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IMPACT OF EFFICIENCY CALCULATION METHODS ON THE ADOPTION OF ENERGY STORAGE TECHNOLOGIES[1]

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ABSTRACT

An essential parameter in the performance of energy storage systems is their round-trip efficiency. Batteries are the reigning energy storage option globally and, are believed to be the primary competition to green hydrogen energy storage in terms of system economics. For lithium-iron phosphate (LFP) batteries, two different round-trip efficiency calculation methods were observed i.e., constant efficiency and yearly repeating efficiency in existing literature and professional photovoltaic (PV) designing softwares respectively. Unfortunately, both do not follow the practical scenario. Therefore, a degradation trend shifting method was used to analyse the round-trip efficiency over 10 years of an LFP battery system associated with a 5MW solar PV plant. The primary performance simulation for this method was done using PVsyst. The calculated round-trip efficiencies and the investment cost for the storage systems were then used to calculate the levelized cost of storage (LCOS). The LCOS for the three efficiency trends in batteries was also compared with the LCOS of a green hydrogen energy storage to get an idea about how the differences in the relative system economics affects the perception of an energy storage system. The results indicate that for the constant efficiency and yearly repeating efficiency methods, the difference in the LCOS between batteries and green hydrogen is large. However, for the proposed trend shifting method, the LCOS after 10 years for batteries is slightly less than green hydrogen and after 20 years the LCOS for hydrogen and batteries is comparable.

Keywords: batteries, hydrogen, efficiency, cost of storage

NOMENCLATURE

LFP	Lithium Iron Phosphate
PV	Photovoltaic
SOC	State of Charge
SEI	Solid Electrolyte Interface
SNL	Sandia National Lab
LCOS	Levelised Cost of Storage
MW	Mega-Watt
LOHC	Liquid Organic Hydrogen Carrier
MWh	Mega-Watt Hour
PEMEL	Proton Exchange Membrane Electrolyser
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
n	Project lifetime in years
r	Discount rate
E_{OA}	Energy supplied by storage system to the grid
E_{OAB}	Energy supplied by batteries to the grid
E_{OAH}	Energy supplied by green hydrogen system to the grid
$\eta_{battery\ daily}$	Battery efficiency on a day
$E_{excess\ daily}$	Excess energy produced by PV array daily
$E_{GT\ output/\ kg\ hydrogen}$	Energy output of gas turbine from 1 kg hydrogen
E_{PEMEL}	Energy required by the electrolyser to generate 1 kg of hydrogen
LCOE	Levelised Cost of Energy
O&M	Operation and Maintenance
HFGT	Hydrogen Fuelled Gas Turbine

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[1] The initial analyses of the results presented in this paper were discussed in the Energy Technology M. Phil thesis of A. Singh at the Cambridge University Engineering Department.

1. INTRODUCTION

Energy storage plays a crucial role in aiding the integration of low carbon technologies into the electricity grid. An important factor which affects the implementation of any energy storage is the system economics. It is used for comparing different energy storage technologies to figure out which one would be the most suitable, based on the requirements of the economy. The round-trip efficiency of the storage system has a massive impact on the economics. A system with high initial investment cost and high efficiency may be better than a system with low initial investment cost and low efficiency. Currently, pumped hydro energy storage holds around 75% of the global stored energy whereas, the remaining share is dominated by batteries [1]. Countries are heavily investing in battery technology for grid scale storage due to their scalability and versatility with different locations and applications [1].

Out of the current available battery chemistries, Lithium Iron Phosphate (LFP) is the preferred option for large scale energy storage [2]. This is mainly due to the high cycle life, energy density and efficiency compared to its predecessor- the lead acid battery and lower cost compared to other available lithium-ion chemistries [2].

Multiple studies have been done that compare the performance of energy storage systems based on efficiency and cost but, there the efficiency of LFP batteries is assumed to be constant at round 75-85% for the entire system life of 15-20 years. This constant efficiency model was observed in Hernandez et al., Pellow et al., Andujar et al and Asri et al [3, 4, 5, 6].

