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Proposal for improving the flexibility of the Cuban electrical system through pumped hydropower plants. Review of the Cuba's potential-background

Propuesta para mejorar la flexibilidad del sistema eléctrico cubano mediante centrales hidroeléctricas de bombeo. Revisión del potencial-antecedentes en Cuba

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Abstract:

This paper presents a topic that has not been discussed or taken into consideration before: the potential and background of pumped hydro energy storage (PHES) in Cuba. The use of PHES in the Cuban power grid could increase its flexibility and integration of variable renewable energy sources (VRE), that's why this technology needs to be assessed. Cuba has considerable potential for the installation of PHES that al least doubles the current total installed capacity of all energy sources. In a planned future Cuban scenario with a strong presence of VRE, PHES facilities could play a vital role in increasing grid flexibility and frequency control capacity, especially because Cuba does not currently have any energy storage capacity installed in its electrical system. This *article presents a 200 MW PHES project in the eastern region of Cuba, in a scenario with a high share of VRE, as a case study. The current limited Cuban policy and regulatory support for PHES can be considered the major cause of the PHES investment risk. However, to add economic storage capacities in Cuba, such as PHES, is still vital for future Cuban development and ambitious governmental goals of 100% from renewable sources.*

Resumen:

Este trabajo presenta un tema que no ha sido discutido o tomado en consideración antes: el potencial y los antecedentes del almacenamiento de energía hidroeléctrica por bombeo (PHES) en Cuba. El uso de PHES en la red eléctrica cubana podría aumentar su flexibilidad y la integración de fuentes variables de energía renovable (VRE), por lo que es necesario evaluar esta tecnología. Cuba tiene un potencial considerable para la instalación de PHES que al menos duplica la capacidad total instalada actual de todas las fuentes de energía. En un futuro escenario cubano planificado con una fuerte presencia de VRE, las instalaciones PHES podrían desempeñar un papel vital en el aumento de la flexibilidad de la red y la capacidad de control de frecuencia, especialmente porque Cuba no tiene actualmente ninguna capacidad de almacenamiento masiva de energía instalada en su sistema eléctrico. Este artículo presenta como estudio de caso un proyecto PHES de 200 MW en la región oriental de Cuba, en un escenario con una elevada cuota de VRE. La limitada política cubana actual y el apoyo regulatorio a PHES pueden considerarse las causas principales del riesgo de inversión en PHES. Sin embargo, añadir capacidades económicas de almacenamiento en Cuba, como PHES, sigue siendo vital para el futuro desarrollo cubano y los ambiciosos objetivos gubernamentales de 100% a partir de fuentes renovables.

Keywords: *Pumped hydropower; Frequency regulation; Energy storage; LINDA model; Mayari project.*

Palabras Clave: Hidroacumuladoras de bombeo; Regulación de frecuencia; Almacenamiento energético; Modelo Cubalinda; Proyecto Mayarí.

1. Introduction

PHES has been in use for more than a century to store the surplus of electricity production. Currently, PHES is the most used Electrical Energy Storage (EES) for power system applications [1]. These power plants are the most efficient and practical large-scale energy storage systems, with typical overall efficiency in the range of 70–85%. PHES, like the scheme shown in Fig. 1 a), entails pumping water from a lower reservoir to a nearby upper reservoir when there is surplus power generation (typically at night) and allowing the water to return to the lower reservoir through a turbine to generate electricity when there is a supply shortfall (generally during daytime and evening peak). As shown in Figure. 1 b), the PHES aims to flatten the demand curve of the electrical system, consuming electricity at times when there is little demand and generating at those when demand is maximum. PHES are capable of starting operating in few minutes which gives them advantages that are not always economically evaluated for the reliability of the electrical system to which they are connected [2,3].

