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Assessment of Energy Storage Systems for Contribution to Flexibility in Electrical Power System with High Level Intermittent Renewables Energy

J. AVALOS *
Coordinador Eléctrico Nacional
Chile

J. ARANEDA
Coordinador Eléctrico Nacional
Chile

R. GÁLVEZ
Coordinador Eléctrico Nacional
Chile

D. GUACUCANO
Coordinador Eléctrico Nacional
Chile

N. GUENUL
Coordinador Eléctrico Nacional
Chile

C. LEYTON
Coordinador Eléctrico Nacional
Chile

SUMMARY

Considering the high levels of non-conventional renewables energies (NCRE) expected for the year 2021 in the Chilean electricity system, the national regulation requires that a minimum of 13.5% of energy is based on NCRE in this year [1], it is necessary to know in advance the challenges in terms of operational flexibility requirements to assess technological solutions for facing this challenges. Thus, economic operation evaluations were made through unit-commitment simulations which had a technical modelling of transmission systems, thermal and hydro generation plants, demand and production from intermittent renewables plants for getting an accurate diagnostic about operational flexibility requirements with hourly resolution. After that, pumped storage hydroelectric power plants (PSH) and battery energy storage systems (BESS) were modelled in unit-commitment and dynamic simulation models to analyze its contribution in the operational flexibility and primary frequency control, respectively.

The results show that hydro plants are essentials for managing the intra-day variability of net demand due to its regulation ranges high and fast ramp rate (MW/min). This effect reduces the efforts of flexibility that should provide thermal generation plants, decreasing the annual quantity of cycling and ramping. On top of that, the incorporation of PSH has a direct impact in reducing the quantity of cycling and ramping on thermal generation plants, increasing this effect with more renewables energies, especially photovoltaic (PV) plants. The PSH daily operational pattern consists of nightly generation (period of higher marginal cost) and daily pumped (period of lower marginal cost). The dynamic simulations show that distributed generation reserves scheme has better performance than a concentrated scheme and the BESS has a considerable contribution in primary frequency control as well as in some cases where it has operational savings with respect to scenarios without BESS.

KEYWORDS
Unit-commitment - Intermittent Renewable Energy - Energy Storage Systems - PSH - Hydro - BESS - Cycling - Ramping - Primary Frequency Control.

* juan.avalos@coordinadorelectrico.cl

INTRODUCTION

The main challenges regarding the integration of renewable energies in the electrical power system is the variability and uncertainty of its primary resources, for example solar PV and wind [2]. As a result of the economic benefits of renewables energies it is necessary to increase the resources of flexibility, collaborating with conventional generation plants for managing the fluctuations in real time produced by intermittent renewable energies.

In addition, renewable generation plants do not provide inertia to the electric power system in a natural form when they are operating [3]. Therefore, in the case of high level penetration of renewable energy in real time, its efficient energy production displaces conventional power plants. Consequently, it would reduce the inertia of the power system towards dangerous levels during ride through instantaneous imbalances between generation and demand.

Currently, the energy storage system, as hydro reservoir (Hydro), PSH and BESS, are poised to become an important element of the electricity infrastructure due to its characteristics of flexibility to manage renewable energies in real time. For example, BESS are devices that have capacity for delivering energy in very short times, improving frequency control performance, especially in cases when there is a low inertia level in the power system. On the other hand, PSH and Hydro plants allow managing high changes of net demand (load - renewable power) due to its high ramp rate (MW/min) and the absence or low level of minimum power.

The energy storage systems had been studied from different points of view and for different electrical power systems, for example, regulatory implications [4] and technical and economic storage impact depending the NCRE penetration [5]. Considering the challenge of power systems integration of renewable energies and the current and projected deployment of energy storage systems, this paper assesses the contribution of energy storage systems into the Chilean electricity systems in 2021, considering a high level of intermittent renewable energies as wind and solar PV power plants. Therefore, Section 1 describes the models of BESS and PSH for evaluating primary frequency control performance and economic operation costs, respectively. Section 2 introduces the general methodology used to analyze the effect of Hydro, PSH and BESS in the operational flexibility. Finally, Section 4 presents the main results and conclusions.

