COMPARISON BETWEEN DIESEL GENERATOR AND H_2 STORAGE IN STAND-ALONE PHOTOVOLTAIC SYSTEMS

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Abstract

Hydrogen as a long-term storage medium in photovoltaic systems has been a subject of interest in recent years. Such a system uses an electrolyser - H_2 storage - fuel cell combination along with battery as short-term storage to minimize the loss of load probability. Conventionally, the same goal is achieved including a diesel generator (DG) in the PV systems. In present work, an economic comparison is carried out between DG based system and various possible configurations of H_2 based systems suitable for standalone application in the range of 5 kW. Both the systems are compared with the help of boundary curve obtained from life cycle cost analysis and excess energy available in the PV-DG system. Boundary curve enables in determining cost-effective system for a site, specified by onsite fuel cost including transportation cost and seasonal solar energy difference. It is found, a system with URFC regenerative fuel cell and metal hydride storage offers most cost-effective solution. With steeply rising fossil fuel prices and developments in H_2 technology, globally more regions will be cost-effective for PV-H_2 systems.

Nomenclature

DG	Diesel Generator
DOE	Department of Energy
FC	Fuel Cell
HG	Hydrogen Generator
HPE	High pressure Electrolyser
IEA	International Energy Agency
LOLP	Loss of Load Probability
MEA	Membrane Electrode Assembly
MH	Metal Hydride
PE	Polymer Electrolyte
PEM	Proton Exchange Membrane
PGM	Platinum Group Metals
PV	Photovoltaic
SOC	State of Charge
URFC	Unitized Regenerative Fuel Cell

Introduction

The increasing concern on national and international level about the climate change and energy security is the motivating factor towards a dramatic paradigm shift from fossil fuels to renewable energy sources. The intermittent natures of the renewable energy sources are the main hurdles towards the wide implementations. Lead-acid batteries show excellent behaviour to overcome the diurnal variation and they are widely used in photovoltaic (PV) system to achieve higher energy supply reliability. However, due to high self-discharge they fail to overcome the seasonal mismatch in the renewable energy systems.

To minimize the loss of load probability (LOLP) in standalone PV systems, conventionally diesel generator (DG) is used as a backup in combination with battery. In such a system peak loads can be met by the DG set together with the stored energy in the battery or the renewable energy converter. The system is sized to reduce the fuel consumption of the diesel generator by 70-90%, therefore, relying heavily on the renewable resource [1]. Nema et al. [2] has reported various cases which clearly indicate that the optimal sizing of the different components in a PV-DG hybrid system is must to minimize LOLP and costs. To achieve high power supply reliability either the energy converter or the battery is usually oversized [3]. As a consequence, a large amount of energy is wasted in the system and the average state of charge (SOC) of the battery also remains high for prolonged period during good season.

The generator can be replaced by a long-term storage system which is complementary to the battery. Such a system consists of hydrogen storage in combination with an electrolyser for onsite hydrogen generation and fuel cells to overcome the disadvantages in a DG based hybrid system. In such a system, the surplus energy during the good season is utilised in the electrolyser to produce hydrogen for the long-term use. The deficit in the system during the bad season is overcome by using stored H_2 through the fuel cells. Since, such systems are capable of producing fuel (H_2) on-site; they are more attractive for remote applications where continuous fuel transportation is difficult and expensive. Various configurations of such systems for stationary applications have been studied [4, 5].

Ghosh et al. [6] has compared H_2 storage with diesel generator in a PV-Wind hybrid system and the least cost for H_2 storage is obtained when used with only PV systems. Using a similar approach, an effort has been made in this present work to compare different PV- H_2 standalone systems, considering the life cycle costs.

In present study, various possible configurations for long-term storage loop is considered and compared with the conventional diesel generator system. The long-term storage configurations include hydrogen IC engine systems, Unitized Regenerative Fuel Cell (URFC) based systems, High Pressure Electrolyser (HPE) based systems and Metal Hydride (MH) storage. Though Polymer Electrolyte Fuel Cells (PEFCs) offer many advantages over other types, the high cost resulted from the platinum catalyst poses main obstacles towards the commercialisation.

