2. Technology Catalogue for energy storage

Selection of technologies

Appendix A

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MEDIO AMBIENTE
SECRETARÍA DE MEDIO AMBIENTE Y RECURSOS NATURALES

INECC
INSTITUTO NACIONAL DE ECOLOGÍA Y CAMBIO CLIMÁTICO

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

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Appendix A: Selection of storage technologies.

In order to elaborate a coherent and adequate proposal of the technologies to be included in the storage catalogue for the electric grid in Mexico, it is necessary to consider the Mexican context, and chose those that exhibit the best advantages for Mexico and the Mexican electricity system. A process of three main stages is developed:

- Identification of the different energy storage technologies and worldwide storage trends.
- Preliminary selection of technologies: definition of selection criteria and construction of a preliminary selected technologies.
- Experts consultation: development of a workshop with energy storage experts to present the preliminary selection of technologies; creation of experts working groups to elaborate the final selection of storage technologies.

The preliminary selection of the most appropriate technologies was conducted through a discussion process, taking into account the opinions of the national consultant team, the National Institute of Ecology and Climate Change (INECC) supervision team and the Danish Energy Agency's (DEA) supervisors. The discussion process leaded to a selection of relevant criteria to evaluate the storage technologies aiming to come up with a preliminary list of relevant technologies for Mexico. This preliminary list was presented to a group of national energy storage experts from the academy, the governmental institutions, the non-governmental organizations and the private sector during a one-day workshop. The experts consultation process continues with the creation of groups working on eight specialties: pumped hydro storage, batteries, thermal storage, compressed gas energy storage, super capacitors, hydrogen, flywheels and grid services. These groups will work coordinated by the technical consultants team on the validation of the preliminary selection, to obtain the final technologies list that will be the core of the storage technologies catalogue.

Identification of the different energy storage technologies and worldwide storage trends

To obtain a first list of storage technologies, different sources of information were consulted including: the Danish Energy Agency storage catalogue "Technology data for energy storage", the USA storage database by the Department of Energy (DOE), the "Electricity Storage and Renewables: Costs and Markets to 2030" report by the International Renewable Energy Agency (IRENA) and the "Energy storage: Tracking the technologies that will transform the power sector" by Deolitte & Touche LLP. These documents allowed to identify a wide range of technologies as well as technical characteristics and services that can be provided by the energy storage technologies. The wide list of technologies identified in a first exploration included:

Table 1. Identified technology DOE Data base. Source: (DOE, 2019)

	Technology		Technology
1	Lithium-ion Battery	29	Vanadium Redox Flow Battery
2	Lithium Iron Phosphate Battery	30	Flow Battery
3	Lithium Ion Titanate Battery	31	Hydrogen Bromine Flow Battery
4	Lithium Polymer Battery	32	Iron-chromium Flow Battery
5	Lithium Nickel Manganese Cobalt Battery	33	Dalian Vanadium Flow Battery Peaking-shaving Station
6	Lithium Manganese Oxide Battery	34	Chilled Water Thermal Storage
7	Lithium Nickel Cobalt Aluminum Battery	35	Ice Thermal Storage
8	Lithium-titanate	36	Heat Thermal Storage
9	Electro-chemical	37	Thermal Storage
10	Electro-chemical Capacitor	38	Concrete Thermal Storage
11	Lead-acid Battery	39	Closed-loop Pumped Hydro Storage
12	Hybrid Lead-acid Battery/Electro-chemical Capacitor	40	Open-loop Pumped Hydro Storage
13	Lead Carbon Battery	41	Pumped Hydro Storage
14	Advanced Lead-acid Battery	42	Seawater Open-loop Pumped Hydro Storage
15	Valve Regulated Lead-acid Battery	43	Liquid Air Energy Storage
16	Sodium-ion Battery	44	Modular Iso-thermal Compressed Air
17	Sodium based Battery	45	Compressed Air Storage
18	Sodium-nickel-chloride Battery	46	In-ground Compressed Air Storage
19	Sodium-sulfur Battery	47	Modular Compressed Air Storage
20	Sodium Nickel Battery	48	Adiabatic Compressed Air Storage
21	Zinc Iron Flow Battery	49	Advanced adiabatic compressed air energy storage
22	Zinc Manganese Dioxide Battery	50	In-ground Iso-thermal Compressed Air
23	Zinc-nickel Oxide Flow Battery	51	In-ground Natural Gas Combustion Compressed Air
24	Zinc Bromine Flow Battery	52	Ozone
25	Zinc Air Battery	53	Gravitational Storage
26	Nickel Iron Battery	54	Molten Salt Thermal Storage
27	Nickel Metal Hydride Battery	55	Hydrogen Storage
28	Nickel-cadmium Battery	56	Flywheel

Table 2. Ranked technologies. Own elaboration with data of DOE. Source: (DOE, 2019)

	A: Rank by installed capacity	B: Rank by generation	C: Rank by number of installations	A+B+C	Global Rank
Hydro Storage	1	1	3	5	1
Lithium based Battery	3	3	2	8	2
Electro-chemical	5	2	1	8	3
Thermal process	7	4	4	15	4
Molten Salt Thermal Storage	2	8	9	19	5
Compressed Air Storage	4	5	11	20	6
Sodium based Battery	8	7	6	21	7
Other kind (Va, Fe, Br) Battery	12	6	7	25	9
Flywheel	6	15	8	29	10
Zinc based Battery	11	10	10	31	11
Others	9	12	14	35	12
Hydrogen Storage	15	11	12	38	13
Electro-chemical Capacitor	13	13	15	41	14
Nickel based Battery	14	14	13	41	15

Table 3 Preselected. Technologies. Own elaboration with data of DOE. Source: (DOE, 2019)

Main technology	Variations on the technology
Pumped Hydro Storage	Closed-loop pumped storage
	Open-loop pumped storage
Batteries	Lithium based
	Sodium based
	Lead Acid based
	Redox flow
Heat Storage	Molten Salt
Compressed Air Storage	
Super Capacitors	
Hydrogen	
Flywheels	

The technologies identified focused on the energy storage for a utility scale. Thermal storage options such as Seasonal Heat Storage, Hot Water Tanks, were discarded since Mexico is a country that generally does not require thermal energy services for household heating, however, heat applications for industrial processes should not be ruled out, nevertheless these technologies are not in the scope for this study which is focused in energy storage for the electricity system.

