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Storage of wind power energy: main facts and feasibility – hydrogen as an option

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Abstract. The befalling of natural disasters has been experienced at an alarming level in the last decade due to discharging excessive amounts of CO₂ into the atmosphere. The world needs to decarbonise itself sooner than later. To combat environmental impact and the climate change, several key initiatives were taken by countries like the UK, Japan, Europe, and Canada. That includes decarbonising the power sector entirely by bringing in renewable energy in place of fossil fuel on an agreed timeline. Many countries have committed to zero emission by 2050. However, it will not be easy to depend on 100% of renewable energy grid without renewable energy storage capability to assure grid stability. Therefore, this publication's key fundamental objective is to discuss the most suitable energy storage for energy generated by wind. A review of the available storage methods for renewable energy and specifically for possible storage for wind energy is accomplished. Factors that are needed to be considered for storage selection and the requirements are discussed. Wind farm capacity is one of the essential parameters that could affect selection procedures. It is recommended that detailed calculations be made of available energy and the excess power amount to be stored. However, the article discusses the most viable storage options such as liquid metal batteries grid embedded storage for frequency and voltage stability and produces green Hydrogen from surplus wind energy, especially in Sri Lanka.

Keywords: Wind energy storagehydrogen fuel cell / renewable energy / zero emission / offshore wind energy / Net Zero / Sri Lanka

1 Introduction

Wind power is one of the most abundantly available renewable energy sources, but it has major weaknesses: it is variable and unstable. Table 1 illustrates the top 'pros and cons', hence difficulties hitherto in not being able to utilise its full potential. In other words, wind energy is one of the fastest-growing energy technologies, but the fundamental weaknesses are known that its fluctuation in generation is directly connected to climate variability and increasing primary technological and economic issues.

Energy storage is nothing new to the world. Early human civilisation practised energy storage in numerous ways, including stocking firewood for day-to-day energy needs such as security, heating, and cooking. Since then, modern human needs are met by way of many evolved technologies. With the improvements in battery technology, connecting wind turbines with energy storage devices is now much more practical and efficient. Battery technology is

anticipated to become even more important as it develops, enabling greater use of renewable energy sources like wind power and facilitating the shift to a more sustainable energy future.

Wilhelm Knoning [2], the German Archaeologist, discovered an ancient engineering marvel in 1938 in Baghdad, Iraq, dating back to 220BC. This functioning fuel cell is believed to have been used for pain relief with an output of low voltage, and it was named the "Battery of Baghdad". This battery's construction was mainly formed with iron and copper, and the electrolyte was vinegaring or fermented grape juice. Danila [3], stated "These acids allow the migration flow of electrons from the copper tube of iron ramrod when the two metals were connected at one end, generating a current of low intensity. Experiments have shown that this battery could generate between 1.5 and 2 volts". This can be considered as an early stage of energy storage for a short time for a specific purpose.

One example related to storage of wind power energy and feasibility of hydrogen as an option is the use of the "Power-to-Gas" technology. This technology involves using excess electricity from wind turbines to electrolyze water,

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Table 1. Pros and cons of wind energy [1,3,40,41,52].

PROS AND CONS OF WIND ENERGY	
Pros	Cons
Renewable: Wind energy is a renewable resource that does not deplete over time, unlike non-renewable energy sources like fossil fuels. Clean: Wind energy is a clean source of energy and does not produce greenhouse gases or other pollutants that harm the environment. Cost-effective: Once a wind turbine is installed, it can generate electricity at a relatively low cost, which makes it an attractive option for many countries. Job creation: Wind energy projects can create job opportunities in manufacturing, construction, and operation and maintenance. Can be installed in various locations: Wind turbines can be installed in both urban and rural areas, making it a versatile option for electricity generation. Abundant: Wind is a ubiquitous resource and is available in many parts of the world, making it a widely accessible source of energy. Land Use: Wind turbines can be installed on land that is otherwise unusable for other purposes, such as agricultural land, reducing the competition for land resources. Energy Security: Wind energy can help to reduce dependence on imported fossil fuels and improve energy security. Scalable: Wind energy systems can be scaled up or down depending on the energy demand, making it a flexible energy source. Low Operational Costs: Once installed, wind turbines have low operational costs and can generate electricity for many years. No Fuel Cost: Unlike fossil fuel plants, wind turbines do not require any fuel, which means that there are no ongoing fuel costs associated with wind energy. Improves Air Quality: Wind energy does not produce any emissions, which means that it does not contribute to air pollution, a significant environmental and health problem. Reduces Greenhouse Gas Emissions: Wind energy can help to reduce greenhouse gas emissions, a major contributor to climate change, by displacing fossil fuels.	Intermittent: Wind energy is a variable and fluctuating source of energy, meaning that the amount of electricity generated can vary depending on the wind speed and direction. Land and wildlife impact: Wind turbines require a large amount of land, which can have an impact on wildlife habitats and ecosystems. Noise pollution: Noise pollution is highlighted in many articles, and I have personally experienced the noise of a wind farm, which has been protested by residence in the proximity to the wind farms. Visual impact: The rotating blades of wind turbines can visually distracting and disturbing to some people. Also, clusters can be significant, as the number of turbines can create a visually overwhelming effect. Moreover, flicker effect. Energy storage: Energy storage technology is still developing, and without a reliable and affordable way to store excess energy, wind energy cannot always be relied upon as a sole source of energy Need for Infrastructure: Wind turbines require long transmission lines and other infrastructure to connect them to the power grid, due to remote wind potential sites such as Offshore wind farms, which can be expensive and disruptive. Initial Costs: While wind energy can be cost-effective in the long-term, there can be high initial costs associated with the installation of wind turbines and related infrastructure. Land Use and Land Rights: Wind turbines require greater land extent per MW for their installation compared with the thermal power plants. Hence, land acquisition has become a challenge. Energy Storage: Wind energy is a variable source of energy and requires energy storage systems such as batteries, pump storage etc. in-order to be demand responsive to the grid. Turbulence and Wind Shear: Wind turbines are affected by turbulence and wind shear, which can reduce their efficiency and increase maintenance requirements. Transportation and Logistics: The transportation and logistics required for the installation of wind turbines can be complex and expensive. Decommissioning: Wind turbines have a lifespan of around 20-25 years and must be decommissioned and recycled in an acceptable environment friendly manner to qualify the project to be sustainable, which can be expensive and time-consuming. Aesthetics: Wind turbines may be considered unattractive by some people, which can impact the property value.

which produces hydrogen and oxygen. The hydrogen can then be stored and used as a fuel source for vehicles or for generating electricity when the wind is not blowing [42]. The concept of using hydrogen as an energy carrier is not new. In fact, it was first proposed by Sir William Grove in 1839, who demonstrated the principle of the fuel cell. However, the feasibility of using hydrogen as a widespread energy source has been limited due to the high cost of production and storage [43]. Recent advancements in technology, such as improvements in the efficiency of electrolysis and the development of more cost-effective storage solutions, have made hydrogen a more attractive option for storing wind power energy. Hydrogen can be stored as a gas or in liquid form and can be transported through existing pipelines or stored in tanks.

