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Technoeconomic and Life Cycle Analysis of Energy Storage Systems

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Abstract. The effects of climate change have begun to become more apparent in recent years. Extreme weather events are observed in greater frequency, affecting the livelihoods of tens of millions around the globe. Renewable energy sources, such as wind energy and photovoltaics, are the preferred option for power generation since they can be decentralised and drastically reduce the emission of greenhouse gases. However, power output from wind turbines and photovoltaic panels apart from being variable cannot be simply switched off even when demand is much lower. This results in increased grid instability risk. In extreme cases of imbalance between power demand and power output blackout can occur with significant consequences. Therefore, the implementation of large-scale energy storage systems has increased value for the protection of the stability of the grid as well as for optimisation of the benefits drawn from renewable energy sources. In this paper, we discuss the advantage and disadvantages of different energy storage systems based on batteries, hydrogen and other means, together with a qualitative technoeconomic and life cycle analysis.

1 Introduction

Climate change effects are already becoming obvious around the globe [1-2]. Some of the key indicators for assessing climate change is the frequency, duration and intensity of extreme weather events, such as the occurrence of category 3 and above hurricanes, major rainfalls in short periods of time and over limited surface areas, and occurrence of heatwaves with increased duration. Recent examples of such events include the unseasonable flash flooding that took place in Afghanistan and Pakistan in March-May 2024, the recent major heatwave in New Delhi, with temperatures in some cases exceeding 50°C, and the more frequent occurrence of powerful Atlantic hurricanes. According to the recently published Intergovernmental Panel on Climate Change (IPCC) report global surface temperature showed an increase of 1.1°C in comparison with 1850-1900 [1]. Higher surface temperature rises were observed over land in comparison with ocean. However, the amount of heat captured by oceans is much higher in comparison with land masses due to the higher heat capacity of seawater, higher absorption of sun light, and larger surface area.

To combat the effects of climate change, a continuous drive towards decarbonisation of utility-scale power generation and transport has been a key global objective in recent decades. As such there has been a gradual turn from fossil fuels towards renewable energy sources, which has been primarily related to wind and solar energy. Hydroelectric power generation has already seen wide commercial exploitation throughout the latter part of the 20th century. Thus, although it is still growing, it can only contribute to the decarbonisation of the energy mix by a limited amount.

Green hydrogen as a clean energy carrier, has received a lot of attention but it currently represents only about 1% of the global hydrogen production, with the rest coming from fossil fuels [3].

In transport there has been a considerable effort to move towards electric vehicles (EVs), taking advantage of electricity generated by renewable energy sources. However, there are still a lot of challenges to address including the adequacy of existing electric infrastructure for charging EVs. Fuel Cell Vehicles (FCVs) are yet to be commercially exploited widely. Only very few models have been manufactured so far, such as the Toyota Mirai and Hyundai Nexo, mainly due to the lack of appropriate hydrogen infrastructure for refuelling FCVs as well as adequate hydrogen production and storage capacity.

2 Wind and solar power growth and variability

Wind energy together with photovoltaics have grown fast during the last 25 year. The current global wind power installed capacity exceeded the 1 TW milestone in 2023 and is on track to exceed 2 TW by 2030 [4].

Global photovoltaic installed capacity reached 1.6 TW in 2023 and is on track to exceed 2 TW by the end of 2025 [5].

Due to the variability of power generation from wind turbines and photovoltaic panels, the annual capacity factors can fluctuate considerably, depending also on availability. Typically, for most onshore industrial wind farms the annual capacity factor is 24% and for offshore 38% [6].

The global average capacity factor for solar farms between 2010-2022 has been from around 14% to almost 18% [7]. Fig. 1 shows the global renewable electricity generation from 1965 to 2022 [8]. As it can be seen hydroelectricity remains dominant in its contribution to the energy mix but it is growing at a slower pace in comparison with wind and solar power.

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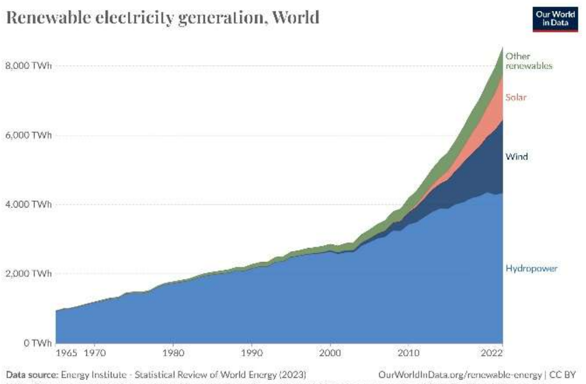

Data source: Energy Institute - Statistical Review of World Energy (2023) OurWorldInData.org/renewable-energy | CC BY
Note: 'Other renewables' refers to renewable sources including geothermal, biomass, waste, wave and tidal. Traditional biomass is not included.

