Latin American Journal of Energy Research - Lajer
periodicos.ufes.br/lajer

Latin American Journal of Energy Research – Lajer (2025) v. 12, n. 2, p. 103–115
https://doi.org/10.21712/lajer.2025.v12.n2.p103-115

Deep Ocean Gravity Energy Storage: an affordable seasonal energy storage

Julian David Hunt[1], Andreas Nascimento[2,3], Joao Paulo Reus Rodrigues Leite[4], Diego Nascimento[5], Wenxuan Tong[6], Marcos Aurelio Vasconcelos de Freitas[7], Mohd Amro[3]

[1] Biological and Environmental Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia.
[2] Institute of Mechanical Engineering (IEM), Federal University of Itajuba (UNIFEI), Itajuba, MG, Brazil.
[3] Institute for Drilling Technology and Fluid Mining (IBF), TU Bergakademie Freiberg (TUBAF), Freiberg, Germany.
[4] Institute of Systems Engineering and Information Technolog, Federal University of Itajuba (UNIFEI), Itajuba, MG, Brazil.
[5] Mechanic Department, Faculty of Engineering and Sciences, São Paula State University, Guaratingueta, SP, Brazil.
[6] School of Electrical and Electronic Engineering, North China Electric Power University, 102206, China.
[7] Energy Planning Program, Federal Univeristy of Rio de Janeiro, Rio de Janeiro, RJ, Brazil.
*Autor para correspondência, E-mail: julian.hunt@kaust.edu.sa, andreas.nascimento@unifei.edu.br

Received: 13 May 2025 | Accepted: 23 June 2025 | Published online: 03 August 2025

Abstract: The escalating demand for seasonal energy storage induces the exploration of innovative solutions. Gravitational energy storage systems are a practical solution for storing energy in long cycles, such as seasonal and interannual. This is because the cost of having materials sit at different altitudes is low. This paper proposes and investigates a new technology named Deep Ocean Gravity Energy Storage (DOGES). It operates underwater, utilizing material transported between storage sites on the continental shelf and the ocean floor using cargo ships, underwater cranes, and bucket excavators. This paper presents the methodology, design considerations, and global potential of the proposed technology. Results show that a DOGES plant with a 4 km depth could provide energy storage for 1.3 USD/kWh with a power cost of 4000 USD/kW. Comparisons with other energy storage solutions highlight DOGES as a realistic option for seasonal energy storage and have the potential to support the transition to a decarbonized energy future.
Keywords: seasonal energy storage; gravity energy storage; deep ocean technology; decarbonization.

1 Introduction

Seasonal energy storage requirements are rising with the increase in renewable energies, posing significant challenges to the stability and reliability of power grids worldwide (Brey, 2021). The rapid expansion of renewable energy sources such as wind and solar power has fundamentally altered the dynamics of energy generation, shifting emphasis towards intermittent and weather-dependent sources (Li et al., 2022; Fakhar et al., 2023). Consequently, the need for effective and scalable energy storage solutions capable of accommodating seasonal variations in energy production and consumption has become increasingly apparent (Balamurugan, Ashok and Jose, 2009; Karayel, Javani and Dincer, 2023). In this paper, we explore the escalating demand for seasonal energy storage, examine current storage technologies, and propose avenues for addressing this critical challenge in the transition toward a sustainable energy future.

The primary problem being investigated in this research is the lack of cost-effective, scalable, and efficient solutions for long-duration, seasonal energy storage (Boretti, Nayfeh and Al-Kouz, 2021). While current technologies offer some potential, they each have significant drawbacks that limit their widespread adoption and effectiveness in the context of increasing renewable energy integration. Seasonal pumped hydropower storage and hydrogen are the main solutions for seasonal energy storage in the context of decarbonizing the energy sector. However, seasonal pumped hydropower storage requires appropriate topography and results in substantial water evaporation that could be used for other means (Farinotti et al., 2019; Hunt et al., 2020; Hunt et al., 2023a). Hydrogen currently has a high investment cost involved and a low overall cycle efficiency of 30-50% (Hunt et al., 2023b; Ishaq and Dincer, 2021; Ji and Wang, 2021; Razi and Dincer, 2022). Gravity energy storage systems use gravitational potential energy to store and release electricity, offering significant potential for large-scale, long-duration energy storage applications

(Hunt et al., 2023a; Tong et al., 2022a, 2022b). These systems involve lifting heavy masses, such as sand, and concrete blocks, to an elevated position using surplus energy and then allowing them to descend under gravity to drive generators and produce electricity when needed (Li et al., 2024). Gravity energy storage systems can be divided into two main types: existing and non-existing height differences. In the first case, the difference in height between the upper and lower storage sites already exists (mountains, abandoned mines, deep sea). In the second case, the difference in altitude between the upper and lower storage sites must be built.

Gravity energy storage should not be considered for less than 12 hours of storage. This is because the installed capacity cost for gravity energy storage solutions is high, and the cost of batteries is reducing rapidly. Batteries are a more practical and cheaper alternative to provide energy storage cycles shorter than 12 hours. Gravity energy storage technologies should focus on weekly, monthly, and seasonal energy storage cycles. Ideally, the existing difference in altitude should be used. If there is no existing height difference to be used, the height difference can be constructed, as it is performed by Energy Vault, however, the plant should be designed to store at least 48 hours of energy or more, so that it does not compete with batteries. In other words, the number of weights should be high and the power capacity small. More details on gravity energy storage can be seen in (Berrada and Loudiyi, 2019; Rimpel et al., 2020; Tong, Lu, Chen, et al., 2022; Roushenas, Gholamyankarkon and Arabkoohsar, 2023).