The international trends on energy storage (Figure 1) reveals that 96 % (176 GW) of the total installed storage capacity by 2017 corresponded to pumped hydro storage, 1.9% (3.3 GW) to thermal storage, 1.1% (1.9 GW) to batteries and 0.9% (1.6 GW) to other mechanical storage technologies.

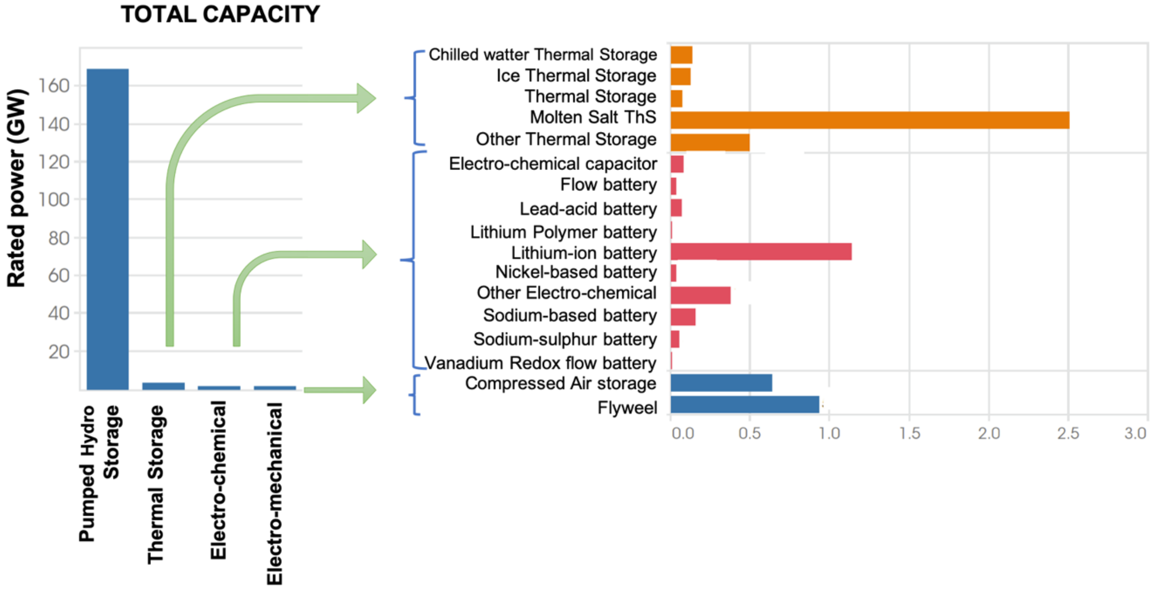
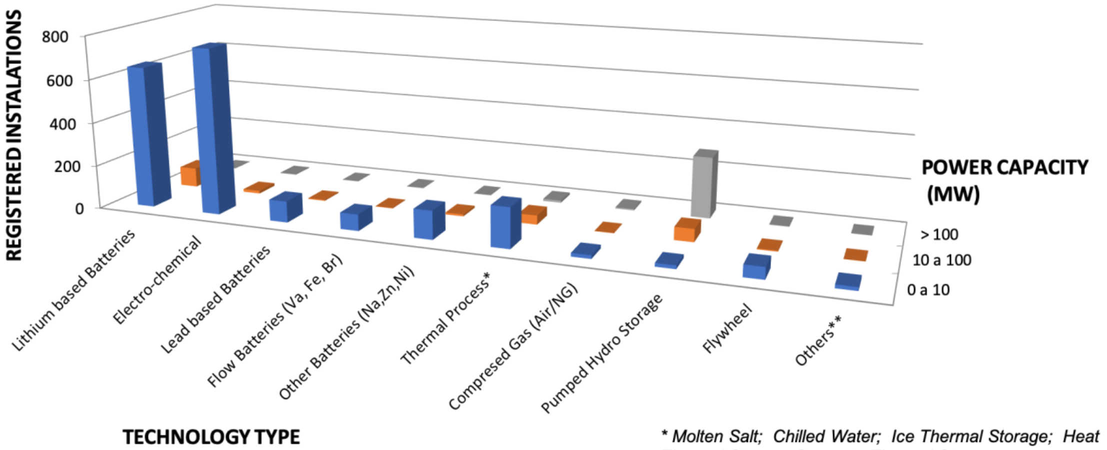


Figure 1. Global operational electricity storage capacity by technology 2017. Source: Electricity Storage and Renewables: Costs and markets to 2030. Source: (IRENA, 2017).

On the other hand, the number of total projects by capacity and technology type (Figure 2) shows that the larger number of installations corresponds to batteries, specifically to electrochemical and lithium based batteries, followed by hydro pumped storage and thermal processes; also, the majority of the storage technologies are installed for projects with total capacities lower to 10 MW, while hydro pumped storage is particularly suited for large size projects.



** Molten Salt; Chilled Water; Ice Thermal Storage; Heat Thermal Storage;Concrete Thermal Storage,*

***Others: Hydrogen storage, Ozone, Gravitational storage*

Figure 2. Global electricity storage number of projects by power capacity (MW) and technology. Self-elaboration with information from (DOE, 2019)

Preselection criteria

The catalogue has the porpoise to serve as a reference for the development and application of energy storage technologies for helping with the incorporation of higher shares of renewable energies into the Mexican electricity system. Consequently, the storage technologies that will be included in the catalogue must show a particular advantage for Mexico and the Mexican electricity system.

To reach this objective, a number of criteria were chosen for evaluating the technologies and selecting a pertinent group for the Mexican context; some technologies could present clear technical advantages, some others could be economically attractive, while others could be in earlier stages of development. For the Mexican electricity system, a particular set of technical characteristics can be of interest; on the other hand, Mexico could take advantage of a particular technology through the development value chains, of due to a natural potential for a technology. However, in technical terms considering the needs and services required by the Mexican electricity grid, but also environmental or economic development, as well as of capacity development.