Commercialisation of PEFC systems will result in an increase in the demand of Platinum Group Metals (PGMs). Hence, platinum recycling is critical to the long-term sustainability of PEFCs in addition to the cost. A lion share of the platinum used in PEFCs can be recovered [7] at the end of their lifetime. Hence, there is a high salvage value at the end of life for PEFCs which is often neglected in the life cycle cost analysis. In present study the salvage value of the fuel cell is considered for the comparisons.

Different locations on the northern hemisphere are considered for analysing the economic feasibility of different configurations. In this purpose, different locations are being characterised based on the seasonal solar radiation variation and the accessibility of the location which is reflected on the fuel cost at the site of application.

Systems configurations

In present study, PV-DG system is considered as a benchmark system and compared as a replacement with various H_2 based systems as discussed below.

PV-DG hybrid system

In a PV-DG hybrid system a PV array is configured in parallel with DG systems to meet the load. Energy flow in a PV-DG hybrid energy supply system is shown in Fig. 1.

Diesel generator based systems have low capital cost as the technology is fairly well established. However, such systems are typically oversized, and during the months with high solar

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insolation (good season), a significant amount of energy is wasted in the system which has been termed as excess energy in present study.

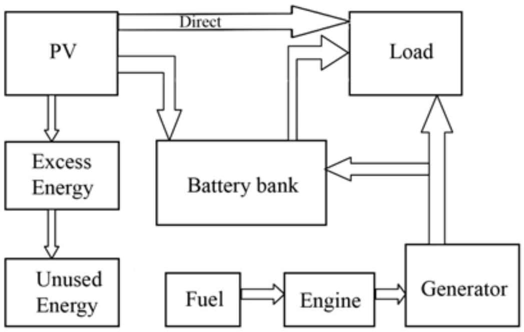

Fig. 1 Schematic diagram of energy flow in a PV-DG hybrid system

Moreover, diesel based systems cause greenhouse gas emission and have high operational and maintenance (O&M) cost. They also suffer from lower efficiency at partial load.

PV-H_2 system

In hydrogen based system, DG set is replaced by a H_2 based long-term storage to tackle the seasonal variation in the PV systems. This eliminates the disadvantages in a DG based hybrid system like emissions of greenhouse gases, lower fuel conversion efficiency at partial loads and noisy operation. The H_2 based systems utilize the excess energy leading low O&M cost. However, the most of the technologies associated with different components are yet to be matured leading to a high capital cost. Hydrogen based long-term storage consists of electrolyser, H_2 storage and fuel cells to convert the excess energy in the system after storing in the battery. The use of H_2 as energy carrier enables season-to-season storage of energy [8]. Different combinations of the long-term storage considered in present study are discussed below.

Fuel cell based systems: A typical stand-alone PV- H_2 system comprises an array of photovoltaic panels, electrolyser, H_2 storage, and PEFC as shown in Fig. 2a. The surplus energy during the good season which is wasted in a PV-DG hybrid system is used in the electrolyser and the fuel (H_2) is produced at the site of the application. The main issues associated with such a system are the high cost arising from the fuel cell, electrolyser and H_2 compressor.

H_2-IC engine based system: As the IC engine technology is cost-effective and matured, it is considered as a replacement of fuel cell in H_2 based long-term storage system as shown in Fig. 2b. Such a system combines the advantages in both systems like IC engines being a mature technology, but with almost no pollution and the low investment and operational costs. Hydrogen IC engines has less stringent H_2 purity requirements than fuel cells whose performance can be degraded by even slight impurities. Conventional IC engines cost in the range of \$30 kW^{-1} and the cost of hydrogen IC engines can be at the most up to 1.5 times the cost of a gasoline IC engine [9].

Unitized regenerative fuel cell based system: A Unitised Regenerative Fuel Cell (URFC) combines the electrolyser and fuel cell functions in a single unit lowering the capital cost. In the conventional PV-H_2 system, a electrolyser is used for the H_2 generation, and a separate PEFC stack is used for the H_2 conversion. Since, the basic structures of the electrolyser and fuel cell are the same, the URFC, specially-designed single stack capable of functioning in electrolyser and fuel cell mode. Such a unit can bring down the investment cost by around 40% without significant reduction in performance [10]. Any surplus solar energy can be fed into the URFC in electrolysis mode to produce H_2 gas. When the input solar radiation is insufficient to meet the load, the deficit can be met by operating the URFC in fuel cell mode. In principle the water can be recycled for further use in electrolysis for developing autonomous system. The URFC concept is ideally suited here since the electrolyser and the fuel cell function are not required simultaneously. The energy flow in such a system is shown schematically in Fig. 2c.