A different type of Deep Ocean Gravity Energy Storage (DOGES) has been proposed by Cazzaniga et al. (Cazzaniga et al., 2017). However, the approach used to store energy is different to the one proposed in this paper. It works similarly to a pumped hydropower storage plant (Wang et al., 2023). Where water is removed from steel pipes until only steam and air dissolved in the seawater at low pressures are left inside the pipeline. Electricity is generated by allowing seawater to inter the pipeline. This system is designed to store energy for hours or days, as the pressure pipelines are expensive. We propose the same name for our technology because we believe that the technology proposed in (Cazzaniga et al., 2017) should be named "Deep Ocean Pumped Storage" or something similar. Other technologies, such as Buoyancy Energy Storage Technology (BEST) (Hunt et al., 2021), Isothermal Deep Ocean Compressed Air Energy Storage (Hunt et al., 2022; Hunt et al., 2023b; Hunt et al., 2023c) also look at different ways to store energy in the deep ocean using buoyancy force and compressing air, respectively.

The main contribution of this paper is the proposal of an innovative gravity energy storage solution, which is similar to the mountain gravity energy storage concept (Hunt et al., 2020), but instead of operating on land, it operates underwater. The system was named DOGES (DOGES), which consist of transporting material, such as gravel or mine waste, from an underwater storage site on the edge of a continental platform to another storage site on the bottom of the ocean, and vice versa, storing seasonal energy in the process. The paper described the technology in detail, presents the costs and global potential for the technology. Section 2 presents the methodologies involved in DOGES. Section 3 presents the results of the paper. Section 4 discusses the proposed technology and Section 5 concludes the paper.

2 Methodology

Figure 1 presents the methodology applied in the paper. Step 1 describes the DOGES technology. It presents the components required by the system, the upper and lower storage sites, the operation of the system and the theoretical equations applied to the technology. Step 2 describes the relevant consideration required to design a DOGES system. It describes the material weight selection, estimates the amount of energy that can be stored and the power capacity of different DOGES, configurations and presents a case study. Step 3 presents the global potential for DOGES detailing its costs, a comparison with coal transportation, and a possible application where it could be applied.

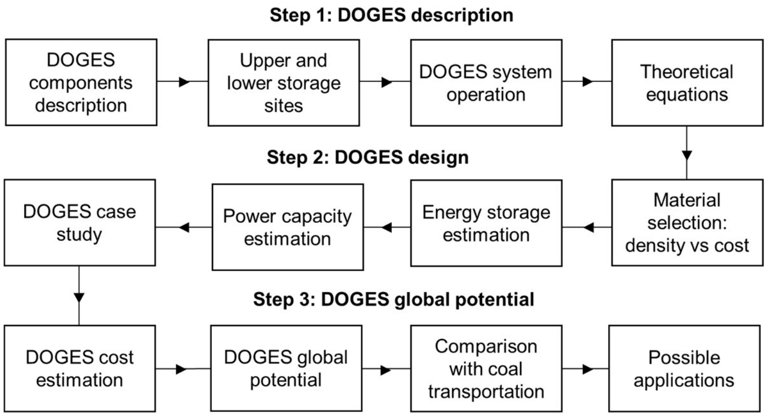

Figure 1. Underground gravity energy storage methodological framework.

Figure 2 present the DOGES proposed in this paper. DOGES consists of seven main components: (i) storage sites, (ii) gravity generation ships, (iii) cargo ships, (iv) weight material, (v) cables, (vi) container vessels, (vii) underwater bucketwheel excavator, and (viii) underwater transmission line. There are two storage sites, one on shallow depths and the other in the deep ocean. These storage sites are used to store the weight material. There are also two gravity generation ships, one above the shallow storage site and another above the deep storage site. They are used to transport the material to and from their respective storage sites to the cargo ships, storing energy or generating electricity. The cargo ships are used to transport the weight material from one gravity generation ship to the other. The weight material is the gravitational energy storage medium. This consists of gravel or waste from mining activity. The larger the granularity of the material, the better it is to reduce the suspension of the particles underwater with the current and underwater turbulence. The cables are an essential component of the system and are used to lower or raise the material from the gravity generation ship to the storage site. The container vessels are attached to the cables and used to transport the material up and down. The underwater bucketwheel excavator is used to transfer the material weight from the container vessels to the storage site and vice versa. The underwater transmission line connects the shallow and deep gravity generation ships to the grid in the continent or to offshore wind power plants.