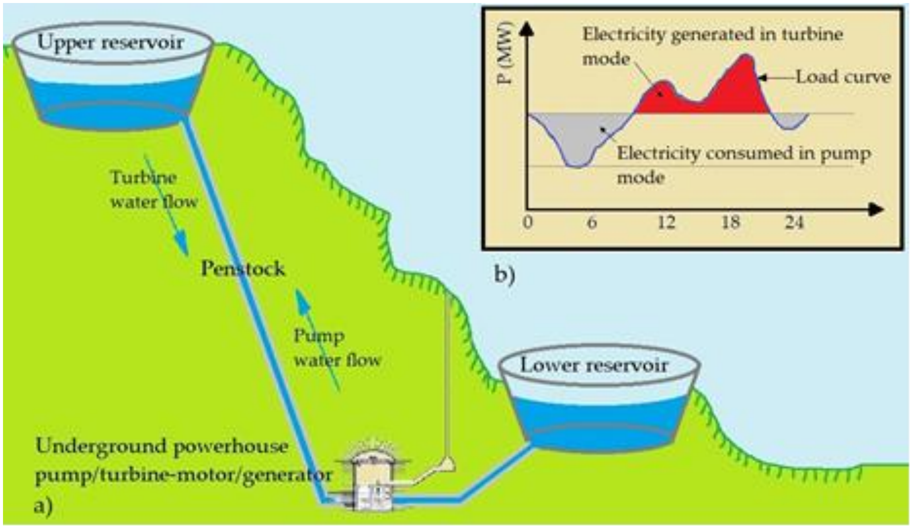

Figure 1. PHES operation principle (a) and typically Cuba's daily load curve (b)

The 95% of current Cuban electric power system is from fossil-based fuels [6]. Hydropower and other renewable energy sources (including wind and solar power) contributed slightly less than 2 per cent combined [7,8]. Electricity from renewable sources in 2021 represented 4 per cent, including sugar cane biomass. To change the current electricity situation, the Cuban government has elaborated a policy to increase generation by renewable sources of energy to 37% of the primary energy sources by 2030 [3]. With the future installation of the 700 MW with photovoltaic generation and the 680 MW with wind energy [9], according to the future planning of the Cuban Electric System and under normal operating conditions, intermittent energy could be stored in PHES plants. Some research work states that the Cuban electrical system needs to add energy storage capacities, control strategy and to increase flexibility capacity [3,4].

The flexibility of PHES plants allows base power generation plants to operate most efficiently at rated power. This was the main motivation for the development of PHES in the 1980s in Cuba [5-7] with the first PHES project in Fomento municipality named Caracusey. Unfortunately, the Caracusey pumped hydro project was stopped in the construction phase when the Cuban government decided not to install the nuclear power plant of Juraguá in Cienfuegos Province during the 1990s. Nowadays, PHES plants in the Cuban electrical grid could play a greater role than previously thought. PHES may be the enabling technology that allows for the higher penetration of VRE into the grid. Considering the stochastic nature of VRE's generation, flexible energy storage capacity is needed to improve its grid integration. So, variable-speed PHES technologies could be the best solution to VRE integration in Cuba.

This paper addresses for the first time the updated potential of PHES deployment in Cuba and the future role. The remainder of the paper is organized as follows: In materials and method section is presented the main problem and a possible solution of lack of flexibility in Cuban power sector. Then is argued a review of the main PHES advantages and some drawbacks for the current Cuban electrical grid. After that is investigate and present for

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the first time the historical and technological background of PHES projects in Cuba. Next, is displayed the discussion about Cuban Eastern region for PHES deployment potentialities and presented the Mayarí PHES case study for high VRE integration. Lastly, the authors offer some conclusions and an outlook for further research.

2. Methodology

After a category 3 Ian hurricane hit Cuba on September 27, 2022, a blackout for about three days occurred. Frequency instability caused the electrical system to go down showing a lack of flexibility and low frequency control capacities [3,8], both primary and secondary frequency control. This could be improved by adding energy storage capacities. This paper focus on the updated potential of PHES deployment in Cuba and the future role of this technology in a necessary change in the energy mix which is now based on fossil energy. In addition, there are, assessed a 200 MW PHES project in the eastern region of Cuba, in a scenario with a high share of VRE, as a case study. Some technical characteristics of the PHES project named Mayarí project, are presented as well other VRE energy sources and fossil-based to be integrated in Holguín province (eastern region). This province is considered as a case study due to the current and future development to be achieved in the industrial, agricultural, energy, and mining sectors. It is also the province with the highest wind power potential and should have a considerable increase in PV energy towards 2050.

