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Review Article

Usage count of hydrogen-based hybrid energy storage systems: An analytical review, challenges and future research potentials

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HIGHLIGHTS

- Hydrogen is a potential energy due to its energy density and storage capacity.
- Usage count is a novel indicator for future research trends and directions.
- This study highlights usage count of hydrogen-based hybrid energy storage system.
- Issues and challenges of the existing hydrogen-based storages are highlighted.
- Suggestions and directions are provided for future hydrogen storage applications.

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ABSTRACT

Electricity generation and consumption must undergo a substantial transformation as part of the global energy transition towards decarbonization. Hydrogen-based hybrid energy storage systems (HESS) have the potential to replace the existing fossil fuel-based energy generation due to their high energy density and long storage capacity. This study has introduced a novel indicator "usage count" instead of "citation analysis" to obtain the top 100 articles in the field of hydrogen-based HESS because of the factors such as reduction of time lag, recentness and domain independency. After the filtration process, the top 100 articles with the highest usage count are obtained by providing an extensive search in the Scopus database from the year 2012–2021. An extensive comparative study between "usage count" and "citation analysis" among the selected top 100 articles is provided. Moreover, a detailed keyword co-occurrence network (KCN) analysis along with comprehensive reviews concerning HESS modelling, optimization objectives, algorithms, system constraints, and research gaps are presented. The review emphasizes the benefits and

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drawbacks of hydrogen-based HESS and analyzes the obstacles associated with their application, such as the system's high cost, technical complexity, socio-economic and environmental impact and safety concerns, which can provide the researchers with a clearer picture for future research and development. Finally, the article conveys some suggestions and directions, which can act as a roadmap toward achieving reliable and sustainable next-generation hydrogen-based HESS.

Contents

Introduction

In the era of industrialization, the rapid increase in population and urbanization leads to the precipitous growth of energy demand. To meet the high demand, the existing fossil fuel-based energy generation system emits a huge amount of greenhouse gas (GHG) into the environment which leads to global warming and other environmental catastrophes. Due to the finite supply of fossil fuels, volatile energy pricing, and low-carbon energy generation interest in renewable energy sources has risen dramatically [1,2]. According to experts, 3D namely decarbonization, digitization, and decentralization will be the future drivers for global development [3]. According to the International Energy Agency (IEA), solar and wind combined are expected to generate between 23% and 42% of global energy by 2040 [4].

Hydrogen energy storage (HES) is a form of chemical energy storage (CES) where the main method is electrolysis for converting electricity into hydrogen. The produced hydrogen then goes through the hydrogen re-electrification process (HRE) in a fuel cell (FC) [5]. Although the overall efficiency (40%–60%) is lower compared to the other ES technologies due to the superior storage capacity, the research, development, and application of hydrogen-based HESS are becoming popular [4]. The main idea of developing the hydrogen-based HESS is to use the excess energy generated by the RE sources such as solar photovoltaic (PV) or wind turbine (WT) for hydrogen production and store the hydrogen and when the demand is high, meet the demand by producing necessary electricity through the HRE process. Various ES technologies such as battery energy storage systems (BESSs) and supercapacitors (SCs) can be integrated with HES along with available RES to improve the overall system efficiency. Moreover, it is generally agreed that more than 20% penetration from intermittent renewables can greatly destabilize the grid system [6], so, the use of HES along with ES technologies can be used when the RES is not available and during the peak hour can ensure the grid reliability and reduce the overall GHG emission. To meet the 2050 global decarbonization objective, the hydrogen-based hybrid energy storage system (HESS) can be a great alternative to the traditional energy generation system because of its sustainability, low cycle efficiency, and high energy density [3,7].

The most common research front detection system by the scientific community is “citation analysis” where the highly cited articles from a particular field of research are considered the most impactful articles of the corresponding field.