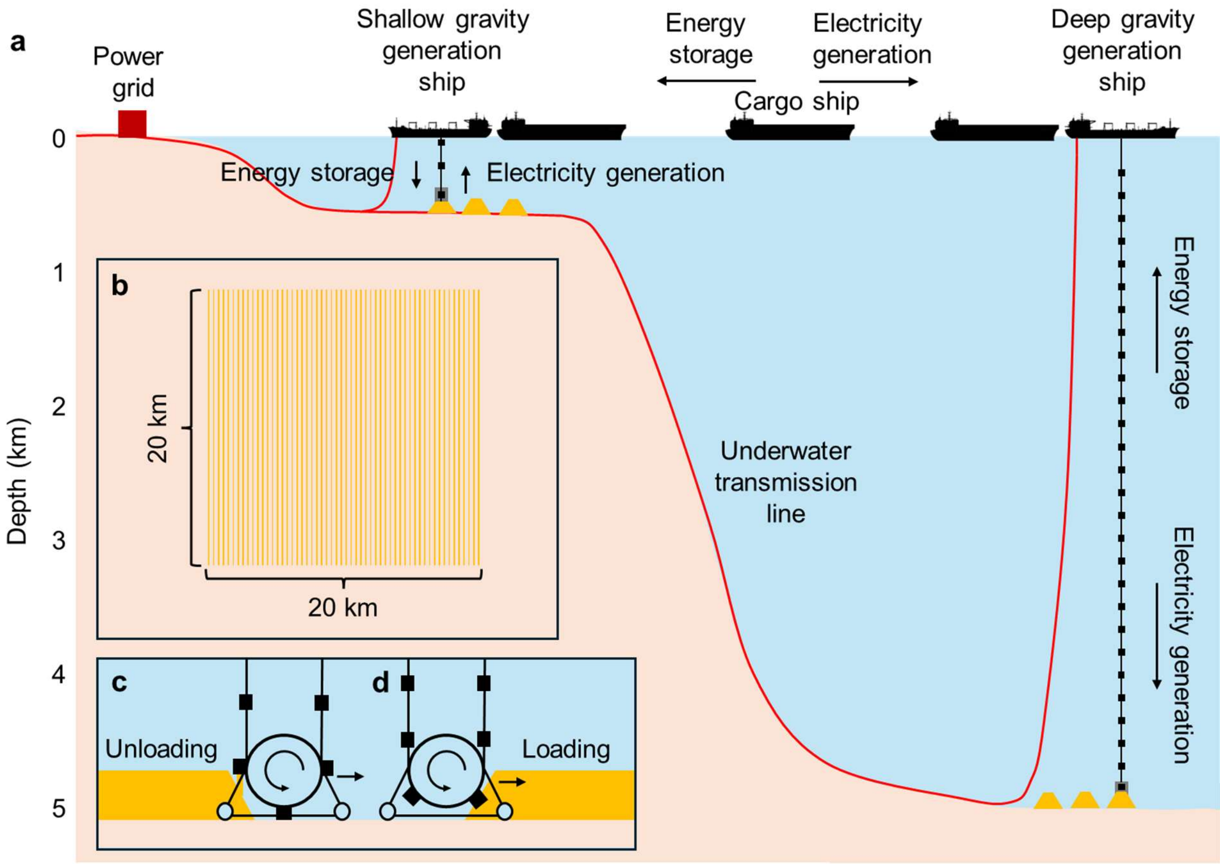

Figure 2. DOGES system description.

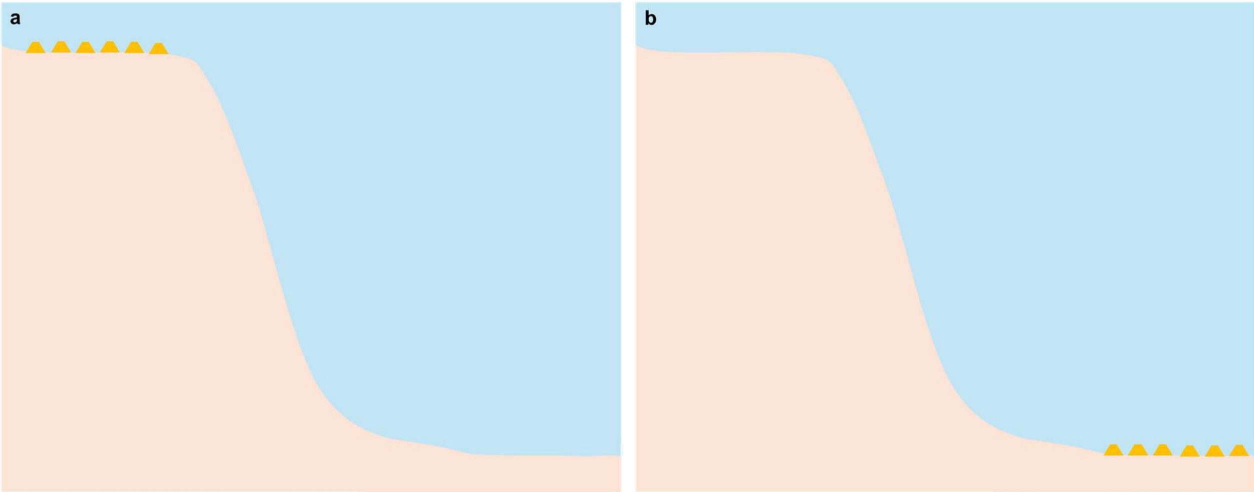

Figure 3. DOGES plant (a) fully charged and (b) uncharged.

The DOGES plant is completely charged when the upper storage site (shallow storage site) is storing all the weight material (Figure 3a). On the other hand, the plant is completely discharged when all the weight material is stored in the lower storage site (deep storage site) (Figure 3b). Figure 4 presents the operation of DOGES plant during storage and generation modes. During energy storage operations, the deep gravity generation ship uses electricity to elevate materials from the lower storage site. These materials, once elevated, are transferred to a cargo ship. It is crucial to remove water from these materials during loading to prevent any water from accumulating in the cargo ship. If water does seep into the ship, it is promptly pumped out to reduce both the ship's weight and the energy required for material transport between sites. The cargo ship, powered by batteries, transports the materials to the shallow gravity generation ship. These batteries are recharged when the cargo ship docks with either the shallow or deep gravity generation ships. At the shallow gravity generation ship, the materials are lowered back to the upper storage site. This process not only stores the materials but also generates electricity. Subsequently, the shallow ship draws electricity to lift the materials back from this upper site for reloading onto the cargo ship. The cycle continues with the cargo ship transferring the materials back to the deep gravity generation ship, which then lowers the materials to the lower storage site, generating electricity in the process. As power costs are high, both the shallow and deep gravity generation ships should operate at maximum capacity throughout the year. This consists of storing energy for six months and generating electricity for six months. The shallow and deep gravity generation ship will generate and consume electricity or vice versa, at the same time during generation and storage operation.