Meanwhile, in photovoltaic (PV) system designing softwares like PVsyst, the battery degrades during the first year of use and for the subsequent years, the software re-calculates the degradation from 100 percent efficiency. This equates to having a new battery bank at the start of each year, which is not economically feasible. The primary reason for this trend in PVsyst is the limitation of the simulation time period from 1st January to 31st December. Hence, when the simulation is performed for any subsequent year, the model is unable to include the previous battery performance data and assumes that it is a new battery bank. Such softwares are used by professional PV system designers and, due to the efficiency calculation method used here, the simulations give exaggerated data for energy supplied from the batteries to the consumer. This can lead to problems in assessment of system economics as was the case in a previous study related to electric vehicle charging [7]. Here, the investment cost required for every kilometre of travel facilitated by an off-grid solar powered electric vehicle charging station with batteries was calculated [7]. The daily energy supplied by the charging station was calculated using PVsyst for every 7 years which gave exaggerated energy output values due to the yearly repeating model of the battery system. Therefore, the actual investment cost per kilometre would be higher than the reported values. These instances show that to model the plant performance accurately, it is necessary to model the battery efficiency as close to the real scenario as possible.

Batteries degrade from the first day of use due to various factors such as operation at extreme temperatures, operation till extreme state of charge (SOCs), high discharge or charge current and continuous cycling [8, 9]. These factors propagate irreversible side reactions within the LFP cell that can decrease the available lithium and iron ions, damage the solid electrolyte interface (SEI) layer due to depositions or cracks and cause structural changes in the electrodes [8, 9, 10]. According to a study conducted by the Sandia National Lab (SNL) [8, 10], LFP batteries degrade the most due to extreme temperatures. The number of cycles of the battery are related to the charging-discharging pattern. This depends on the energy demand and the application of the energy storage system such as- seasonal energy storage, daily energy storage, peak shaving, or hybrid mode [11]. Therefore, efficiency models that include these varying factors are extremely important to predict the battery performance. In this study, we have modified the existing PVsyst battery degradation method to present a battery efficiency model that is closer to realistic conditions than other existing models.

During the initial stages of storage technology implementation, cost is a key factor [12]. Low cost enables the storage method to win market share. The cost is analysed with respect to other widely available storage methods. If the efficiency and energy output of the technology is high, then resource constraints become the boundary condition for its implementation [12].

This study compares the levelised cost of storage (LCOS) of an LFP battery bank connected to a 5-megawatt (MW) PV plant for the three battery efficiency scenarios mentioned above- constant efficiency as seen in existing literature, yearly repeating efficiency as seen in PVsyst and the proposed degradation trend shifting method. The LCOS of the battery has also been compared to green hydrogen production with liquid organic hydrogen carrier (LOHC) storage and electricity generation in gas turbine power plants. The aim of this comparative study is to understand the impact of different round-trip efficiency models of lithium-ion batteries on the system economics and, on the adoption of other energy storage technologies such as hydrogen.

2. METHOD

The first part of this study was the simulation of the plant performance using the inputs given in Figure 1 and 2. Figure 1 shows the scaled down generic daily load profile in India for a 5MW grid. The parent data for the average daily load profile for India was obtained from [13]. Figure 2 is a schematic diagram for the simulation steps in PVsyst.

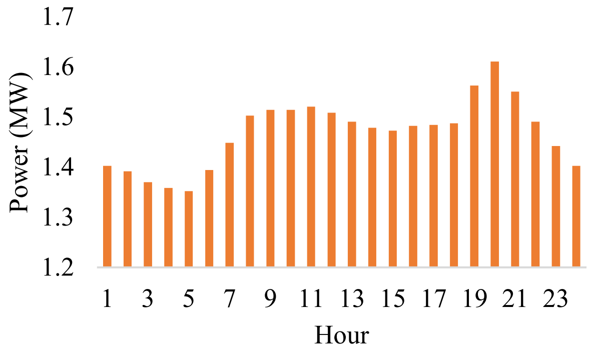


FIGURE 1: HOURLY POWER CONSUMPTION PROFILE FOR EACH DAY (2016 DATA)