1. PSH AND BESS TECHNOLOGIES

1.1 BESS model

A BESS dynamic model was used to evaluate the dynamic performance of this technology in primary frequency control. Fig.1 shows the model used, which has the following characteristics:

- Dead band of 0,3 Hz because the BESS support is used only in contingencies but is not used in normal operation.
- A set of parameters was used that allow a fast actuation in shape of ramp. All its energy is delivered in less than 0,5 seconds.
- Dynamic response is not influenced by frequency, therefore if the threshold of 0.3 Hz is reached BESS injects its complete capacity.

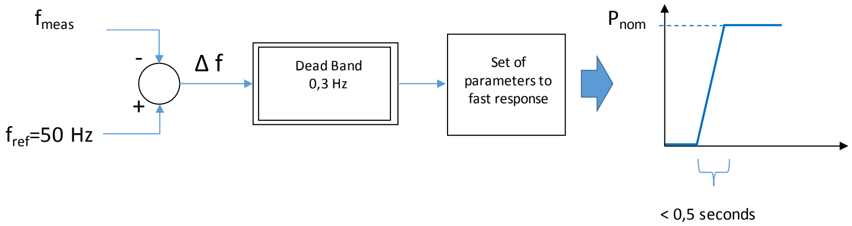

Fig.1 BESS model.

1.2 PSH model

The model of hydro-pumping plants considers two reservoirs, head and tail, and a generator-pump unit. The Fig. 2 shows a scheme that represents the generic system modeled in the unit commitment simulations. In addition, this model has a pump efficiency which is the round-trip percentage efficiency of the pumped storage plant. The main inputs are: Maximum and minimum volumes, initial volumes, generator-pump parameters. On the other hand, the main results are: generated/pumped power, on/off state, inflow and outflow, volume and shadow prices of reservoirs and so on.

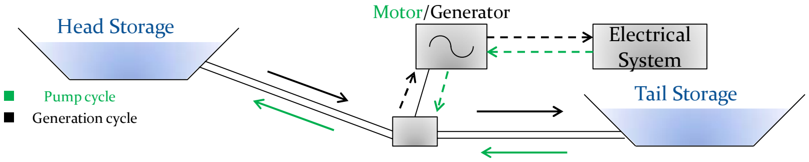

Fig.2 PSH model.

2. METHODOLOGY

2.1 System Economic Operation

The optimization problem was solved through PLEXOS® software [6]. It was carried out in a two stages simulation: 1) in the first stage, a medium-term optimization with a duration curve and annual step is performed (this stage delivers to the second stage the heads of the reservoirs for minimizing the system operation cost); 2) in the second stage, an annual unit commitment with hourly resolution is performed and it has four day steps. It should be noted that this stage has detailed modeling with the following parameters: minimum down time, minimum up time, minimum power, maximum power, shut down and startup cost, transmission system capacities, among others, necessary to analyze the challenges of flexibility with hourly resolution.

A total of six study cases were built to analyze different operational conditions to assess of energy storage system. In addition, two scenarios of NCRE integration were analyzed, namely 13,5% of the annual energy (NCRE Law Scenario) and 17,6% of annual energy (NCRE Law+30% Scenario). In the hydro-thermal optimization, three deterministic hydrological scenarios were used, namely wet (WH), medium (MH) and dry (DH).

2.2 Electrical analysis

Dynamic simulations were carried out to evaluate the performance of primary frequency control in Power Factory® software [7]. As described in Section 3, the system has mainly a mix thermal-NCRE in the north zone and the hydroelectricity in the south zone. Therefore, the best location and technology for the provision of reserves in the system was evaluated.

In this context, generator’s outages with 375 MW (the biggest generator in the system) in the north and the south zone independently were performed in the moment that the system had a lowest inertia (synchronous rotating masses) in the year in a NCRE Law scenario. In addition, these simulation cases had the characteristics of a maximum power flow (1500 MW) for the interconnection line between the north and the south zone, representing a more challenging operational condition for frequency control.