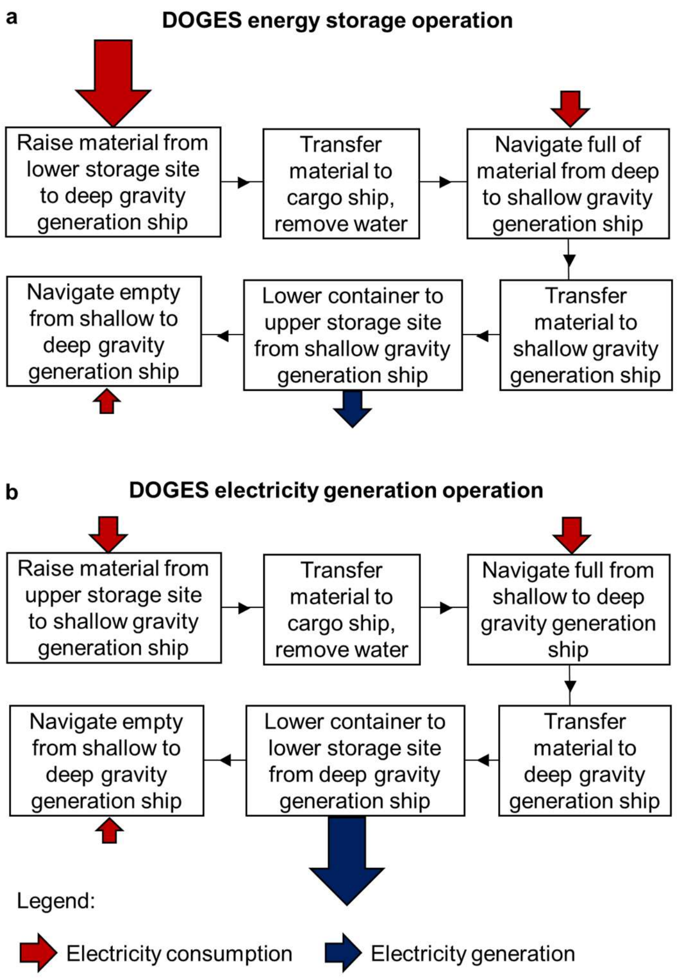

Figure 4. Flowchart description of the DOGES plant operation.

Equation 1 applies to estimate the energy storage for the DOGES plant. Where E is the electric energy storage potential of the DOGES plant (GWh), H is the depth of the lower storage site (m), which varies from 2000 to 6000 in this paper, h is the depth of the upper storage site (m), assumed to be 100 m, e is the efficiency of storing and generating electricity (separately) with the gravity generation ship, assumed to be 90% (Toubeau *et al.*, 2020), v is the total volume of the weight material in the changed upper storage site (m3), g is gravity acceleration (m/s2), ρ_M is the density of the material (granite), assumed to be 2,700 kg/m3. ρ_{SW} is the seawater density, assumed to be 1,028 kg/m3, d is the distance between the shallow and deep gravity generation ship, assumed to be 10% of the total depth (m), which is a typical angle for continental shelf / deep sea transition. c_F is the electricity consumption by the full cargo ship to transport the weight material, assuming a cargo ship with 325 m length that navigates at 20 km/h and has an electricity consumption of 0.0054 Wh/km.kg (Bännstrand *et al.*, 2016). c_E is electricity consumption by the empty cargo ship to return to pick up more weight material, assumed to be 0.0027 Wh/km.kg.

$$E = \frac{\left(H \times e - \frac{h}{e}\right) \times v \times (\rho_M - \rho_{SW}) \times g}{3.6 \times 10^{12}} - \frac{v \times \rho_M \times d \times (c_F + c_E)}{10^9} \quad (1)$$

Equation 2 is used to estimate the power of the DOGES plant. Where T is the time taken to discharge all the energy storage into the system. The time to discharge is equivalent to six months. C is the estimated capacity factor of the plant, assumed to be 70%.

$$P = \frac{E}{T \times C} \quad (2)$$

Equation 3 presents an estimate of the drag forces exerted in the containers underwater (Toubeau *et al.*, 2020). Where, D is the drag coefficient (N), u is the speed of the falling container, assumed to be 0.87

m/s. c_D is the underwater drag coefficient, assumed to be 1 (Hoerner, 1965). A is the surface area facing the drag for (m2), equal to 36 m2. This results in a drag force of 18,504 N, which is equivalent to only 0.4% of the weight of the container underwater. Using this equation, the terminal speed of the container underwater, where no energy would be generated with the falling containers, is equal to 15 m/s, assuming that the density of the gravel and seawater in the container is 2,000 kg/m3. This shows that energy losses due to underwater drag can be neglected.

$$D = 0.5 \times \rho_{SW} \times u^2 \times c_D \times A \quad (3)$$

Table 1. DOGES design parameters applied in the paper.

Characteristics	Value
Container dimensions (m x m x m)	12 x 6 x 6
Container volume (m^3)	438
Total material weight (Mt)	350
Number of containers lowered per year	400,000
Upper storage site (m)	100
Lower storage site (m)	2000 to 6000
Distance from storage sites (m)	10% slope
Density of seawater (kg/m^3)	1028
Density of the material (granite) (kg/m^3)	2,700
Density of the gravel and seawater (kg/m^3)	2,000
Surface area facing the drag forces (m^2)	36
Vertical container designed velocity (m/s)	0.87
Vertical container terminal velocity (m/s)	15
Horizontal cargo ship velocity (km/h)	18
Capacity factor of the DOGES plant (%)	70

A model has been developed to evaluate the global potential of DOGES, assuming the designs parameters presented in

Table 1. This model incorporates an analysis of global bathymetry at a 30 arc-second resolution, which corresponds to approximately 900 meters at the equator and becomes more refined with latitude changes. The bathymetric data was sourced from GEBCO (GEBCO, 2021). This data resolution is lowered to 40 km resolution, assuming the average bathymetry of the data points. The height difference and the distance between the pixels to the north, south, west and east are calculated, and the cost for DOGES is estimated, as described in the following section.

3 Results

An important design parameter to analyze a DOGES plant is the density and cost of the material used to store gravitational energy. A benefit of using materials with high density is that less overall energy is spent transporting the material with the cargo ships from the shallow to the deep generation ships. For instance, if the density of the material is close to the density of seawater, the material will contribute a small additional weight for generating electricity in the DOGES plant because its weight is canceled by the buoyancy. However, the weight above ground will be significant when transporting from the shallow to the deep gravity generator ship. Table 2 presents a comparison of different affordable material densities. We selected granite as the weight material because it is a well-known material and abundant on Earth's surface. However, the material should be as cheap as possible. It could be unwanted rock sediments or waste material from mining activities. Note that sand is not considered for DOGES. This is because sand is a very fine material that would be dragged by underwater currents, losing the material, losing generation potential, and impacting the environment surrounding the upper and lower storage sites. The particles applied in DOGES should have large diameters to avoid the material being dragged by underwater currents. If limestone is applied, it would also contribute to reducing the acidity of the seawater surrounding the storage sites and possibly increase the absorption of CO2 by the ocean.