The selection criteria were divided into 3 main groups:

The environmental impacts: Considers essentially the potential to reduce GHG emissions and other aspects related to the particular conditions of technology such as: the possibility of generating hazardous waste; the surface and change of land uses and the possible contamination of these; the percentage of recycling of infrastructure and materials; besides the possibilities of generation of noise, heat, and / or dust.

The technical aspects: It relates directly to the technical characteristics of the technology such as capacity ranges, response time, energy density, energy to power ratio, round-trip efficiency, and state of charge or depth and self-discharge and the time of life, with the services it can provide, the latter essentially represent the technical characteristic that make a differentiation between technologies can offer, to decide which may be the most appropriate choice. In addition, other important technical aspects are related to the generation of capacities for the use and development of technology, the level of technological maturity, and costs.

Advantages and benefits: It considers the criteria that describe the advantages, disadvantages, impacts and benefits related to the particular conditions of the country such as: the potential of technology with respect to the creation of value chains, the physical conditions for the deployment of the technology, the available and necessary infrastructure, suppliers, manufacture and import of equipment. The Figure 3 shows a diagram with the list of criteria selected.

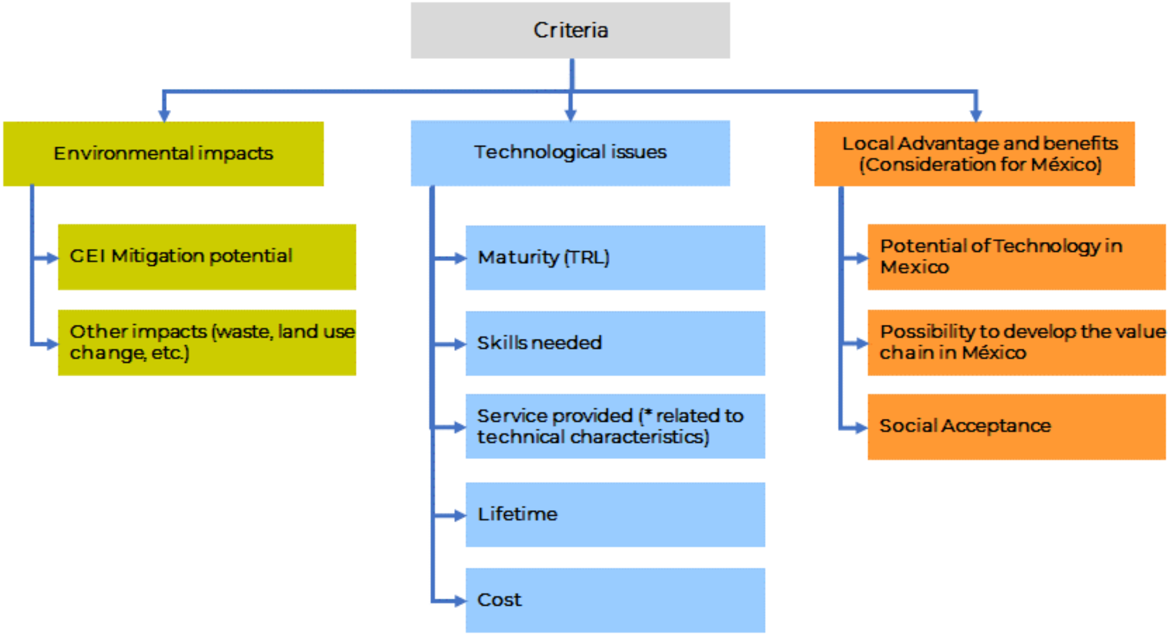


Figure 3. Criteria for evaluating the storage technologies' pertinence for Mexico and the Mexican electricity system. Source: own elaboration.

Table 4. Criteria and evaluation scales for environmental impacts. Source: own elaboration.

Criteria	Description	Evaluation method
Mitigation potential	Possible estimate of emissions reduction in tonCO$_2$eq per year	*Not Suitable: Minimal reduce emissions* *Less suitable: Medium reduction emissions* *Suitable: Great reduction due to bulk storage, according to international generation*

Criteria	Description	Evaluation method
Other impacts	• Hazard residue generation, • Possible soil contamination, • Surface consumption • Noise, heat, dust emissions; • Reclamation costs, • % of the materials incorporated into the technology that can be recycled.	*Suitable: Considers that it has minimal impacts on the environment* *Less suitable: Considers that it has high impacts on the environment* *Not suitable: Considers that it has dangerous impacts on the environment*

Table 5. Criteria and evaluation scales for technological issues. Source: own elaboration.

Technological issue	Description	Evaluation method
Maturity (Potential improvement of performance-cost relation)	Indicates the level of development and application of technology	➢ *Suitable: There are operational facilities that directly attract investments and generate jobs (TRL 7 a TRL 9)* ➢ *Less suitable: It is applicable and there are facilities operating reliably in a relevant environment (TRL 6 a TRL7).* ➢ *Not Suitable: It does not have applications at the utilitarian level. Is restricted to research and laboratory tests, prototypes and test facilities (TRL 1 a TRL 5)*
Skills needed	Indicates the level of capacity supply in the country for the development, installation and management of storage technology.	➢ Suitable: Commercial services are offered for the management and installation of technology by a considerable number of people, research is developed, legal and market skills exist, and technical training is available within the country. ➢ *Less suitable: There are capacities for the management and installation of technology, research is developed in the country about technology, legal* and market skills on development. ➢ *Not Suitable: The capacities in the country for the management and*

Technological issue	Description	Evaluation method
		installation of the technology do not exist.
Services provided	Indicates the suitability of the technology for services required by the electric network that the technology can provide. The services considered more important were: • Energy arbitrage, • Primary regulation (seconds), • Secondary regulation (minutes), • Peak Shaving, • Congestion management, • Long term storage, • Investment deferral of T&D, • RE capacity firming. * It is pertinent to mention that there are certain services that are common to all technologies, or do not represent a significant differentiation and that is why they are not considered for an evaluation.	➢ *Suitable: It is able to offer the service required by the network in the best conditions of low costs and high reliability.* ➢ *Less suitable. It is able to offer the service required by the network in conditions of accessible costs and reliability.* ➢ *Not suitable: It is not capable of providing the indicate service required by the network, or does it in conditions of high costs and low technological reliability*
Lifetime	Indicates the estimated life of the storage technology in full equivalent charge-discharge cycles.	➢ *Suitable: More than 100,000* ➢ *Less suitable: Up to 10,000 to 100,000* ➢ *Not Suitable: Less than 10,000*
Cost (CAPEX-Energy)	Capital required for the purchase of the equipment / technology necessary for the installation.	➢ *Not suitable: greater than 10 ,000* ➢ *Less suitable: de 1000 a 9999* ➢ *Suitable: smaller than 1000* * *Evaluation criteria used for installed kW Cost (USD / kWh)*

Table 6. Criteria and evaluation scales for local Advantage and benefits (consideration for México). Source: own elaboration.