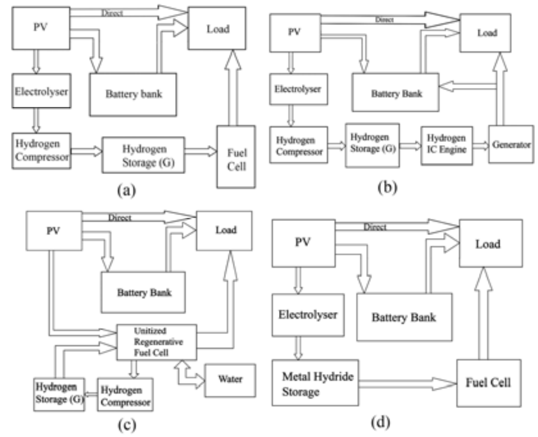

Fig. 2 Schematic diagram of energy flow in (a)EL-H_2-FC;(b) H_2-IC engine;(c) URFC, (d) MH storage based long-term storage system

High pressure electrolyser based system: Hydrogen compressor is considered to be one of the most cost intensive components in the H_2 loop in conventional system. High Pressure Electrolysers (HPEs) are capable of producing H_2at higher pressure eliminating the need of the compressor in the long-term storage loop. This technology will bring down the capital cost considerably. At present, HPEs are available in the range of 30 bar against dedicated compressors that have output pressures in the range of 700 bar. Hence, HPEs based systems require large storage size. However, this is an acceptable option in the case of stationary applications. The economic advantage of offsetting the compressor is higher in the case of smaller systems (5 kW) than for larger systems. This is because hydrogen compressors are not commercially available in custom sizes and hence oversized compressors are used for smaller systems.

Solid state hydrogen storage based system: H_2 storage is one of the key challenges in a FC based standalone system. It can be stored as (i) pressurized gas, (ii) cryogenic liquid, (iii) solid fuel as chemical or physical combination with materials, such as metal hydrides (MH), complex hydrides. Available technologies permit directly to store $H_2$by modifying its physical state. Liquid H_2 requires additional refrigeration unit to maintain a cryogenic state leading to 40% loss in energy content [11]. Storage of H_2at high pressure poses safety concern arising from leakage. Metal hydrides (MH) are the promising candidates due to their safety advantage, with high volumetric storage capacity. Intensive research effort has been made on the metal hydrides for improving adsorption or desorption properties based on H_2 storage capacity, kinetics, thermal properties, toxicity, cycling behaviour and cost.

In general, MH systems for H_2storage can be classified as either high (~300°C) or low (<150°C) temperature, depending on their operating temperatures at modest pressures (0.1-1.0 MPa). Since, MHs require heat to release H_2 the chance of accidental releases of it, is trivial. Thus, they are considered as relatively safe means of storage. Though, MH system has low gravimetric energy density (1%-7%) [12], it is not a hurdle for stationary applications. Cycling stability of MHs is also an important characteristic for life cycle cost analysis. A high cycling ability is desirable for cost-effective applications. Most of the hydrides have cycle lifeless than 50. Only limited numbers of reports are found on high number of cyclic tests. Reiser et al. [13] investigated the behaviour of Ni-doped Mg and Mg_2CoH_5 and reported more than 800 cycles with a marginal drop in storage capacity. The cyclic stability of MgH_2 with 5 wt% storage capacity is reported up to 2000 cycles [14]. A schematic representation of a long-term storage system using metal hydride storage is shown in Fig. 2d. In this configuration, the excess energy is converted to H_2 by the high pressure electrolyser and stored in the metal hydride.

Comparison methodology

Different locations can be categorized based on the seasonal energy variations and on-site fuel cost. The seasonal energy variation and on-site fuel cost at the site of application reflect the local solar energy scenario and the accessibility of the site respectively. For any location on the globe, the whole year can be divided into two parts based on the solar radiation received on the horizontal surface. One part contains the higher solar energy months and the other part contains lower solar energy months. To recover the surplus energy there is a requirement of investment in the electrolyser, fuel cell and H_2 storage. The H_2 tank cost is determined by the volume and the maximum storage pressure. H_2 compressor, the other cost intensive component is considered for life cycle cost analysis.

