Hydraulic Rock Energy Storage for Utility Scale Wind farm

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Abstract

It is a known fact that renewables suffer from intermittency. This causes fluctuating energy generation which forces grid operators to encounter the problem of unbalanced power and frequency disturbances. Energy storage is always necessary if a high percentage of renewable energy sources are used. Therefore, the current study is quite significant as it introduces a new large-scale storage technique that happens to be sustainable in many ways and also encouraging as it forms an impressive combination of utility-scale renewable energy generation and energy storage. The ability to store power on a large scale will be an essential feature of any sustainable and reliable energy system. This can be accomplished by storing the energy in a local storage system with sufficient capacity. The Hydraulic Rock energy storage system is the solution to this ambitious level of self-sufficiency as it relies primarily on local resources and has an efficiency of over 80%.

Keywords: *Bonavista peninsula, Gravity energy storage, Godisthal, Rock cylinder, Wind energy*

Nomenclature

GES	Gravity energy storage
DSM	Demand-Supply management
PHES	Pumped Hydro energy storage
HRES	Hydraulic Rock energy storage
EQPS	Elmhurst Quarry Pumped Storage Project
ORES	Ocean renewable energy storage
PAS	Pump accumulation station
RES	Renewable energy sources
LCOE	Levelized Cost of Energy
LCOS	Levelized Cost of Storage
ROI	Return on investment
SOC	State of charge
RMR	Rock Mass Rating
PPA	Power Purchase Agreement
OECD	Organisation for Economic Co-operation and Development
Capex	Capital Expenditure
GFCF	Gross Fixed Capital Costs
EIA	Environment Impact Assessment
ρ_Z	density of rock, kg/m^3
g	acceleration due to gravity, 9.81 m/s^2
E_Z	cylinder's potential energy, J
V_Z	volume of the rock cylinder, m^3
h_Z	elevated height of the rock cylinder, m
r_Z	radius of the rock cylinder, m
l_Z	height of the rock cylinder, m

E_W	potential energy losses, J
ρ_W	density of water, 1000 kg/m^3
$\vec{r_S}$	center of gravity, m/s^2
V_H	displaced volume, m^3
E_{ZES}	potential energy stored by the system, J
P_D	pressure at the seal level, Pa
P_Z	the pressure of the rock cylinder, Pa
P_W	the pressure of the water, Pa
P_T	total pressure, Pa
A_Z	surface area of the exposed cylinder, km^2
e_{ZES}	energy storage capacity, kWh/m^2
$e_{Godisthal}$	energy storage capacity of Godisthal PHES, kWh/m^2
w_{ZES}	energy density, kWh/m^3
$w_{Godisthal}$	energy density of Godisthal PHES, kWh/m^3
Q	flow rate, m^3/s
η_T	efficiency of the transformer
$\eta_{M,G}$	efficiency of the motor or generator
$\eta_{P,T}$	efficiency of the pump or turbine
η_R	efficiency of the piping
η_C	combined efficiency

1. Introduction

The development of the renewable energy sector throughout the years has led to a clear enhancement in the research and development of control strategies and management [1],[2]. Electricity generated from renewable sources is predicted to increase exponentially in the next coming decades and hence variability in energy production and subsequent grid integration pose one of many impending challenges [2]. In this scenario, energy storage technologies play a vital role in having both technical and economic advantages while meeting the ends of energy generation and DSM thereby, enhancing the reliability of the utility grid [2],[3]. There are several benefits of using energy storage such as reducing energy costs, improving indoor air quality when using benign energy for heating or cooling, reducing energy consumption, increasing the operating flexibility, conserving and substituting fossil fuels by reducing their use, as well as decreasing greenhouse gas emissions and last but not least, reducing operating and maintenance costs.

However, akin to many power systems, the energy storage system does pose certain challenges i.e. difficult to understand and cannot be investigated, demand for power in all of its forms is usually not steady, nor is the supply thus load management becomes crucial in the whole electric chain. Storage processes are not 100% fully efficient; therefore, some energy is lost while being stored [4]. The decision of adoption of energy storage systems, is basically made based on savings, except when policy regulations are imposed. Hence, economic viability and financial feasibility are one of the most important aspects that should be considered for commercializing energy storage systems. There are two main types of energy storage systems. The first category deals with distributed energy storage, whereas the second one is about bulk or utility-scale energy storage.

GES technology is considered as one of the most interesting storage concepts because it relies on the same concept of PHES [4]. However, the attractiveness of this system comes from the fact that it overcomes the constraints of site availability [5]. This technology is labeled as bulk storage as it can store large amounts of energy. GES has gained attention because it proved to be an environmentally friendly technology unlike batteries [5],[6].

Under the broader concept of GES, Heindl Energy Inc. has come up with an original suggestion named HRES. Fig. 1 illustrates the operating principle of this energy storage system. The concept involves pressurizing the water using a big piston, unlike the idea of pumping water up or down depending on the geographic conditions. The implementation of this system is based on drilling a large circular area to create a rock piston, which is isolated from the surrounding rocks [31]. The surface water and the underground area must be connected using a tunnel. This system proposes an average energy storage capacity of 1600 GWh with the mass of rock as a piston having a radius of around 500m [7],[31]. A unique characteristic of this electricity storage system is that it uses a massive rock to store potential energy at a density many times higher than the energy density of water. This results in higher storage capacities [5].

In this concept, water is used only as a hydraulic liquid. To charge the system, water under pressure is forced by pumps to displace the exposed rock cylinder. The hydraulic force raises the rock cylinder, storing electricity in the form of potential energy. The level of pressure required is determined by the mass of the exposed rock cylinder and typically ranges from 21 to 103 bar [6]. To discharge the facility or reconvert the energy to electricity, the rock cylinder is allowed to sink, and the water under pressure fed through a turbine connected to a generator. The electric energy produced is then fed into the electricity network using a transformer.

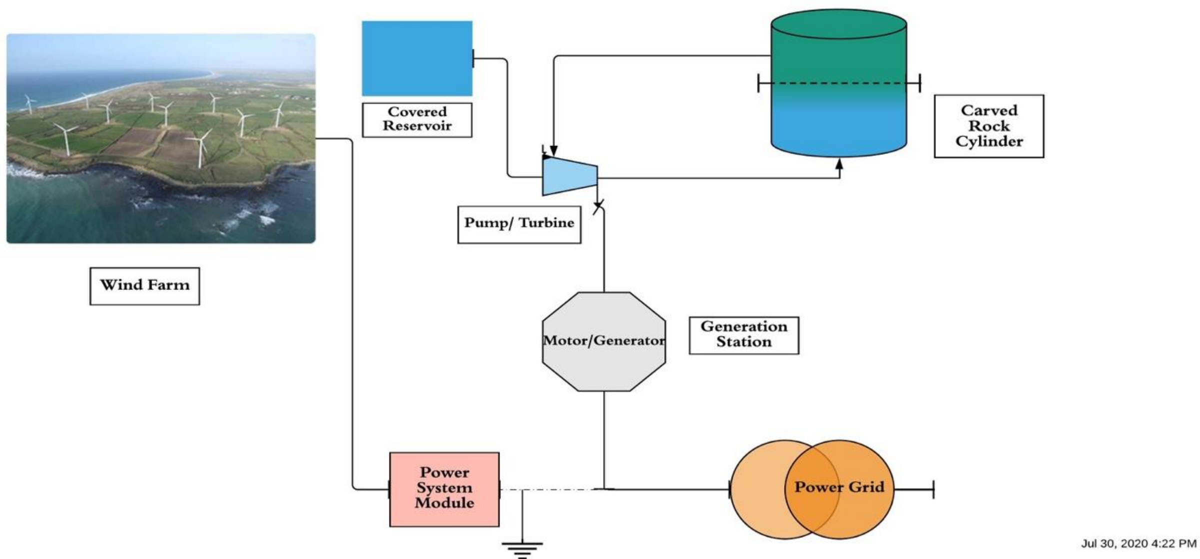

Fig 1. A block diagram of Hydraulic Rock energy storage system

Further, no chemicals or other hazardous substances are used in this technique, with water and rock being the key components required. The most likely business case of this storage technology is with photovoltaic or wind energy production as it can ensure reliable electricity supply at a levitated cost over a period of time [6],[7]. However, this technology is still in conceptual mode and various influential dimensions of this technique are in the process of validation [7]. Nevertheless, a number of aspects related to this storage technology are analyzed which includes the system feasibility, design, profitability, value, application, development, inherent risk, and policy measures.