Advantage or benefit	Description
Potential of Technology in Mexico	In reference to the advantages and benefits that would allow the deployment of storage technology in Mexico, like available physical conditions for deployment (resources, infrastructure, available companies, geological conditions)
Possibility to develop the value chain in México	In reference to the advantages and benefits that would allow the development of a value chain around the implementation of storage technology like, availability of purchase equipment in México, local production availability, existing commercialization chains, fiscal advantages, and the legal conditions available for deployment of the market.
Social Acceptance	Significant acceptance from: key actors (like indigenous population involve) localization of installation (near cities, ANP, industrial parks) purchase and use of land availability.

Table 7. Evaluation scales for advantages or benefits. Source: own elaboration.

Impact	Probability		
	LOW	MEDIUM	HIGH
Minimum. Minimal disruption Does not affect the implementation times of the technology	Suitable +	Suitable	Less suitable
Considerable. It affects the times of implementation, increases the complexity of the coordination of activities and the quality of the technology can be compromised or has to be revised.	Suitable	Less suitable	Not suitable
Significant. It affects the purpose and quality of the implementation of storage technology with the potential to cancel or interrupt it.	Less suitable	Not suitable	Not suitable +

These criteria allowed to conduct an evaluation of the technologies and to select a first proposal of the most appropriates for the Mexico's context. A three-colors semaphore was chosen to evaluate the suitability of the technologies regarding each criterion.

Assumptions and considerations for Pre-selection of energy storage technologies.

Table 8 shows the matrix evaluation for the technologies according to the selected criteria. Five technologies where particularly found relevant for Mexico, these five are: PHS, Molten Salt, Flywheels, Lead – acid batteries and Lithium based batteries.

Figure 4. Matrix Evaluation of storage technologies according to the selected criteria. Source: own elaboration.

	Bill Management	Bill Management	Bill Management	Bill Management	Bill Management	Seasonal Storage	T&D deferral	Secondary response				
TECHNOLOGY\CRITERIA	Energy arbitrage ($)	Primary regulation (sec)	Secondary regulation (min)	Peak Shaving	Congestion management	Long term storage	Investment deferral of T&D	RE Capacity Firming	Potential improvement of performance-cost relation	Consideration for México	Cost	Environmental impacts
🟦 Pumped Hydro Storage (PHS)	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟡
Compressed Air Energy Storage (CAES)	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🔴	🟡	🟡	🟡
🟦 Molten Salt	🟢	🔴	🟡	🔴	🟡	🟡	🟢	🟡	🟡	🟢	🟡	🟡
Hydrogen	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🔴	🟡
🟦 Flywheels	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🟡	🟢	🟢	🟡	🟢
🟦 o LeadAcid based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢	🟡	🟢	🟢	🔴
🟦 o Lithium based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟢	🟡	🟢	🟡
🟦 o Sodium based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟡	🟡	🟢	🟡
🟦 o Flow batteries	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟡	🟡	🟡
o Other Based batteries (Zn,Ni)	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢	🟡	🟡	🟢	🟡
Super Capacitors	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🟡	🟡	🟡	🔴	🔴

🟦 Relevant for México

🟢 Suitable

🟡 Less suitable

🔴 Not suitable

Service provided

Different types of services are required in the operations of the electric network for its optimal operation and to guarantee the levels of efficiency, reliability, continuity and security of the National Electric System, its main purpose being to provide uniformity in the demand for power generation, maximizing efficiency and reducing energy costs in the long term. At the same time, these services refer to issues such as management voltage levels across networks, frequency, congestions in the network, load balancing, among others directly linked to the availability and management of electrical energy, thus becoming the application niche for technologies for energy storage.

Exists numerous specific applications for the energy storage systems within the value chain of the electric power supply, however, based on similar technical requirements, they can be grouped under a core application (Oliver Schmidt, 2019), to facilitate their analysis and evaluation. (Table 8).

Table 8. Application description.

Application	Description	Alternative name	Core application
Wholesale arbitrage	Purchase power in low-price periods and sell in high price periods on the energy wholesale market	Electric Energy Time-shift	Energy arbitrage
Retail arbitrage	Purchase power in low-price periods and sell in high price periods on the energy retail market	End-consumer arbitrage	Energy arbitrage
Regulating reserve	Automatically correct the continuous, fast, frequent changes in load or generation within the shortest applicable market interval	Frequency regulation, Frequency control	Primary response
Primary reserve	Automatically stabilise frequency after rare, sudden change in load or generation	Primary contingency reserve, Frequency response	Primary reserve
Following reserve	Manually correct anticipated imbalances between load and generation	Load following, Balancing reserve	Secondary response
Secondary reserve – spinning	Automatically return frequency to nominal after rare, sudden change in load or generation with operating generator	Spinning reserve	Secondary response
Secondary reserve – non-spinning	Automatically return frequency to nominal after rare, sudden change in load or generation with non-operating generator	Secondary contingency reserve, Non-spinning reserve	Secondary response