Table 2. Comparison of different material's density.

Material	Main component	Density (kg/m^3)	Density - buoyancy (kg/m^3)	Comparison (%)
Limestone	$CaCO_3$	2.5	1.5	59
Granite	SiO_2	2.7	1.7	62
Basalt	SiO_2	2.9	1.9	65
Hematite	Fe_2O_3	5.3	4.3	81

Table 3 presents the energy storage and installed power capacity with different DOGES arrangements. As 350 Mt of granite are moved from the upper to the lower storage. Applying Equation 1 with a lower storage site depth of 2000 m and 6000 m results in an energy storage capacity of 941 and 2954 GWh, respectively. The material is lowered in six months, with a 70% capacity factor and a power capacity of 309 and 969 MW, respectively. This means that at maximum capacity, a container with material reaches the lower storage site every 28 seconds. Assuming 12 meters between each container, results in a maximum lowering and rising underwater vertical speed of 0.87 m/s and a drag force of 13,966 N. The drag is only 0.4% when compared with the gravitational force minus the buoyancy of a container (4,176,470 N), which results in negligible losses with drag.

Table 3. Energy storage and installed power capacity with different DOGES arrangements.

Weight material (Mt)	Lower storage site depth (m)	Distance (km)	Energy storage capacity (GWh)	Power capacity (MW)
350	2000	20	941	309
	4000	40	1947	639
	6000	60	2954	969

3.1 DOGES cost estimation

Table 4 presents the costs for the DOGES plant with a 4 km deep lower storage site. The table includes the costs of the weight material, containers, cargo ships, cables, and installed capacity, which includes the bucket excavators and motors/generators. Assuming 40 km between the upper and lower storage sites, the cargo ship travels at a speed of 20 km/h (i.e., 2 hours per trip), and the ship takes 2 hours to load and unload. Four ships are required to operate the DOGES plant. This is because, to operate the plant continuously, while one ship is unloading, one ship is loading, one is navigating from the upper to the lower storage site and one is navigating from the lower to the upper storage site. Four ships can make 12 trips per day with material from the lower to the upper storage site and supply 639 MW of power (Table 3). Figure 5 presents the varying costs for energy storage and power with depth in DOGES plants. The energy storage costs vary from 5.18 to 0.52 USD/kWh and power costs from 1579 to 15789 USD/kW a depth of 1000 and 10,000, respectively.

Table 4. Costs description for 4 km deep DOGES plant.

Component	Description	Costs
Weight material	We assume that the weight material is mining sediment waste with similar properties to granite and a cost of 1 USD/ton (PHU LONG GLOBAL INVESTMENT CO., 2024).	350 milion USD
Containers	342 containers with dimensions 12 x 6 x 6 m are required in the deep and shallow gravity generation ships and a cost of USD 5,000 per container.	1.7 million USD
Cargo ships	Four cargo ships with 300,000 tons capacity at a cost of 150 million USD each.	600 million USD
Cables	Each cable costs 8 USD/m, and provides a force of 285 KN. The plant requires 917 cables with 4000 km. and 100 km	30 million USD
Installed capacity	Assuming an installed capacity cost of 1500 USD/kW and capacity of 639 MW. The costs cover the costs for the gravity generation ship and bucket excavators and the electricity generation equipment.	958.5 million USD
Equipment costs	-	1940 million USD
Construction costs	Construction costs are assumed to be 30% of the equipment costs.	582 million USD
Total investment costs	-	2522 million USD
Energy storage investment cost	The energy storage capacity is 1947 GWh. Thus, the investment cost is 1.3 USD/kWh	1.30 USD/kWh
Installed capacity cost	The installed capacity is 639 MW. Thus, the investment cost is 3947 USD/kW	3947 USD/kW

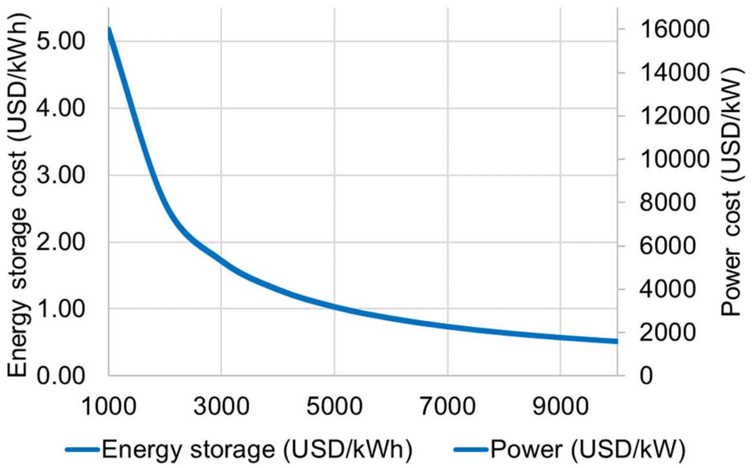

Figure 5. Change in cost with depth from 1000 to 10,000 m.

3.2 DOGES global potential

Figure 6 presents the estimated global potential for DOGES plants. In Europe, there is potential in the coastal area of Portugal, Spain, France, Ireland, UK, Italy, Greece, Cyprus and Turkey. In the Americas, there is significant potential in Chile, Peru, Ecuador, Brazil, Central America, Mexico, USA, particularly in Florida, Alaska, and Hawaii. Asia has a significant potential in Indonesia, Philippines, Taiwan, Papua New Guinee, China, Japan, Russia, Pacific Islands, Iran, Oman, Yemen, and Georgia. Australia and New Zealand have significant potential around its southern coasts. Africa has some potential surrounding most coastal countries.