2. Problem statement

More than 4300 mayors of European cities representing more than 170 million people have signed the declaration ‘Covenant of Mayors’. The Covenant contains a sustainable energy action plan which exceeds the EU’s 20% carbon dioxide (CO_2) reduction target for 2030. To reach this plan, a series of measures have been proposed which include a change in electricity generation and a move to renewable sources like solar and wind power and augmentation of renewable energy storage capacity [26].

Renewable energy is now making a rapidly increasing contribution to global power supplies, with a growth rate of approximately 20% per year [10]. In order to ensure a continuous supply of electrical power based on such renewable energy sources, a highly efficient storage system is required to store the excess energy generated until it is required when the energy source is not available [11]. As these resources suffer from intermittency, considerable storage capacity is quintessential to thwart the spiraling threat of climate change. In the case of wind energy, this typically corresponds to storing energy at peak wind time to meet off-time energy demand [12],[13].

Energy storage systems provide several benefits to enhance the electric grid such as ancillary services, load following, price arbitrage, regulation, load leveling, and many others [14]. However, the current storage systems still face many challenges. The most prominent one is the technology optimal design, construction, and sizing [15]. Many energy experts have also predicted the extent of percolation of storage principles would actually fulfill the global obligations of meeting clean and sustainable energy on a large scale. In this scenario, the inclusion of state-of-the-art bulk energy storage technologies may widen the current research domain in the field energy storage sector [16].

3. Literature Review

As PHES occupies lion's share in bulk energy storage field, researchers and industrials are currently developing technologies that are similar to PHES mainly to overcome the demerits of geographical requirement and population displacement [16]. In this endeavor, a very interesting technology is underground PHES. The working principle of this technology is similar to that of PHES except that the elevation difference is achieved by digging underground [17]. The lower reservoir can be either constructed or it can make use of already existing cavern or mine. However, the technical and economic constraints such as legal permissions, construction risks, and long gestation of return on investment have made this technology less feasible in the current energy market scenario Nevertheless, many similar projects are being developed and are in various mode of conceivable stages. One such related technology is a conceptual underground PHES project in Illinois, the USA under the name of EQPS, which makes use of an abandoned mine and quarry [18] thus making the requirement of the huge geographical area an oblivious necessity. Similarly, Riverbank Wiscasset Energy Inc. is also working on a 1000 MW underground PHES with a depth of 2200 ft underground located in Wiscasset, Maine [19]. Delft University has reported its study on a new innovation, which is compressed air combined with PHES technology [20]. Here pressurized water container is used as a substitute for the upper reservoir. Thus, energy is being stored in compressed air instead of water at high elevation. The air gets pressurized when water is being pumped to the pressure container. Thus, compared to PHES, this technology does not depend on specific geographic locations [20]. Another technology called undersea PHES has been proposed by Subhydro AS Inc, which is a Norwegian company. The usefulness of this concept is seen in the case of offshore wind farms. It basically uses the pressure of water at the ocean bottom [21] and the obtained results of this study have shown that the system can generate economic profits at relatively low depths of around 200 m. This technology has many potential advantages although more research and investigation are needed when it comes to the construction of the sphere. Apart from challenges, undersea storage technology is considered as a great innovation [20],[21].

In 1999, the first seawater PHES was developed in Japan under the name of 'Yanbaru' [22]. The proposition came from Morishige at Mitsubishi Heavy Industries with the idea of large structures mounted at the sea bottom. Other researchers suggested PHES systems, mounted at the seafloor and coupled with offshore wind farms [21],[23]. Unfortunately, these projects could not be implemented due to technical difficulties. On the other hand, the Massachusetts Institute of Technology investigated another system named ORES, but the technical deliberations of this technology are still under the implementing stage [22]. Schmidt-Bocking and Luther [23], also worked on a similar ocean bottom storage system. They suggested a storage technology with a capacity of 58 GWh, a sphere of 280m in diameter, and a depth of

2 km underwater. Along with that, the researchers have suggested many solutions to enhance PHES technology such as improvements related to elevation difference, water pressure, and discharge rate of water [23][24]. In the Netherlands, two brothers [25] used a huge confined water area as PHES. This system is also called PAS, in which the fluid is being pumped to a certain elevation when there is excess generation and then released through turbines when energy is needed. This system has been implemented by Kibrit in the Netherlands. Another system called 'Energy Island' has been developed by Boer and is still under research [26]. This storage system operates by storing energy while lowering the water, unlike the previously mentioned systems which elevate it. A similar system named "The Eleventh Province" is being developed in Belgium. A study by Hanley inspected the possibility of constructing a similar system suggested by Gravity Power Inc. [22].

To solve the issue of elevation difference and other demerits associated with large scale energy storage techniques, Heindl's idea of Hydraulic Rock energy storage is more significant [7]. As this energy storage technology is the prime focus of this study various nuances associated with this technique are vividly deliberated in the following sections.

Hence, to shift away from fossil-based fuel resources, and the liability to enforce sustainable energy production, increased reliance on RES has become an indispensable part of an existing electricity value chain. The energy obtained from RES fluctuates on a temporary basis and reaches its maximum in certain hours during the day. Therefore, in order to meet the maximum energy demand, a flexible energy generation in combination with favorable energy storage would not only bridge the gulf between demand-supply mismatch but also encourages the greater participation of sustainable energy storage technologies.

4. Methodology

6.1 Scope of the study

6.1.1 Overview of utility scale wind energy

In the previous study, the utility-scale onshore wind farm at the Bonavista peninsula, Newfoundland is designed [1]. The study mainly concentrated on a series of demerits of 824 MW Muskrat hydroelectric project, thus an equal capacity of alternative renewable energy is proposed with the detailed environment and economic benefits. Now this study deals with the storage aspect of wind energy.

Proceeding further, this study tries to explore the best possible and satisfactory storage technique for utility-scale wind farms suitable for the province of Newfoundland and Labrador. The storage site selection includes the Predictive-specific model, which uses geospatial analysis in bringing out the multi-dimensional selection patterns to extract the optimum storage capacity in the chosen areas [7],[10]. These approaches adopt both inclusionary and exclusionary principles to develop energy storage infrastructure and are very much in tandem with international energy storage standards.

The predominant average hourly wind direction in Bonavista varies throughout the year. The wind is most often from the south from March to September, with a peak wind distribution percentage of 48% in the month of July and from the west with a peak percentage of 51% in the month of January [1],[11]. Table I. presents a brief mention of site parameters extracted in the Bonavista region.

TABLE I. BONAVISTA PENINSULA

Site Parameters	
Latitude and Longitude	48.62451°, -53.04989° (from the centre of the chosen area)
Wind speed	9.75 m/s @ 100m height
Power/Area	1051W/m2
Nearest Weather Station	Bonavista

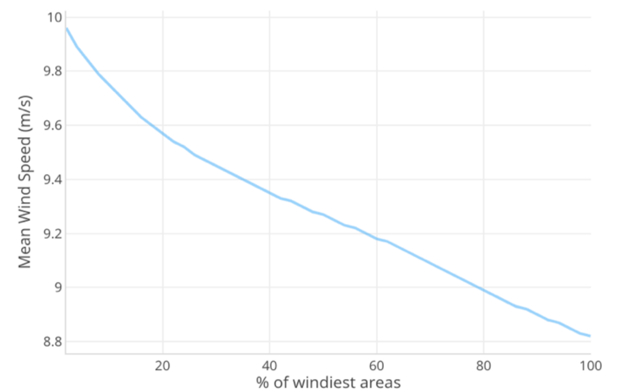

Fig 2. Aerial view of the selected region in the Bonavista peninsular region [1].