However, utilizing citation as a typical indicator to discover research fronts would invariably result in a time lag. According to Shibata et al. [8], it could take up to 2 years for an article to be highly cited. To obtain more recent research, "usage count" can be a great alternative to measure the research impact of the corresponding field. The usage count indicates the number of times the article has satisfied a user's information demands, as evidenced by going through the whole article or storing the article by using any bibliographic management tool [9]. It allows the users to analyze the usage data of the articles such as abstract views, full article views, downloads, and types of user-accessed data to thoroughly understand the impact of the research. The advantages of usage data over citation data include easy accessibility and data collection [10]. Moreover, as a general concept, the review-type articles have got more citations compared to the technical articles. In the citation analysis, most of the articles are considered review-type articles such as in Ref. [2], 51% of articles are technical whereas in this article 63% of articles are technical articles because researchers are focused on understanding the recently developed methods in a particular field of research. There are a few benefits of using the usage count instead of citation analysis, such as.

- Firstly, as compared to the "citation analysis", the "usage count" tends to consider more recent articles.
- Secondly, there is a certain time lag between the article published and the citation, considering usage count data can reduce that gap.
- Thirdly, a few research domains needed a long time to obtain a good number of citations. As the usage count consider the document view, store, and share data, it can be concluded that the usage count is domain-independent.
- Finally, the researchers tend to read and obtain recent research articles to understand the recent development in a particular research field. The usage count analysis can provide a clearer idea about the recent research trends and developments as the more impactful research tends to have more views.

Therefore, the conducted research is based on the usage count that is used as an indicator to identify the articles with significant contributions in the field of hydrogen-based HESS. Furthermore, no usage count-based analysis was shown to have been carried out in the field of hydrogen-based HESS. The main objective of this study is summarized as follows.

- The application of "usage count" for the first time to identify the most impactful articles in the field of hydrogen-based HESS, and provide a detailed analysis of the selected article based on methodologies, modelling, and optimization.
- A brief comparative study between "usage count" and "citation analysis" is presented.
- An extensive summary of the current state of art HHES research is offered and identified research gaps that deserve extended research along with several potential future suggestions which can be helpful to the policymakers, researchers, and industry professionals involved in the development and implementation of clean and sustainable energy systems.

Surveying method

The goal of this study is to extract the important aspects of the articles with the highest usage count and to provide insight into the evaluation of hydrogen-based HESS. To achieve the aim of the study, an exhaustive search in the Scopus database yielded a dataset of the top hundred articles with the highest usage count from the year 2012–2021. Following that, a detailed analysis of methods and systems, modelling and optimization objectives are provided to obtain the research gap in the field of hydrogen-based HESS. To understand the current trends of research in the field of hydrogen-based HESS an expanded search was conducted in the 3rd week of November 2021 in the Scopus database. Various selection and exclusion criteria were applied to obtain the final top articles based on usage count in the corresponding field. The detailed article selection process is shown in Fig. 1 and described below.

- In stage 1, the initial search was conducted in the Scopus database using the keywords such as "energy storage system", "hybrid" and "hydrogen". From the initial search, 4380 (n = 4380) articles were obtained.
- In stage 2, the article within the year 2012–2021 are selected and 3768 (n = 3768) articles were sorted.
- In stage 3, the article which is written only in the "English" language were selected and 3663 (n = 3663) articles were found.
- In stage 4, the articles that are within the exclusion criteria were excluded and finally, 988 (n = 988) articles were selected. The keywords such as "chemicals", "electrochemical", nanomaterials", "electrolysis", "molecule", "microbiology", "geographical" and "genetically" are included in the exclusion criteria.
- In stage 5, the selected 100 articles were sorted according to the "usage count" and the articles with the highest usage count were chosen.