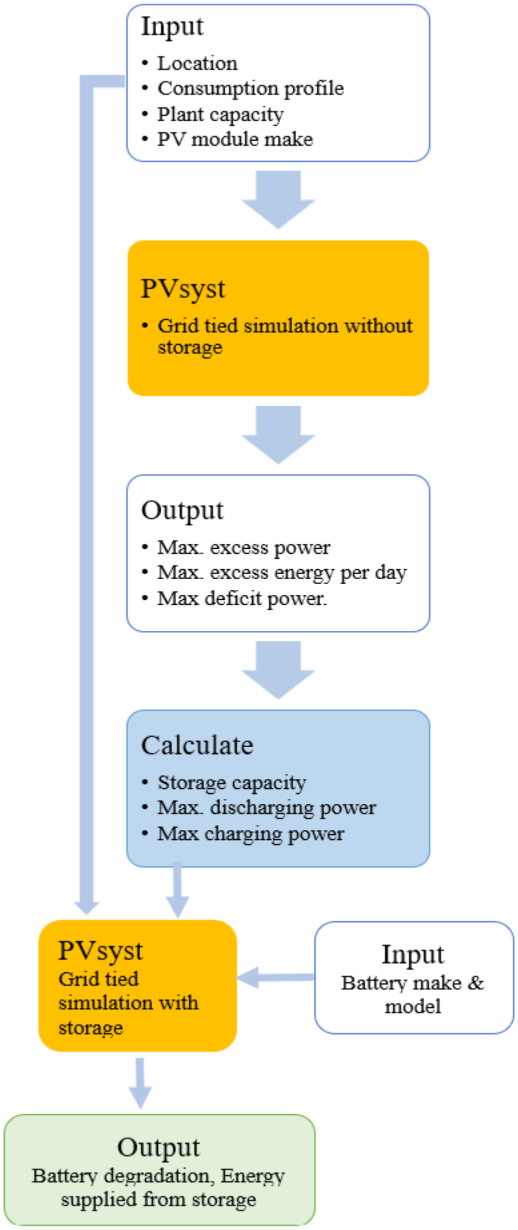


FIGURE 2: SCHEMATIC DIAGRAM FOR THE SIMULATION STEPS

The selected location was 23.5 °N, 82.5°E in India and the plant capacity was 5MW. In the results obtained from the first round of the PV system performance simulation, the maximum excess power was the charging power of the storage system, the maximum deficit power was the discharging power of the storage system and lastly, the maximum excess energy per day was the capacity of the storage system i.e. 16.78 MWh. The storage system was designed for short-term discharging.

The batteries were set to operate at a maximum SOC of 95% and a minimum SOC of 20%. After the second round of simulations, it was verified that the batteries discharge to 20% SOC daily. For the hydrogen chain- green hydrogen production using a 3MW polymer electrolyte membrane electrolyser (PEMEL), storage using liquid organic hydrogen carriers (LOHC) and combustion using 1.6MW gas turbines were considered.

During the second round of simulations, the battery operating temperature was set at the external ambient temperature and the battery ageing data was generated for 10 years. The battery round-trip efficiency was plotted for 3650 days i.e., over 10 years of system life for the 3 schemes discussed and the below scatter plot i.e., figure 3 was obtained. The orange line is horizontal to the x-axis as it represents constant efficiency discussed in most existing literature. The blue line represents the efficiency calculated by PVsyst. At the beginning of each year the blue line starts from 100% battery efficiency and the blue line shows a repeating trend. The first blue line close to the y-axis, represents battery degradation for the first year of the system life.