Fig 3. Varying mean wind speed at Bonavista region [1].

The location of storage site obtained from the wind atlas is shown in fig 2., and fig 3 depicts varied wind distribution across Bonavista peninsula region. A preliminary analysis of wind parameters such as energy density, LCOE, profit margin, the area taken, etc., and storage parameters such as energy storage capacity, LCOS, environmental benefits, incremental capital cost, etc., of HRES system, at the intended site location provides an encouraging picture about the scale of economics of this combined project. Further, the metrics show favorable results with over combined savings of 4.02 billion tons of CO_2 and approximately 120 million USD in profit and over 20% ROI [1],[18]. These benefits can greatly be increased with an increase in the radius of the rock piston along with better efficiency measures [7]. Thus, the proposed combined project will cost around 30% less than the sole conventional PHES project besides negating the effect of environmental and social pressure [5],[7].

6.1.2 Innovative bulk energy storage technique

A new option, HRES as unveiled by Eduard Heindl, professor of business informatics at Furtwangen University, Germany could be the potential replacement of PHES [3]. The basic idea is to lift a large rock mass and the store potential energy. In HRES the granite cylinders are said to be able to move up and down on an underground water column at one millimeter per second - up with electric pumps, down through the potential energy of their sheer mass [5]. Many approaches that try to move large masses by mechanical means, such as ropes or tracks failed due to the cost per stored kWh thus, lifting a large mass by hydraulic means becomes an interesting choice. The implementation of this system is based on drilling a large circle to create a rock piston, which is isolated from the surrounding rocks. The surface water and the underground area must be connected using methods known from mining and tunneling [4],[7].

In this arrangement, water is pumped into the bottom between the cylinder and the base, resulting in a lift of the heavy rock piston. The piston is sealed against the surrounding rock. The raised piston stores the electric pump energy in form of potential energy. To earn the energy back from the system, the pressurized water is fed into a turbine, connected with a generator to generate electricity. This is similar to the basic principle of a conventional hydro storage [6],[7].

The objective here, however, is not the removal of the raw materials (as in the case of mining) or the removal of the stone (as in the case of tunneling), but rather the preservation of the rocks [12]. In any event, tunnels or shafts must be installed in which vehicles and people can be transported to the bottom of the piston, so that they can setup the technical equipment [16].

The key advantage of this approach lies in the extraordinarily large amount of energy that could be stored and the relatively small investments compared to a similar hydro storage. The interesting point of this arrangement is the amount of energy grows by the fourth power of the radius while the production costs, mainly through the removal of the cylinder from its environment, grow only with the second power of the radius. This means, in comparison to all other known forms of storage, almost arbitrary low costs per kilowatt hour can be achieved if the radius of the system is large enough [8].

The estimation shows that across Europe ranges from 15 to 480 TWh capacity of energy is needed for next few decades. Storage forms such as hydrogen, compressed air or batteries are still immature, offer too little capacity or are too expensive. Currently, on a large scale only PHES plants work reliably and economically. The efficiency is around 80 percent, the investment costs are around 70 euros per kilowatt hour [13],[19].

However, as [7] observed, there are hardly any new locations for PHES plants in Central Europe, because the valleys have to be flooded and forests have to be cut down. To illustrate, a new 1400 MW power plant with a capacity of 13 GWh is currently under construction at Schluchsee in the Black Forest, for which a 76m high dam must be built. The project is controversial among the local population [20]. This is why experts believe HRES technique can replace the role of PHES systems as former intervene less with nature.

6.2 Design Considerations

Compared against other storage technologies HRES system exhibits a direct correlation between maximum energy storage capacity and optimum enormity of the size of rock piston. The cost associated in building HRES also favors the construction of large storage plants rather than smaller ones. Therefore, a rock cylinder with radius of approximately 150 m or more is recommended for corresponding extraction of storage capacity in GWh terms. Thus, when used in combination with utility scale wind energy generation this storage facility can ensure stable, sustainable and highly competitive production costs for many years [9], [11].

However, the cost of construction of a HRES plant is heavily dependent on the cost of separating the piston from the surrounding rock, it can be estimated that the increase in rock piston size only causes construction costs to increase by a factor of four [7]. In other words, HRES systems quickly becomes much more cost-effective as rock piston size increases. For example, if the radius doubles, the cost associated per kWh reduces by a factor of four i.e. to just 25%. Though HRES is not yet built to validate its theoretical capacity. However, the current study is focused on analyzing the potential benefit of augmenting this technology with wind energy while comparing storage parameters of PHES system. So as to effectively meet the design standards of large-scale energy technique.

Fig 4. represents the crude design details of HRES system. In this system, the mass of the rock that forms the cylinder and the mass of water that can be pumped under the cylinder determine the quantity of energy that can be stored. [4],[7].

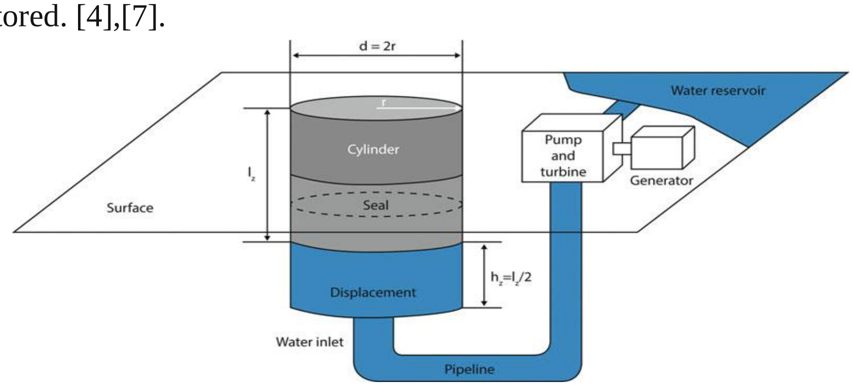

Fig 4. The design details of Hydraulic Rock energy storage system [7].

Assuming the stone density ρ_Z is $2600\ \mathrm{kg/m^3}$, i.e., equivalent to the conventional density of the earth's continental crust and gravity at the earth's surface is $g = 9.81\ \mathrm{m/s^2}$, then the potential energy, E_Z of a rock cylinder with a volume, V_Z and elevated height, h_Z is given by;

$$E_Z = g * \rho_Z * V_Z * h_Z \qquad (1.1)$$

The volume, V_Z is determined by the radius, r_Z and height, l_Z of the rock cylinder;

$$V_Z = \pi * r_Z^2 * l_Z \quad (1.2)$$

As the system floats on water, sustaining the center of gravity of the rock cylinder is crucial. Therefore, application of buoyancy principle helps to raise the sealing line of the cylinder through its middle level;

$$h_Z = {l_Z}/{2} \quad (1.3)$$

From (1.1), (1.2) and (1.3), the cylinder's potential energy E_Z is given by:

$$E_Z = g * \rho_Z * \pi * r_Z^2 * {l_Z}/{2} \quad (1.4)$$

Like all energy storage system, the stored energy E_Z is a dependable factor of potential energy losses E_W of the water with a density of ρ_W=1000 kg/m^3 , which is pumped from the surface water source to under the rock cylinder, and which has a center of gravity at a height, $\underset{r_S}{\rightarrow}$ and a volume, V_H,:

$$E_W = \underset{r_S}{\rightarrow} * g * \rho_W * V_H * h_Z \quad (1.5)$$

The volume, V_H of the displacement area is determined by the radius, r_Z and height, l_Z of the cylinder, and is given by;

$$V_H = \pi * r_Z^2 * {l_Z}/{2} \quad (1.6)$$

The water in the displacement area is between the depths of, l_Z and $l_Z/2$. Therefore, rock cylinder's center of gravity is determined by the following formula;

$$\underset{r_S}{\rightarrow} = -\frac{\left(l_Z + {l_Z}/{2}\right)}{l_Z} \quad (1.7)$$

From (1.4), (1.5), (1.6) and (1.7), the potential energy losses of the water, E_W is;

$$E_W = -\frac{\left(l_Z + {l_Z}/{2}\right)}{l_Z} * g * \rho_W * \pi * r_Z^2 * \left({l_Z}/{2}\right)^2 \quad (1.8)$$