State of art hydrogen-based hybrid energy storage system

Energy is considered one of the key development and technological advancement indicator of a country [11]. To achieve the Sustainable development goals (SDGs), countries all around the world focus on attaining net zero emissions in the energy generation sector. Hydrogen-based HESS has gotten attention from recent researchers due to the great potential to replace the current fossil fuel-based energy generation system. Researchers conduct vast research and analysis on developing a safe, reliable, efficient, and cost-effective system. Europe, Japan, China, and Korea have already established their strategy and roadmap toward sustainable hydrogen storage systems [12]. The roadmap includes fuel cell vehicle (FCV) implementation, the establishment of a hydrogen refuel station (HRS), reduction of the cost of hydrogen production, and improvement in hydrogen capacity.

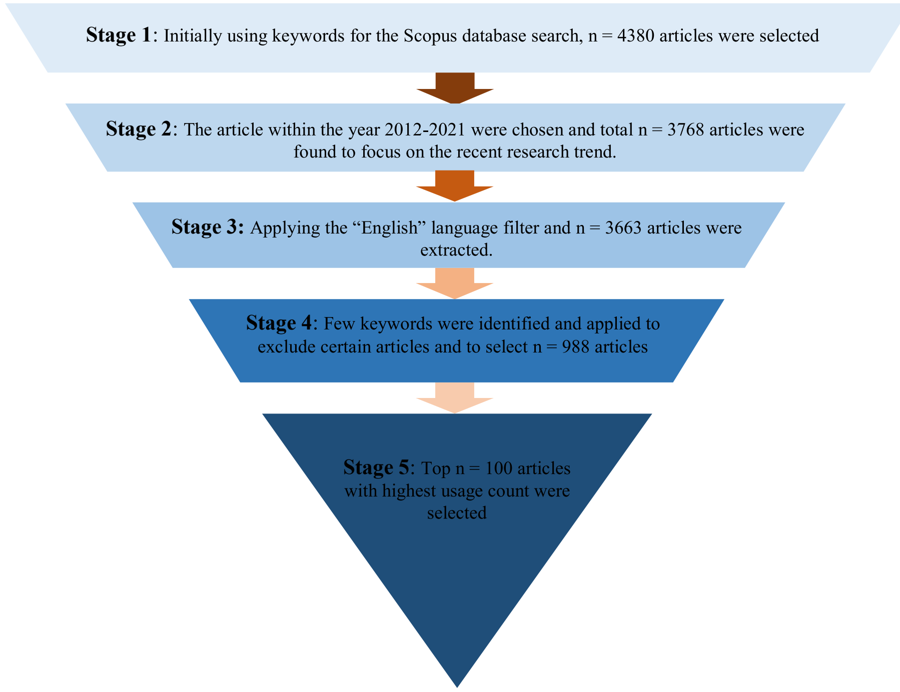

Fig. 1 – The overall selection process of the top 100 articles with the highest usage count in the field of hydrogen-based HESS.