The dynamic performance of frequency regulation after the outage of a generator was performed with different strategies for the distribution of reserve. These strategies are the following: 1) Reserve only in hydroelectric plants located in the southern zone (SR); 2) Reserve only in thermal plants located in the northern zone (NR); and 3) Reserve in a mix hydro-thermal plants distributed along whole system (DR). In all strategies, the total reserve amount is equal to 426 MW, which are supplied by current BESS (52 MW) and by conventional generators (374 MW).

Furthermore, other study cases were evaluated to verify the dynamic behavior of the system with challenging conditions: reduction the number of generators involved in primary frequency control, 30% of NCRE additionally (NCRE Law+30%) and replacement of the reserve from conventional generators by BESS.

3. CHARACTERISTICS OF THE CHILEAN ELECTRICAL SYSTEM

Currently, there are two interconnected systems in Chile: the Central Interconnected System (SIC) and the Great Northern Interconnected System (SING). These systems will be interconnected in one large system through a 1700 MVA 2x500kV HVAC tie during 2018, between substation Los Changos and Polpaico (see Fig.3). The connection of the systems will create a new one electric systems with 3200 km of extension that will have three different zones: a north zone characterized for a mix thermal generation plants (7,8 GW installed capacity) and NCRE (4,4 GW installed capacity) as well as mining and industry demand represents a 38% of the country; a central zone characterized for a mix thermal (3,8 GW installed capacity) and hydroelectric plants (1,7 GW installed capacity) as well as commercial, industry and residential demand represents a 40% of the country; a south zone characterized for a mix hydroelectric (5,5 GW installed capacity) and thermal (1,8 GW installed capacity) as well as residential demand represents a 22% of the country.

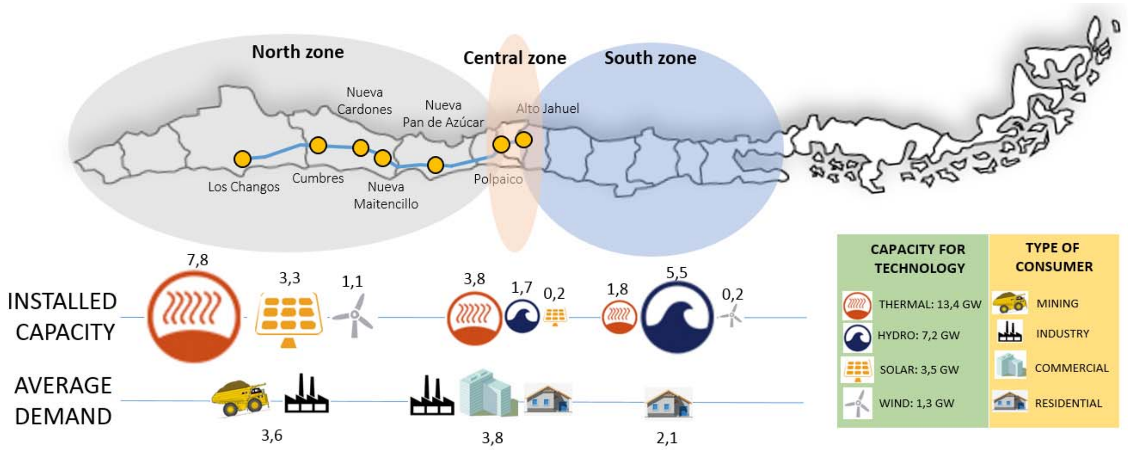

Fig.3 National electrical power system in 2021, capacities projected for NCRE Law+30% scenario.

On the other hand, net demand (gross demand minus NCRE generation) was built with real information for the installed NCRE plants as well as ‘Explorador de Energía Eólica y Solar’ [8] estimations for the installed NCRE plants. For example, Fig.4 shows the gross demand and net demand for a summer day to demonstrate the challenge to operate this projected system, in term of ramps and big NCRE blocks.

