td>422.09</td><td><table><tr><th>Characteristic</th><th>ESS (MW)</th></tr><tr><td>PV-dominated</td><td>102-229.5</td></tr><tr><td>EO-dominated</td><td>25.5-51</td></tr></table></td></tr>
</table>

<table>
<tr><th>Region/ Study case</th><th>Identified problems (1)</th><th>Reserve required</th><th>Percentage reserve reduction per control area (2)</th><th>Amount of ESS required for Frequency control (MW) in the case of 1 % failure (3) Interval 0.03 Hz to 0.04 Hz</th><th>ESS Capacity for voltage control (MVAr or MW) (4)</th><th>ESS Capacity for Ancillary services (MW) (5)</th><th>ESS Power Capacity for % of VRE (6) (2020) (7)</th></tr>
<tr><td></td><td>Increase peak demand in Monterrey City
New infrastructure in the transmission corridor Reynosa-Monterrey due to new generation projects
Electric units present derating
Congested transmission lines
Alerts and emergencies due to transmission flows between the North and North and Northeast GCR, Ramos Arizpe Potency to Primero de Mayo’s valves and the valve RAP-SLR + DMD-PMY.</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Peninsular</td><td>Transmission lines reaches maximum capacity
Energy curtailment
Demand surpasses transmission capacity by 80 MW for 250 hr.
Frequency control problems
Demand exceeded between 14 to 34 MW supply in June
Risk of unavailability of natural gas</td><td>Frequency and voltage regulation</td><td>According to the scenarios (SC):<table><tr><th>SC</th><th>(%)</th></tr><tr><td>1</td><td>0.01</td></tr><tr><td>2</td><td>0.03</td></tr><tr><td>3</td><td>0.07</td></tr></table></td><td>1.33 - 1.29</td><td>148 MVAR</td><td>59.89</td><td><table><tr><th>Characteristic</th><th>ESS (MW)</th></tr><tr><td>PV-dominated</td><td>62.8-141.3</td></tr><tr><td>EO-dominated</td><td>15.7-31.4</td></tr></table></td></tr>
</table>

<table>
<tr><th>Region/ Study case</th><th>Identified problems (1)</th><th>Reserve required</th><th>Percentage reserve reduction per control area (2)</th><th>Amount of ESS required for Frequency control (MW) in the case of 1 % failure (3) Interval 0.03 Hz to 0.04 Hz</th><th>ESS Capacity for voltage control (MVAr or MW) (4)</th><th>ESS Capacity for Ancillary services (MW) (5)</th><th>ESS Power Capacity for % of VRE (6) (2020) (7)</th></tr>
<tr><td></td><td>ERV increase participation in generation</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>BCS</td><td>Old conventional power plants
Increased demand for the residential and tourist sector
Load saturation in transformation banks
RNT deficiencies
Voltage regulation problems
Electric units such as Punta prieta y General Olachea present derating</td><td>Frequency and voltage regulation</td><td>According to the scenarios (SC):<table><tr><th>SC</th><th>(%)</th></tr><tr><td>1</td><td>1.31</td></tr><tr><td>2</td><td>3.28</td></tr><tr><td>3</td><td>6.56</td></tr></table></td><td>6.03 - 6.01</td><td>36 MVAR</td><td>60</td><td><table><tr><th>Characteristic</th><th>ESS (MW)</th></tr><tr><td>PV-dominated</td><td>12.4-27.9</td></tr><tr><td>EO-dominated</td><td>3.1-6.2</td></tr></table></td></tr>
</table>

(1) Secretaría de Energía. (2019). Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033. SENER Sitio web: https://www.gob.mx/sener/documentos/prodesen-2019-2033

(2) Ramírez, J., Pizarro, A., y Ruíz, R. (2020). A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. INECC, 1(1), 24.

(3) Ramírez, J., Pizarro, A., y Ruíz, R. (2020). A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. INECC, 1(1), 23.

(4) Ramírez, J., Pizarro, A., y Ruíz, R. (2020). A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. INECC, 1(1), 47.

(5) Ramírez, J., Pizarro, A., y Ruíz, R. (2020). A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. INECC, 1(1), 44.