Fig. 1. Global renewable energy generation (CC-BY) [8].

As shown in figure 2, the contribution of renewable energy sources to the global energy mix reached approximately 30% in 2023 [9]. Wind energy accounted for approximately 8% and solar photovoltaics for another 5% [9]. If forecasts materialise, it is expected that the global energy mix contribution of renewable energy sources will reach 42% by 2028. In 2028 solar photovoltaics are expected to also slightly exceed the wind energy contribution for the first time and reach ~12% of the global energy mix [9].

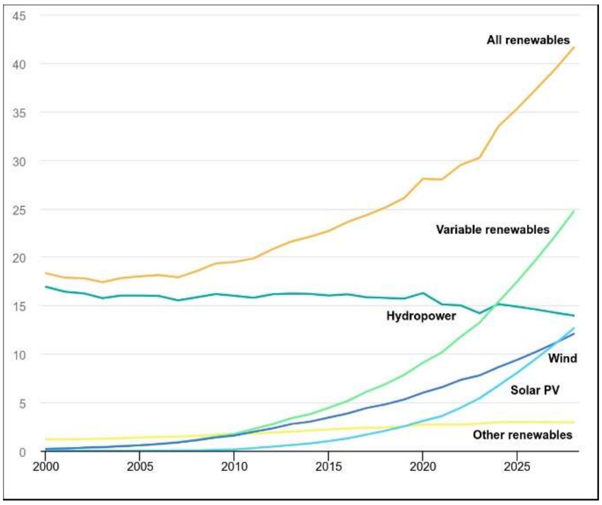

Fig. 2. Renewable energy contribution to global energy mix from 2000-2028 (CC-BY 4.0) [9].

The original design of electricity grids has been based on the notion of a few large-scale, centrally located power generation plants. However, with the advent of renewable energy sources, power generation has become increasingly decentralised. An ever-increasing number of relatively small variable wind power or photovoltaic generators are installed at various locations. The effect of injecting large amounts of variable electric power to the grid may result in transient events that can potentially result in large-scale power outages [10]. Under certain environmental conditions, which lead to lower than expected renewable energy output, whilst at the same time demand remains high and cannot be covered either by imports or other power generation sources, then black-outs may occur. Conversely, when demand is low and there is a much higher amount of renewable electricity supply available again black-outs can occur, unless the surplus energy is exported, or it is stored using appropriate energy storage systems (ESS).

With increasing amounts of variable renewable energy sources being injected in the grid either a temporary reduction in power output or reduced demand in comparison with power generation levels the increasing likelihood of black-outs cannot be ruled out. Thus, the importance of ESS becomes evident. Reduced power output from renewable energy sources is usually addressed by bringing online fossil-fuel power plants, e.g. gas or coal-fired plants. However, fossil-fuel plants cannot be turned on instantaneously and need to be maintained on standby. This reduces the possibility of an unexpected black-out but contributes to higher electricity production costs and of course results in higher greenhouse gas emissions. Moreover, it is not long-term financially viable for operators to maintain such plants primarily on standby for emergency power generation unless they can sell their output either at much higher prices or more often.

The potential mismatches that can occur throughout the day between renewable power output with demand is a critical problem that requires to be addressed sooner than later, particularly as the contribution of renewable energy sources to the energy mix grows further.

3 Primary types of energy storage systems

Traditionally, the primary way of storing excess electric energy is by pumping water to higher altitude. Then subsequently use the dynamic energy of the water stored when demand surpasses the current electricity production by switching on hydroelectric plants sitting in reserve. Such hydroelectric plants are usually small-scale and can only produce energy for as long as there is enough water in storage. The water can be pumped back to the higher altitude reservoir when power output exceeds demand again. The energy cycle of pumped hydroelectric is 90% which means it is a highly efficient process which incurs a low cost. However, the abundance of available reservoirs is limited and environmental impact has to be taken into consideration.

One of the alternative means of energy storage is compressed air. In this case, rather than pumping water, compressors are used to compress air either in pressure vessels or underground caverns. The compressed air is subsequently released when the power output drops to generate energy.

Flywheels have been used to a much lesser extent for storing energy due to the technical challenges that they are associated with. Thermal energy storage has received more interest. However, it has been so far primarily associated with Concentrated Solar Power (CSP) plants. CSPs have seen limited penetration in the global energy mix primarily in Spain in Europe and the U.S. followed by some projects in the UAE, China, Morocco and India.