Application	Description	Alternative name	Core application
Ramping reserve	Manually correct for unexpected, severe and infrequent changes in load or generation that are not instantaneous		Secondary response
Renewables integration - uncertainty	Change and optimise output from variable supply resources when generation is out of line with forecasts	Correct for forecasting inaccuracy, Renewables capacity firming	Secondary response
Tertiary reserve	Automatically replace primary and secondary contingency reserve	Tertiary contingency reserve, Supplemental / Replacement reserve	Tertiary response
Peaker replacement	Ensure availability of sufficient generation capacity at all times	Electric supply / System capacity, Capacity mechanism, Microgrid	Peaker replacement
Black start	Restore power plant operations after network outage without external power supply		Black start
Seasonal storage	Compensate longer-term supply disruption or seasonal variability in supply and demand		Seasonal storage
Transmission upgrade deferral	Defer transmission infrastructure upgrades required when peak power flows exceed existing capacity	Transmission support, Network efficiency	T&D deferral
Distribution upgrade deferral	Defer distribution infrastructure upgrades required when peak power flows exceed existing capacity	Distribution substation, Network efficiency	T&D deferral
Transmission congestion relief	Avoid risk of overloading existing infrastructure that could lead to re-dispatch and local price differences	Transmission support, Network efficiency	Congestion management
Bill management	Purchase power in low-price periods and use during high-price periods	Energy management, Retail ToU charges	Bill management
Demand charge reduction – D	Reduce demand supplied by the network during periods of highest distribution network cost	Peak reduction, Red zone management	Bill management
Demand charge reduction – T	Reducing demand supplied by the network during periods of highest transmission network cost	Peak reduction, Triad avoidance, Transmission access charges	Bill management

Application	Description	Alternative name	Core application
Renewable energy selfconsumption	Minimise export of renewable electricity and increase self-consumption to maximize financial benefits		
Power quality	Protect on-site load against short-duration power loss or variations in voltage or frequency		Power quality
Power reliability	Fill gap between variable resource and demand	Off-grid, On-site power	Power reliability
Backup power	Provide sustained power during total loss of power from source utility	Home backup, Emergency supply, Resiliency	Power reliability
Renewables integration - variability	Change and optimise output from variable supply resources to mitigate output changes and match supply with demand	Off-peak storage, Variable resource integration, Onsite generation shifting	Power reliability
Voltage support	Maintain voltage levels across networks via reactive power supply/reduction		
VAR support	Maintain voltage levels across transmission network via reactive power supply/reduction		

Table 8. Review of 27 unique-purpose electricity storage services and allocation to core services based on similar technical requirements. (Schmidt, 2019)

So, the assumptions to evaluate the suitability of the appropriate technologies to provide the different types of services considered diverse bibliographic information of which we can highlight:

- Energy storage technologies can be used in many different applications (or services) covering the whole electric power supply chain, however the difference of the technical requirements of these services is what determines the suitability of the applicable technologies.
- Due to its own characteristics, various technologies are capable of providing several different types of services (Table 9), but their application in a specific service optimally is mainly related to technical characteristics such as response time (seconds), nominal power (MW), the duration of the discharge (hours), and the amount of use or discharge cycles (per year); which are also particularly important in attention to the specific technical requirements of each service or application (Table 19).

Table 9. Electricity storage technologies performance characteristics. Source: modify from (Schmidt, 2019).

Technology	Power Range (MW)	Discharge (Hr.)	Cycle Lige (Núm Cycles)	Respond time (sec.)
Pumped hydro (PHS)	10 – 5,000	1 - 24	20,000 -50,000	$> 10^{7}$
Compressed Air (CAES)	5 - 400	1 -24	> 13,000	$> 10^{7}$
Flywheels	0.01 - 20	< 0.5	20,000 – 225,000	$< 10^{7}$
Lead Acid	0.005 - 100	0.25 - 10	< 5,500	$< 10^{7}$
Lithium-Ion	0.001 - 35	0.25 - 5	2,000 – 3,500	$< 10^{7}$
Sodium Sulphur	0.05 - 50	0.0167 - 8	2,500 – 4,500	$< 10^{10}$
Redox Flow	0.02 - 50	0.0167 - 10	5,000 – 13,000	$< 10^{7}$
Hydrogen	0.3 - 500	0.0167 - 24	< 20,000	$< 10^{7}$
Supercapacitor	< 4	< 1	< 100,000	$< 10^{7}$

Note: cycles refers to full equivalent charge – discharge cycles

Table 10. Technical requirements for electricity storage applications: Source: modify from (Schmidt, 2019).

Application	Size (MW)	Duration (Hr.)	Cycles (Cycles/year)	Respond time (sec.)
Energy arbitrage	0.001 – 2,000	1 - 24	50 -400	$> 10^{5}$
Primary response	1 – 2,000	0.02 - 1	250 – 15,000	$< 10^{2}$
Secondary response	10 – 2,000	0.25 - 24	20 – 10,500	$> 10^{2}$
Tertiary response	5 – 1,000	> 1.5	20- 50	$> 10^{2}$
Peaker replacement	1 - 500	2 - 6	5 - 100	$> 10^{5}$
Black start	0.1 -400	0.25 - 4	1 - 20	$> 10^{5}$
Sessional storage	500 – 2,000	24 – 2,000	1 - 5	$> 10^{5}$
T&D upgrade deferral	1 - 500	2 - 8	10 - 500	$> 10^{5}$
Congestion management	1 - 500	1 - 4	50 - 500	$> 10^{5}$
Bill management	0.001 - 10	1 - 6	50 - 500	$> 10^{5}$
Power quality	0.05 - 10	0.003 – 0.5	10 - 200	$< 10^{1}$
Power reliability	0.001 - 10	2 - 10	50 - 400	$> 10^{1}$

Note: cycles refers to full equivalent charge – discharge cycles

- This shows that the technical requirements of each specific service, and their level of operation within the network are inherently related, so a comparison of these main technical requirements against the operating characteristics of the different technologies will allow an approximation of the suitability of the technologies for each one of the different services considered for their evaluation, but, it does not represent an infallible approach since the technological advances in the matter of power electronics and electric power management technology in general allow several technologies to extend remarkably its fields of application.