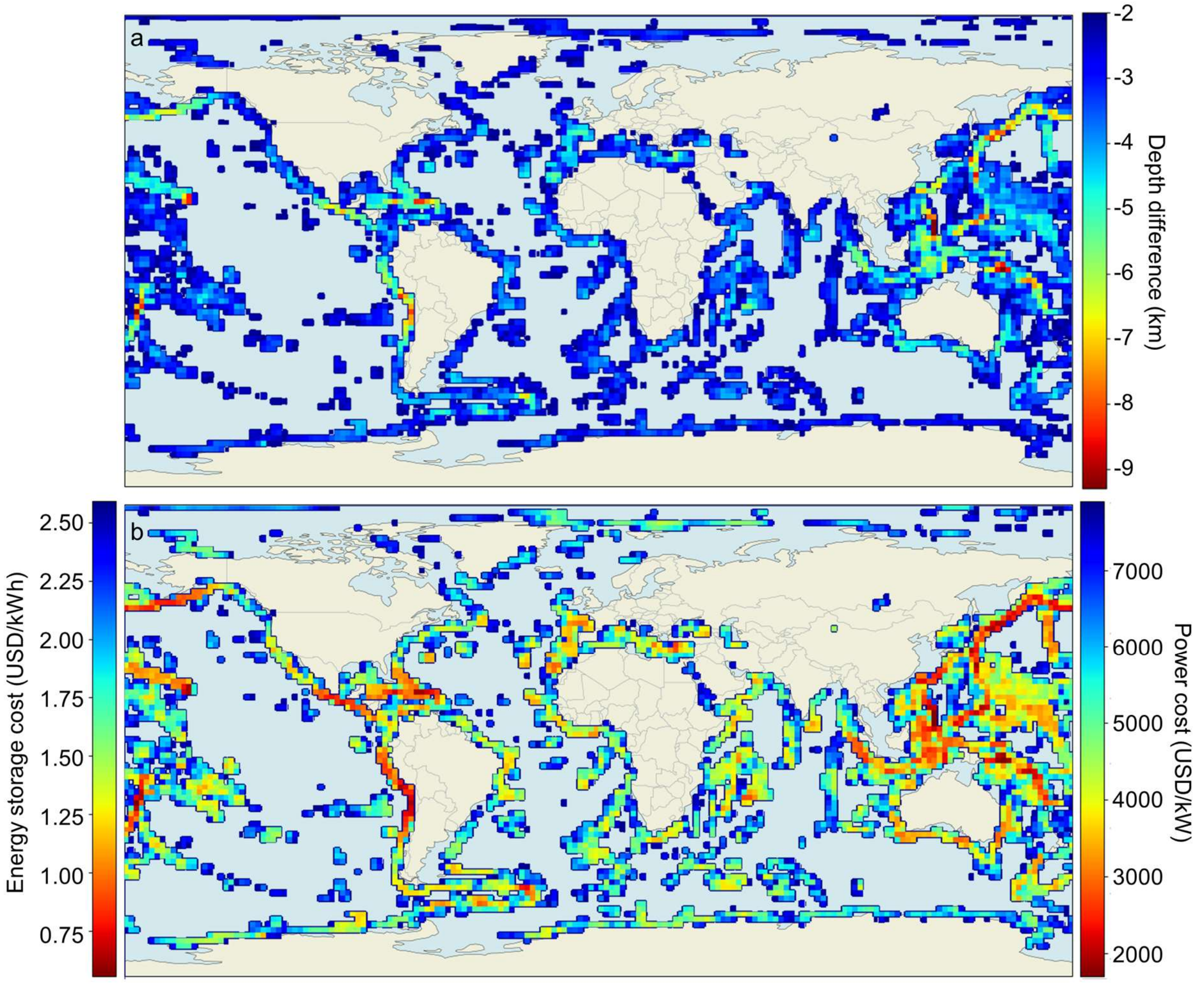

Figure 6. Global potential for DOGES plants, (a) difference in depth and (b) power and energy storage costs.

4 Discussion

Comparing the energy required to transport the same weight of material in a 40 km DOGES plant and coal for 10.000 km, for example, from Colombia to Germany. The coal ship would consume around 250 times more fuel than the DOGES ship. However, the coal plant would generate 1 TWh of electricity and the DOGES system 3.0 GWh. This means that the DOGES plant would generate 75% of the energy per distance traveled when compared to the coal operation, this is shown in Table 5. This shows that DOGES can be a realistic option. It should be noted, however, that DOGES is an energy storage solution while coal generates electricity.

Table 5. Comparison between transporting weight material with DOGES vs coal for thermal electricity.

	DOGES (4 km depth)	Coal
Distance (km)	40 (upper to lower site)	10,000 (Colombia to Germany)
Weight transported (tons)	500,000	500,000
Electricity generation (GWh)	3.0	1,000 (EIA, 2024)
Generation per distance traveled (GWh/km)	0.075	0.1

Table 6 presents possible scenarios where DOGES can be applied to provide seasonal energy storage. Table 7 presents a comparison of different seasonal energy storage technologies.

Table 6. Possible scenarios where DOGES can be applied.

Scenario	Description	Recommendation
Islands	Islands with high renewable energy generation, with demand for seasonal storage, and without the potential for building large reservoirs for storing seawater or desalinated water seasonally.	Explore partnerships with local governments to facilitate DOGES implementation, ensuring alignment with local renewable energy strategies.
Offshore wind power	Stores energy seasonally from offshore wind power plants. DOGES is convenient in this case because there are already offshore electricity connections from the coast to the offshore wind power plant.	Integrate DOGES with existing infrastructure to optimize costs and efficiency. Promote as a sustainable supplement to wind energy production.
Deep sea mining	Provides seasonal energy storage for deep sea mining activities close to the DOGES plant. This is also convenient because there are offshore electricity connections for the deep sea mining activity.	Develop integrated solutions that combine energy storage with mining operations to reduce operational costs and enhance energy reliability.
Grid connected to coastal areas	Provides seasonal storage for a large energy grid with high shares of renewable energy generation and low potential for seasonal pumped storage. For example, no appropriate topography or lack of water.	Advocate for DOGES as part of regional energy plans to policymakers, highlighting its benefits over traditional pumped storage options.