(6) According to Cebulla et al. For Europe and the U.S., the increase in EES power capacity is about 1–2 and 4–9 GW/%VRE for wind- and PV-dominated scenarios, respectively. Germany focus on more balanced generation mixes, attaining additional EES power capacities of 0.3 GW/%VRE. In terms of EES energy capacity, for VRE shares over 80%, PV-dominated grids require about 1.0 to 3.0 TWh for Europe and the U.S. Systems strongly dominated by wind generation need at least 0.2 to 1.0 TWh. Germany are balanced mixes, and those which include other flexibility options (e.g. curtailment, exports/imports to neighboring countries) recommend 0.05 to 1.1 TWh.

(7) Cebulla F., Haas J., Eichman J., Nowak W., Mancarella P. How much Electrical Energy Storage do we need? A synthesis for the U.S., Europe, and Germany. Journal of Cleaner Production · February 2018.

(8) Centro Nacional de Control de Energía. (2019). Programa de Ampliación y Modernización de la RNT y RGD 2019 - 2033. CENACE Sitio web: https://www.cenace.gob.mx/Paginas/Publicas/Planeacion/AmpliacionModernizacionRed.aspx

From the analysis for the ideal network operation with respect to frequency and voltage, reference nodes were selected for the evaluation of the case studies, and an attempt was made to associate with nearby conventional and renewable plants that would allow inferring the displacement of fossil fuels and the support of renewable energy generation:

Table 5.2. Identified problems, nodes, regional generation technology per study case.

Study case	Previously identified site problems	Site and surrounding nodes to evaluate	Conventional (CVP) and renewable (RWP) Power plants near nodes (1)	Technology /Fuel (2)
Zimapán, Hidalgo	Congestion	Querétaro (03QRO-115) San José Iturbide (03SJI-115)	CVP: RWP: Zimapán (Fernando Hirlart Balderrama)	Hydroelectric
Juárez, Chihuahua	High Congestión	Juárez (05CEJ-115) Moctezuma (05MCZ-115)	CVP: Samalayuca I and II RWP:	Combined cycle and conventional thermoelectric/ Fuel oil and Gas
Saltillo-Monterrey	High Congestión	Saltillo (06SAL-115) Guemez (06GUE-115)	CVP: Saltillo RWP:	Combined cycle/Gas
Mérida, Yucatán	High technical losses, congestion, blackouts, Diesel Generation	Mérida (08IGN-115) Cancún (08PMU-115)	CVP: Valladolid (Felipe Carillo Puerto) RWP:	Combined cycle and conventional thermoelectric/ Fuel oil and Gas

Study case	Previously identified site problems	Site and surrounding nodes to evaluate	Conventional (CVP) and renewable (RWP) Power plants near nodes (1)	Technology /Fuel (2)
La Paz, BCS	Low operating reserves, Diesel generation, curtailment of renewable generation	Villa Constitución (07INS-115) La Paz (07OLA-115)	CVP: Punta Prieta RWP:	Thermoelectric/ Fuel oil

(1) Centro Nacional de Control de Energía. (2019). Programa de Ampliación y Modernización de la RNT y RGD 2019 - 2033. (p. 30,32) CENACE Sitio web: https://www.cenace.gob.mx/Paginas/Publicas/Planeacion/AmpliacionModernizacionRed.aspx

(2) Centro Nacional de Control de Energía. (2019). Programa de Ampliación y Modernización de la RNT y RGD 2019 - 2033. (p. 30,32) CENACE Sitio web:

Thanks to the available information, the growth of the participation of renewable energies in each region was estimated to seek the relationship regarding the storage necessary for its incorporation.

Table 5.3. Identified problems, nodes, regional generation technology per study case.

	(PRODESEN 2019-2033- PIIRCE) (1)	Year of data 2018 (2)					
Region	Possible future increase of VRE in the region	Gross Generation (3) (GWh)	Emissions CO_2 CFE (10^3 tons)	Emissions CO_2 PIE (10^3 tons)	Installed Capacity (4) (MW)	Gross consumption (GWh)	Peak demand integrated (5) (MWh/h)
Central	Year – EIC ER (MW) 2020 – 952 2025 – 1832 2030 – 2383	6,698.87	3,449.3	ND	8,449	61,293	8,805
Eastern	Year – EIC ER (MW) 2020 – 1248 2025 – 3951 2030 – 8548	25,101.08	10,970.5	ND	17,390	50,285	7,594