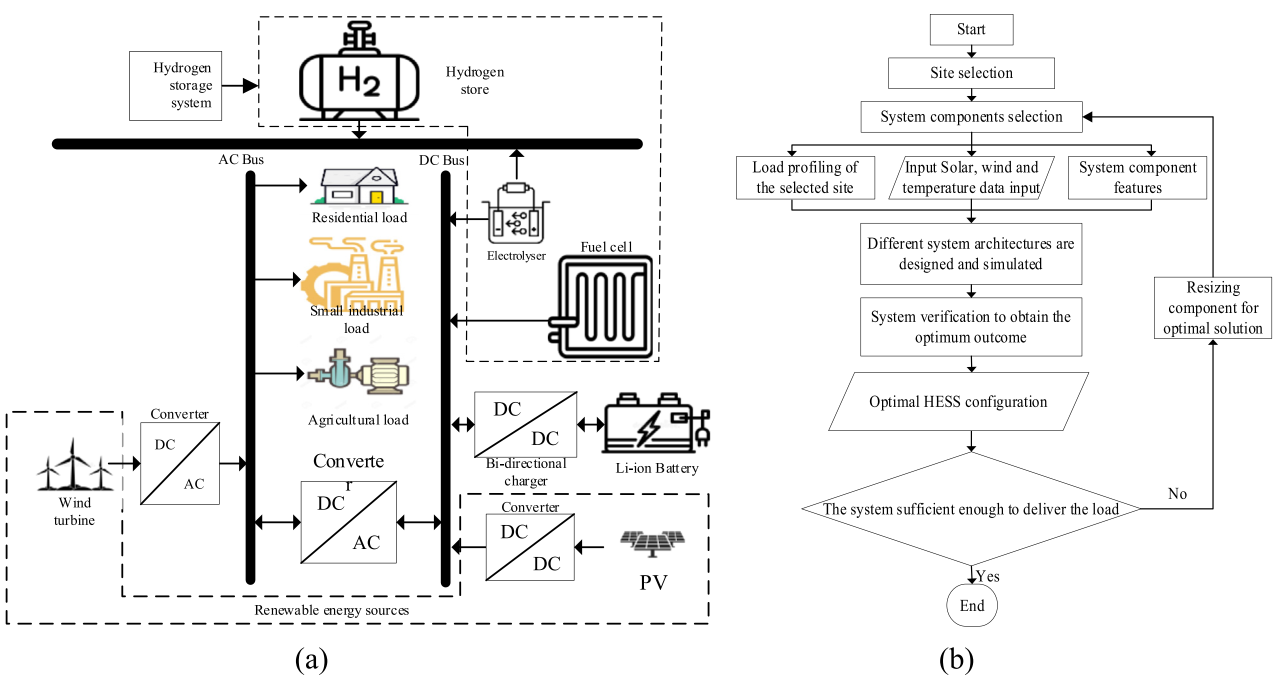

Fig. 2 – (a) overall system architecture of a hydrogen-based HESS (b) flow chat to develop an optimized hydrogen-based HESS.

The hydrogen-based hybrid energy storage system is an integration of RES, batteries and HS in the most optimally sized way that it can meet up the required demand efficiently. In Fig. 2(a) the system architecture of a PV-WT-BESS-HS-Converter-based HESS is shown where the HS includes hydrogen store, FC and Electrolyzer. To develop an optimized HESS system, initially, the site needs to be selected along with the energy generation components. After that, the temperature, solar, and wind data along with the load profiling is needed [13]. The stages of an optimized HESS system are shown in Fig. 2(b). An energy management system (EMS) is needed to control the power flow of the HESS to ensure reliability. The general power flow control of a PV-WT-BESS-HS-Converter-based HESS is given below.

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- Initially, the PV and WT produce electricity to meet the demand.
- The energy is delivered to the BESS for charging.
- Excess power is delivered to the electrolyzer to produce hydrogen through electrolysis and stored.
- When the load's power demand exceeds the power supplied by the PV and WT, the BESS provides power to the load.
- If the battery is depleted and there is insufficient power from the PV and WT, the hydrogen in the hydrogen store can power the FC to generate electricity for the demand.
- Depending on the availability of power and the state of charge (SOC) of the battery and HS, the power demand is supplied by either the battery, the FC, or a combination of the two.

It can be concluded that the use of HS along with the BESS can improve the system reliability drastically compared to the use of battery or other energy storage (ES) technologies only. The first article mentioning hydrogen as an important ES technology was published back in 1978 [14]. After that, many researchers developed several methods to develop an optimally sized and cost-effective hydrogen-based HESS system. The main concern of the hydrogen-based HESS system is cost optimization [15,16]. An optimized off-grid hydrogen-based PV-WT system was designed in Ref. [15] where the main objective function is considered as a cost. Particle swarm optimization (PSO) is used to optimize the component's reliability constraint, which is directly related to the overall cost of the system. A risk-constrained scheduling approach for off-grid hydrogen-based HESS is proposed in Ref. [17] including socio-economic aspects and resilience using mixed-integer linear programming (MILP) and dual cutting-plane-based enhanced decomposition algorithm. The outcome shows that using hydrogen-based short-term ESS can reduce the Levelized system cost (LCE) from 0.6281 $/kWh to 0.5535 $/kWh.