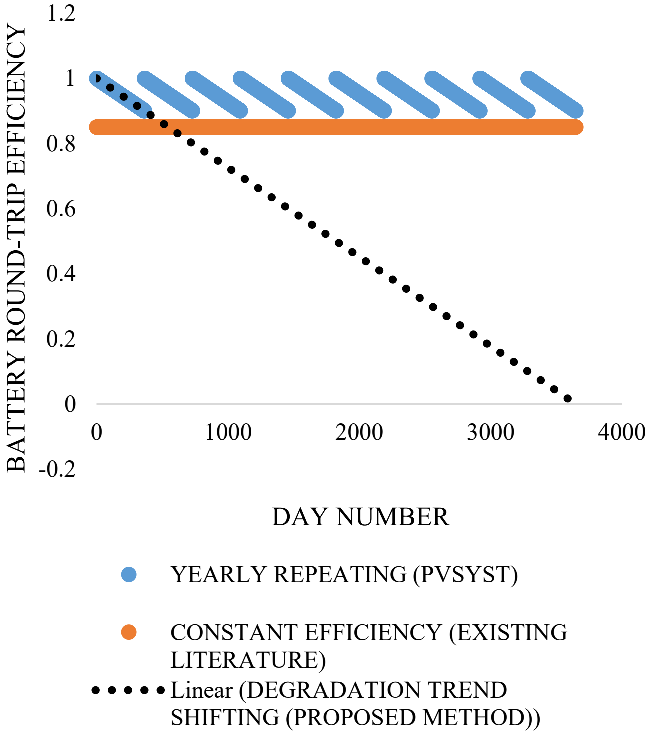


FIGURE 3: BATTERY EFFICIENCY DEGRADATION PROFILE FOR THE 3 SCHEMES OVER 10 YEARS OF SYSTEM LIFE

To calculate the actual loss in battery efficiency, the degradation trend shifting method was used where, the simulation was done for each year separately and the battery degradation curve for each year was shifted vertically such that, it followed the final efficiency of the previous year. Since, the corresponding hourly energy demand was same for all years, it was predicted that the degradation profile would be the same for all years. Figure 3 shows that the degradation profile in the first year is linear and for the subsequent years, this was extrapolated. This is represented by the dotted black line in figure 3. The linearity of the degradation profile was validated by the study conducted at SNL [8]. The slope of the graph depends on the combined effect of multiple variables that govern the loss in battery capacity.

The second part of the methodology was the economic comparison. For cost estimation of the storage system, the initial capital expenditure (CAPEX) and the variable operating cost (OPEX) both were considered. Using the cost of the different aspects of the storage system, the levelized cost of storage (LCOS) was calculated as shown in equation 1-3 [3]. The LCOS is similar to LCOE but the expenditure included is only for the storage system rather than the entire energy generation, storage and transmission system as is the case with LCOE.

$$LCOS = \frac{\sum_{i=1}^{n} \frac{(CAPEX + OPEX)_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{(E_{OA})_i}{(1+r)^i}} \quad (1)$$

$$E_{OAB} = \sum_{i=1}^{365} (\eta_{battery\ daily} \times E_{excess\ daily})_i \quad (2)$$

$$E_{OAH} = \sum_{i=1}^{365} (E_{GT\ output/kg\ hydrogen} \times \frac{E_{excess\ daily}}{E_{PEMEL}})_i \quad (3)$$

Here,

n = project lifetime in years

r = discount rate i.e., assumed to be constant at 10% for the project lifetime [3].

E_{OA} = Energy supplied by the storage system to the grid in a year (MWh)

E_{OAB} = Energy supplied by the batteries to the grid in a year (MWh)

E_{OAH} = Energy supplied by the green hydrogen system to the grid in a year (MWh)

$\eta_{battery\ daily}$ = Battery efficiency on a day as shown in Figure 1.

$E_{excess\ daily}$ = Excess energy produced by the PV array daily as calculated in the PVsyst simulations (MWh)

$E_{GT\ output/\ kg\ hydrogen}$ = Energy output on combustion of 1kg hydrogen in the gas turbine. This is roughly 13kWh [14].

E_{PEMEL} = Energy required by PEMEL to generate 1 kg of hydrogen. This ranges between 40-60 kWh. For the calculations in this study, 50kWh was assumed [14, 15].

For calculating the LCOS, we considered two project lifetimes- 10 years and 20 years, to see the impact of battery replacement and PEMEL stack replacement in the 11th year, on the LCOS. Table 1 and Table 2 show the CAPEX and OPEX costs associated with the green hydrogen method and LFP batteries respectively.