From above equations, the potential energy stored by the storage energy system, E_{ZES} is;

$$E_{ZES} = \left[\left(g * \rho_Z * \pi * r_Z^2 * {l_Z}^2/{2}\right) - \frac{\left(l_Z + {l_Z}/{2}\right)}{l_Z} * \left(g * \rho_W * \pi * r_Z^2 * \left({l_Z}/{2}\right)^2\right)\right] \quad (1.9)$$

Therefore, the sum result is,

$$E_{ZES} = \left[\left(\rho_Z - \frac{3}{4} * \rho_W\right) * \frac{g*\pi*r_Z^2*\left({l_Z}^2/{2}\right)}{2}\right] \quad (2.0)$$

If the eq. (2.0) is used to calculate the energy capacity of the proposed storage system for the utility scale wind farm, in relation to design standards of the rock cylinder radius, $r_Z = 250$ m and a height, $l_Z = 500$m, it is to be noted that a spectacular theoretical storage capacity of $E_{ZES} = 125$GWh is obtained. Further, it is observed that if either the height or radius is doubled, then there is a four-fold increase in storage capacity, E_{ZES} and astonishingly, for every doubling of both radius and height would result in a 16-fold increase in the quantity of stored energy E_{ZES} which ultimately make the theoretical storage capacity to oscillate in the terawatt hours scale. To testify the above claim, it can be seen in fig 5., for the given area, the storage capacity of the storage system exponentially rises for increased radius size of the rock cylinder. Further as observed in fig 6., the prominent storage facility parameters i.e. pressure, specific volume, energy density is proportional to the size of the cylinder

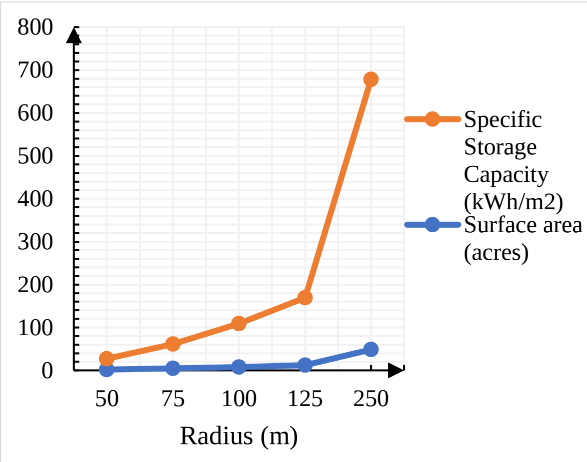

Fig 5. The theoretical specific storage capacity, Area required v/s Radius of the rock cylinder.

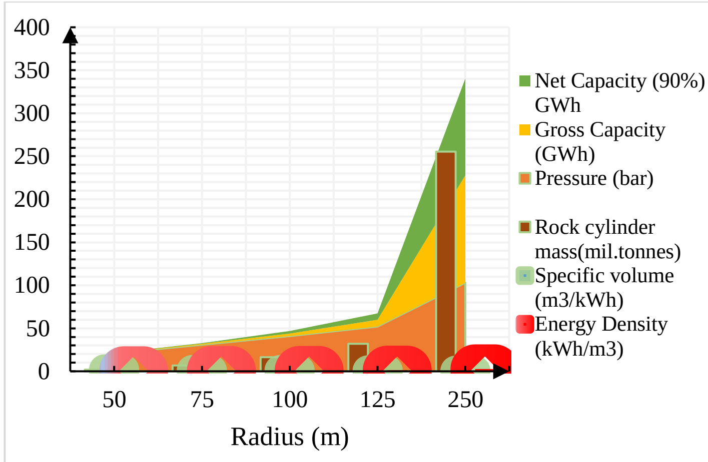

Fig 6. The plot of various facility parameters v/s Radius of the rock cylinder.

As [7] observed, even after taking into account the losses encountered in reconversion of electricity, comparatively speaking, the obtained storage capacity is enough to cover Germany's electricity requirements for a day. However, in its downside, the current technology is not yet implemented in its current scale except a demonstrable prototype facility is built at the University of Innsbruck with a rock cylinder of diameter 2.3 m, a height of 6 m, and a weight of 40 tons [5],[7].

The pressure level within a system vary concurrently with its size and SOC. A good indication of the maximum pressure level in the pump and turbine is the pressure P_D at the seal level. Fig. 7, left shows the storage facility when fully charged as the pump or the turbine located at ground level and at the same elevation.

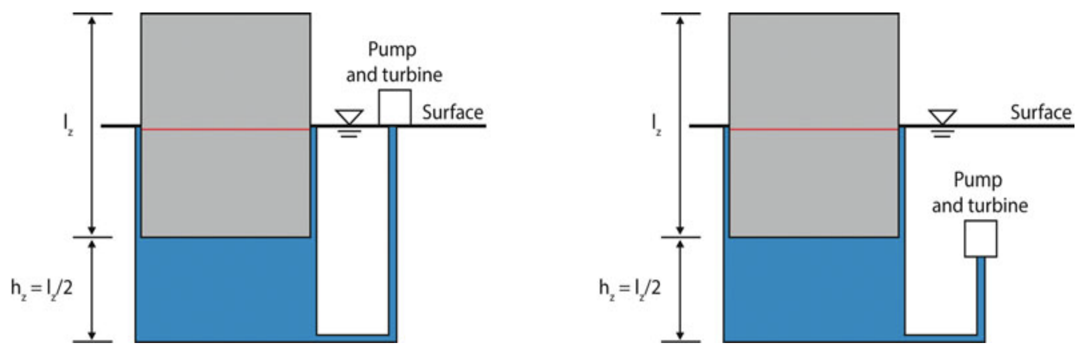

Fig 7. A study on the effect of pressure parameter with pump and turbine placed at the ground level and below the ground level [7].

The pressure of the rock cylinder on the water is given by;

$$P_Z = g * \rho_Z * l_Z \qquad (2.1)$$

The pressure of the water on the rock cylinder varies as the water column in the displacement area changes. It depends on the height h_Z to which the rock cylinder is raised, and is given by;

$$P_W = g * \rho_W * (l_Z - h_Z) \qquad (2.2)$$

The lower the position of the cylinder, the lower the pressure at the seal. This is because the water column working against the cylinder rises at the same time. The pressure resulting at the seal is

$$P_D = P_Z - P_W = g * \left(\rho_Z * l_Z - \rho_W * (l_Z - h_Z)\right) \qquad (2.3)$$

Therefore, the best approximations can be done if the pump and turbine are placed 50m below ground level (Fig. 7, right), then the corresponding total pressure P_T is given by;

$$P_T = g * (l_Z * \rho_Z + \rho_W * (50 - h_Z)) \qquad (2.4)$$

The theoretical space requirements of a mechanical storage energy facility can be roughly determined by calculating the surface A_Z of the exposed cylinder;

$$A_Z = \pi * r_Z^2 \qquad (2.5)$$

Therefore, from above equations, a mechanical energy storage facility with a radius of $r_Z = 250\text{m}$ generates a capacity of around 125GWh requires a surface area of $A_Z = 0.1963\ \text{Km}^2$. By comparison, the upper reservoir of the largest existing German pumped-storage plant in Godisthal has a capacity of 8.5GWh and a surface area of $0.55\ \text{km}^2$ [7].

Further a better reference value for comparison is extrapolated in relation to surface area. This value expresses the amount of energy stored per square meter of surface area. The storage capacity e_{ZES} depends on the radius and height of the system, and is given by;

$$e_{ZES} = \frac{E_{ZES}}{A_Z} = g * \frac{l_Z^2}{2} * \left(\rho_G - \frac{3}{4} * \rho_W\right) \qquad (2.6)$$

From eq. (2.6), the capacity for a mechanical stored energy system with a theoretical radius of rZ = 250m and a height of $l_Z = 500\text{m}$ would be $e_{ZES} = 630\text{kWh/m}^2$. By comparison, the real pumped-storage plant in Goldisthal has a specific storage capacity of $e_{Godisthal} = 15.5\text{kWh/m}^2$ [7]. This means that the theoretical specific storage capacity for a mechanical energy storage system is 1.6 times higher than the pumped-storage plant in Godisthal, Germany.