The hybrid optimization of multiple energy resources (HOMER) is a popular software among researchers to develop HESS models for both grid-connected of stand-alone modes [16,18,19]. In Ref. [16], a comparative analysis along with a techno-economic analysis is presented between the diesel generator (DG) and HS using the HOMER. Two different systems such as PV-diesel and PV-HS is developed and compared based on the cost of energy (COE) and net present cost (NPC). The result shows that the PV-HS system has a much higher COE (2.436 €/kWh) compared to the PV-diesel system (0.871 €/kWh). A stand-alone HESS system consisting of concentrated photovoltaic thermal (CPVT), biomass, WT, BESS and HS is modelled and simulated in Ref. [18] for powering an electric vehicle charging station (EVCS) using the PVSyst, HOMER and engineering equation solver (EES) software. Three different system configurations such as PV-HS-CONV, WT-HS-CONV and PV-WT-HS-CONV are developed using HOMER by Basu et al. [19] where the PV-WT-HS-converter-based system is considered the most optimal system with the overall lowest LCOE ($0.3387) compared to the other systems.

Various techno-economic analysis was presented in Ref. [20], and [21] to develop an optimally sized HS-based HESS and analyze the socio-economic and environmental impact of the system. A techno-economic optimization model of a PV-BESS-FC-based hybrid system is developed in Ref. [20]. The main goal of the study is to obtain the optimal plant configuration with the lowest possible COE using the MILP. Jansen et al. have developed a HESS combining the solid hydrogen-based ESS, PV and BESS [21]. The main objective function of the techno-economic analysis is COE and NPC. The result shows that the most optimal and cost-effective system has a lower overall system efficiency (17.33% compared to the previous 21.05%). Although the overall loss due to the degradation of efficiency has not been mentioned.

The EMS control strategy is another crucial part of the hydrogen-based HESS system as both the battery and HS need an initial power supply from the connected RES. For the batteries, the upper and lower limit of the SOC is needed to be mentioned to fix the battery operating condition whereas, for HS, the electrolyzer needs external power to produce hydrogen and store it and supply it to the FC to produce electricity when it is needed. Many researchers have developed several methods for the perfect integration of HS and BESS with the RES with an optimal EMS strategy [22–24]. An MG supervisory control system of a PV, lead acid battery and HS-based is developed in Ref. [22] where the various control strategy is defined at various battery SOC level (75%, 70%, 50% and 45%). The EMS system is divided into two different categories such as; long-term and short-term energy management and the overall developed system is programmed and implemented using the PLC Schneider M340. Garcia-Torres et al. in Ref. [23], an MG consisting of PV-WT-BESS-FC-converter are designed and an optimal EMS is developed using the model predictive control (MPC) to maximize the economic benefits and minimize the degradation of each system component. In Ref. [24], the MPC was used to develop the optimal load sharing of an HS-BESS-ultracapacitor-based MG to minimize the overall system cost.

The study focuses on reviewing and analyzing the articles with the highest usage count in the field of hydrogen-based HESS. A detailed discussion of the methods, the scope of research, applicability, and research gap of the selected top 10 articles based on usage count in the field of hydrogen-based HESS is presented in Table 1. The article with the highest usage count was written by Iverson et al. [25] in 2013 and was published in the journal "Renewable Energy" with an impact factor (IF) of 8.001. In this article, a novel photovoltaic (PV), wind turbine (WT), hydrogen storage system, (HSS), and ultracapacitor (UC)-based HRES is modelled and a control scheme for power demand is defined. The optimal sizing is validated under two different scenarios; fixed demand and controllable demand. The result shows a substantial decline in life cycle cost (LCC) while using a controllable demand scheme. Moreover, it can be observed that although PV has a less instalment cost than WT, the overall LCC is reduced in the WT-based system due to 24 h operation time of WT. The second article with the highest usage count is developed by Kyriakopoulos and Arabatzis [26] which is published in the "Renewable and Sustainable Energy Reviews" journal with an IF of 14.98. The article discussed the policies, research, and applications of the various ESS technologies such as electrochemical, hydrogen, and thermal energy storage systems along with the socio-economic aspects of energy production. The article by Tie