There are still challenges to be addressed, such as the need for infrastructure to support the production, storage, and distribution of hydrogen, and the need to ensure the safety of hydrogen storage and transportation. However, the potential of hydrogen as a storage option for wind power energy is promising and could help to reduce our dependency on fossil fuels and support the transition to a more sustainable energy system [44].

Wind power is one of the most freely available renewable energy with a significant weakness being unfirmed and not fully dispatchable [5]. Storage technologies have evolved since the early days of industrialisation. However, it is fascinating to note some energy-storing principles have not evolved at all. For example, the early automobile stored energy generated by the Internal Combustion (IC) engine in its flywheels and smoothly transferred to the wheels through the gearbox. The flywheel was introduced to overcome power starvation in the drivetrain. This principle has not changed from an early automobile to a modern car with an IC engine [6].

The most common electrical energy storage in hydro-power is “pump storage”. More technologies have been introduced lately, such as heat storage, lead acid, Nickel-cadmium, Nickel-metal hydride, or lithium-ion batteries. Portable electronics and personal portable computing have revolutionised the world with the benefit of battery technology advancement. The battery technology has influenced energy storage and is used on-demand and supply in other fields such as transportation and the electrical grid [34]. It is reported that the short power interruptions and frequency instability in the electrical grid in the US cost around \$80 billion to the commercial and high-tech industries. As a precautionary measure, such industries continue to invest in extensive energy storage facilities [20]. In this respect, the European Investment Bank is among the institutional investors in an Italian equity fund that has indicated it will invest up to €20 million (US\$24.34 million) in a business that combines green hydrogen production with compressed air energy storage [15].

A 32MW energy storage in 98MW installed capacity wind park with an expected total energy generation of 260 000 MWh was discussed in [32]. It has been quoted that “energy storage technology is the silver bullet that helps resolve the variability in power demand” and “combining wind and solar with storage provides the greatest benefit to

grid operations and has the potential to achieve the greatest economic value” [32]. Therefore, the energy storage capacity is approximately 1/3rd the Installed capacity in that project. This could well encourage further research and implementation of such storage types in wind power.

In many countries, the power generated from renewables such as wind power lies in remote areas far from the load centre, where wind potential is high, and no intelligent grids are available to manage the evacuation of electricity, even though the grid has a demand for continuous power supply. This has been a vital issue to deal with, in wind farm site selection for many countries such as Sri Lanka, where the excessive power generated needs to be stored and standby to feed the grid when in demand of power. Renewable energy, particularly wind power, is increasingly being generated in remote areas of many countries due to the high wind power density potential in those areas. However, in these remote locations, there may be setbacks such as not having intelligent grids capable of evacuating continuous power. This presents a significant challenge in wind farm site selection, as it is essential to ensure the grid availability [45].

In Sri Lanka, for example, excess power generated from wind farms must be stored to feed the grid during periods of power shortage. The need to store and manage this excess power is a critical issue that requires careful consideration and planning to ensure a reliable and efficient power supply. One potential solution to this challenge is the use of energy storage technologies, such as batteries or hydrogen storage. These technologies can be used to store excess power generated during periods of high wind power density and release it during periods of low power generation while the grid is in high demand, ensuring a continuous supply of electricity to the grid [5]. Another potential solution is the development of intelligent grids that can manage the distribution of power more efficiently. These grids use advanced technologies such as multiple sensors and automation using advanced electronics to monitor the power, supply and demand and dynamically adjust its power distribution to ensure a stable and continuous supply together with an advanced system control centre [46].

In conclusion, the lack of intelligent grids in remote areas with high wind power potential is a significant challenge in wind farm site selection. However, solutions such as energy storage technologies and intelligent grids can help to address these concerns and ensure a stable and reliable power supply from wind energy. Careful planning and implementation are essential to ensure the efficient and sustainable use of wind power in remote areas [47,48]. Hence, it is essential to have energy storage for dependable renewable energy utilisation. Therefore, it has become quite relevant to the authors’ interest to consider applying storage methods to the Sri Lankan situation, especially not having smart grids in place. As a case study, Sri Lanka has over 92GW of offshore wind potential [36]. This enormous capacity can only be tapped with suitable energy storage capacities to overcome the inherent characteristics of variable power output. However, detailed wind energy data analysis must identify the potential wind areas and determine the feasible storage capacity needed to fulfil the national electricity demand as the country heads

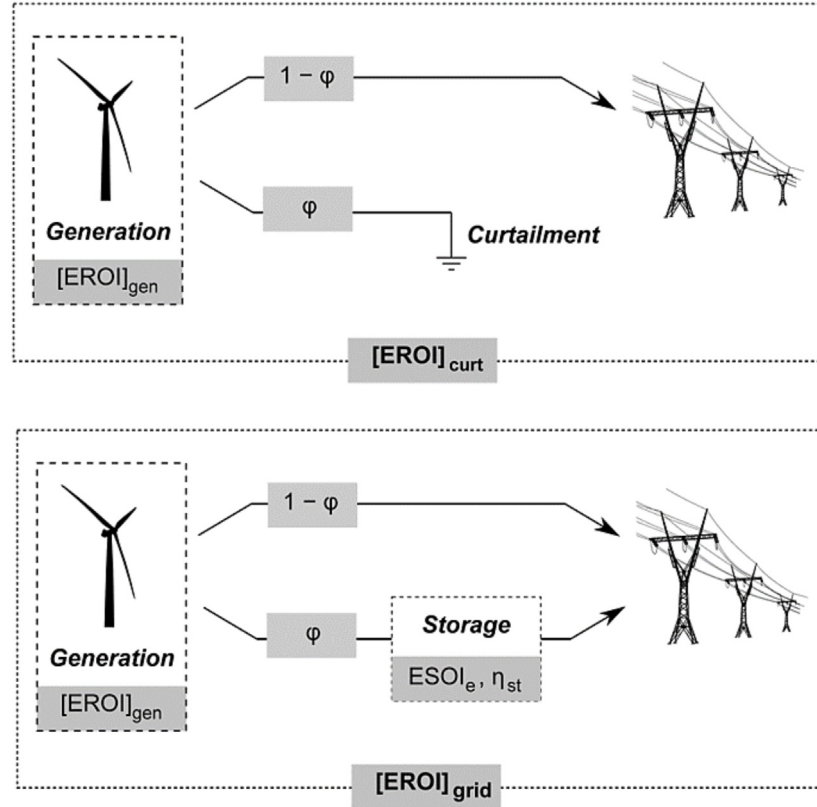


Fig. 1. Illustrates two grid scenarios, one without energy storage and the other with energy storage [25].