TABLE 1. BREAKDOWN OF THE COSTS IN THE HYDROGEN VALUE CHAIN

CAPEX	**COST/ UNIT**
Electrolyser plant	1240 $/ kW electrolyser capacity [3, 16] (Cost of the PEM stack is 60% of the electrolyser plant cost)
Soft cost	30% of electrolyser plant cost [3]
Materials for LOHC storage (catalysts and organic fluid)	5 $/ kg of hydrogen stored [17]
Reactor for hydrogenation and dehydrogenation	134 $/ kg of hydrogen stored [17]
Storage tank for organic fluid	3 $/ kg of hydrogen stored [17]
HFGT plant + catalytic converter	1320 $/ kW rated capacity [3]
Land	250000 $/acre [15, 18, 19]
OPEX	**COST/ UNIT**
O&M of electrolyser	75.2 $/kw-year (kW is for electrolyser capacity) [3]
Water for electrolysis	0.002 $/liter [3]
Fixed O&M of HFGT plant	14 $/kW-year (kW is for HFGT capacity) [3]
Variable (non-fuel) O&M of HFGT plant	2 $/kW-year [3]

Around 5.55 kWh of electricity is used to electrolyse 1 kg of water [3, 15]. Due to the lack of data around commercial PEMEL facilities, ACES Delta facility was considered as a reference point and it was assumed that 26.5 litres of water are required to produce 1 kg green hydrogen and the required land area for every

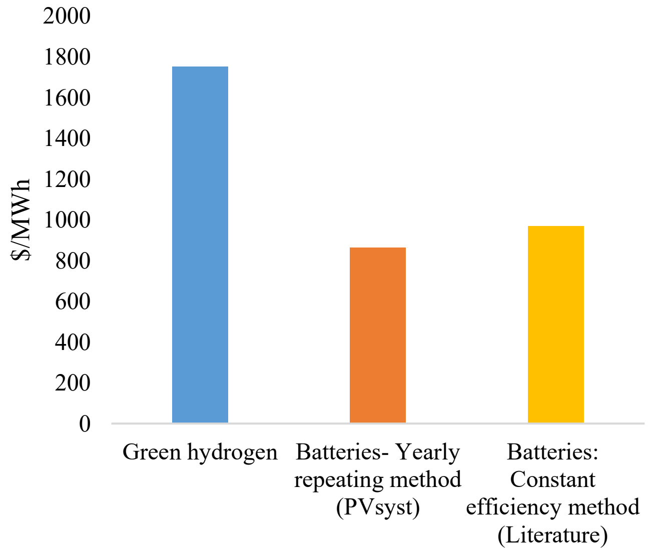
MW of electrolyser capacity is around 1-acre [15]. The thermal efficiency of the gas turbine was 40% based on the experiments done by Kawasaki [20].

TABLE 2. BREAKDOWN OF THE COSTS IN BATTERY STORAGE

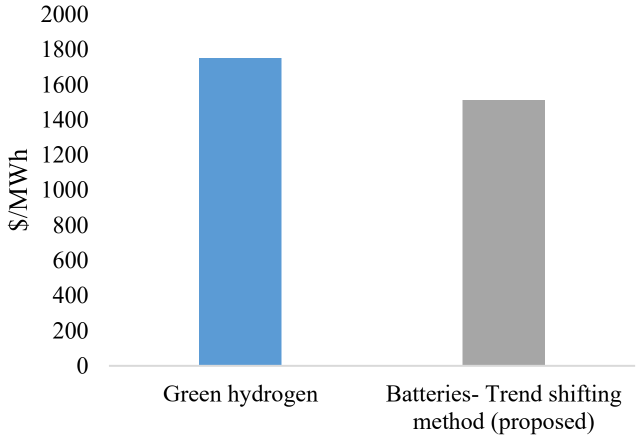
CAPEX	**COST/ UNIT**
Batteries	8,607 $/ battery [14]
Other (Land + shed structure + wiring)	4,000,000 $ [12, 13]
OPEX	**COST/ UNIT**
O&M	117 $/ MWh-year (MWh is for battery capacity) [2]

3. RESULTS AND DISCUSSION

Figure 4(a) portrays the 'green hydrogen versus batteries' comparison perspective that exists due to the two prevalent battery efficiency models- constant efficiency and yearly repeating efficiency. Whereas, figure 4(b) shows the comparison perspective with the trend shifting method. Overall, these graphs present the comparison currently being made versus the comparison that should be done to have a better understanding of the available energy storage systems.