Large-scale battery stacks have been constructed for energy storage purposes but these have limited capacity. The advantage of large-scale battery stacks is that they are highly efficient with up to 90% of the energy stored. Unfortunately, battery stacks cannot cope with extremely high and discharging rates as this can cause thermal runaways and catastrophic failure of the stacks.

Batteries tend to have low to moderate lifetimes although this depends on their exact chemistry as well as operational pattern. Their distinct advantage apart from being highly efficient in storing electric energy is that they can be switched on almost instantaneously and their discharge rate can be controlled. However, their limited storage capacity suggests that battery systems cannot be used over prolonged periods of time as they will eventually get discharged. Fig. 3 shows the electricity storage capacity in the U.S. by type of storage technology [11]. Pumped hydroelectric is by far the dominant energy storage system with the rest of the technologies making up only 6%. The majority of the electricity storage capacity by alternative means other than pumped hydroelectric is almost equally split between thermal storage and batteries, with compressed air and flywheels used only to a tiny extent.

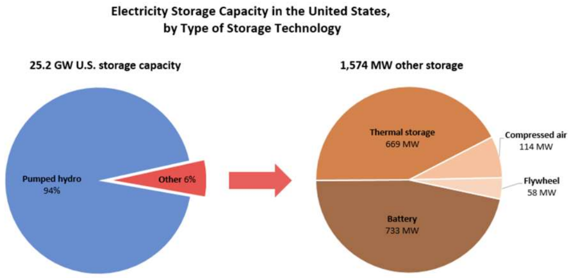

Fig. 3. Electricity storage capacity in the U.S. by type of storage technology (CC-BY) [11].

Other problems associated with the large-scale implementation of battery storage include the availability of manufacturing capacity, which is competing with the EV market and their end-of-life handling. There is so far no easy means of recycling Li-ion batteries which are the ones with the highest energy density. Although, Ni-Cd batteries which are currently used in some utility-scale battery storage systems are almost 100% recycled have lower performance than Li-ion batteries.

The cost of the batteries per MWh stored remains much higher than pumped hydroelectric [12]. This makes it difficult to justify projects beyond the absolute requirement which is for temporary stabilisation of the electric grid.

4 Green hydrogen

Hydrogen is extensively use for processing purposes in oil refineries and chemical processing plants. Most of hydrogen production is derived almost exclusively from fossil fuels. Global hydrogen production was 47% from natural gas, 27% from coal, 22% from oil (as by-product) and only around 4% came from electrolysis. A significant amount of hydrogen is reused where it is produced for various refining and chemical processes. As mentioned earlier green hydrogen represents no more than 1% of the total hydrogen production. Green hydrogen is the only type of hydrogen which is generated using electrolysis powered from renewable energy [12]. The rest of the hydrogen produced by electrolysis is through using fossil-fuel power generation.

For any application, hydrogen has to be stored either as a gas in high-pressure gas cylinders up to 700 bar, in liquid form in cryogenic tanks, or captured in metal hydrides. Thus, production of hydrogen is not the only process that requires energy since storage of hydrogen in any form will also require a certain amount of energy to be spent. In the case of hydrogen storage in pressure vessels energy is only expended during compression.

For the production of liquid hydrogen, energy has to be spent to liquify the gas and subsequently for maintaining the cryogenic temperature so hydrogen does not evaporate. However, in practice industrial-scale cryogenic tanks are not temperature-controlled. Thus, they have to allow evaporated hydrogen to be released in large amounts to avoid pressure exceeding the structural stress limit of the tank. This process in itself, apart from incurring an energy penalty in the form of hydrogen being lost to the atmosphere without being used has also been reported to impact the presence of atmospheric methane, which is a far more potent greenhouse gas than CO_2. This is due to the fact that when hydrogen is released in large amounts it can affect atmospheric composition since it decreases the tropospheric concentration of hydroxyl (OH) radicals, which the major tropospheric oxidant. This results in an increase in the atmospheric lifetime of methane and hence, prolongs its effect and impact as a greenhouse gas [12].

Metal hydrides require energy to be expended for both storing hydrogen as well as retrieving it. Hydrides release the hydrogen atoms stored by heating them up, a process which requires energy. Proposals have been made to store hydrogen in the form of ammonia (NH_3) which is potentially hazardous since its combustion produces irritating, corrosive and toxic gases, among other hazards. Its accidental release in liquid form can damage the environment as it is highly toxic.