It is assumed that for the PV-DG hybrid system, the same amount of the surplus energy comes from the diesel generator. The lifetime fuel cost and the energy storage cost in the battery are included for the operational cost analysis. The engine-rebuild costs as well as the maintenance costs of the diesel engine and generator over the lifetime of the system are considered. The life cycle costs of both the systems are estimated and the critical fuel (diesel) cost for which both the systems are equally cost-effective is estimated as a function of the variation in the seasonal solar radiation.

Critical fuel cost and boundary curve

The life cycle costs of both the systems are compared to calculate the critical fuel cost for which both the systems are equally cost-effective. The critical fuel cost represents the theoretical cost of diesel, for which the life cycle costs of H_2 storage system and the DG system are equal i.e.,

$$K_{LTS,HG} = [K_{DGS}|\square]_{K_{fuel/l}=K_{CFC/l}} \qquad (1)$$

Where,

$K_{LTS,HG}$ Life cycle cost of long-term storage ($)
K_{DGS} Life cycle cost of DG based system ($)
$K_{CFC/l}$ Critical fuel cost per litre ($\$l^{-1}$)
$K_{fuel/l}$ Cost of fuel ($\$ l^{-1}$)

The critical fuel costs are obtained as a function of the seasonal solar radiation difference for the PV hybrid system to generate a boundary curve. The boundary curve divides the whole domain of sites in two parts - one part is cost-effective for PV- H_2 and other part is for PV-DG system and on the boundary curve both the systems are equally cost-effective. If the actual fuel cost at a particular site is higher than the cost obtained from the boundary curve, the site is cost effective for the PV- H_2 system and vice-versa.

The boundary curve is very useful in identifying a cost-effective system between PV-DG and PV-H_2 system as shown in Fig. 3. There will be a constraint imposed by the base fuel cost of a country. The actual fuel cost at various locations in the country will lie in a region above this limit. This is mainly due to the added cost to the base fuel cost arising from the transportation of fuel to the site of application. It is apparent from the Fig.3, that there is a minimum value of seasonal energy difference below which PV-H_2 based system is infeasible (Region-I). In the region-II as shown in the Fig.3, either of the systems may become feasible depending on the ground fuel cost at the site of application and in the region-III, PV-DG system is always infeasible. The H_2 based system is cost-effective in all the regions lying above the boundary curve and DG based system is cost-effective in the regions lying under the boundary curve.

Results and Discussions

In present investigation, the peak load in the system is considered in the range 5 kW, keeping remote telecommunication repeater stations in mind. Hence, the DG set and PEFC sizes are also considered to be 5 kW to ensure minimum LOLP. The size of photovoltaic array is considered to be 10 kW_p and nominal power rating of the electrolyser is 8 kW.

For small-scale applications, the present cost of the fuel cell stacks and electrolyser are considered to be \$2000 k W^{-1}[15] and \$1000 k W^{-1} [16] respectively. It is assumed that for installation, the cost will almost be double the stack price considering accessories and other costs for H_2 storage. It is considered that no replacement of the electrolyser and the fuel cell will be needed during the whole lifetime of the system as they expect to deliver high operating lifetime.

A few sample locations representing different countries are considered. The critical fuel costs obtained while comparing H_2 based system (Fig. 2a) with DG system are plotted against the seasonal solar radiation difference for various locations as shown in Fig.4. The representative cities of different countries are also indicated on the diagram. It can be seen that the boundary curve is influenced by the inflation rates and discount rate of different economic zones (countries). It should be noted that while analysing the cost-effectiveness of a system at any location, the boundary curve corresponding to that country has to be considered.

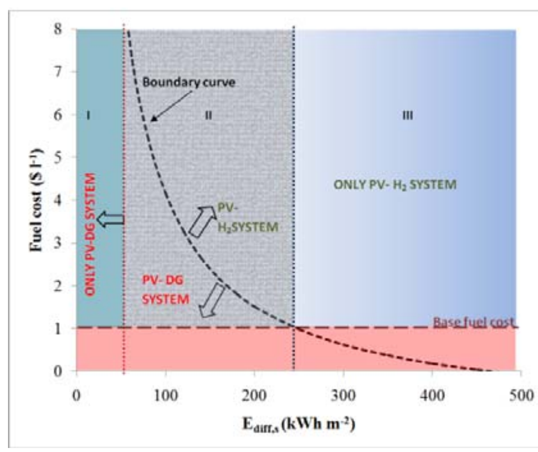

Fig. 3 Variation of critical fuel cost (boundary curve) with seasonal solar energy difference for cost-effective system selection between DG and H_2 system