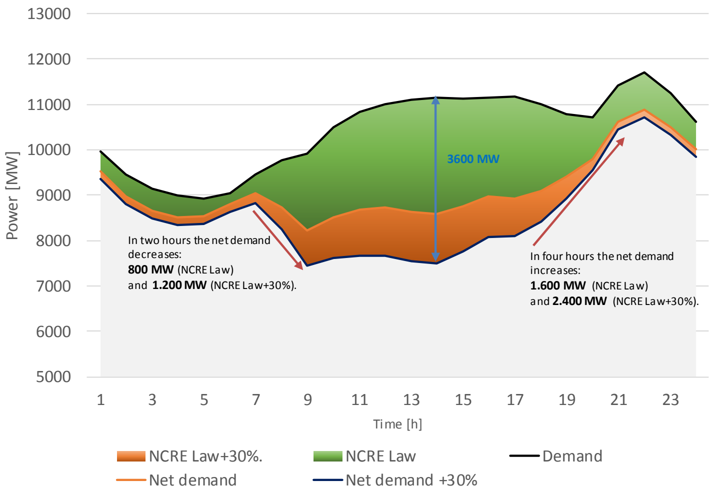

Fig.4 Net demand in a summer day (NCRE with high plant factor).

4. RESULTS

4.1 System Economic Operation

4.1.1 Power flows in the transmission system

In conformance with the intraday and seasonal variability of generation and demand, it was found a high bidirectionality in power flows of the most important transmission lines in the north. In addition, there are congestions in the 500 kV Nueva Pan de Azúcar - Polpaico corridor about 25% of the year (NCRE Law+30% Scenario) in the north-south direction, mainly in hours of the day with high solar photovoltaic penetration.

4.1.2 Cycling

The number of shutdown and startup was determined to evaluate the conventional generators cycling. Fig.5 and Fig.6 show the distribution of the shut down and startup within the day for coal and LNG generators, respectively, in the dry hydrology and NCRE Law+30% scenario. For the coal generators, the startups are concentrated between 16 and 21 hours, which is in line with the increase of the demand and decrease of solar generation; meanwhile the shutdowns are concentrated between 6 and 12 hours, when the solar photovoltaic plants increase their generation. On the other hand, LNG plants have a similar behavior than coal generators but more flexible, therefore they are turned on and off throughout the day.

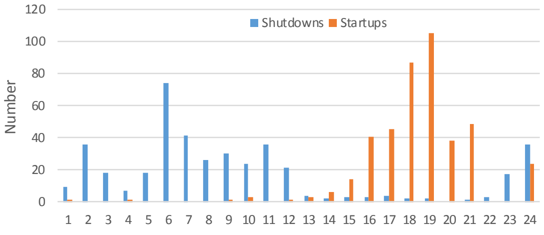

Fig.5 Number of shut down and startup hourly for coal generators.

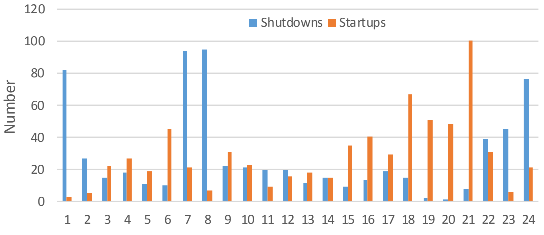

Fig.6 Number of shut down and startup hourly for LNG generators.

For all conventional technology (coal, LNG and hydroelectric generators) and all scenarios, the maximum and average number of shutdowns and startups is shown in the Fig.7, Fig.8 and Fig.9. Accordingly, the cycling in the coal generators is higher with wet hydrology compared with dry hydrology. In the case of LNG and hydroelectric generators the cycling is more intense for a dry condition.

This situation is explained because for dry hydrology coal generators were working at maximum power while LNG and hydroelectric generators were operating to follow demand and NCRE variations because the availability of the water in the reservoirs is low. For a wet hydrology and as optimization result, the hydroelectric generation decreases its participation following the net demand and increases its energy production.