Table 7. Comparison of seasonal energy storage technologies Font: Amin et al. (2022); Armstrong et al. (2016); Dubbers (2021); Hunt et al. (2020); Nasser et al. (2022); Rehman et al. (2015).

Technology	Mechanism	Cost (USD/kWh)	Efficiency	Environmental impact	Infrastructure needs
Seasonal Pumped Hydropower	Utilizes elevation differences to store water in reservoirs.	0.05-0.20	70-85%	Moderate to High	Requires suitable topography; substantial water management.
Hydrogen Storage	Stores energy by converting electricity into hydrogen through electrolysis and re-converts into electricity.	2.00-6.00	30-50%	Low to Moderate	Requires electrolyzers, storage tanks, fuel cells
DOGES	Uses gravitational force to move materials underwater.	1.3 (as proposed in the paper)	60-70%	Low	Requires ships, cranes, underwater infrastructure.

DOGES can be an alternative to increase the flexibility of cargo ship utilization. For example, currently, there is a conflict in the Red Sea, which impedes ships from traveling through the Suez Canal in Egypt. This required cargo ships traveling from China to Europe to travel below Africa, which significantly increased the travel times and the utilization of cargo ships. If cargo ships could be used for seasonal energy storage during periods of low maritime activity, this would increase the operational flexibility of cargo ships. Another option for DOGES would be to generate electricity instead of only storing energy. This could be done by extracting material from the continental shelf and depositing it in the deep ocean. This would not be sustainable, as the soil would be transported from the continental shelf to the deep sea only once. This might have unforeseen impacts in the future, such as coastal erosion, earthquakes, and other impacts.

5 Conclusions

In conclusion, DOGES represents a groundbreaking solution to the critical need for cost-effective, scalable seasonal energy storage, which is essential for advancing towards a sustainable energy future. By utilizing gravitational potential energy storage in an underwater setting, DOGES introduces an innovative method for large-scale, long-duration energy storage. Results demonstrate that a DOGES plant with a 4 km depth could provide energy storage at 1.3 USD/kWh with a power cost of 3947 USD/kW. The analytical depth of this study is reflected in our thorough evaluation of various operational scenarios, a detailed cost analysis, and the exploration of environmental impacts. The novelty of the DOGES concept lies in its use of deep ocean environments, which have not been traditionally considered for energy storage, thus opening new avenues for research and application. The largest potential for the technology can be seen in the Pacific Ocean, Southeast Asia, East Asia, West Asia, Australia, Central America, South America, Europe, North America, South Asia, and Africa. However, the potential for DOGES is uneven and depends significantly on the ocean's bathymetry. While challenges remain, particularly concerning environmental impacts, technological optimization, and economic viability, these do not overshadow the substantial contributions this technology could make. Further research and development are needed to address these concerns and optimize the system for commercial use. Future works should focus on: (i) developing more precise models to predict the environmental impacts of DOGES, particularly on marine ecosystems, (ii) improving the efficiency and durability of underwater components to enhance overall system reliability and reduce maintenance costs, (iii) exploring policy and regulatory frameworks that could facilitate the integration of DOGES into national energy strategies, especially in regions with significant potential for deployment. DOGES offers a scalable and sustainable solution to meet the increasing demands for seasonal storage, thereby supporting a decarbonized energy future. The strategic integration of this technology could significantly enhance the reliability and efficiency of renewable energy systems worldwide.

Acknowledgements

We acknowledge the following institutions, since this study was financed in part by the Alexander von Humboldt Foundation, by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior Brasil* (CAPES) - Finance Code 001, and by National Council for Scientific and Technological Development – CNPq.

References

Amin, M et al. (2022) 'Hydrogen production through renewable and non-renewable energy processes and their impact on climate change', *International Journal of Hydrogen Energy*, 47(77), pp. 33112–33134. https://doi.org/10.1016/j.ijhydene.2022.07.172.

Armstrong, RC et al. (2016) 'The frontiers of energy', *Nature Energy*, 1(1), p. 15020. https://doi.org/10.1038/nenergy.2015.20.

Balamurugan, P, Ashok, S and Jose, TL (2009) 'Optimal operation of biomass/wind/PV hybrid energy system for rural areas', *International Journal of Green Energy*, 6(1), pp. 104–116. https://doi.org/10.1080/15435070802701892.

Bännstrand, M et al. (2016) *Study on the optimization of energy consumption as part of implementation of a ship energy efficiency management plan (SEEMP)*.

Berrada, A and Loudiyi, K (2019) *Gravity energy storage*. Elsevier.

Boretti, A, Nayfeh, J and Al-Kouz, W (2021) 'Computation of storage power and energy to stabilize a wind-and-solar-only Australian National Electricity Market grid', *Energy Storage*, 3(1). https://doi.org/10.1002/est2.131.

Brey, JJ (2021) 'Use of hydrogen as a seasonal energy storage system to manage renewable power deployment in Spain by 2030', *International Journal of Hydrogen Energy*, 46(33), pp. 17447–17457. https://doi.org/10.1016/j.ijhydene.2020.04.089.

Cazzaniga, R et al. (2017) 'DOGES: Deep ocean gravitational energy storage', *Journal of Energy Storage*, 14, pp. 264–270. https://doi.org/10.1016/j.est.2017.06.008.

Dubbers, D (2021) 'Comparison of underwater with conventional pumped hydro-energy storage systems', *Journal of Energy Storage*, 35, p. 102283. https://doi.org/10.1016/j.est.2021.102283.

EIA (2024) *How much coal, natural gas, or petroleum is used to generate a kilowatthour of electricity?* EIA. https://www.eia.gov/tools/faqs/faq.php?id=667&t=2

Fakhar, A et al. (2023) 'Smart grid mechanism for green energy management: A comprehensive review', *International Journal of Green Energy*, 20(3), pp. 284–308. https://doi.org/10.1080/15435075.2022.2038610.

Farinotti, D et al. (2019) 'Large hydropower and water-storage potential in future glacier-free basins', *Nature*, 575(7782), pp. 341–344.