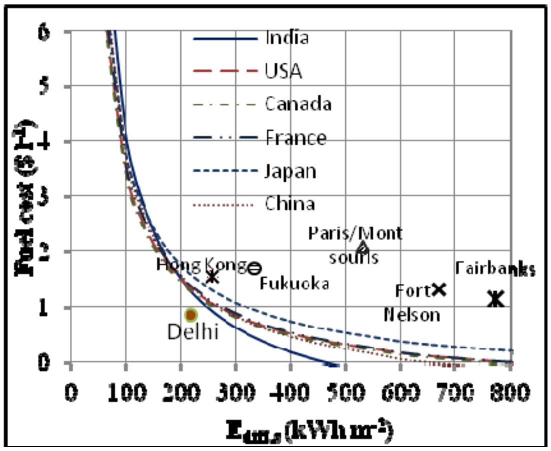

Fig.4 Variation of critical fuel cost curves (boundary curve) comparing DG system (Fig. 1) with fuel cell system (Fig. 2a) for different countries

It is clear from the Fig. 4 that the critical fuel cost for fuel cell based system is very high for most of places with seasonal energy difference less than 250 kWh m^{-2}. All representative locations with high seasonal solar energy difference above 350 kWh m^{-2}, fall in the region feasible for PV-FC based system for present cost. Places in India with a lower seasonal energy difference have critical fuel cost in the range of \$1.5 to \$7 per litre of diesel which is very high compared to local diesel prices. The diesel prices in India are in range of \$0.9 per litre in cities which may increase in the remote locations.

An attempt is made to compare different systems as illustrated in the Fig. 2 based on critical fuel cost. Since, inflation rates and discount rates vary across the countries, for further comparisons an inflation rate of 11.7% and a discount rate of 6% is considered.

H_2-IC engine based system

The critical fuel costs obtained comparing H_2-IC engine based systems with DG based system are shown in Fig. 5a. The H_2-IC engine based systems are found to have higher critical fuel cost than fuel cell based systems for all locations even with present costs for fuel cell stack and electrolysers. The critical fuel cost with hydrogen generator systems is 1.3 to 5.2 times higher compared to fuel cell based systems in the range of excess energy equal to 50 kWh m^{-2} to 350 kWh m^{-2}.

H_2-IC systems are found to be more costly than DG based systems. The advantages that H_2-IC based systems offer like low investment, being a mature technology is offset due to the high operational costs. Moreover, fuel cell based systems are found to be more economical than H_2-IC system. Fuel cell systems hence remain a commercially feasible option that can be used for reliable, clean energy in near future.

URFC based system

The boundary curve for a H_2 storage system with URFC cost equal to \$4000 kW^{-1}[17], is shown in Fig. 5b. Present estimation shows that the URFC based systems are cost-effective compared to the conventional fuel cell based systems. The average decrease in critical fuel cost for the range of seasonal energy difference from 50 kWh $m^{-2}$to 350 kWh m^{-2} is about 55%

HPE based system

In such a system hydrogen is directly stored in at 30 bar tank to avoid the compression of H_2. To determine the boundary curve, the cost of the electrolyser (30 bar) and tank in this pressure ranges is considered to be \$2500 kW^{-1} [18] and \$500 kg^{-1} of stored H_2 [8] respectively.

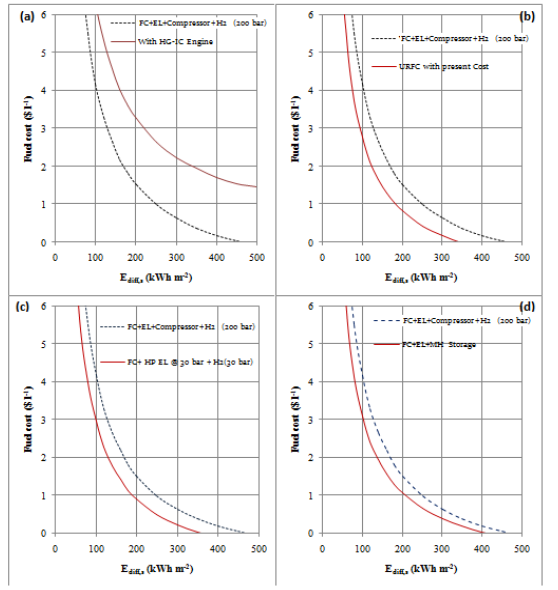

Fig. 5 Critical fuel cost curves (boundary curve) comparing DG based system with (a) H_2-IC engine,(b) URFC, (c) HPEL and (d) MH storage based system