The storage facility requires a large water source nearby to supply water during charging, and to take in water during discharging. If not, an adequately sized reservoir must be built to handle the water exchange. This would dramatically increase the amount of space required. There is also little space available and few suitable locations for large storage lakes in densely populated countries [5],[7].

The PHES systems often require large quantities of water. The volume of water required is determined by the volume of the displacement area V_H which varies based on the radius and the height of the cylinder and is calculated using eq. (1.6).

According to eq. (1.6) a theoretical mechanical energy storage system with a radius of $r_Z = 250\text{m}$ and a height of $l_Z = 500\text{m}$ requires 0.05 km^3 of water when fully charged. Since this value is difficult to compare, the energy per cubic meter of water stored can be considered instead.

The energy density of a mechanical energy storage system is determined by the volume of the displacement area filled with water and the total amount of energy stored;

$$w_{ZES} = \frac{E_{ZES}}{V_H} = g * l_Z * \left(\rho_G - \frac{3}{4} * \rho_W\right) \qquad (2.7)$$

On applying the theoretical dimensions results in the energy density of $w_{ZES} = 2.52\text{kWh/m}^3$ (Fig 6). The pumped storage plant in Godisthal, Germany has an energy density of $w_{Godisthal} = 0.71\text{kWh/m}^3$ [7]. This is equivalent to about two-sevenths of the energy density of HRES system. This difference is due to the fact that water is used only as a hydraulic liquid and not as a storage medium [3],[7]. The inflow and outflow quantities of water are determined by the power of the pump and turbine. Thus, for a radius of $r_Z = 250$ m, a height of $l_Z = 500$ m, and a turbine power of 736MW would require Q = $81.2\text{m}^3/\text{s}$ of water over an operating period of a week. The pumped storage plant in Godisthal, Germany with an installed turbine power of 1,060MW requires eight full load hours which amounts to a water-discharge of $416.67\text{m}^3\text{s}^{-1}$ [7]. The efficiency of HRES system is determined by the efficiency of the transformer η_T, the motor or generator $\eta_{M,G}$,the pump or turbine $\eta_{P,T}$, and the piping η_R; Hence, the combined efficiency η_C is given by;

$$\eta_C = \eta_T * \eta_{M,G} * \eta_{P,T} * \eta_R \quad (2.8)$$

With the help of eq. (2.8), it can be inferred that the efficiency parameter of HRES system is comparable with the efficiency of pumped-storage plant which stands approx.80%. This is because the machine components used in both the energy storage systems are more or less identical [7].

6.3 Geological considerations

To construct HRES plants the geological attributes of the prospective region must first be assessed in detail by a team of geologists. In this regard, Heindl Inc. has carried out a study analyzing different types of magmatic, metamorphic, and sedimentary rock [7]. A total of 117 globally distributed sites were analyzed and a classification performed based on the internationally recognized RMR system. The outcome of the study finalized the suitability of the geological conditions for the construction of a HRES was found to be “very good” RMR I at 3% of the evaluated sites, and “good” RMR II at 43% [7],[10]. The remaining sites would require extensive, expensive rock stabilization measures. Interestingly, the proposed storage site falls in the RMR II category, satisfactorily meeting all rating standards. However, on-site inspection by geologists to know more about the localized seismicity issues and age of rock, etc. are much needed to avert constructional accident.

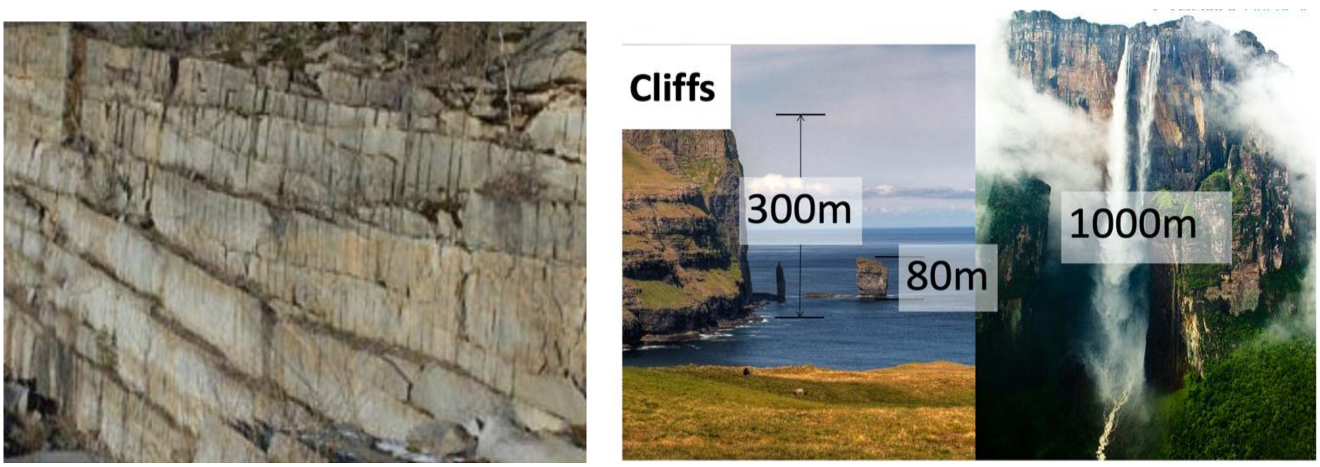

Fig. 8 A representation of stratified granite rock (Left) [7], comparison of suitable cliff area of varying heights (Right) [10]

In addition to the assessment of geological factors, a large volume of water depending on the size of the storage – in this case around 5.0 million cubic meters for a piston with a radius of $250m$ must be made available. This water is constantly re-used, and thus frequent redistribution of water as in PHES system is averted.

According to [7], the best sites are the areas consists of solid sedimentary bedrock which are geomorphologically stable. These rocks are little-faulted and formed in compact layers of solid rock material as shown in fig 8 (left). The intended location in the Bonavista peninsula of Newfoundland is formed by stable rock morphology where a firm cylinder can be exposed to build this mechanical energy storage system [10]. As the region located at the coast of steep cliffs made up of compact layers of granite, sandstone or limestone (both are metamorphic rock of sedimentary type) rock with even layers and limited fissures. hence preferred region for safe construction and operation [28]. Granite rock is the most stable form of rock, and forms cliffs up to 1000 to $1200m$ high as shown in fig 8 (right).

The facility construction would rely primarily on mining processes and the main construction steps involved are explained in brief in following segments.

6.3.1 Construction of tunneling system

The construction and operation of a mechanical storage energy system would be facilitated by an access of tunnel spiraling around the installation for providing access to heavy vehicles.

Fig 9. With the use of reef miner cutting machines the piston can be separated from the surrounding rock [7].

6.3.2 Sealing and installation of rolling membrane seal around the piston

The solution to the key challenge of sealing the gap between the piston and the cylinder and retaining the highly pressurized water below is a "*rolling membrane*" which is securely connected to both piston and cylinder. The membrane elements, similar to conveyor belts as used in the mining industry consists of vulcanized rubber reinforced with steel cables or aramid fibers [31].

The seal is a critical component of mechanical stored energy construction. The seal gap must be as narrow as possible so that the force on the seal is not excessive. But the seal gap cannot be constructed with precise accuracy across a distance of several 100m [7]. In addition, the seal and surfaces must be accessible to workers and machines so that they can be properly maintained. Otherwise, even the smallest malfunction could result in a total loss of the facility [32]. Therefore, civil engineers recommend a rolling diaphragm technique where a seal inserted in a relatively narrow gap 20 cm wide as this diaphragm membrane material is similar to conveyer belt and can withstand forces resulting from pressures of 50 bar or more. Conveyer belts are additionally reinforced with steel cords running along their length. An advantage of this seal concept is that it automatically keeps the piston centered in the middle of the cylinder [30].