3. Results and Discussion

Main advantages of PHES for the Cuban electrical grid

According to Luukkanen, et al. (2022) [9], the future Cuban electrical grid needs storage capacity investments in pumped storage and hydrogen. Using the Long-range Integrated Development Analysis (LINDA) model to evaluate future scenarios for Cuba [10], in [5,9] it is proposed to invest in PHES projects in Cuba. This model for Cuba is named

CubaLinda model [11]. It is an Excel-based tool built to create future scenarios for energy analysis. A scenario constructed with *CubaLinda* model for the electricity consumption and production for the first week of 2050 in Cuba is shown in Fig. 2. Electricity demand could be flattened using storage charge (like PHES) at high shares of VRE sources and supply electricity at maximum peak demand.

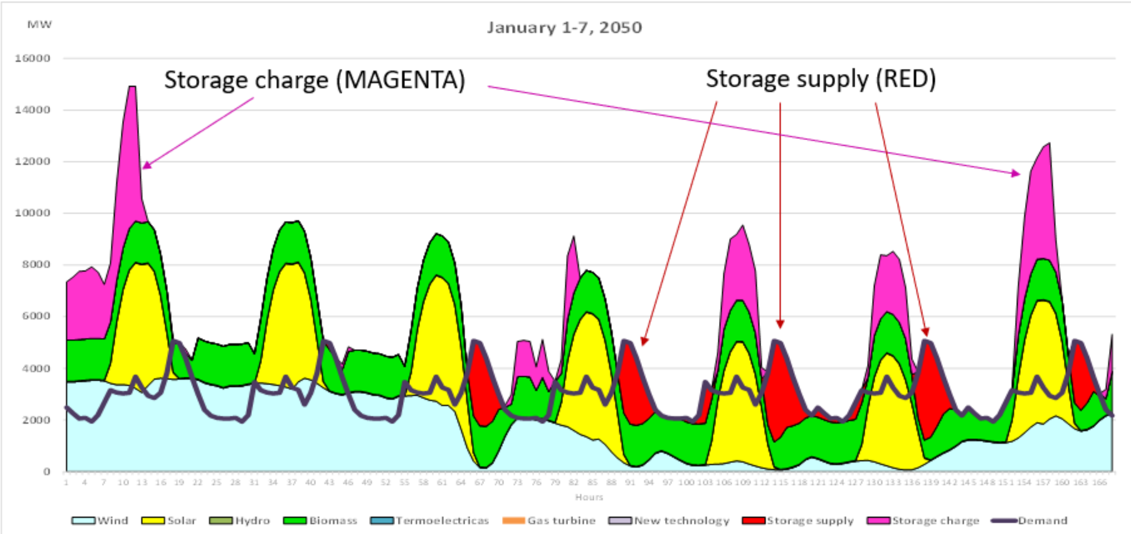

Figure 2. Cuba's future energy scenario at 2050. Source:[9]

PHES plants can provide inertia and load balancing services to the grid. In the case of variable speed technology, they can provide response times in seconds or even milliseconds [12,13]. Despite other storage technologies, PHES is a technically matured and economically viable option for large scale energy storage [13]. This technology has offered cost-effective grid services and balancing for decades. Whereas the oldest installations (1970s) were mostly provided with reversible pump-turbine units at a fixed speed (synchronous machines), current installations are often provided with variable speed units [14], which increase PHES availability, efficiency and grid flexibility.

Historical and technological background of PHES projects in Cuba

Among some of the storage technologies currently available for Cuba [7,15], with capacities of up to several GWh, hydro is the only technologically and economically mature medium capable of massive storage. Cuba has adequate hydropower resources and mountainous regions with more than 300 m altitude drop [5,16] (Fig. 3), which can be used to deploy the necessary PHES. Thirty-one sites with very good hydrological, geological and topographical conditions have been studied for the construction of PHES [5,6,17], located in the three geopolitical regions of the country (Fig. 3): region 1 (East), region 2 (Center) and region 3 (West).