<table>
<tr><td></td><td>(PRODESEN 2019-2033- PIIRCE) (1)</td><td colspan="6">Year of data 2018 (2)</td></tr>
<tr><td>Region</td><td>Possible future increase of VRE in the region</td><td>Gross Generation (3)
(GWh)</td><td>Emissions CO_2 CFE
(10^3 tons)</td><td>Emissions CO_2 PIE
(10^3 tons)</td><td>Installed Capacity (4)
(MW)</td><td>Gross consumption
(GWh)</td><td>Peak demand integrated (5)
(MWh/h)</td></tr>
<tr><td>Northwestern</td><td><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>1425</td></tr><tr><td>2025</td><td>1722</td></tr><tr><td>2030</td><td>2753</td></tr></table></td><td>13,283.48</td><td>6,869.9</td><td>ND</td><td>4,940</td><td>24,684</td><td>4,759</td></tr>
<tr><td>Northeast</td><td><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>4199</td></tr><tr><td>2025</td><td>5034</td></tr><tr><td>2030</td><td>8288</td></tr></table></td><td>21,770.42</td><td>22,185.5</td><td>ND</td><td>16,463</td><td>56,430</td><td>9,202</td></tr>
<tr><td>Peninsular</td><td><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>368</td></tr><tr><td>2025</td><td>815</td></tr><tr><td>2030</td><td>815</td></tr></table></td><td>4,715.82</td><td>2,659.86</td><td>ND</td><td>2,336</td><td>12,989</td><td>2,061</td></tr>
<tr><td>Western Center</td><td rowspan="2"><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>2430</td></tr><tr><td>2025</td><td>3447</td></tr><tr><td>2030</td><td>5321</td></tr></table></td><td>31,963.56</td><td>16,093.8</td><td>ND</td><td rowspan="2">11,277</td><td rowspan="2">68,107</td><td rowspan="2">10,373</td></tr>
<tr><td>Western Pacific</td><td>15,034.3</td><td>6,766.9</td><td>ND</td></tr>
</table>

<table>
<tr><td></td><td>(PRODESEN 2019-2033- PIIRCE) (1)</td><td colspan="6">Year of data 2018 (2)</td></tr>
<tr><td>Region</td><td>Possible future increase of VRE in the region</td><td>Gross Generation (3)
(GWh)</td><td>Emissions CO_2 CFE
(10^3 tons)</td><td>Emissions CO_2 PIE
(10^3 tons)</td><td>Installed Capacity (4)
(MW)</td><td>Gross consumption
(GWh)</td><td>Peak demand integrated (5)
(MWh/h)</td></tr>
<tr><td>North</td><td><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>1719</td></tr><tr><td>2025</td><td>1971</td></tr><tr><td>2030</td><td>3294</td></tr></table></td><td>23,855.37</td><td>9,466.9</td><td>ND</td><td>5,450</td><td>27,000</td><td>4,639</td></tr>
<tr><td>BCS</td><td><table><tr><td>Year</td><td>EIC ER (MW)</td></tr><tr><td>2020</td><td>23</td></tr><tr><td>2025</td><td>23</td></tr><tr><td>2030</td><td>67</td></tr></table></td><td>2,599.54</td><td>1,874.2</td><td>ND</td><td>739</td><td>2,759</td><td>500</td></tr>
</table>

*Owners: Federal Electricity Commission (CFE) and Independent Energy Producers (PIE); *ND: No data; EIC: Effective Installed Capacity ER

(1) Secretaría de Energía. (2019). Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033. (p. 47-55) SENER Sitio web: https://www.gob.mx/sener/documentos/prodesen-2019-2033; (2) CFE RESUMEN 2015-2018; (3) CFE RESUMEN 2015-2018

(4) Secretaría de Energía. (2019). Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033. (p. 22) SENER Sitio web: https://www.gob.mx/sener/documentos/prodesen-2019-2033

(5) Secretaría de Energía. (2019). Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033. (p. 33 y 38) SENER Sitio web: https://www.gob.mx/sener/documentos/prodesen-2019-2033

Table 5.4. Identified regional energy storage requirements. Fuente: References: 3,4,5,6