Metal Hydride based system

For comparing the MH based system with the DG system, a cost of \$16 kWh^{-1} is considered for metal hydride storage [19-21]. The system is assumed to have a stable life of 500 cycles. The life cycle cost of metal hydride storage is calculated using Eqn. 21 and the corresponding boundary curve is given in Fig. 5d. It is estimated that this system is cost-effective compared to conventional fuel cell based systems. Metal hydride systems are marginally cheaper than high pressure electrolyser with storage tank. However, this system is much safer than the systems with gaseous storage tank as the risk of leakage is reduced. In addition, the volume of storage is also considerably reduced.

URFC-MH based system: cost-effective option

Present study indicates that the introduction of the new H_2 technologies in the long-term storage configuration lead to cost-effective solutions. A combination of more than one of these technologies will even deliver more cost-effective solution. MH storage can be incorporated in HPE or URFC systems. However, since HPE systems need separate electrolyser and fuel cell units, adding metal hydride storage may not be cost effective. Thus, a system comprising URFC and MH storage as shown in Fig. 6 is considered as cost-effective option for long-term storage.

The boundary curve for such a system is shown in Fig. 7. It can be seen that the critical fuel cost is drastically reduced when these two technologies are combined for long-term energy storage and it offers the most cost-effective solution.

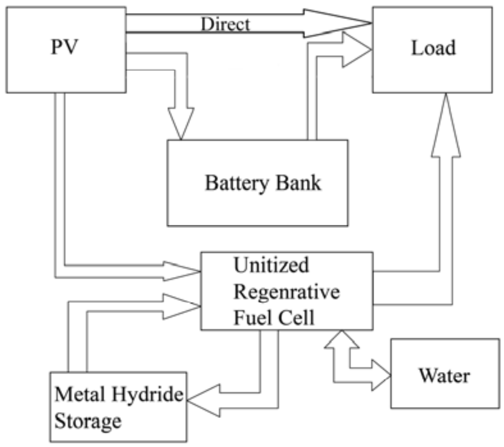

Fig. 6 Cost-effective system combination for H_2 as long-term storage in PV system

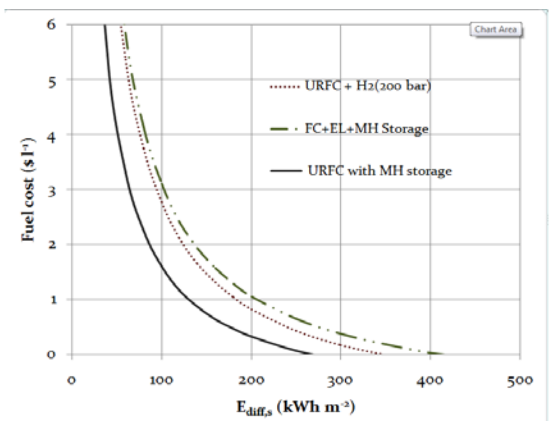

Fig. 7 Variation of critical fuel cost (boundary curve) with seasonal solar energy difference for a URFC-MH system

Conclusions

In this study, various configurations of H_2 storage in a standalone PV system are discussed and they are compared with conventional PV-DG hybrid system. The standard fuel cell based technology is compared to the competing hydrogen IC engine technology. It is seen that fuel cell based systems are more economical. The suitability of upcoming technologies like URFC, HPE and MH storage are studied. Long-term storages with all the upcoming technologies such as URFC, HPE in combination with MH storage are found to be cost-effective compared to the conventional systems.

At present, a configuration combining URFC with MH storage is found to be the most cost-effective option for hydrogen based long-term storage systems. Such a system eliminates the need for separate electrolyser unit. It has the added advantage of being safer than systems using gaseous storage techniques.

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