- At the same time it is pertinent to note that the services necessary for the optimal operation of the national electricity grid can be visualized in different sections in relation to their technical requirements and are distinguished mainly by their level of operation and field of application. In its study ELECTRICITY STORAGE AND RENEWABLES: COSTS AND MARKETS TO 2030 the International Renewable Energy Agency, distinguishes in a main 3 levels (IRENA, 2017):
  - Bulk Power management, where large module sizes and system power ranges are distinguished (> 50 MW) and in general a longer response time (> 60 seconds) is required;
  - Transmission & distribution grid support-load shifting: where the module sizes and power ranges are more moderate (> 100 kW <50 MW) and the response times are faster (> 10 seconds) although not necessarily instantaneous.
  - Uninterruptible power supply-power quality: which request an immediate response time (<10 seconds), but in general with smaller modules and power ranges (<100 kW).

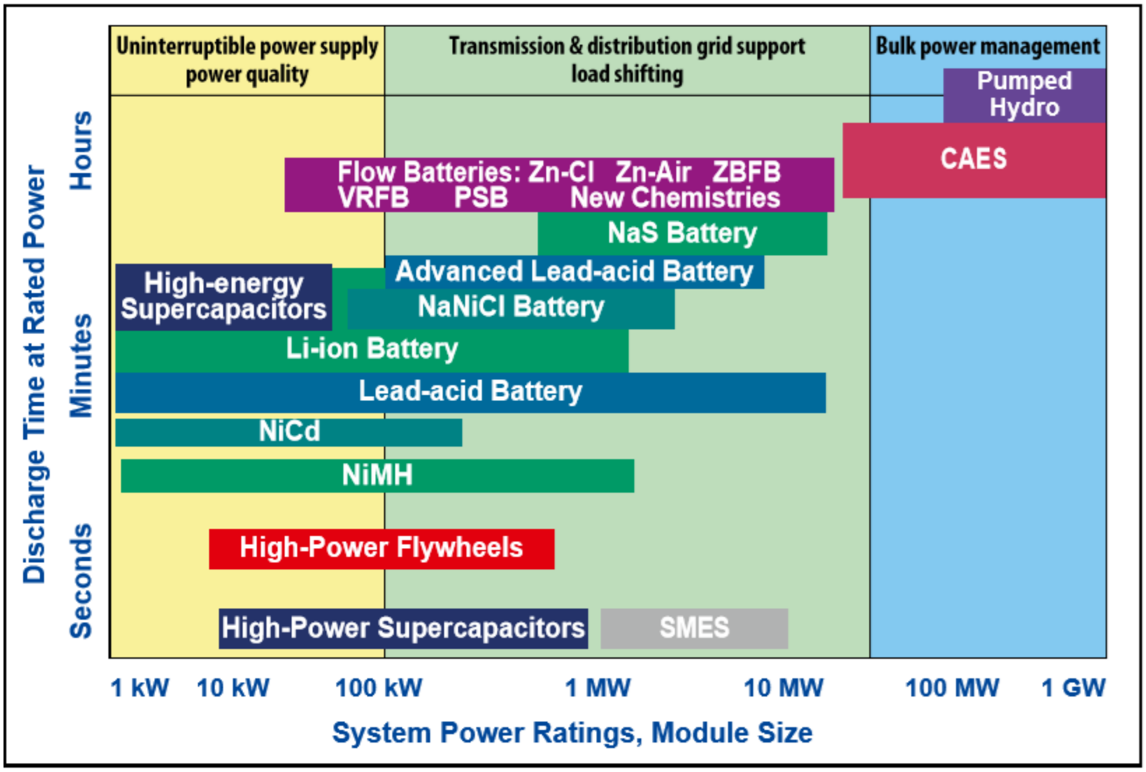


Figure 5. Positioning of diverse energy storage technologies per their power rating and discharge times at rated power. (IRENA, 2017).

In this way it can be observed that although various technologies can provide various types of services, they will be more appropriate at certain levels depending on their technical characteristics and a final decision must be coupled with other criteria such as costs, local benefits, environmental impacts and the potential for improving the performance of technology in the short and medium term and its technological maturity.

In an internal work developed jointly by the consultants team, the Danish Energy Agency and the National Institute of Ecology and Climate Change, a selection of applications considered relevant for the development of energy storage in the National Electric System network (SEN) of Mexico was determined, and contrasting the information presented above, the suitability of the technologies in these applications was evaluated according to the proposed methodology.

	bill management					Seasonal storage	T&D deferral	Secondary response
TECHNOLOGY\CRITERIA	**Energy arbitrage**	**Primary regulation**	**Secondary regulation**	**Peak Shaving**	**Congestion management**	**Long term storage**	**Investment deferral of T&D**	**RE Capacity Firming)**
	($)	**(sec)**	**(min)**					
Pumped Hydro Storage (PHS)	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🟢
Compressed Air Energy Storage (CAES)	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🟢
Molten Salt	🟢	🔴	🟡	🔴	🟡	🟡	🟢	🟡
Hydrogen	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Flywheels	🔴	🟢	🟢	🟢	🔴	🔴	🔴	🟡
o LeadAcid based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟡	🟢
o Lithium based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢
o Sodium based batteries	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢
o Flow batteries	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢
o Other Based batteries (Zn,Ni)	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🟢
Super Capacitors	🔴	🟢	🟢	🔴	🔴	🔴	🔴	🟡
Relevant for México	🟢	**Suitable**	🟡	**Less suitable**	🔴	**Not suitable**		

Figure 6. Evaluation of suitability of the most important technologies and services.

In general, it is observed that technologies such as pumped hydro and underground compressed air energy storage are characterized by relatively slow response times and large minimum system sizes. Therefore, they are ill suited for fast response applications such as primary response and small-scale consumption applications. Flywheels and supercapacitors are characterized by short discharge durations and are not suitable for applications requiring longer-term power provision. The variety and versatility of the batteries allows them to cover a wide spectrum of applications and the characteristics of each service and battery type will define their suitability for application.

It should be noted that this analysis considers service requirements and characteristics of common technologies. The implementation of commercial applications can result in numerous cases of services and requirements outside the ranges considered, in the same way the characteristics of the technologies can be developed outside the ranges considered to satisfy the requirements of specific applications. However, these cases are not expected to be significant in the case of most existing electric energy storage systems.

It was also considered that for a preliminary general selection of the most appropriate technologies for the context of the energy sector in Mexico it is necessary to take into account, in addition to the specific technical aspects of the operation of technologies and services, other technological components that influence the possibilities of application, which may be more subjective but may have very important relevance at the local level with a view to the implementation of energy storage in the National Electric System (SIN).