towards its zero-emission vision by 2050 [39]. This paper initially reviews the most appropriate storage system options. It explores the main factors that influence the design and selection of a suggested wind power storage systems that could be introduced to countries like Sri Lanka.

2 Net energy analysis

Net energy analysis can be determined when the energy benefit of avoiding curtailment outweighs the energy cost of building a new storage capacity [31]. It considers a generating facility that experiences over generation which is surplus energy and determines whether installing energy storage will provide a net energy benefit over curtailment. If the generating facility itself has an energy return on investment $[EROI]_{gen}$, and due to over generation, an element ϕ of the generated power must be diverted away from the transmission; Figure 1 exemplifies that the diverted power may be stored for later use in high demand or curtailed and lost. When generation is curtailed $[EROI]_{curt}$ (and not stored), the EROI of the generation source decreases to the following relation [31]:

$$[EROI]_{curt} = (1 - \phi)[EROI]_{gen}. \quad (1)$$

However, the cost of environment impact is not taken into consideration in the above formula and if that is taken into the above calculation, it would undoubtedly further enhance the value of introducing storage to the project.

3 Overview of energy storing for renewable electrical energy

World over, the most renewable energy projects run without storage due to the exorbitant cost of storage options. Generally, it is widespread that the energy companies run the generation according to the grid demand on the principle of least cost generation. Renewable energy may become uncompetitive when the storage is introduced unless the Government strictly regulates the energy sector to reduce CO₂ emissions by law. Regulating the electricity industry seems essential if net-zero emission targets are to be met by respective countries. Some electricity grids use energy storage for frequency stability, to enhance capacities, and manage peak loads [16].

Belenky et al. [34] highlight the important point, is that “Effective technologies for storing electricity can contribute greatly to reduce the country’s dependence on fossil fuel in general and on imported fossil fuel in particular. A systematic approach to analysing the grid’s listed abilities and other issues relating to storing electricity in it has a high potential to affect the Government’s policies in regulating and deregulating the country’s electrical grid. These policies, in turn, affect the investment climate around the grid and may increase the investors’ confidence in considering the grid as a whole and its part, associated with storing electricity as potential areas of investment”.

On the other hand, in some other industries such as national security infrastructure, data centres, and standby

power generators, expensive technologies such as super-capacitors are being used to avoid power outages to costly and sensitive equipment. Network management systems manage uninterruptable power supplies (UPSs.) Failure to do so could result in irreversible consequences and have an impact on national security [4].

Renewable energy is an essential and sizable part of modern grids. It is a compulsory component in the energy mix to achieve strategic zero-emission targets in all countries around the world. However, most renewable energy, mainly wind and solar, is not readily available (variable energy sources) when the demand arises in the grid. In other words, these energy sources are non-dispatchable, and they may not require much energy when the wind blows or the sun shines. Hence, it becomes an absolute need for modern grids to have storage capacities when energy is produced abundantly later and to meet the demand [13]. Energy storage for non-conventional energy sources will increase the plant factor and increase the overall project financial viability. Koh [18] stated that “with energy storage systems (ESS), the power quality can be improved, and load variability can be reduced. Reduced power quality problems and load variability brings the benefits of reduced network losses, increased plant factor, deferment of network upgrade and improved network stability”. Farrag [12] reported that energy storage at multiple levels across the electrical distribution levels improves the overall performance.

Combining wind and solar with storage provides the most significant benefit to grid operations and can achieve the most important economic value [26]. The battery technology influenced energy storage and use on-demand [22], National Security, Data Centres etc. In addition to standby power generators, they use expensive technologies such as Super Capacitors [4]. It became a need of any modern grid to have some storage methodology to store renewable energy when produced abundantly and use later to meet the demand in the grid [13,25]. Hydrogen (H_2), especially when created utilizing renewable energy sources, has the potential to be a significant replacement for fossil fuels. Green hydrogen is the term used to describe hydrogen that has been produced by the electrolysis using renewable energy [27]. Depending on the source of renewable electricity utilized for its generation, green hydrogen can provide a carbon-neutral or even a carbon-negative energy option. It is true that hydrogen can be produced from various sources, including renewable sources and fossil fuels such as coal or natural gas.

Hydrogen produced from renewable sources such as wind, solar, or hydropower is often referred to as green hydrogen, as it has a zero carbon footprint or low carbon footprint and does not contribute to climate change. On the other hand, hydrogen produced from fossil fuels through processes such as steam methane reforming (SMR) or coal gasification is known as grey or brown hydrogen, and its production emits significant amounts of greenhouse gases.

Therefore, it is crucial to differentiate between green hydrogen and grey or brown hydrogen, as the grey/brown H_2 does not contribute to a sustainable and clean energy future.

The production of hydrogen from renewable sources is essential for the transition to a sustainable and clean energy future. The use of grey or brown hydrogen can only be considered as a transitional solution, as it does not offer a long-term alternative to fossil fuels. It is vital to prioritize the production and use of green hydrogen to reduce greenhouse gas emissions and achieve a more sustainable and cleaner energy system [49]. Hydrogen's energy storage provides a dramatically higher energy density than any other energy storage medium [25]. Even if you consider the conversion losses in Green H_2 into electricity, the marginal advantage will be a considerable edge to remain carbon neutral. The use of electrolytes with a low melting point evades multiple challenges in liquid metal batteries (Na-LMBs) [8]. It is calculated that 53.3 billion kg of hydrogen could displace about 133 billion gallons of gasoline [24]. This comparison should be based on Green H_2 .