Figure 3. Potential regions for PHES projects deployment in Cuba. Source: [5]

Some studies have been carried out in Cuba for the construction of PHES since the 1970s. Its further development was mainly motivated by the goal to build the Nuclear Power Plant (NPP) in Juraguá, Cienfuegos. Some other different potential sites were calculated by means of the GIS PHES site search [18,19].

Since the 1980s, extensive studies have been carried out in all the mountainous areas of Cuba thanks to the collaboration of specialists from the ex-socialist countries, mainly from the former Czechoslovak Socialist Republic. This global survey of greenfield off-river PHES was undertaken by the Australian National University. A worldwide Atlas [20] of off-river PHES sites is available at [18]. During the years 2016-2019 all of these sites were visited by some of the authors, carrying out field assessment studies. The total potential capacity of identified sites for PHES in Cuba reaches 16.18GW. This figure represents approximately 2.5 times the current Cuba's installed generation power from all sources.

The studied potential of PHES in the western region reaches 5320MW. The most evaluated site for PHES in Cuba has been at Pinar del Rio province. The close difference in energy prices between peak and down and energy subventions are the main reasons for economic non-feasibility until today. From the author's point of view, limited policy and regulatory support can also be considered as causes of the high investment risk.

The central region's potential capacity for PHES projects reaches 1860MW. The Caracusey PHES project, historically known as the Fomento project due to the municipality's location, was initially designed to operate within the Juraguá nuclear power plant in Cienfuegos Province. The Caracusey PHES project was previously stopped in 1990's because the Juraguá NPP project was not continued. Currently, this PHES could be useful for VRE integration in the central region of Cuba and to achieve the ambitious governmental goals of 100% renewable energy generation.

Cuba's eastern region has been deeply evaluated for years for the deployment of hydropower plants. The total potential capacity of the eastern region reaches 9000MW, the greatest in Cuba. The most feasible PHES in the east region of Cuba was the Mayarí project. The main advantage of the Mayarí PHES project is the already constructed dam in Holguín province that could be used as a lower reservoir for the Mayarí PHES project.

The Mayarí PHES project case study

After two years of evaluation of variants (since 2019) and real construction conditions of the available 31 sites, two sites with high potential and ideal conditions for the construction of PHES were defined, one in the Cuba's central region at the Guamuaya massif and another one in the eastern region in the Sierra Cristal belonging to the Holguín province. This last site has the advantage of a reservoir already built: Mayarí dam (Fig. 4). This has excellent hydrological characteristics ac-cording to the studies carried out by RAUDAL® engineers and designers.

Seven variants of layouts were studied depending on the type of conduction and location of the upper and lower reservoirs, shown in Fig. 4. Three locations for upper reservoirs were analyzed. As a lower reservoir, it is proposed to use the al-ready built reservoir of the Mayarí dam. The layouts of each variant (Fig. 4) were selected based on two main types of water conduction: steel pipes or tunnels. Combined conduction was also evaluated according to the topographical characteristics of each possible layout.

The use of pipelines is usually more expensive and causes a greater impact on the surrounding environment. Many species are there, some of which are endemic. The ratio between the length of the pipeline and the hydraulic head (L/H) is less than 10, which is the threshold considered as the technical-economic feasibility index for these power plants. In all the studied variants, the L/H ratio ranges between 5 and 7. Another relevant factor is the fact that the lower reservoir is built and in operation with proven hydrological guarantees through simulations for 100 years.