Potential improvement of performance-cost relation (Maturity; Skills needed)

The first technical aspects of this type refer to the relationship between the potential for improving performance and the cost of technology in the medium term. To carry out a simplified exercise that is not restrictive to the selection, it is considered representative of other aspects as a whole such as the maturity of the technology (TRL) and the local capacities necessary for its implementation and development.

All the technologies considered represent a proven level of technical application, however is very evident that research and technological development advances its more faster in those technologies that achieve a considerable improvement in costs and consequently have reached a level of commercialization of larger scale, then demonstrate a stronger penetration in applications around the world, this case is notable in Flywhell technologies and in Li-ion batteries.

Flywhel's technology still represents high installation costs and has a very high rate of self-discharge (15% per hour), which does not make it suitable for medium-large-scale storage, however, it is expected that installation are reduced by approximately 35% by 2030, and that the number of cycles and the life time improve substantially according to the scenarios set by IRENA in its study of costs and markets by 2030 (IRENA, 2017. Page 62). On the other hand, its response time and reliability make it an outstanding option for services that demand an immediate response. Furthermore, due to its mechanical nature, it is considered that there has availability in the country to develop a value chain and research and technological development around the elements of technology.

Although there is a huge variety of lithium-based battery technologies with different characteristics, in general lithium-ion batteries have quickly become the most important technology for mobile applications (portable electronics and electromobility), partly because they have The advantage of having a high density index of power and energy in relation to other battery technologies. They also exhibit a high rate and high-power discharge capability, excellent round-trip efficiency, a relatively long lifetime and a low self-discharge rate. As the costs of Li-ion energy storage systems decline, they are increasingly becoming an economic option for stationary applications, and their presence in that segment is increasing. (IRENA, 2017. Pag. 65).

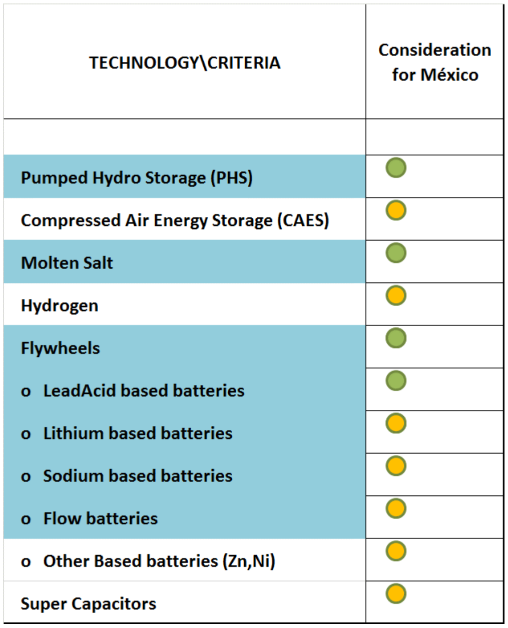
In the case of PHS y CAES no major technology improvements are therefore anticipated in the coming years in terms of cost, structure or transformation efficiency. Because its implementation is directly linked to the site and its characteristics, it is extremely challenging to estimate the costs of the civil engineering involved and, in general, there is a huge dependence on local environmental restrictions. Even with this, they can be of low unit cost if the best circumstances are found, such as having suitable sites for their implementation that reduce civil works; also by their nature in general represent large-scale projects and that require a considerable construction time.

TECHNOLOGY\CRITERIA	Potential improvement of performance-cost relation
Pumped Hydro Storage (PHS)	🟡
Compressed Air Energy Storage (CAES)	🔴
Molten Salt	🟡
Hydrogen	🔴
Flywheels	🟢
o LeadAcid based batteries	🟡
o Lithium based batteries	🟢
o Sodium based batteries	🟡
o Flow batteries	🟡
o Other Based batteries (Zn,Ni)	🟡
Super Capacitors	🟡

Figure 7. Evaluation of the suitability of the potential for improving the performance-cost relation.

Consideration for México

It was also keep in mind particular characteristics that may be important for the context of the country and that may also influence the accessibility of technology, its possibilities of implementation and the economic and social effects that could have an impact, such as the potential of the technology in Mexico, the possibilities of developing a value chain and the social acceptance. Considerations like the experience in the development of hydraulic projects in the country (PHS), the potential of the solar resource (Molten Salt), the possible accessibility to the materials of the elements of the technology (Flywhell) or the existence of a supply chain (Lead Acid) were considered.



TECHNOLOGY\CRITERIA	Consideration for México
Pumped Hydro Storage (PHS)	🟢
Compressed Air Energy Storage (CAES)	🟡
Molten Salt	🟢
Hydrogen	🟡
Flywheels	🟢
o LeadAcid based batteries	🟢
o Lithium based batteries	🟡
o Sodium based batteries	🟡
o Flow batteries	🟡
o Other Based batteries (Zn,Ni)	🟡
Super Capacitors	🟡

Figure 8. Evaluation of suitability of special local considerations.

Costs

Because energy storage applications are consolidated along with the transformation of electrical systems and networks, and the multiple factors that influence it, it is not easy to establish a level cost of the technologies in the enormous variety of applications; the costs of operation and maintenance and still of installation can be volatile especially in the most emergent technologies; even a technological spike can change the scenarios from one moment to the next. Although it is possible to find references of costs especially of investment capital.

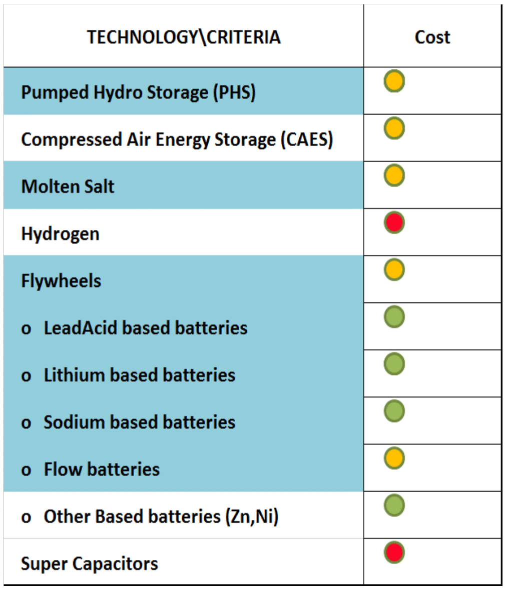
Table 11. Technical characteristics of costs, lifetimes and capacity ranges for the different technologies considered. Own preparation with information from: * (Deloitte, 2015); ** IRENA (2017); *** Schmidt (2019).