Table 1 – The top 10 articles with the highest usage count in the field of hydrogen-based HESS.

Rank	Ref	Author and Year	NC	Usage count	Methods and System	Scope, applicability, and research gap
1	[25]	Iverson et al. (2013)	43	2410	Optimal LPS and LOCE simulation	Six controlled demand cases were analyzed and show the profitable performance of WT over PV. Moreover, the optimal sizing of stand-alone MG can be varied for the grid-connected scenario.
2	[26]	Kyriakopoulos and Arabatzis, (2016)	176	2346	EESS policy, algorithms, issues, and regulatory regimes	Cost analysis and forecasting of the EESS storage quality and impact as well as the environmental concerns can be described more elaborately.
3	[27]	Tie, and Tan (2013)	774	2066	EV technologies, EESS sources, control EMS, and EV performance optimization.	The environmental impact of EVs, energy sources of EV technologies, EV control, and management strategies are described. The EV storage availability, weather dependency, and the complete dependency of EVs on alternative energy are considered future suggestions.
4	[28]	Ismail et al. (2015)	60	1708	Quantification and utilization of excess energy of RES and cost reduction are described	Reviewed the excess energy of the hybrid ESS and suggested utilizing the excess energy through water heating, water pumping, space heating and cooling, and hydrogen extraction but the key issue is cost and lack of suitable technologies for system stability.
5	[29]	Papaefthymiou, and Papathanassiou, (2014)	119	1327	Maximization of return of the HPS investment, RES penetration, and cost optimization using GA	From an economic, initial investment, and performance perspective the design is highly dependent on WT which may cause issues with the system reliability because of the weather dependency on wind energy.
6	[30]	Petrillo et al. (2016)	77	1146	AHP model with an FWA based on LCA, LCC, and SLCA analysis	Identifying, characterizing, and discussing the impact of LCA over off-grid REPP is the key contribution whereas the lack of an available suitable database is considered the key issue.
7	[31]	Wasbari et al. (2017)	40	1144	A detailed study on compressed-air hybrid technology, models, challenges, and issues are presented.	Low energy density, low energy efficiency due to losses in the propulsion system, valve and fitting, commercialization of new techniques, and reliability are the key issues for compressed air application. Although regenerative breaking saves energy, hybrid compressed air-based systems are proposed for a cost-effective, reliable, and low-maintenance vehicular system.
8	[32]	Rahman, and Khondaker, (2012)	38	1107	The energy investments, policies, and trends for reducing GHG emissions in Saudi Arabia are described.	Due to the oil-based economy of Saudi Arabia, the recent development in the energy sector from fossil fuel-based energy to clean energy and reduced GHG emission is stated.
9	[33]	Kallel et al. (2015).	43	1033	DSM-based control strategies of PV-DG_BESS-based hybrid RESS	The proposed DSM strategy tends to improve reliability and reduce LPSP and GHG emissions. The results show the contribution of each source according to the summer and winter load profiles. Although the system sizing and optimal system detection are missing.
10	[34]	Abedi et al. (2012)	133	1016	Fuzzy multi-objective technique based on DEA to optimize PV-WT-Hydrogen-BESS-DG-based system	The main objective functions are NPC, total fuel emission, and LPSP. The optimal results were given in terms of size, installation data, and operational strategy. The optimum value of each component along with the maximum/minimum SOC and rated power is defined.