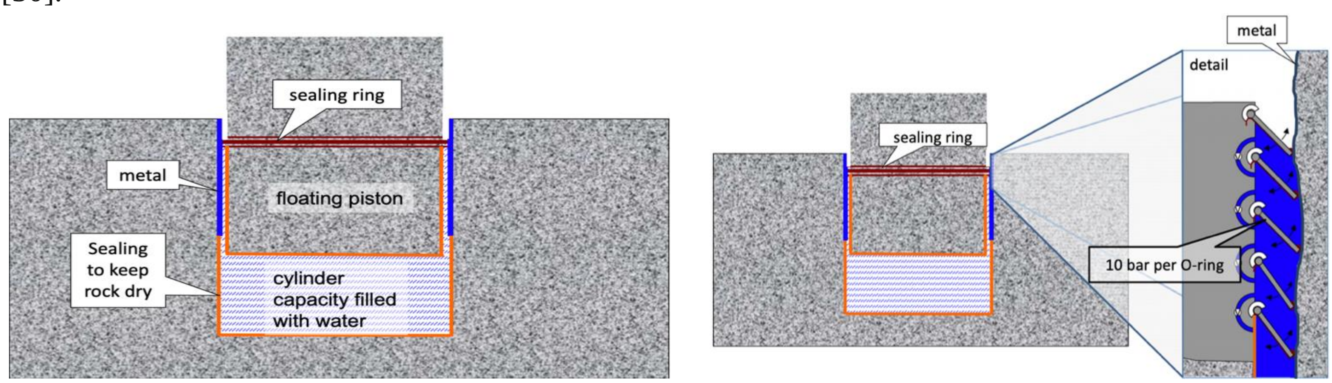

Fig 10. Rolling diaphragm seal placed in the narrow gap created when the cylinder rises efficiency [24].

6.3.3 Construction of Cylinder Wall

The separation of the piston base from the underlying rock is a particular challenge. It is based on the well-established "bord and pillar" method of mining/extraction [28]. Two access shafts are excavated, right down to the base level of the planned cylinder. Then the excavation of the ring-shaped space between the cylinder and the piston can be executed in parallel with the separation of the piston base from the rock beneath [32]. Separation of the piston's side from the surrounding rock, downwards from the surface, can be done using precise blasting to loosen the rock and through classical drilling, rock is excavated and transported to the surface *cribbed chute technique* [30].

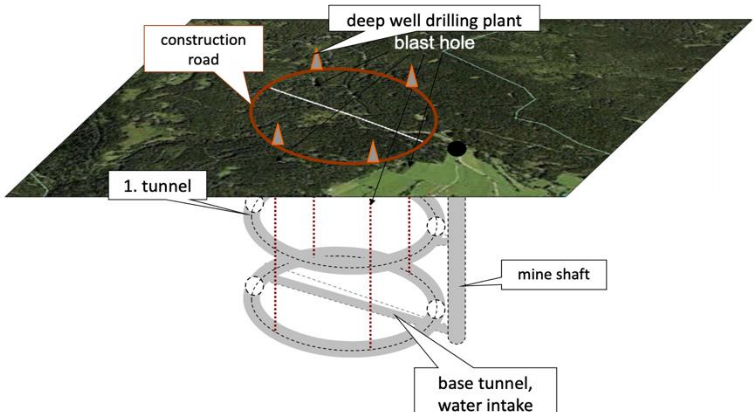

Fig 11. Pictorial representation of process involved in carving rock cylinder [16]

6.3.4 Installation of machinery and electrical plant

The turbines, pumps, generator and transformer can be located at the surface or underground in a specially constructed cavern [7]. In principle, these items of plant are used in very much the same way as they are used in pumped hydro storage plants.

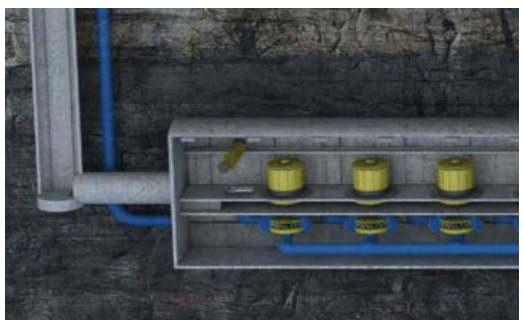

Fig 12. Mechanical and Electrical equipment [7].

6.3.5 Construction of water reservoir and hydraulic lifting

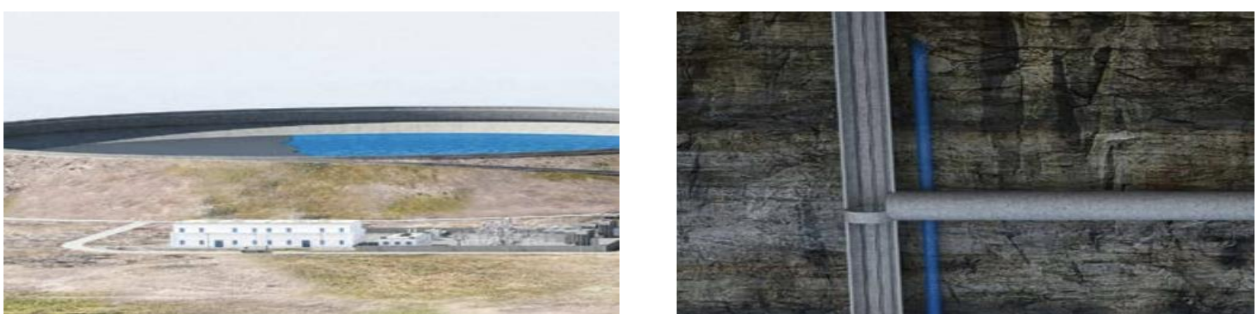

Fig 13. Artificially built water reservoir (Left), Water used for Hydraulic lifting (Right) [7]

Water is used as a hydraulic medium to lift the piston and, when routed through the turbines, to generate electricity, as shown in fig (13 right). For the proposed design capacity of 125GWh requires approx. 5.0 million cubic meters of water. This is phenomenally less compared to pumped hydro storage plant of equal energy storage capacity [7]. In order to store the water, a reservoir must be constructed nearby – unless a natural basin or lake is situated in fig (13 left). Thus, construction of whole system expected to last approximately five years [32]. The operating life of the system is practically unlimited, since its main component, the rock mass – is extremely durable. The operating equipment, such as pumps, turbines and generator, can be designed for a service life of 60 years or more, and can then be replaced as required [27].