This article has sighted one of the oldest energy storage cells dating back to 220BC [4], which goes on to prove the importance of energy storage. It is also highlighted that while combining wind and solar with storage provides the most significant benefit to grid operations and has the potential to achieve the most outstanding economic value [32]. The battery technologies have substantially influenced energy storage and use on-demand [28]. The cost of storage is ascertained to be very high in systems with the importance of National Security & Data centres etc., compared to the conventional grid storage. It is mainly due to its high risk and high-value information that needs to be secured. Therefore, energy storage structures are designed with standby power generators and Super Capacitors to make it failsafe operation [4]. It becomes necessary for any modern grid to have some storage methodology to store Renewable Energy when produced abundantly and used subsequently to meet the demand in the grid [13,25]. Hydrogen is the alternative to fossil fuel to a great extent, and it will be the cleanest, especially with the fuel cell, and if it is manufactured with Renewable energy [27].

Combining wind and solar with storage provides the most significant benefit to grid operations and has the potential to achieve the most outstanding economic value [32]. The cost of storage is ascertained to be very high in systems with importance such as national security and data centres, compared to conventional grid storage. It is mainly due to its high risk and high-value information that needs to be secured. Therefore, energy storage structures are designed with standby power generators and super capacitors to make them failsafe [4]. The use of electrolytes with a low melting point evades multiple challenges of liquid metal batteries (Na-LMBs) [20].

4 Way forward for net zero emission for Sri Lanka

Sri Lanka has the vision to achieve 80% and 100% of its power and energy needs by 2030 and 2050 respectively, with the renewable energy [19]. A net-zero carbon economy is quite challenging as it needs all sectors from industries to domestic, including transport, to be decarbonised rapidly with strict timeline targets. One of the biggest challenges remains in decarbonising the industrial and transport

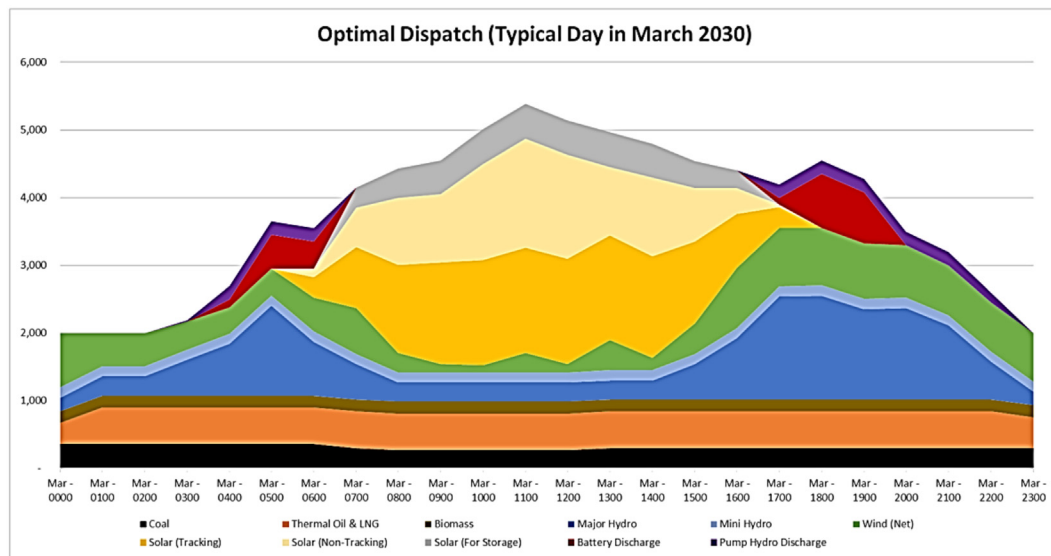


Fig. 2. Illustrates optimal dispatch on a day in March 2030. March recorded the least wind potential in Sri Lanka [19].

sectors. Hence, it is pertinent that the Government of Sri Lanka considers offshore wind as the energy source with most potential renewable to overcome this challenge. It is estimated that the potential wind energy in Sri Lanka is around 92 GW [30]. Sri Lanka's forecasted power demand in 2030 is estimated at about 5500 MW, and the typical energy mix in the grid is depicted in Figure 2 [19]. One method of utilising the enormous offshore wind energy capacity is to store it in the form of Hydrogen and convert internal combustion machinery and plant to make them non-hydrocarbon dependent. It is also predicted that almost all fossil fuel-powered vehicles may be replaced with H_2 and EVs by 2050. The adoption of hydrogen fuel technology is gaining traction as leading manufacturers are investing in it, with over 500 prototypes currently in operation worldwide [15]. This trend highlights the need to consider electric mobility as a crucial element in decarbonizing projects globally. However, it is vital to prioritize the use of renewable energy options for EV charging, both for domestic and commercial use, to avoid relying on fossil fuels for the grid's baseload.

The prevailing use of fossil fuels for baseload electricity generation is a challenge, but it is not impossible. Wind and solar energy, supported by storage and fully dispatchable renewable energy sources like hydro, biomass, and geothermal, should be prioritized as the baseload for electricity generation. The promotion of renewable energy options for EV charging, as well as other energy needs, is crucial to decarbonizing projects and transitioning towards a more sustainable energy system.

Figure 3 highlights the potential of zero-emission mobility using hydrogen for light-duty vehicles (LDVs) and the analytical workflow of potential hydrogen demand against the possible green hydrogen production with wind energy. This analysis emphasizes the need to prioritize renewable energy sources for hydrogen production and usage, as it can significantly contribute to reducing carbon emissions in the transportation sector.

In summary, while the adoption of hydrogen fuel technology is gaining momentum, it is crucial to prioritize renewable energy sources for both hydrogen production and usage to decarbonize the transportation sector effectively. The promotion of EV charging stations using renewable energy options, as well as prioritizing renewable energy for the grid's baseload, can accelerate the transition towards a more sustainable and clean energy system [50].