GEBCO (2021) *GEBCO 2020 Gridded Bathymetry Data Download*. https://download.gebco.net/

Hoerner, S (1965) *Fluid-Dynamic Drag*. Bricktown, New Jersey.

Hunt, JD et al. (2020) 'Global resource potential of seasonal pumped-storage for energy and water storage', *Nature Communications*, v. 11, n. 947.

Hunt, JD et al. (2020) 'Mountain Gravity Energy Storage: A new solution for closing the gap between existing short-and long-term storage technologies', *Energy*, 190, p. 116419. https://doi.org/10.1016/j.energy.2019.116419.

Hunt, JD et al. (2021) 'Buoyancy Energy Storage Technology: An energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression', *Journal of Energy Storage*, 40, p. 102746. https://doi.org/10.1016/j.est.2021.102746.

Hunt, JD et al. (2022) 'Hydrogen Deep Ocean Link: a global sustainable interconnected energy grid', *Energy*, 249, p. 123660. https://doi.org/10.1016/j.energy.2022.123660.

Hunt, JD, Zakeri, B et al. (2023) 'Compressed air seesaw energy storage: A solution for long-term electricity storage', *Journal of Energy Storage*, 60, p. 106638. https://doi.org/10.1016/j.est.2023.106638.

Hunt, JD, Zakeri, B, Nascimento, A et al. (2023) 'Isothermal Deep Ocean Compressed Air Energy Storage: An affordable solution for seasonal energy storage', *Energies*. https://doi.org/10.3390/en16073118.

Hunt, JD, Lagore, B et al. (2023) 'Mapping the potential for pumped storage using existing lower reservoirs', *Journal of Energy Storage*, 73(C), p. 109047. https://doi.org/10.1016/j.est.2023.109047.

Hunt, JD, Montanari, PM et al. (2023) 'Solid air hydrogen liquefaction, the missing link of the hydrogen economy', *International Journal of Hydrogen Energy* [Preprint]. https://doi.org/10.1016/j.ijhydene.2023.03.405.

Hunt, JD, Zakeri, B, Jurasz, J et al. (2023) 'Underground Gravity Energy Storage: A solution for long-term energy storage', *Energies*. https://doi.org/10.3390/en16020825.

Ishaq, H and Dincer, I (2021) 'Comparative assessment of renewable energy-based hydrogen production methods', *Renewable and Sustainable Energy Reviews*, 135, p. 110192. Available at: https://doi.org/10.1016/j.rser.2020.110192 (accessed 24 July 2025).

Ji, M and Wang, J (2021) 'Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators', *International Journal of Hydrogen Energy*, 46(78), pp. 38612–38635. https://doi.org/10.1016/j.ijhydene.2021.09.142.

Karayel, GK, Javani, N and Dincer, I (2023) 'Green hydrogen production potential in Turkey with wind power', *International Journal of Green Energy*, 20(2), pp. 129–138. https://doi.org/10.1080/15435075.2021.2023882.

Li, FF et al. (2024) 'Potential of different forms of gravity energy storage', *Sustainable Energy Technologies and Assessments*, 64, p. 103728. https://doi.org/10.1016/j.seta.2024.103728.

Li, G et al. (2022) 'Capacity configuration optimization of a hybrid renewable energy system with hydrogen storage', *International Journal of Green Energy*, 19(14), pp. 1583–1599. https://doi.org/10.1080/15435075.2021.2018323.

Nasser, M et al. (2022) 'A review of water electrolysis–based systems for hydrogen production using hybrid/solar/wind energy systems', *Environmental Science and Pollution Research*, 29(58), pp. 86994–87018. https://doi.org/10.1007/s11356-022-23323-y.

PHU LONG GLOBAL INVESTMENT CO., L (2024) *Wholesale Granite crushed stone aggregate rock crusher stone for building crushed stone construction*, Alibaba.com. https://www.alibaba.com/product-detail/Wholesale-Granite-crushed-stone-aggregate-rock_1600787825198.html?spm=a2700.galleryofferlist.normal_offer.d_title.1b61b05470LDw8.

Razi, F and Dincer, I (2022) 'Renewable energy development and hydrogen economy in MENA region: A review', *Renewable and Sustainable Energy Reviews*, 168, p. 112763. https://doi.org/10.1016/j.rser.2022.112763.

Rehman, S, Al-Hadhrami, LM and Alam, MM (2015) 'Pumped hydro energy storage system: A technological review', *Renewable and Sustainable Energy Reviews*, 44, pp. 586–598. https://doi.org/10.1016/j.rser.2014.12.040.

Rimpel, A et al. (2020) 'Mechanical energy storage', in *Thermal, Mechanical, and Hybrid Chemical Energy Storage Systems*. London: Elsevier.

Roushenas, R, Gholamyankarkon, E and Arabkoohsar, A (2023) '14 - Gravity energy storage', in Arabkoohsar, ABT-FGS (ed.) *Sustainable Energy Storage Systems*. Academic Press, pp. 543–571. https://doi.org/10.1016/B978-0-323-90786-6.00005-4.

Tong, W, Lu, Z, Chen, W et al. (2022) 'Solid gravity energy storage: A review', *Journal of Energy Storage*, 53, p. 105226. https://doi.org/10.1016/j.est.2022.105226.

Tong, W, Lu, Z, Sun, J et al. (2022) 'Solid gravity energy storage technology: Classification and comparison', *Energy Reports*, 8, pp. 926–934. https://doi.org/10.1016/j.egyr.2022.10.286.

Toubeau, J-F et al. (2020) 'Sizing of underwater gravity storage with solid weights participating in electricity markets', *International Transactions on Electrical Energy Systems*, 30(10), p. e12549. https://doi.org/10.1002/2050-7038.12549.

Wang, H et al. (2023) 'Gravity-induced virtual clocking effect in large-capacity/low-head pumped hydro energy storage system with horizontal shaft', *Sustainable Energy Technologies and Assessments*, 60, p. 103441. https://doi.org/10.1016/j.seta.2023.103441.