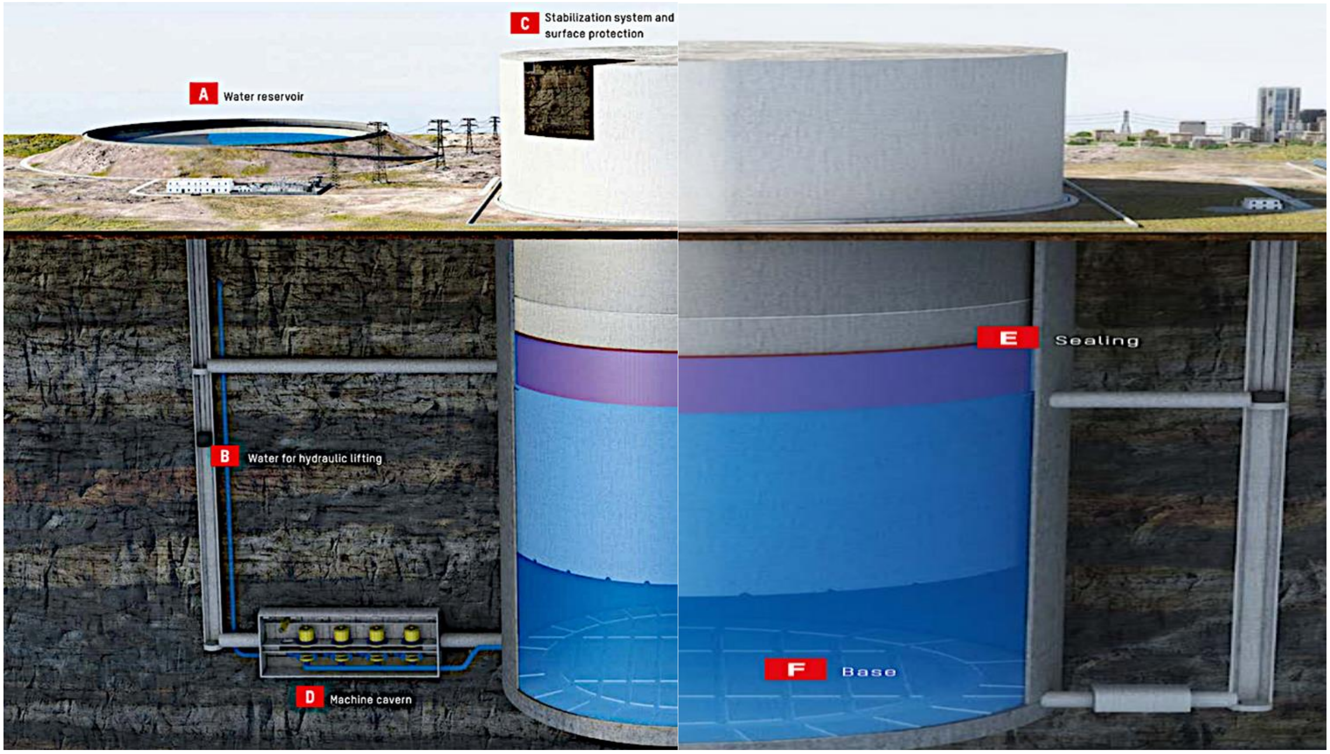

Fig 14. A Complete set up of Hydraulic Rock Energy Storage System [7].

5. Economic perspective of Hydraulic Rock energy storage

The economic feasibility of HRES system primarily depends on the intended application of plant operator. Based on the market floating mechanism many energy experts have provided a set of peculiar energy economic models which augurs well for renewable storage projects. As this technology delivers all day electricity at a constant price for 20 years or more, amongst all, PPA is the best suited model for the combination of large-scale storage project with Solar PV or wind energy [30]. However, there exists a price arbitrage in which selling, and purchase of energy depends on lower or higher wholesale prices. Apart from that the operator can also accrue fees for provision of system services and other ancillary services [33].

The construction cost of the plant depends primarily on the size of the piston and the geological conditions at the specific location [7]. Because of this reason, the business model does not overlap with neither pumped hydro storage (which needs elevation-Hydraulic Rock does not) nor with compressed air storage (because they need cavern and fissured rock). As can be seen in fig 15, the total investments costs decrease logarithmically with increased storage capacity and thus, marginal cost benefit is achieved. Further, the specific construction costs at various stages is shown in fig 16, amongst all, sealing and tunnel costs are major investments which involve many technological challenges.

Nevertheless, for $250m$ radius and 10% gradient, assuming the cost of building a tunnel is 2,100 USD/m, then the theoretical approximation of total costs would be 3.2 million USD [35]. However, this can be reduced drastically when constructed in tandem with power generation utility infrastructure in this case wind farm [17]. The conservative expectation on return ROI is more or less similar to PHS system i.e for at least 60 years, and maintenance costs should be very low akin to PHS system.

It is also observed that the profit margin gained by having utility scale wind farm at Bonavista region, Newfoundland instead of Muskrat hydroelectric project stands 28.45 million USD with 12 cents/kWh grid price [1]. Thus, the Wind-Hydraulic Rock combination outperforms PHS and conventional Hydro project in many ways economically. However, variability in cost structure may vary on practical considerations.

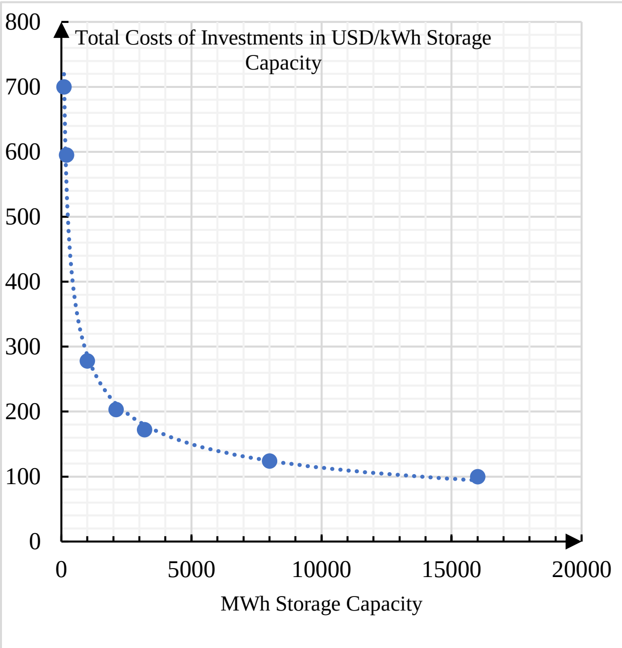

Fig 15. Investments costs

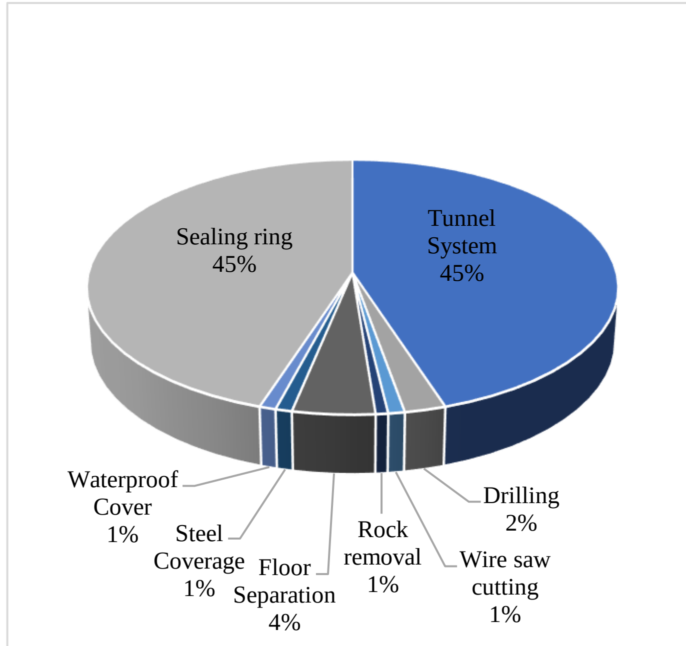

Fig 16. Construction specific

7.1 Market potential of Hydraulic Rock energy storage

In analysing the market potential of HRES, a satisfactory requirement such as large size renewable installations and demand for such large-scale market potential is expected to grow in fast emerging markets i.e. India, China and other Southeast Asian nations. The rate of energy consumption because of population pressure, increased penetration of renewable energy and geological constraints etc., are all certainty influences for adaption of this novel storage technology. Also, many European nations need a new bulk storage solution, especially for offshore and on shore wind energy generation around the North Sea [22]. Further, many OECD countries are in the process of constructing large-scale wind-plants of GW-size, all of which forecasts an encouraging demand of energy storage in mid-term future [20]. The basic market model for HRES in the case of wind energy- excess power from wind farm is stored (purchased) and discharged (sold) in the light of varied wind distribution, satisfies the business case of large-scale production of energy from renewable sources [17],[18]. These models are ready for market listing as soon as a low-cost bulk storage solution is available.

The demand for storage is guaranteed by the requirement for utility companies and wind farm operators and this guarantee pact is established between these two stakeholders is fundamentally to meet the DSM. Grid operators also need bulk storage to balance out fast-changing loads in the system. Hence, the business model for HRES combined with wind power generation is proved to be analogous [18]. Apart from this, the return on investments from service and grid charges and other ancillary service agreements such as frequency regulation, voltage support, black start capability and spinning reserve capacity etc., as these services require storage solutions from few seconds up to several hours it can further increase the marginal profit for operators.