	Amount of ESS required for Frequency control (MW)	Amount of ESS required for voltage control (MVAr or MW)	Amount of ESS required for Ancillary services -Reserves (MW)	PV dominated - Amount of ESS required for Ancillary services -Reserves (MW)	EO dominated - Amount of ESS required for Ancillary services -Reserves (MW)
Study case	A prom	B	C	D1 prom	D2 prom
Western / Zimapán	2.50	400.0	289.1	139.75	32.25
North / Juarez-Chihuahua	6.90	148.0	139.7	204.50	47.25
Northeast/ Saltillo-Monterrey	5.09	365.0	422.1	165.75	38.25
Peninsular	1.31	148.0	59.9	102.05	23.55
BCS	6.02	36.0	60.0	20.15	4.65

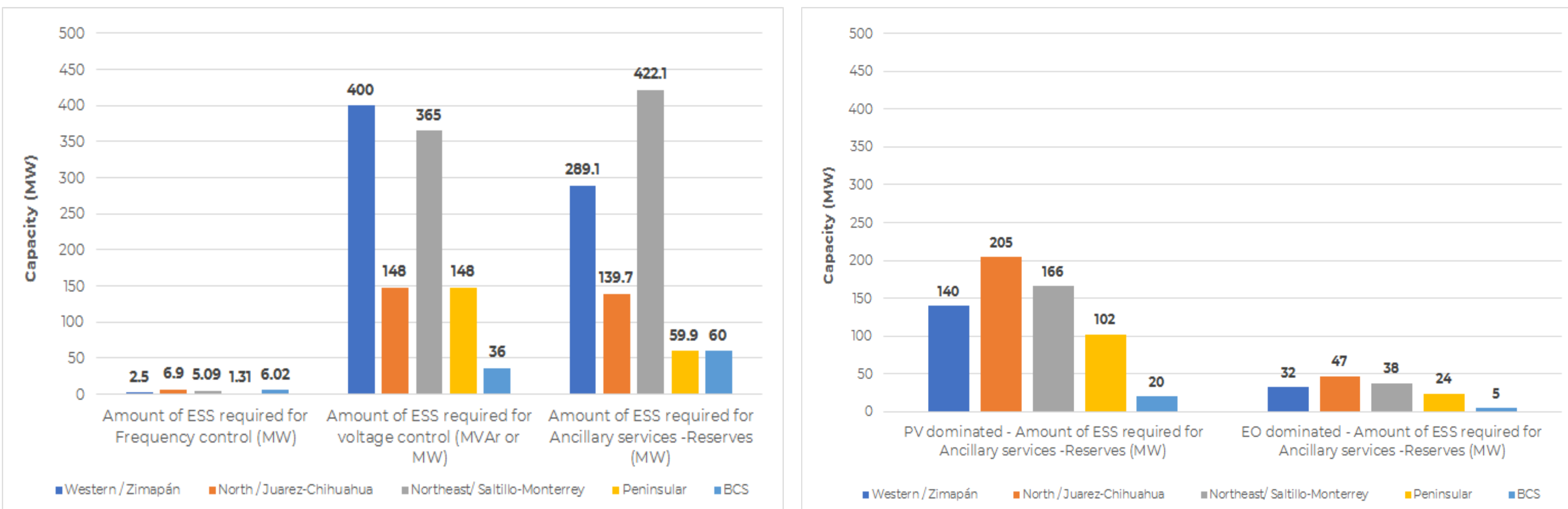


Figure 5.1. Amount of ESS required

6. References

Aghahosseini & Breyer. (2018). *Assessment of geological resource potential for compressed air energy storage in global electricity supply*. Energy conversion and management, Elsevier. Volume 169, pages 161-173. Recuperado el 2020, de https://doi.org/10.1016/j.enconman.2018.05.058

ANU. (2020). *Global pumped hydro atlas*. Australian National University, College of Engineering & Computer Science. Recuperado el 27 de 07 de 2020, de http://re100.eng.anu.edu.au/global/index.php

AREA. (2020). *Australian renewable energy mapping infrastructure. Retrieved*. Australian Renewable Energy Agency. Recuperado el 27 de 07 de 2020, de https://nationalmap.gov.au/renewables/#share=s-oDPMo1jDBBtwBNhD

Benavides García, L. (1983). *Domos salinos del sureste de México; origen, exploración, importancia económica*. Boletín de la Asociación Mexicana de Geólogos Petroleros, XXXV(1), 9-35. Obtenido de https://www.amgp.org/api/administration/publicaciones/5dae9676d79d7_1983Ene_02.pdf