(a)



(b)

FIGURE 4: (a) THE LCOS COMPARISON THAT IS BEING DONE (b) THE LCOS COMPARISON THAT SHOULD BE DONE

The value of LCOS for the yearly repeating PVsyst model is almost half of the LCOS for the proposed trend shifting method. The LCOS for existing literature in this case is slightly higher than the LCOS for PVsyst however, its value strongly depends on the assumed constant efficiency. If the assumed constant efficiency decreases, then the value of LCOS will increase. The LCOS for hydrogen is slightly higher than the LCOS for the battery trend shifting method. However, this includes the land cost for the hydrogen plant which is highly variable. If the production costs of hydrogen decrease or PEMELs and gas turbines are made more efficient, the LCOS for hydrogen will reduce. Currently, the yearly repeating model and the constant efficiency model are used to analyse batteries and the values of LCOS clearly show that the gap between these two models and the extrapolation method and hydrogen is drastic. These exaggerated results could be one of the reasons of hydrogen being labelled as expensive compared to established energy storage such as batteries. Therefore, most of the energy storage research and investments are related to batteries.

The exact value for LCOS depends on all factors that impact the installed storage capacity and its efficiency such as- the excess energy from PV, charging-discharging pattern, components used in the hydrogen chain and additional costs such as land and water. However, the common thought resulting from figure 4(a) would be underlining the high cost of hydrogen whereas in figure 4(b), it would be highlighting the inefficiency of batteries.

Figure 5 shows the LCOS for hydrogen chain and the battery trend shifting method for a system life of 10 years and 20 years. The LCOS values decreased as the system aged from 10 years to 20 years and, the gap between the LCOS of hydrogen and the battery extrapolation method also decreased.

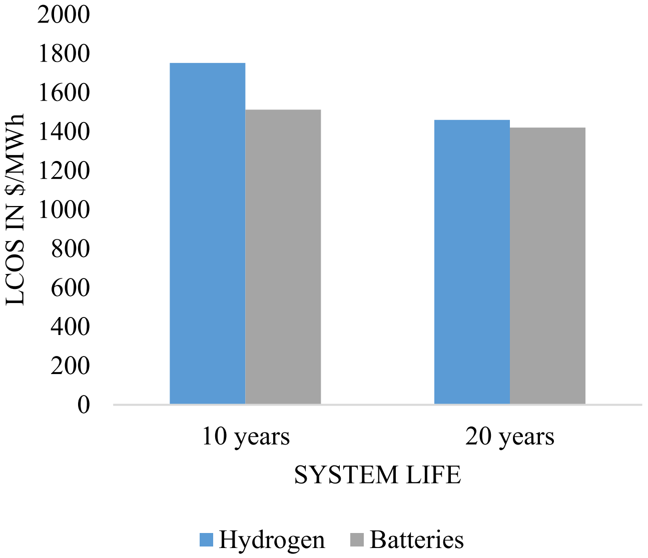
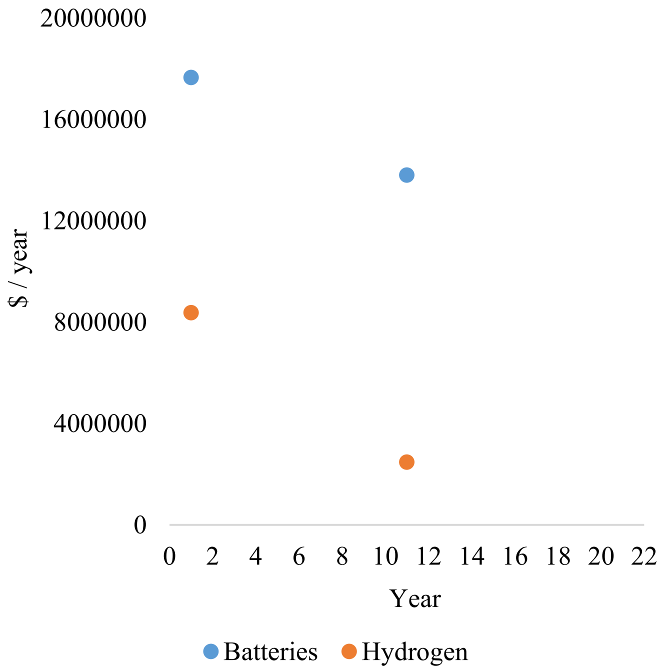
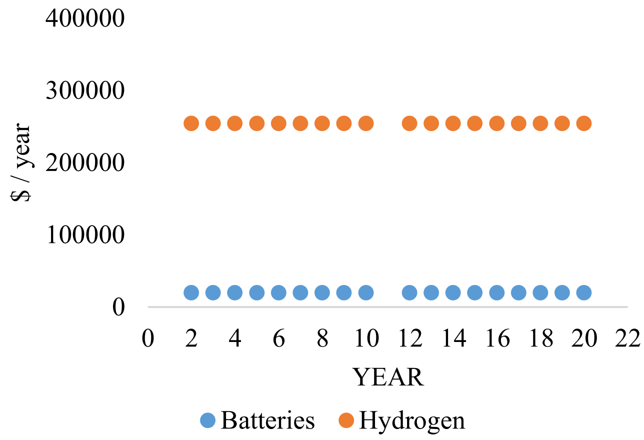