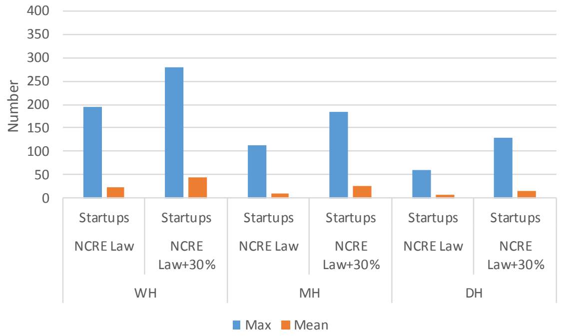

Fig. 7 Number maximum and average of shut down and startup of all coal generators during the year.

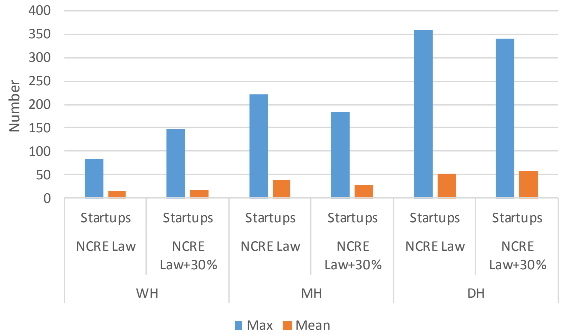

Fig. 8 Number maximum and average of shut down and startup of all LNG generators during the year.

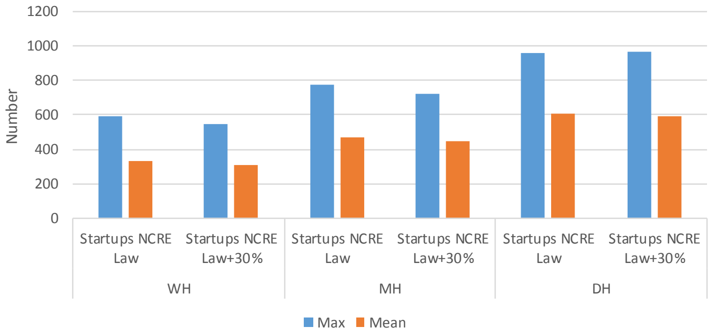

Fig. 9 Number maximum and average of shut down and startup of all hydroelectric generators during the year.

4.1.3 Ramping

The variations of the operational point between two consecutive hours (positive or negative) were determined to evaluate the conventional generators ramping. Fig.10 and Fig.12 show the hours in the year when generators were out service, no ramping and ramping condition. Fig.11 and Fig.13 show a characterization of the hours in the year when coal and hydroelectric generators were in ramping condition. Three ranges were defined: between 0-25% of the regulation range (difference between maximum and minimum power), between 25-75% of the regulation range and between 75-100% of the regulation range. For example: range 25-75% mean that a generation plant with 100 MW of regulation range, the variation of power between two consecutive hours did not was beyond 25 or 75 MW.

Accordingly, about 50% of the ramping condition coal generators were operated with variations in one hour at least 75% of their regulation range. In addition, the need for ramping is increased for

NCRE+30% scenarios. However, for coal generators in all scenarios the ramping condition reached only a 5% of the year.

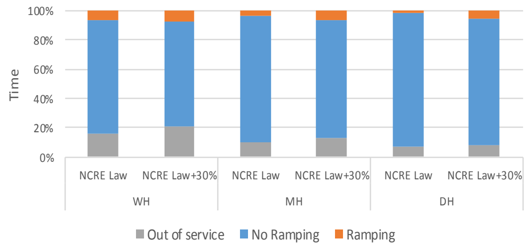

Fig. 10 Out service, no ramping and ramping condition of the coal generators.

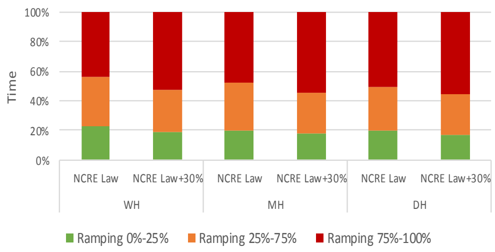

Fig. 11 Ramping of the coal generators, according to defined regulation range.