Blakers, A., Stocks, M., Lu, B., Cheng, C., & Stocks, R. (2019). *Pathway to 100% Renewable Electricity*. IEEE Journal of Photovoltaics. Volume: 9, Issue: 6, Nov. 2019. Obtenido de https://ieeexplore.ieee.org/document/8836526/authors#authors

California Legislative. (2010). *Assembly Bill No. 2514*. California Legislative Information website. Obtenido de https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=200920100AB2514

Cebulla F., H. J. (2018). *How much Electrical Energy Storage do we need? A synthesis for the U.S., Europe, and Germany*. Journal of Cleaner Production, Vol. 181, 20.04.2018, p. 449-459. Obtenido de https://www.sciencedirect.com/science/article/abs/pii/S0959652618301665?via%3Dihub

CENACE. (2019b). *Programa de Ampliación y Modernización de la Red Nacional de Trasmisión y las Redes Generales de Distribución, 2019 - 2033*. CENACE. Pages 30-32. Obtenido de https://www.cenace.gob.mx/Paginas/Publicas/Planeacion/AmpliacionModernizacionRed.aspx

CENASE. (2019a). *Programa de Ampliación y Mordinación de la Red Nacional de Transmisión y Redes Generales de Distribucion 2019-2033*. Centro Nacional de Control de Enrgía. doi:https://www.cenace.gob.mx/Paginas/Publicas/Planeacion/ProgramaRNT.aspx

CENSASE. (2020). *Consulta PML nodales en el Sistema de Información del Mercado (SIM)*. Centro Nacional de Control de Energía (CENACE). Obtenido de https://www.cenace.gob.mx/Paginas/SIM/MercadoCP.aspx

CNH. (2019a). *Recursos prospectivos de México: Área perdido, cordilleras mexicanas y cuenca salina, aguas profundas del Golfo de México*. Comisión Nacional de Hidrocarburos (CNH). Obtenido de https://www.gob.mx/cms/uploads/attachment/file/517230/Libro_de_Recursos_Prospectivos-Perdido-Cordilleras-Salina.pdf

CNH. (2019b). *Atlas Geológicos*. Comisión Nacional de Hidrocarburos (CNH). Obtenido de https://www.hidrocarburos.gob.mx/cnih/informaci%C3%B3n-digital/atlas-geol%C3%B3gicos/

CONAGUA. (2018). *Estadísticas del agua en México*. Comisión Nacional del Agua. Recuperado el 2020, de https://files.conagua.gob.mx/conagua/publicaciones/Publicaciones/EAM2018.pdf

CONAGUA. (2020). *Principales Presas en México. Datos 2019*. Comision Nacional del Agua (CONAGUA), Sistema Nacional de Información del Agua (SINA). Recuperado el 27 de 07 de 2020, de http://sina.conagua.gob.mx/sina/tema.php?tema=presasPrincipales&ver=mapa&o=0&n=nacional

CRE. (2019). *Acuerdo A/039/2019*. Recuperado el 2020, de https://drive.cre.gob.mx/Drive/ObtenerAcuerdo/?id=YTZkNmE5ZmEtNWM3Ni00OTcyLTc1My05OTM2ZTYwZDM0MzY=

CYDSA. (2020). *LP gas underground storage facility*. Almacenamientos Subterráneos del Sureste S.A. CYDSA. Recuperado el 21 de 07 de 2020, de http://almacenamientossubterraneosdelsureste.com.mx/#

Donadei, S. &. (2016). *Compressed air energy storage in underground formations.* . Storing energy with special reference to renewable energy sources, South Africa: Elsevier. Chapter 6, págs. 113-133. Obtenido de https://doi.org/10.1016/B978-0-12-803440-8.00006-3

EnerAB. (2016). *Beneficios Directos e Indirectos del Almacenamiento de EnergíaEvaluación Regulatoria e Implementaciónen México*. Secretaría de Energía (SENER). Obtenido de https://www.gob.mx/cms/uploads/attachment/file/118034/Aportaci_n_EnerAB.pdf