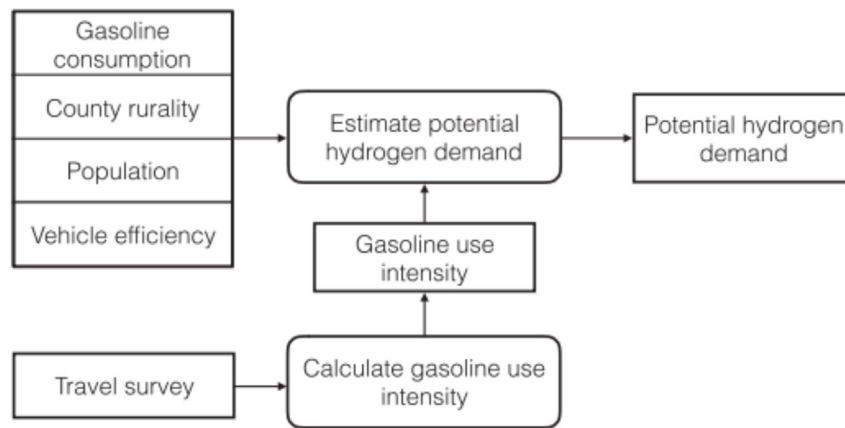
Figure 4 is a typical electrical power profile, showing significant variations during a 24-h period. In a load-levelling scenario, an electrical energy storage device would be charged during low-power demand periods. It would discharge during high-power demand periods, thus filling in troughs and levelling out peaks. A utility would need less overall power generation capability and could delay the installation of extra generating capacity [28]. The black dotted line defines the typical power curve in a conventional grid in Figure 4. The red line indicates the ideal expected load levelling, with the storage 'kicking in' during peak demand, thereby eliminating the dispatch of the expensive plant to meet these peaks. The deep trough in a conventional grid requires de-loading the high-capacity baseload plants making them not viable to operate. Still, the introduction of charging battery storage, including the EVs during off-peak, would solve it very quickly while stored energy will entirely take out peaking plants from the grid [28].

5 Viable energy storage options

The literature suggests the existence of regenerative hydrogen fuel cells, as referenced in the article by as referenced in Soloveichik, 2004 [36].

However, it is worth noting that there are no regenerative hydrogen fuel cells in the strictest sense. Instead, there are fuel cells that can be run using either green or dirty hydrogen, depending on the source of the hydrogen used in the fuel cell. It is important to distinguish

(1) Hydrogen demand for LDV transportation



(2) Hydrogen production from wind energy



→ Data flow

□ Input / Output data

○ Process

Fig. 3. Analytical workflow for estimating the potential hydrogen demand for light-duty vehicles (LDVs) and quantifying the possible production from wind energy in response to electricity market price [24].

between these two types of hydrogen to ensure that the fuel cells are being powered by green, renewable energy sources rather than dirty, non-renewable sources [49]. Pump storage, compressed air and several battery technologies can be considered as viable options in storing renewable energy. However, it is essential to consider the electrical energy stored on the invested ratio ($ESOI_e$) (The ratio of electrical power returned by the device over its whole lifetime to the electrical-equivalent power required to build the device) and the overall energy efficiency (the ratio of electrical energy produced by the device over its lifetime to total lifetime electrical equivalent energy input into the system).

The author [25] reminds us that the energy capacity and power capacity of a regenerative fuel cell can be configured independently. Storing energy in hydrogen does provide a high energy density compared to other energy storage methods. Hydrogen has an energy density of about 39 kilowatt-hours (kWh) per kilogram (kg), which is three times higher than the energy density of gasoline (about 13 kWh/kg) and almost three times higher than that of lithium-ion batteries (about 0.5–0.7 kWh/kg).

However, it is important to note that the overall efficiency of energy conversion and storage processes must also be considered. The process of converting electrical

energy into hydrogen using electrolysis, storing hydrogen, and then converting it back into electricity using fuel cells is not reasonably efficient, and some energy is lost during each step. Additionally, there are safety and infrastructure challenges associated with storing and transporting hydrogen.

So, while it is true that hydrogen provides a high energy density compared to other storage media, the overall efficiency and practicality of hydrogen as an energy storage solution will depend on a range of factors such as specific applications, available technology, and costs. The cost of energy storage in a regenerative hydrogen fuel cell is already potentially competitive with batteries in an optimised energy arbitrage system [31].

Multiple options are available for energy storage with different technologies competing against each other in performance and cost. Finally, it is very important to pick the most suitable and viable option for the particular project, having analysed its primary objective and needs. Figure 5 [21] categorises various storage options classifying them into numerous technologies. However, from 2014 to date, more options have evolved and matured adequately, such as Hybrid Battery-Hydrogen for critical energy storage for high-capacity discharge into the grid [17,23].

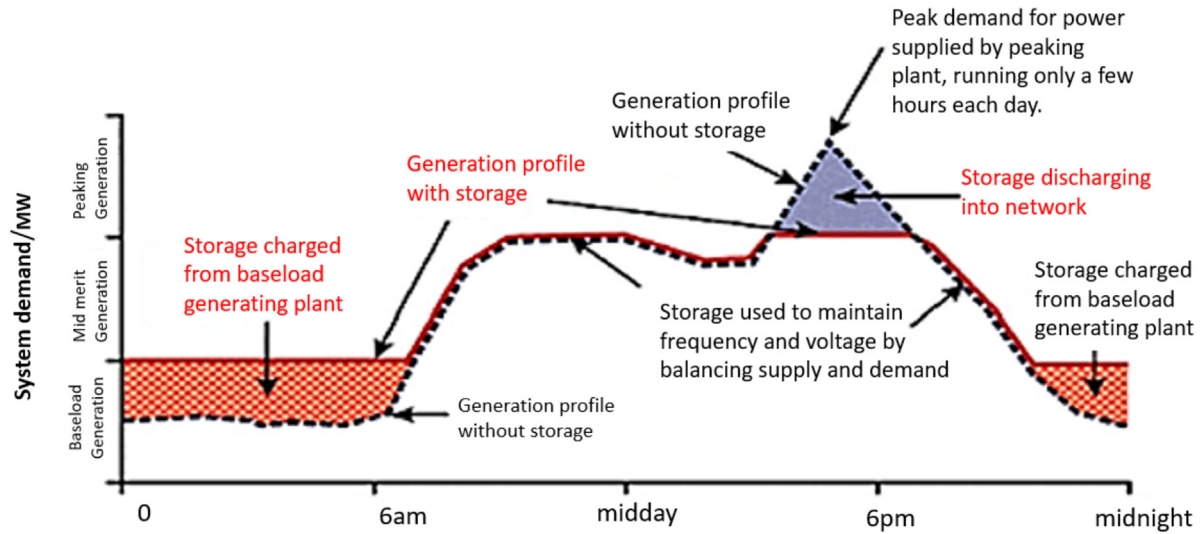


Fig. 4. Typical electrical power profile, showing the large variations during a 24-h period [28].