On the other hand, about 70% of the ramping condition the hydroelectric generators were operated with variations in one hour at the most 25% of their regulation range. For hydroelectric generators in all scenarios the ramping condition reached a 40%, therefore, this kind of technology is very important to get flexibility in the electrical system, as shown in Fig.12 and Fig. 13.

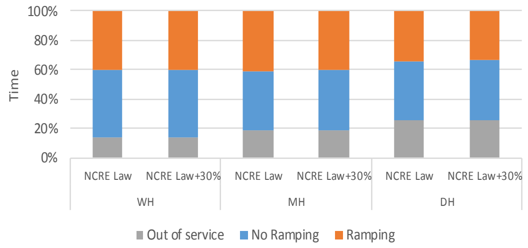

Fig. 12 Out service, no ramping and ramping condition of the hydroelectric generators.

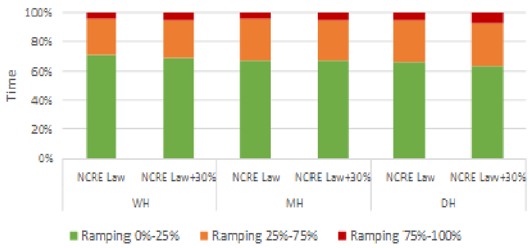

Fig. 13 Ramping of the hydroelectric generators, according to defined regulation range.

Fig.14 and Fig.15 show the distribution of the ramping within the day for coal and hydroelectric generators in the dry hydrology and NCRE Law+30% scenario. Accordingly, coal generators have a higher ramping condition between 7 am and 18 pm (in line with solar photovoltaic generation). The hydroelectric generators have a ramping condition more constant within the day.

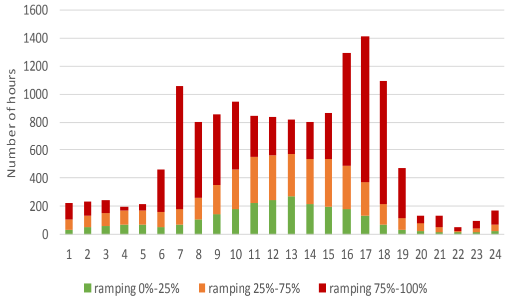

Fig.14 Ramping hours for coal generators during the year.

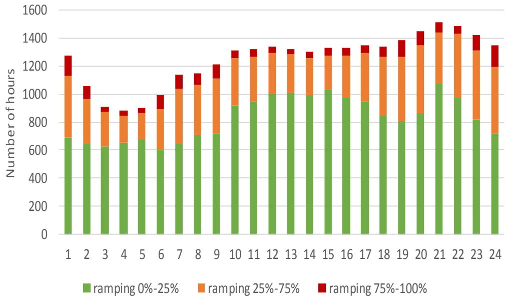

Fig.15 Ramping hours for hydroelectric generators during the year.

4.1.4 Pumped Storage Hydroelectric Power Plant Effects

The effects in the system operational behavior the PSH plants installation were assessed (each one of 300 MW installed in the north of the country). Fig. 16 and Fig. 17 show the operation of this plant both, generation and pumping mode respectively, for the dry hydrology and NCRE Law + 30% scenario. The solar photovoltaic influence was evidenced based on the PSH plant behavior because this plant was in generation mode mainly between 18 pm to 7 am while in pumping mode between 7 am to 18 pm. This phenomenon due to PSH plant absorbs power from the system when there is a lower marginal cost (solar energy excess) and injects power to the system when there is a higher marginal cost (peak load time).

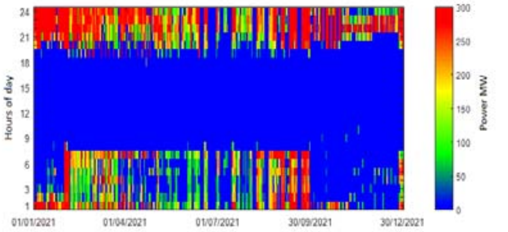

Fig.16 Generation hourly of the Pumped-Storage Hydroelectric (PSH).