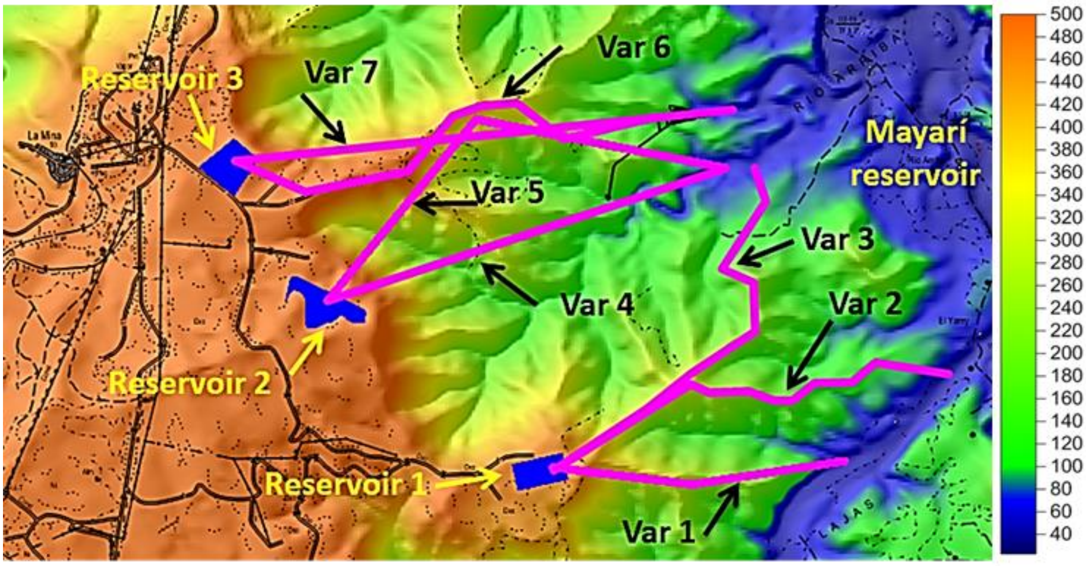

Figure 4. Studied variants for a 200MW PHES project. Source: RAUDAL®

4. Conclusions

The main advantages of PHES projects for Cuba have four aspects: increased energy independence, greater integration of the VRE, increase in flexibility of the Cuban electrical system and the increase in stability of the electricity system. Cuba has an identified and updated great potential for PHES projects in three country regions. Potential PHES projects studied in Cuba reach the amount of 16.18 GW. This represents 2,5 times the current total installed power plant capacity in Cuba. Some Cuban PHES projects have a net head of more than 450 metres, but the mean value of all Cuban projects reaches 385 metres. The Mayarí PHES project in the eastern part of Cuba is an attractive project since it has proven technical characteristics, but new policy and regulatory support for ancillary services in Cuba could improve feasibility results.

5. Bibliographic references

1. He, W.; King, M.; Luo, X.; Dooner, M.; Li, D.; Wang, J. Technologies and economics of electric energy storages in power systems: Review and perspective. *Advances in Applied Energy* **2021**, *4*, 100060, doi:https://doi.org/10.1016/j.adapen.2021.100060.
2. Nibbi, L.; Sospiro, P.; De Lucia, M.; Wu, C.-C. Improving Pumped Hydro Storage Flexibility in China: Scenarios for Advanced Solutions Adoption and Policy Recommendations. *Energies* **2022**, *15*, 7918, doi:https://doi.org/10.3390/en15217918.
3. Figueredo Reinaldo, O.; Carmona Tamayo, E. Cuba en Datos: El ineludible cambio de la matriz energética que necesitamos. Available online: http://www.cubadebate.cu/especiales/2022/07/01/cuba-en-datos-el-ineludible-cambio-de-la-matriz-energetica-que-necesitamos/ (accessed on july, 5).
4. IHA, H. *2021 Hydropower Status Report: sector trends and insights. 2021. London*; 2021.
5. Peña, P.L.; Fariñas, W.E.Y.; Brito, S.A.L. The role of hydropower in the cuban electricity System and future plans toward 2030. In *Cuban energy systems Development-Technological Challenges and Possibilities*, Luukkanen, J., Saunders, A., Santos, A., Majanne, Y., Rozas, M.L.F.S.d., Laitinen, J., Eds.; Finland Futures Research Centre (FFRC). University of Turku. Finland https://urn.fi/URN:ISBN:978-952-249-568-6, 2022; Volume 2, p. 255.
6. Peña, P.L.; Hidalgo, G.R. Acumulación de energía hidráulica en Cuba. Proyección hacia el año 2030. *Boletín informativo renovable.cu* **2019**, *4*, 2-6.
7. Peña, P.L.; Gutiérrez, U.L.; Ramón, H.G.; Domínguez, A.H. Integration Proposal of a Solar Thermal Power Plant to the Cuban National Electric System. *Revista Tecnología Química* **2018**, *Vol 38*, pp 551-561. septiembre-diciembre de 2018.
8. Menéndez, J.; Fernández-Oro, J.M.; Loredo, J. Economic Feasibility of Underground Pumped Storage Hydropower Plants Providing Ancillary Services. *applied sciences* **2020**, *10*, doi:10.3390/app10113947.
9. Luukkanen, J.; Saunders, A.; Majanne, Y.; Korkeakoski, M. Possibilities and challenges for developing a 100% renewables electricity system for Cuba. In Proceedings of the III Simposio Internacional sobre

Generación Distribuida (SIGEDI 2022), Palacio de las Convenciones de La Habana. Cuba, 28/11-2/12/2022, 2022.