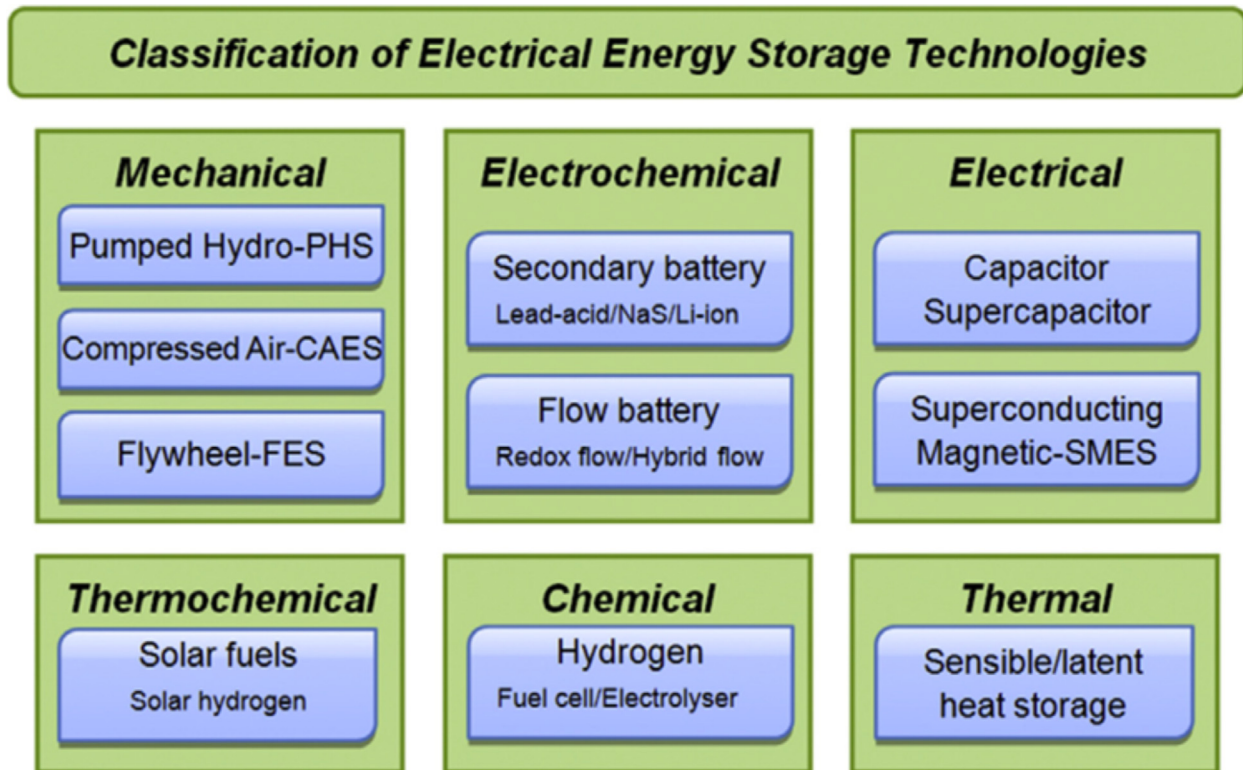


Fig. 5. Categorises the options available in numerous storage technologies [21].

6 Suitable battery selection

Liquid metal batteries are a type of flow battery that use two liquid metal electrodes separated by a molten salt electrolyte. They have the potential to provide large-scale, long-duration energy storage with relatively low costs and high efficiency. One of the main advantages of liquid metal batteries is their long lifespan, with an estimated lifetime of over 10 years and up to 20 years. It is also proposed to co-locate the battery storage in the sub structure of the

offshore wind turbine making it is more cost effective by using it as the battery compartment [25]. Recent research on liquid metal batteries has focused on improving their performance and reducing costs, as well as developing new materials and designs. For example, some researchers have explored the use of new electrode materials, such as carbon and nickel, to increase the efficiency of the battery. Others have investigated the use of different types of electrolytes to improve the battery's stability and reduce the risk of leakage.

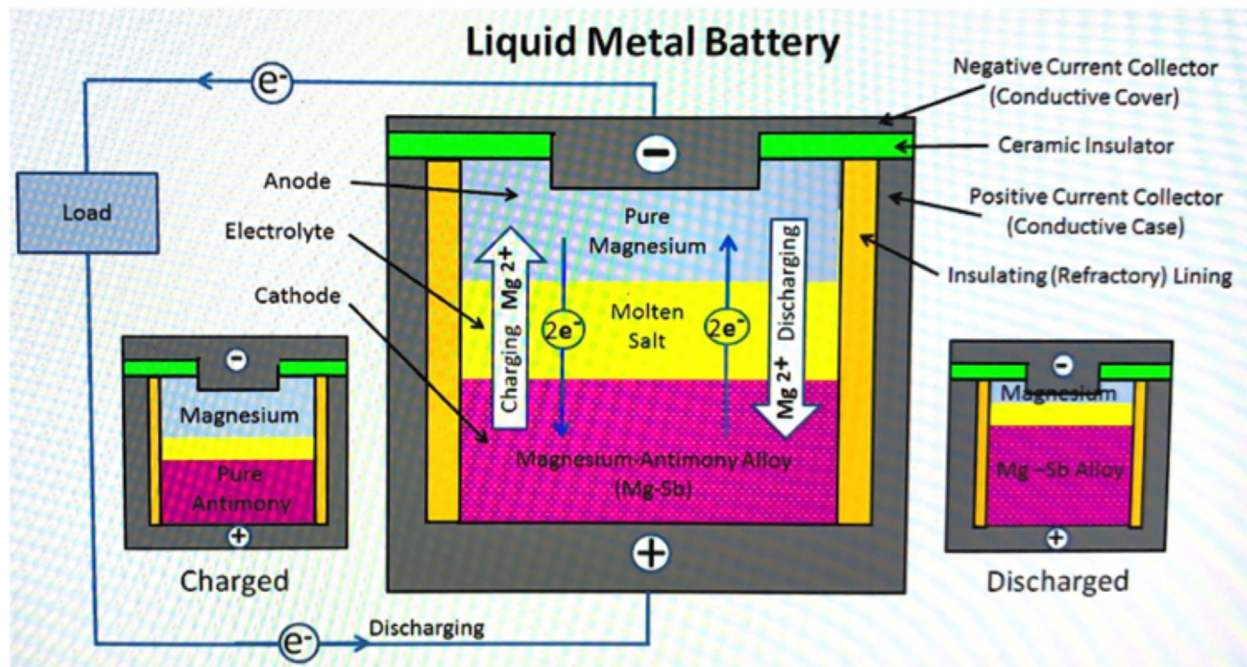


Fig. 6. Illustrates the Liquid Metal Battery in a simple diagram [29].