FIGURE 5: LCOS FOR HYDROGEN AND THE BATTERY TREND SHIFTING METHOD FOR 10 YEARS AND 20 YEARS

A closer look at the yearly CAPEX and OPEX investments in batteries and the hydrogen system represented by Figure 6 shows that the CAPEX investments are higher for batteries and the OPEX investments are higher for hydrogen. There is an additional CAPEX in the 11th year due to the battery and electrolyser stack replacement. Hence, the decrease in the LCOS gap observed in Figure 5.



(a)



(b)

FIGURE 6: INVESTMENT FOR GREEN HYDROGEN AND BATTERIES TILL 20 YEARS OF SYSTEM LIFE (a) CAPEX (b) OPEX.

The CAPEX and OPEX costs involved vary a lot with the technology that is being used in the energy storage and production value chain. A change in the hydrogen storage technology from LOHC to pressure vessels would drastically increase the required CAPEX and hence, increase the LCOS which would demotivate developers and investors from working on green hydrogen projects.

4. CONCLUSION

Batteries are the most common and scalable form of energy storage hence; any new energy storage method such as green hydrogen, should be technically, economically, and ecologically feasible in comparison to batteries. The economic performance of energy storage is directly related to its round-trip efficiency. In all existing literature and PV simulation softwares, the battery efficiency calculation is not close to the real scenario. This makes batteries look a lot more efficient than they actual are compared to hydrogen. This study proposed a trend shifting battery efficiency model and compared the LCOS of a green hydrogen plant and a battery system for a 5MW solar PV plant.

The results indicated that there was a significant difference between the LCOS of the three battery efficiency schemes. Placing hydrogen next to the existing battery efficiency models and the trend shifting model has a huge impact on the way these energy storage methods are perceived, especially by project developers and investors.

Compared to the trend shifting method, the LCOS was higher for hydrogen after 10 years and after 20 years, the LCOS was almost the same for both the battery and green hydrogen plant. This was due to the consistently decreasing battery efficiency and the investment pattern. The overall CAPEX required was higher for batteries but it was concentrated in two years for the considered case. Meanwhile, green hydrogen had a higher OPEX but, that was spread out over the system operating years.

The calculations done in this study and the values presented in the results are not concrete values. The exact values of LCOS, depend on a lot of other factors which are variable such as the battery operating pattern, variable costs, other resources required and auxiliary services. The overarching point in this study is an emphasis on the importance of including efficiency degradation models in the economics and comparative studies of energy storage systems. The values considered in this study enable in visualizing the order of magnitude of the difference caused by including and excluding energy storage degradation.

Including the efficiency degradation of the electrolyser and production of hydrogen using electricity from other sources during other times of the day will add complexity to the calculation of LCOS but, that would be able to give a clearer picture of the economic differences between batteries and green hydrogen.

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