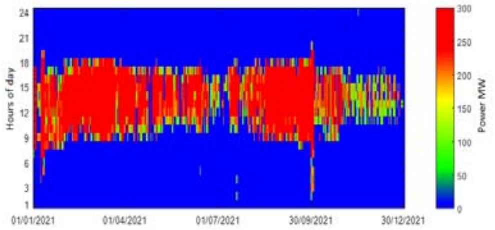

Fig.17 Pumping hourly of the Pumped-Storage Hydroelectric (PSH).

Therefore, PSH plant has modified the net demand. This modification has a direct impact in the cycling and ramping of the system, mainly in the thermal generators. Fig. 18 shows the reduction of shut down and start up for all coal generators in the year for the dry hydrology and NCRE Law+30% scenario, this number was decreased in 25% when one 300 MW PSH plant was assessed and in 30% when two 300 MW PSH plant was assessed; similar situation for the ramping analysis take into consideration that the ramping condition was reduced in 18% for one 300 MW PSH plant in 30% for two 300 MW PSH plant.

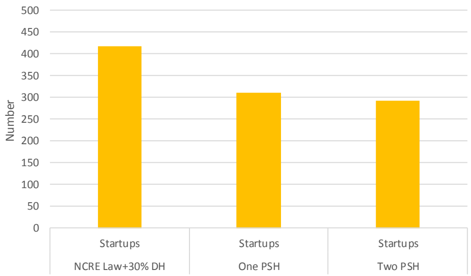

Fig.18 Effect of PSH on shut down and startup in all coal generators.

4.2 Dynamic Analysis

The dynamic performance in the frequency regulation after the outage with different strategies for the distribution of the reserve is shown in Fig. 19. Although the scheme SR has a lower steady state frequency deviation, has a higher minimum frequency (Nadir). On the other hand, to hold spinning reserve in the thermal generators located in the north zone (NR) has a better performance for the Nadir, however a worse performance for steady state frequency. Finally, DR strategy allows the combination of positives aspects of both technologies, that is, the short term behavior of the thermal generators with long term support of the hydroelectric plants.

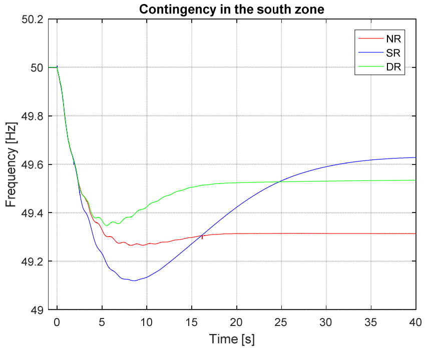

Fig 19. Frequency after outage 375 MW with different strategies for the distribution of the reserve.

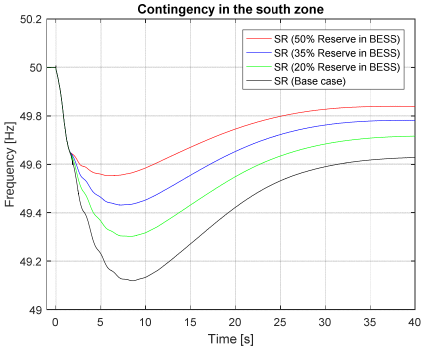

Fig 20. Frequency after outage 375 MW with reserve in the south zone by mixed hydraulics and BESS.

Currently, BESS have been used to provide frequency control in the north zone (32 MW installed and 20 MW in construction). This kind of technology has been installed because there is an obligation for every machine dispatched to keep a percentage of their generation as spinning reserve and these BESS have replaced this spinning reserve. The eventual replacement of spinning reserve of hydroelectric generators for BESS in different amount was assessed from technical point of view.

Fig. 20 shows the results of the most challenging scenario (SR), considering the Nadir criteria, for different percentages of reserve provided by BESS. Accordingly, BESS improve the performance of the frequency control in 2,3 mHz for each MW of BESS installed approximately.