The typical efficiency of the electrolysis process is between 70-80% when using Proton Exchange Membrane (PEM) electrolysers. Thus, a significant part of the energy used to produce the hydrogen is lost. Depending on the type of hydrogen storage, additional energy will have to be expended to allow hydrogen to be stored in gas or liquid form or captured in a hydride. Pressure vessels can be manufactured up to a limited size and thus, do not have a practical application from a utility-scale point of view. Hydrides can be employed up to moderate scale thus, the likely form of storage for any utility-scale application would need to be in liquid form.

Long-term storage of hydrogen in gas or liquid form can pose significant materials challenges including weld-related due to Hydrogen Induced Cracking (HIC) and Stress-orientated HIC (SOHIC).

Hydrogen can be used either in fossil-fuel power plants to reduce their greenhouse gas emissions or using large-scale fuel cells to generate electricity with water vapours being the only by-product. PEM fuel cells can achieve an efficiency of up to 60% and have very quick start-up times. Storage capacity of hydrogen can easily exceed the storage capacity offered by utility-scale battery systems. However, the hydrogen infrastructure is lagging behind and there is also the matter of energy penalty incurred. However, as renewable energy increases it may become more cost-effective to use the excess energy to produce hydrogen via electrolysis and store it is larger amounts.

The issues recently arising with EVs, including battery recycling, may mean that FCVs eventually get a commercial breakthrough in the coming years. This of course will necessitate the appropriate hydrogen infrastructure to be in place. Nonetheless, it may also justify the production of green hydrogen, thanks to the various financial incentives arising through the use of hydrogen in the transport sector apart from utility-scale energy production.

5 Conclusions

The increasing use of variable renewable energy sources renders the reliable and stable operation of electric grids more challenging. The imbalance that may arise between demand and production, particularly due to transient events, requires the grid operators to be able to rapidly switch on additional power when demand increases or reduce the supply accordingly when demand is lower. This is not straightforward and apart from requiring adequate capacity to provide energy or store energy, this has to take place rapidly and with minimum energy penalty to be financially viable. The technical challenges and long-term life-cycle analysis of different solutions has to be taken into account including how they compete financially when compared with state of the art pumped hydroelectric. In this study, we have briefly evaluated the advantages and disadvantages of battery and hydrogen-based energy storage. It is hard to expect batteries being used other than a temporary means of rapidly balancing the grid over limited time periods. Hydrogen storage on the other hand offers much larger capacity potential at a competitive cost. Perhaps this coupled with the possible advent of FCVs as a competitor to EVs, and the ever-increasing installation of wind energy and photovoltaics may render the production and storage of green hydrogen financially viable as well as an appropriate and reliable way of balancing the electric grid in the future.

References

1. IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647
2. P. M. Foster et al. Indicators, of Global Climate Change 2022 : annual update of large-scale indicators of the state of the climate system and human influence, Earth System Science Data, Vol. 15, Issue 6, pp. 2295-2327, 2023.
3. International Renewable Energy Agency Report, 2021, https://www.irena.org/Energy-Transition/Technology/Hydrogen#:~:text=Electricity%20had%20a%20global%20average,capacity%200.7%20GW%20in%202021
4. GWEC Global Wind Energy Report 2024, https://gwec.net/wp-content/uploads/2024/05/GWR-2024_digital-version_final-2.pdf
5. Snaposhot of global PV markets 2024, International Energy Agency, Photovoltaic Power Systems Programme report, https://iea-pvps.org/wp-content/uploads/2024/04/Snapshot-of-Global-PV-Markets_20241.pdf
6. Wind energy in Europe 2019, Trends and statistics, WindEurope Report, 2020, https://windeurope.org/wp-content/uploads/files/about-wind/statistics/WindEurope-Annual-Statistics-2019.pdf
7. Average capacity factor for utility-scale solar PV systems worldwide from 2010-22, Statista, https://www.statista.com/statistics/799330/global-solar-pv-installation-cost-per-kilowatt/ -power-demand/
8. Data source : Energy Institute – Statistical Review of World Energy 2023 (CC-BY) https://ourworldindata.org/renewable-energy
9. Data source : IEA https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028
10. O. Smith, O. Cattell, E. Farcot, R. D. O'Dea, K. I. Hopcraft, The effect of renewable energy incorporation on power grid stability and resilience, Science Advances, 8, 2 March 2022.
11. Source : Database of National Technology & Engineering Sciences of Sandia, LLC (NTESS), operator of Sandia National Laboratories for the U.S. Department of Energy/National Nuclear Security Administration. https://gesdb.sandia.gov/
12. N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle, K. Shine, Atmospheric implications of increased hydrogen use, Technical report, April 2022. https://assets.publishing.service.gov.uk/media/624eca7fe90e0729f4400b99/atmospheric-implications-of-increased-hydrogen-use.pdf