Technologies	Power Rating (Mw)	Cycling (Per Year) Or Lifetime	Investment Cost Energy (Usd$/Kwh)
Pumped Hydro Storage (PHS)	100-1000*	30-60 years*	0-100**
Compressed Air Energy Storage (CAES)	10-1000*	20-40 years*	40-50**
Molten salt	10-1000*	20-40 years*	34-80**
Hydrogen	0.01-1,000*	5-30 years*	5417 (48% SD)***
Flywheel	0.001-1*	20,000-100,000*	1500-6000**
Lead Acid	0.005-100***	< 5,500***	105-475**

Lithium Based battery	0.1-100*	1000-10,000*	350-1050**
Flow battery	01-100*	1,000-10,000*	315-1680**
Other Based battery (Na,Zn,Ni)	10-100*	2,500-4,400*	263-735**
Supercapacitor	0.01-1*	10,000-100,000*	13560 (19% SD)***

Very important parameters that can significantly influence the costs of each technology are the nominal capacity of the installation, the discharge time, the annual usage cycles and the price of electricity, however they will vary between applications, regions, and over both short and long timescales while at the same time stricter environmental standards for PHS costs makes new developments more time consuming and expensive.

Based on these considerations, the high costs related to storage technologies such as Supercapacitors and Hydrogen should be highlighted. Likewise, technologies such as Flywhell and Flow batteries also represent high investment costs but maintain a proven feasibility of operation manifested in different established applications that contribute to technological improvement and predict the reduction of costs in the medium term. On the other hand, the batteries in general and in particular the Ion-Lithium show a vertiginous advance in the last years that place them more in different stationary applications around the world.



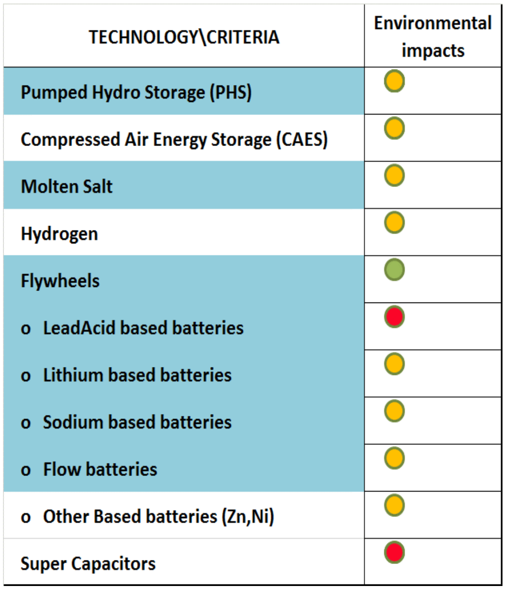
TECHNOLOGY\CRITERIA	Cost
Pumped Hydro Storage (PHS)	🟡
Compressed Air Energy Storage (CAES)	🟡
Molten Salt	🟡
Hydrogen	🔴
Flywheels	🟡
o LeadAcid based batteries	🟢
o Lithium based batteries	🟢
o Sodium based batteries	🟢
o Flow batteries	🟡
o Other Based batteries (Zn,Ni)	🟢
Super Capacitors	🔴

Figure 9. Evaluation of suitability of cost considerations.

Environmental Impacts

In the case of environmental impacts, it is considered that the reduction of GHG emissions is an important parameter in the evaluation of different technologies, however this indicator is directly related to the type of technological application that may be displaced in the service considered, since the possibility of combinations has been observed is very large and the evaluation of these impacts is part of the planned work, it's not considered that the necessary elements are available to evaluate this impact yet.

However, as mentioned in the methodology, other possible impacts such as the Hazard residue generation (Batteries), possible soil contamination (Lead Acid, CAES), surface consumption (PHS, Molten Salt), or percent of the materials incorporated into the technology that can be recycled were considered (Flywhell).



TECHNOLOGY\CRITERIA	Environmental impacts
Pumped Hydro Storage (PHS)	🟡
Compressed Air Energy Storage (CAES)	🟡
Molten Salt	🟡
Hydrogen	🟡
Flywheels	🟢
o LeadAcid based batteries	🔴
o Lithium based batteries	🟡
o Sodium based batteries	🟡
o Flow batteries	🟡
o Other Based batteries (Zn,Ni)	🟡
Super Capacitors	🔴

Figure 10. Evaluation of suitability of environmental impacts.

Experts consultation

Figure 4 was presented to a group of energy storage experts whom attended a first workshop, whose objective was to socialize the goals of the project and the technical approach for developing the Mexican storage catalogue.

Figure 4 was discussed during the workshop including its preliminary characteristic. Important feedback was received in relation with the attention to other grid services and criteria that could be considered for the evaluation and feedback related to the methodology for assigning the colors in the evaluation. Some important observations and contributions are listed next:

To consider that elements of electronics and power control allow extending the capabilities of most technologies;

The recycling capacity of the technologies should be an element of relevant importance in the evaluation of environmental impacts;

Despite the level of application and maturity of lithium-ion batteries, do not rule out batteries that can represent lower-cost applications such as sodium-based batteries;

Although there are limitations of supercapacitors, especially in Energy-intensive applications, consider their more detailed analysis in attention to the vertiginous development of power electronics, which also extends the applications of this type of technology;

Consider the evaluation of hydrogen technology, given that there is an important branch of research in the country, under which different technological applications are explored beyond the unique consideration of the services required by the national electricity grid.

An agreement reached with the storage experts involved the creation of working groups coordinated by the consultant team on pumped hydro storage, batteries, thermal storage, compressed gas energy storage, super capacitors, hydrogen, flywheels and grid services. Through this working groups, the final list of relevant storage technologies for the Mexican electricity system will be developed.

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