4.3 Economic Analysis of incorporation of BESS in primary frequency control

Based on simulations of economic operation, Fig. 21 shows the net savings updated (Operating cost savings – investment (689 USD/kW [9][10], discount rate 10%), operation and maintenance of the BESS), in a horizon of 15 years, by replacing part of the primary reserve (20, 35 and 50% of the primary reserve) of conventional units with BESS. This allows to dispatch full load conventional efficient units that previously provided primary reserve, allowing savings in operating costs of the system; therefore, for certain specific conditions, there are economic benefits to the system and a better frequency response to contingencies.

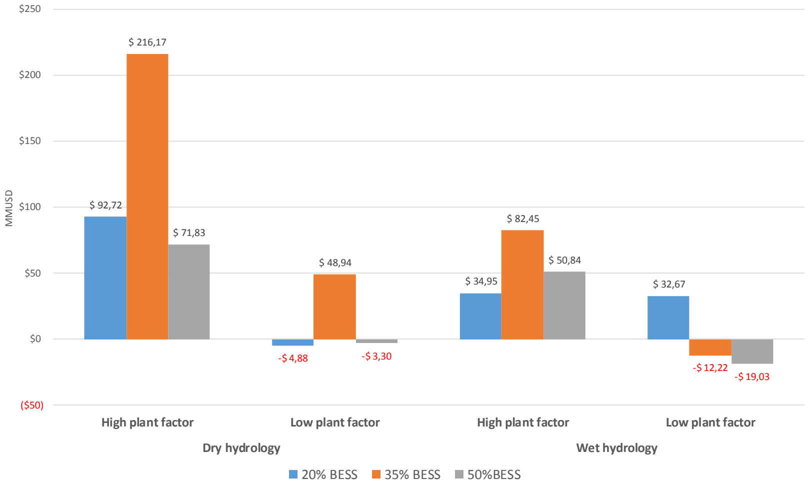

Fig 21. System benefits for different installation scenarios of BESS, NCRE's plant factor and availability of hydraulic resources.

CONCLUSIONS

The main conclusions obtained from analyses performed are as follow:

- The Chilean electricity system in 2021 affords a security and efficient management of the blocks of NCRE evaluated in this paper (~17% annual energy and ~42% instantaneous penetration).
- The operational flexibility provided by hydro-reservoir plants is essential to manage the intra-daily and hourly variability of net demand, significantly reducing the impact on thermal generators.

  However, its contribution could modify in case of introducing the uncertainty of reservoir hydroelectric resources and possible environmental factors such as hydropeaking [11].
- The lowest contribution from thermal generators to operational flexibility is a result of condition of energy exportation of northern zone (effective-cost production from coal generators keep it turn on for sending energy to central and southern zone), as well as minimum down/up time which do not afford turn on and turn off generation plants between minimum net demand time and maximum net demand time into the day. Consequently, it is recommended to study the feasibility and costs associated with decrease minimum down/up time towards values less than international references [12].
- The PSH plants have a direct effect in decrease requirements of operational flexibility of Chilean electricity system as a result of smooth out the net demand daily curve. This effect reduces the quantity of shutdown and startup of conventional generators as well as the operation hours changing load levels (ramping). It contribution could increase if growth NCRE levels with simultaneous production as solar PV plants.
- As result of intra-day variation of inertia, it recommends to implement in the Chilean electricity system a distributed scheme of reserves for primary frequency control in as well as evaluate requirements of dynamic reserves along day.

  Results about participation of the BESS in frequency primary control shown a notably improving of performance of frequency control during generation contingencies due to very fast deploy of electric power from BESS. In addition, the incorporation of BESS as a percentage for replacing of reserve of conventional generators, allows increasing production of efficient conventional generators (coal generators and hydro-reservoir plants) to get to operational savings (differences between NPV of operational costs and capacity and operational costs of BESS) respect to a scenario without BESS.
- Regarding to electric systems with high levels of intermittent renewables energy, it is recommended to study new methodologies of optimizations models that combine: use of electricity system' flexible resource to manage short time (hourly or intra-hour) requirements of operational flexibility, efficient balance of energy (hydro-thermal-NCRE) in long term (1-2 years) and environmental constraints (hydropeaking in hydro plants and NOx and SOx emissions limits in thermal generation plants).

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