10. Alberto Alvarez, E.; Korkeakoski, M.; Santos Fuentefría, A.; Lourdes Filgueiras Sainz de Rozas, M.; Arcila Padura, R.; Luukkanen, J. Long-Range Integrated Development Analysis: The Cuban Isla de la Juventud Study Case. *Energies* **2021**, *14*, 2865, doi:10.3390/en14102865.
11. Luukkanen, J.; Saunders, A.; Majanne, Y.; Korkeakoski, M. Modelling Cuban energy system with CubaLinda model, Prospects for 100% renewable scenario. In *CUBAN ENERGY FUTURES. The transition towards a Renewable Energy System-Political, Economic, Social and Environmental Factors*, Luukkanen, J., Saunders, A., Majanne, Y., Korkeakoski, M., Eds.; Finland Futures Research Centre (FFRC). University of Turku. Finland https://urn.fi/URN:ISBN:978-952-249-569-3, 2022; Volume 3, p. 335.
12. Coban, H.H.; Rehman, A.; Mousa, M. Load Frequency Control of Microgrid System by Battery and Pumped-Hydro Energy Storage. *Water* **2022**, *14*, 1818, doi:https://doi.org/10.3390/w14111818.
13. Vasudevan, K.R.; Ramachandaramurthy, V.K.; Venugopal, G.; Ekanayake, J.B.; Tiong, S.K. Variable speed pumped hydro storage: A review of converters, controls and energy management strategies. *Renewable and Sustainable Energy Reviews* **2021**, *135*, 110156, doi:https://doi.org/10.1016/j.rser.2020.110156.
14. Koohi-Fayegh, S.; Rosen, M.A. A review of energy storage types, applications and recent developments. *Journal of Energy Storage* **2020**, *27*, 101047, doi:https://doi.org/10.1016/j.est.2019.101047.
15. Vazquez, L.; Majanne, Y.; Castro, M.; Luukkanen, J.; Hohmeyer, O.; Vilaragut, M.; Díaz, D. Energy System Planning towards Renewable Power Systems: Energy Matrix Change in Cuba by 2030. *IFAC-Papers-onLine* **2018**, *51*, 522-527, doi:https://doi.org10.1016/j.ifacol.2018.11.756.
16. Peña-Pupo, L.; Martínez-García, H.; García-Vílchez, E.; Domínguez, A.H.; Fariñas-Wong, E.Y. Improvements in Frequency Control of an AC Microgrid by Means of Micro-Hydropower Combined Flow-Reduced Dump Load Control Method. *Renewable Energies and Power Quality Journal (RE&PQJ)* **2022**, *20*, 506-511, doi:https://doi.org/10.24084/repqj20.350.
17. Shishkov, G.; Grigorov, S. *Estudio tecnico-económico comparativo de ubicación de centrales hidroacumuladoras. Partes I-V: Variantes de ubicación de centrales hidroacumuladoras en la region oriental, central y occidental. Conclusiones generales*; Ministerio de la Construcción (MICONS). Instituto de Hidroeneconomía: Internal Report, July 1980; p. 850.
18. RE100, g. RE100 group, Australian National University Global pumped hydro atlas. (available at: http://re100.eng.anu.edu.au/global/index.php). **2023**.
19. Blakers, A.; Stocks, M.; Lu, B.; Cheng, C. A review of pumped hydro energy storage. *Progress in Energy* **2021**, *3*, 022003.
20. Stocks, M.; Stocks, R.; Lu, B.; Cheng, C.; Blakers, A. Global atlas of closed-loop pumped hydro energy storage. *Joule* **2021**, *5*, 270-284.

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