7.2 Comparison of Levelized Costs of Storage

Hydraulic Rock power will be the most economic utility energy storage. The large storage capacity and the high efficiency over 80% will makes it an unrivaled cost wise technology to shape renewables into a

24/7 source of power [7],[22]. The LCOS are calculated at only 9 cents/kWh for 10 GWh plant and nearly 18 cents/kWh for a 1 GWh size [23].

When comes to comparing the LCOS of HRES with other storage technologies it is all about the scalability factor [25]. As raw materials are cheap, the main cost drivers for HRES are equipment and construction. These costs are subject to scale effects and increase at a much lower rate than a respective increase in storage capacity. For example, doubling the radius of the rock cylinder increases the energy stored manifold, while construction costs only increase two-fold. In comparison, doubling the energy or power capacity of a lithium-ion storage system would increase costs by around 50% [20]. For the duration for 8 hrs and for 330 cycles p.a. adjusted to inflationary cost distribution, the LCOS analysis of HRES against various energy storage technologies is made in fig 17, it is observed that in almost all aspects, HRES yields better result especially w.r.t PHES systems.

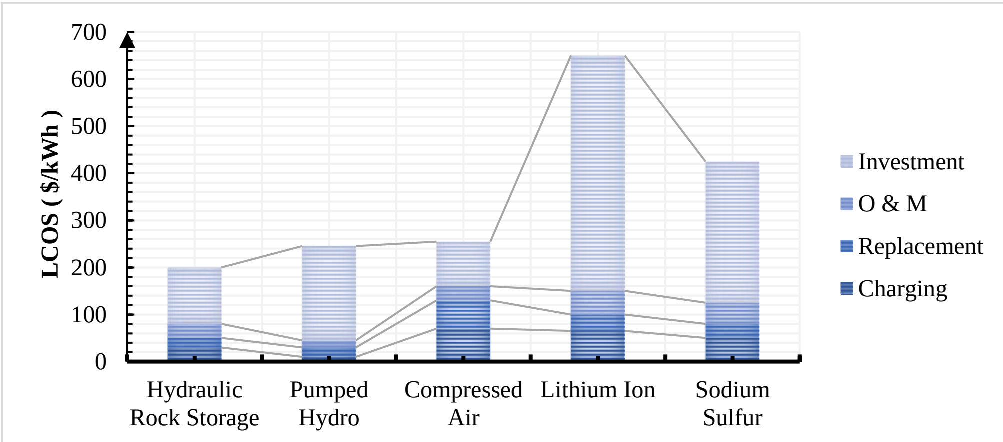

Fig 17. LCOS comparison in US $/KWh

Further, the comparative study on LCOS by Imperial college has concluded that LCOS of HRES is lower than any other commercial bulk storage [5]. The study observed that based on a cost estimation, the total investment costs would vary from 160 USD/kWh of storage capacity for a 10 GWh size and 380 USD/kWh for a 1 GWh size and the operational costs will be below 1% per year of capital expenditure (capex) [6], [7]. However, for all theoretical purposes the calculation costs for a size of 250m rock piston radius stands at 200 USD/kWh capacity.

This explains why HRES is so competitive when it comes to their lifetime cost, Furthermore, gravity-based storage concepts can make good use of existing infrastructure, such as old mine shafts, and mature equipment, such as water turbines, that has a long lifetime compared with electrochemical batteries which further reduces the GFCF exponentially.

6. Results and Discussion

Gravity Storage in general and Hydraulic Rock energy storage, in particular, has much to offer especially in regions where utility-scale energy generation is expanding, and large-scale storage is required to ensure continuous energy supply. These technologies act as a bright spot in areas where the traditional alternative PHES plants are not feasible due to many techno-economic-social concerns. Further, as discussed in the above sections the advantage of HRES over conventional one is the former's fundamental ability to store more energy in a smaller area. However, on the question of the practicality of making a moveable heavy mass of rock cylinder, there are living examples of similar extant of rock excavation technology found in Brazilian granite quarries that fall under the RMR II category. Thus, technology for rock cutting is in principle, not an alien one. A simple calculation showed that if the piston height is twice the radius then the costs for sawing out the mountain are proportional to second power to the radius and the storage capacity grows with the fourth power of the piston radius. This means, if a system has two times the radius, the capacity is 16 times higher. So, to put in a perspective the storage facility with a diameter of one kilometer could hold 1700 GWh of energy capacity – which is more than forty times the capacity of all pumped storage power plants installed in Germany!

The flexibility of this storage technique as observed is instead of building a central storage facility with a diameter of one kilometer, the facility can also be three to five smaller systems that are distributed across the region or a country. Thus, a radius of a hundred meters too can make the granite storage cheaper than a PHES plant.

Another aspect is the requirement of a large amount of water to displace the rock cylinder. The source can be a large water reservoir either natural or artificially built. In this study, the intended wind site is also a storage site located near shoreline which contributes mainly in two ways, optimal absorption of wind energy and seawater for uplifting the rock cylinder. Apart from energy storage capacity, the storage efficiency, response time, and circle efficiency of HRES resemble PHES plants hence a prospectus long-term energy storage for photovoltaic and wind sources that need storage capacity of roughly the volume of one day's demand for electricity.

To sum up the discussion, many aspects of this storage technique has been studied, such as design and sizing, economic and risk analysis as well as structural stability. However, building an HRES is not trivial based on today's electricity consumption and the dimension of long-term demand for bulk storage in Germany. It takes roughly the double of daily production to ensure supply at null times, this will be 60,000 GWh per year. Even, if increasing power demand is not included this amount to cover only 5% of the demand, and it takes 375 HRES plants with a capacity of 8 GWh each.

Nevertheless, this storage technique is a new opportunity to build grid-scale storage systems. Since this storage can be built virtually anywhere, many cities can reach a high level of self-sustainable energy supply. Unlike batteries, the HRES system is sustainable, eco-friendly, and carbon neutral. Another advantage lies in the reduced demand for long-distance power lines due to cheap storage capacity. As all technological solutions charted out so far are only theoretical and pilot projects can only demonstrate the viability of the system. Therefore, further research is needed to investigate the performance and the commercial development of this storage technology to well prove the credentials as described in this study.

7. Uncertainty analysis

The major uncertainty of HRES technology is that it is commercially unproven and pilot projects do not predict practical challenges i.e., undetected tectonic disturbances that might lead to water ingress at later times and cutting of the cylinder walls is challenging as it demands precision, otherwise, the piston movement is disturbed and cause tilting [31]. For low losses of water, the seal between the piston and the stroke volume should be near perfect. There is no EIA study associated with HRES [14]. Further, the key criteria for the HRES to accelerate the shift to an affordable low-carbon energy system and to become a serious contender to large-scale energy storage only when the theoretical cost estimates can live up to commercial scale construction and operation.

8. Conclusions

The fundamental objective of this study is to introduce a 'state-of-the-art' bulk energy storage system for utility-scale wind energy. In this regard, a brief introduction to the working mechanism of the proposed energy storage technique is presented. The basic motivation of this study is to address the concern of the '***Intermittency dilemma'*** of renewable sources and other inhibiting factors associated with conventional energy storage technologies. Therefore, a preface of futuristic energy storage techniques is outlined with the help of relevant literature.

The current work explored the possibilities of augmenting Hydraulic rock energy storage with the utility-scale wind farm at Bonavista, Newfoundland. This is achieved through optimally designing the storage structure while comparing the storage parameters with the Godisthal PHES system in Germany.

This is done mainly to highlight the potential of HRES as a replacement to PHES systems. Upon understanding the geological characteristics of the site and considering various influential modalities, a detailed analysis of the construction of the HRES system is made. The inclusion and acceptance of any new energy storage technology need to satisfy the established energy economies. In this regard, economic feasibility of HRES concerning its market potential and LCOS comparison with other energy storage options are carried out.

Thus, to conclude the study, like all new technologies, the Hydraulic Rock energy storage system is also embedded with many uncertainties. However, sustained research for a better adaption of this novel technology can revolutionize the energy storage market besides addressing the profound negative effect of fossil-fueled climate change.

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