While liquid metal batteries are still a relatively new technology, they have shown promising results in laboratory experiments and pilot projects. However, further research and development are needed to improve their performance and reduce costs before they can become a viable energy storage solution for widespread use. Figure 6 visualise the construction of a Liquid Metal Battery in which the Molten Salt acts as the electrolyte. At the same time, the anode and the cathode are connected to pure Magnesium and Magnesium Antimony Alloy, respectively (Woodbank Communications Ltd, 2020). The use of electrolytes with a low melting point evades multiple challenges of liquid metal batteries (Na-LMBs) [14]. Currently, the Liquid Metal Batteries are being commissioned in several pilot projects and reported as successful, and further optimisation activities are ongoing to develop the technology further. However, according to the data available so far has the following advantages with the currently available liquid metal battery technologies in the industry [14,29]:

- Very high current density.
- Long cycle life (a projected cycle life of over 10 000 cycles is claimed).
- Modular design which can be scaled up to multi-Mega Watt capacities.
- Low-cost active materials.
- Simple construction.
- Fast milliseconds, reaction times as with all electrochemical batteries.
- The liquid electrodes are reconstituted with each charge cycle, thus avoiding the capacity fade due to the formation of dendrites or particle cracking which occurs in conventional batteries, resulting in longer cycle life.
- No Battery Management System (BMS) is required.

It is observed that a detailed explanation and a comparison is published in Bauer [7] comparing the most widely used battery for power storage today, Li-ion, with some of the Liquid Metal Batteries. He asserts, “from a technology standpoint, the lower cost structure and improved safety characteristics make this a compelling energy storage solution, especially for large format applications”.

Figure 7 illustrates a liquid metal battery bank from Ambri, which is already in operation with NEC [9].

Governments around the world are stepping up their efforts. Since early 2019, 12 countries and the European Commission have set out ambitious hydrogen strategies or roadmaps. And at least another nine are due to be released very soon. Global green hydrogen use grows sevenfold by 2070 compared to today in the Sustainable Development Scenario, with demand growth almost completely met by Green Hydrogen. Figure 8 shows the Hydrogen as a key pillar for reaching energy and climate goals [11].

it is important to note that the term “low carbon” can refer to hydrogen produced from a variety of sources, including fossil fuels with carbon capture and storage technology, which may not necessarily be considered green or clean.

It is important to acknowledge that not all low-carbon hydrogen is equal and to consider the environmental impact of the specific production methods used. While hydrogen produced from renewable sources like solar or wind power is considered green or clean, hydrogen produced from fossil fuels with carbon capture and storage technology is still a significant improvement over traditional fossil fuel use but may not be completely emissions-free. “Regenerative Fuel Cells for Energy Storage,” [30]. Therefore, when discussing the growth of hydrogen use, it is essential to specify the source of



Fig. 7. Image of a module of “Ambri” Liquid Metal battery bank, part of the contract with NEC 200 MWh project [9].

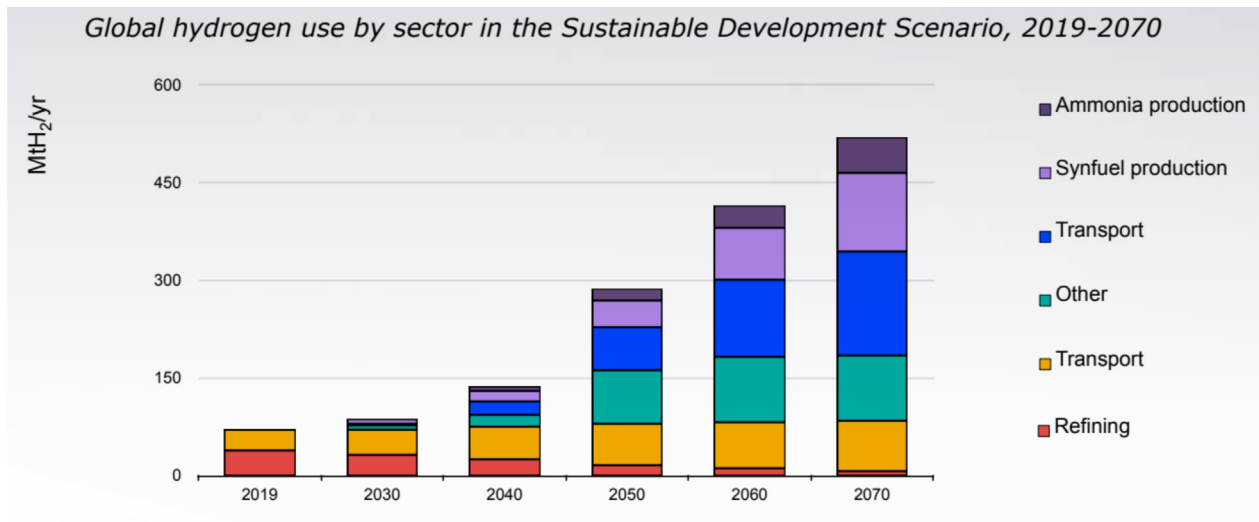


Fig. 8. Global H₂ use past, current and the future projections by deferent sectors [11].

hydrogen and whether it aligns with the goal of reducing greenhouse gas emissions and transitioning to a more sustainable energy system.

For instance, consider a wind farm that has a capacity need of 100 MW but absences of any energy storage. Without storage, this wind farm may curtail or loose excess energy during periods of low demand, which typically occur during off-peak hours. Such curtailed energy represents a lost opportunity for the wind farm to supply electricity to the grid, resulting in potential revenue loss for the operator. This highlights the importance of energy storage systems,

such as batteries or hydrogen, to capture and store excess energy generated by renewable sources like wind and release it to the grid during the times of high demand. By incorporating energy storage solutions, wind farms can better balance energy supply and demand and ensure a more consistent and reliable power supply for end-users [51]. In other words, the storage could bring a harmonized link between the wind farm and the grid by eliminating the mismatch between the generation and the grid demand. As such, the storage of Renewable Energy will play a critical role in the grid. The storage will increase the plant capacity

Table 2. Current and predicted LMB performance compared to other battery type [38].