Garvey, S. &. (2016). *Compressed Air Energy Storage*. Storing energy with special reference to renewable energy sources, South Africa: Elsevier. Chapter 5, Pages 87-111. Obtenido de https://doi.org/10.1016/B978-0-12-803440-8.00005-1

Hunt. (et al., 2020). *Global resource potential of seasonal pumped hydropower storage for energy and water storage*. Julian D. Hunt, Edward Byers, Yoshida Wada, Simon Parkinson, David E.H.J. Gernaat, Simon Langan, Detlef P. van Vuuren & Keywan Riahi: Nature communications, 11, Article number 947. Obtenido de https://doi.org/10.1038/s41467-020-14555-y

INECC. (2017). *Inventario Nacional de Emisiones de Gases y Compuestos de Efecto Invernadero (INEGyCEI)*. Obtenido de https://datos.gob.mx/busca/dataset/inventario-nacional-de-emisiones-de-gases-y-compuestos-de-efecto-invernadero-inegycei

INECC. (2019). *No published. Information requested by written communication. Estimations made with data by from CFE y CRE*. INEGyCEI, 2019. RESUMEN 2015-2018.

INECC. (2020a). *A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. Report 5.2.* INECC. Ramirez Arredondo, J. Page, 24.

INECC. (2020b). *A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. Report 5.2.* Ramirez Arredondo, J. Page, 23.

INECC. (2020c). *A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. Report 5.2.* Ramirez Arredondo, J. Page, 47.

INECC. (2020d). *A study of frequency and voltage enhancement by energy storage systems and the ancillary services sizing in Mexico. Report 5.2.* Ramírez Arredondo, J, Page, 47.

NERA. (2020). *Mexican Electricity Wholesale Market Report 2019.* NERA Economic Consoulting, January 31, 2020, . Obtenido de https://www.nera.com/content/dam/nera/publications/2020/PUB_Mexican-Electricity-Wholesale-Market-Report_013120.pdf

OIT. (2013). *Evaluación del Potencial de empleos verdes en México.* Organizacion Internacional del Trabajo. Obtenido de http://www.herramientasoit.org/_lib/file/doc/El%20potencial%20de%20los%20empleos%20verdes%20en%20Mexico.pdf

Parsons, J. (2017). *Introduction to Electricity Markets, Chapter 4.*

SEMARNAT. (2019). *Consulta al sistema de informacion de tramites.* Recuperado el agosto-diciembre de 2019, de http://www.semarnat.gob.mx/gobmx/transparencia/constramite.html

SENER. (2017a). *Programa de Desarrollo del Sistema Eléctrico Nacional 2017-2031.* Obtenido de https://base.energia.gob.mx/prodesen/PRODESEN2017/PRODESEN-2017-2031.pdf

SENER. (2017b). *Sistema de Información Energética (SIE). Sector Eléctrico Nacional, Ventas Internas de energía eléctrica por tarifa.* SENER. Obtenido de http://sie.energia.gob.mx/bdiController.do?action=temas

SENER. (2018). *Programa de Desarrollo del Sistema Eléctrico Nacional 2018-2032.* Obtenido de https://base.energia.gob.mx/prodesen/PRODESEN2018/PRODESEN18.pdf

SENER. (2019a). *Programa de Desarrollo del Sistema Electrico Nacional 2019-2033.* Secretaría de Energia. Obtenido de https://www.gob.mx/sener/documentos/prodesen-2019-2033

SENER. (2019b). *Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033.* SENER. Capitulo VII, Pages, 47-55. Obtenido de https://www.gob.mx/sener/documentos/prodesen-2019-2033

SENER. (2019c). *Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033.* SENER. Page 22. Obtenido de https://www.gob.mx/sener/documentos/prodesen-2019-2033

SENER. (2019d). *Programa de Desarrollo del Sistema Eléctrico Nacional 2019-2033.* . SENER. Pages 33 and 38. Obtenido de https://www.gob.mx/sener/documentos/prodesen-2019-2033

SGM. (2020). *Cartas geologicas.* Servicio Geologico Mexicano (SGM). Obtenido de https://www.gob.mx/sgm

SHyCP. (2014). *Oficio Circular No. 400.1.410.14.009. Se da a conocer la Tasa Social de Descuento.* Secretaría de Hacienda y Crédito Publico. Obtenido de https://www.gob.mx/shcp/documentos/tasa-social-de-descuento-tsd