Battery type	Specific Energy (Wh/kg)	Energy Density (Wh/L)	Cost (\$/kWh)	Cycle Life	Roundtrip Efficiency	Operational Temperature (°C)	Size Built/Tested
Li-ion	150–180	300–350	600–800 (installed)	1500–5000	90%	Ambient (−20°–50°)	129 MWh, Hornsdale Power Reserve, Australia
Lead-acid	35–40	80–90	150–200 (installed)	500–1200	85%	Ambient (−30°–40°)	40 MWh, Chino, California
LMB Li-Bi	113	592	89 (predicted pack cost)	~10,000	70%	~550°	200 Ah (~79 Wh) Li-Bi battery, Cambridge, MA
LMB Ca-Sb (Ambri projections)	–	–	~21 (projected)	~10,000 (projected)	>80% (projected)	~500°	800 Ah (~760 Wh) battery, Marlborough, MA

factor, as an example, if the storage system provides an extra 5 MWh/year, dispatch opportunity, assuming it is a 100 MW wind park it would be an increase in its plant capacity factor by 5% [37].

Similarly, the wind resource is variable, and as such, the energy output becomes proportionately variable too. This can be compensated and eliminated with planned storage. The storage in renewable energy projects, especially of late, such as Wind and Solar is quite prominent. This process maximises the value of assets, and in technical terms, it increases the plant capacity factor. This will eliminate the need for standby power such as diesel generators, which are costly and pollute the environment. This model has been taken into consideration in making small, isolated grids into 100% renewable energy. There are many examples, such as Endesa, REE, El Hierro, Spain. Younicos, Azores Island, Portugal and ENERCON, Faroe Island [35].

Solid-state battery technologies, including Li-ion, have served all sectors quite well so far. That includes Communication, Household, Consumer electronics, Transportation, Energy etc. However, they face many challenges as they age, such as leaks and fire, capacity losses and storage last for a short time per charge cycle. In contrast to solid-state batteries, Liquid Metal Batteries can charge and discharge with much higher efficiency, notwithstanding ageing and degradation. The Energy sector must find a better technology for energy storage that is durable, cost-effective, safe. Some battery models are already in commercial applications like Ambri, while some are in the prototype stage, and some are in field trials. The authors have highlighted several points in this publication that are highly pertinent for wind energy storage is to be viable. On the day this article submitted for publication, the Liquid-Metal Battery (LMB) is clearly, the most appropriate technology candidate for wind power energy storage [38]. Table 2 highlights the characteristics, such as specific energy, energy density, cost, cycle life, roundtrip efficiency and the built or tested size.

7 Hydrogen option

Hydrogen is one of the most viable options for countries like Sri Lanka. For example, Sri Lanka has a potential of 92 GW of offshore wind energy, and its forecasted electricity demand is below 10 GW by 2035 [26]. The authors wish to

coin the idea that such a significant excess of wind energy to be exported in some form outside the country as the energy demand is barely an insignificant percentage of the total potential wind energy capacity. As such, the energy derived from wind can be used to produce Green Hydrogen, and it can drive many sectors of the domestic economy in the first place, and the excess can be exported to the countries in need of energy. Australia is actively working in this direction [8]. Hydrogen is the alternative to fossil fuel to a great extent. It will be the cleanest, especially with fuel cells and manufactured with Renewable energy [27]. H₂ will compete with the present E-mobility, and already, the shift towards Hydrogen-powered mobility is evident in some parts of the world [24].

Even though the Germany and the EU has advanced in E-mobility to great extent, Germany has taken the reasonable initiative in H₂, and already logistic facilities are being rolled out. The use of e-fuels, such as e-ammonia, e-methanol, and e-methane, as well as the direct use of hydrogen for short distances, are the mainstays of climate-neutral technology solutions for transportation. To reduce greenhouse gas emissions, long-haul aircraft will mostly employ carbon-neutral, hydrogen-based fuels. By 2035, the direct use of liquid hydrogen in short- and medium-range flight may also reduce CO₂ emissions. The requirements and demands of hydrogen producers and users should serve as the foundation for the development of the hydrogen infrastructure, and projected needs should be taken into consideration early on in grid planning. German grid operators have demonstrated how a starting grid for hydrogen can be developed in the Gas Grid Development Plan 2020–2030. First, regional hydrogen clusters are established where the necessary hydrogen is produced relatively close to the point of consumption. By 2030, these will be linked together to create a broader grid, starting with a connection to nearby nations [53].

The other aspect of the H₂ usage option is to power Gas Turbine (GT) type power plants until the power plant life span ends. However, NO_x is a concern in this scenario, and mitigation methodologies such as Exhaust Gas Recirculation (EGR) are in place [10]. In some scenarios, it is observed that the excess energy is stored, especially in those grids coupled with an energy exchange and spot selling and buying facilities, so that they charge the storage at cheap rate electricity and evacuate it during the peak to generate revenue. The business model is as follows [23].

- Use the cheap electricity from the grid, produce Hydrogen, generate electricity, and supply the grid during peak demand.
- Produce Hydrogen as in 1 above and use on fuel cell vehicles etc.

8 Conclusion

Wind power is a promising and widely available renewable energy source and needs intensive investment to select and install the correct storage to regulate the excessive power generated and to support periods with lack of availability of wind. This paper, wind energy storage was discussed with a critical literature review. In countries such as Sri Lanka, if the wind energy is to be utilised to its maximum capacity, it needs to be stored and use it when the grid has a higher demand. The paper has reviewed the possible power storage options and identified the supporting parameters for a feasible system selection. However, the storage systems like Pump Hydro System are not taken in to account here since in most matured grids, it has been already acted upon such options as primary steps and assume that there is no provision for such improvements in the Hydro Power cascade. Therefore, it is suggested that liquid metal battery would be one of the most viable options to store generated wind energy and to discharge when needed back into the grid. This can be in varied capacities as technology permits operators to develop it as modular units and add or remove the capacity easily depending on the demand. Further, it will operate without a sophisticated Battery Management System (BMS) and daily cycles of complete discharge on demand and charge during the off-peak hours. It is therefore concluded that the Liquid Metal Battery are one of the best options to be used throughout the grid for energy storage for voltage and frequency stabilisation as it can be introduced as a modular unit. Accordingly, it is concluded that Hydrogen is the solution to support wind power storage, especially in the scenario of excessive capacity like in the case of Sri Lanka. Green Hydrogen can be produced using offshore wind energy, and it can be smartly utilised for local energy needs such as mobility and to operate existing Gas Turbines (GTs) for power generation with a workable and a sustainable action plan. Thereafter, the remaining quantity of Hydrogen can be exported to countries in demand who are looking for Green Hydrogen. This can be a lucrative export which can generate foreign exchange influx to the economy. The present research work recommends that “Export of Hydrogen and the logistics” are seen as a knowledge gap, and as such, requires detailed research to bridge those gaps.

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