NC: Number of citations; EESS: electrical energy storage system; ES: Energy sources; RES: Renewable energy sources; LCOE: Levelized cost of Energy; EES: Energy storage system; HPS: Hybrid power stations; GS: Genetic algorithm; WT: Wind turbine; LCA: Life Cycle Assessment; LCC: Life Cycle Cost; SLCA: Social Life Cycle Assessment; AHP: Analytic Hierarchy Process; FWA: Fluctuant weight analysis; REPP: Renewable energy power plant; GHG: Greenhouse gas; DSM: Demand side management; BESS: Battery energy storage system; DG: Diesel generator; LPSP: Loss of power supply probability; DEA: Differential evolution algorithm; WT: Wind turbine; HT: hydrogen tank; NPC: net present cost; SOC: State of charge.

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Table 2 – Identification basis and classification details of the selected articles.

Classification details	Reference
HRES component analysis, development, issues and challenges	[28,35–47]
Transportation application, EV technologies, and development	[27,48–53]
Various ESS technologies, development, and application	[31,54–59]
MG application and development using HOMER	[60–62]
Review considering environmental aspects	[63–65]
ESS sustainability issues and energy policies	[26,32]

and Tan [27] is the third article with the most usage count from the selected dataset and was also published in the "Renewable and Sustainable Energy Reviews" journal. The article has presented a detailed discussion of the ESS technologies and prospects and existing EMS in the electric vehicle (EV) perspective, which includes converter controlling, rule-based control, and optimization control method. Among the top 10 articles, the usage count ranges from 1016 to 2410 whereas the citation ranges from 38 to 774. Moreover, five articles are "review" type articles and five articles are "technical" articles.

The review articles from the selected top 100 articles with the highest usage count in the field of hydrogen-based HESS are identified and classified into several categories and are presented in Table 2. According to Table 2, the highest 13 articles belong to the "HRES component analysis, development, issues and challenges" followed by "transportation application, EV technologies, and development" and "Various types of ESS technologies, development and application "with 7 articles each.

In [28], the excess energy of the hybrid ESS is suggested for utilization in water heating, water pumping, space heating, cooling, and hydrogen extraction, respectively. However, the key issue is the cost and lack of suitable technologies for system stability [35]. A stand-alone renewable energy power system (REPS) with HESS is presented including the status such as; passive, semi-active, and active HESS, and the optimization methods, and intelligent control strategies are reviewed in Ref. [36]. A review of HRES implementation in isolated micro-communities in Ref. [37] where for micro-communities, less than 10,000 people are considered. The review includes the criteria of island selection, community characterization, types of HRES, and challenges. The demand estimation and optimization methods are suggested as future directions. A review of EMS in HRES application is presented in Ref. [38] where EMS control structure for centralized, distributed, and hybrid systems in both stand-alone and grid-connected modes are presented. Moreover, the review concluded that HOMER and FLC are the most used methods for the software-based and AI-based EMS approaches respectively. In Ref. [39], an overview of HET principles, integration conditions, optimization objectives, models, algorithms and constraints, issues, and challenges is presented. A survey on RES integration configurations, RES with ES configurations, mathematical modelling and sizing technologies, control and EMS strategies, and challenges are presented in Ref. [40]. In Refs. [41,46], an overview of HRES components analysis, storage types, optimization objectives, and techniques consisting of deterministic, probabilistic, and AI, issues, and challenges of HRES are provided. EMS of hydrogen storage (HS) integrated HRES includes isolated/on-grid system configuration, ESS modules, techno-economic criteria, HS integration, optimization objectives, EMS regarding demand, and system constraints are presented in Ref. [42]. Various HRES optimization approaches and methodologies for micro grid (MG) application are presented in Refs. [43,45] whereas a description of PV and HS production, challenges of SA-HESS, optimization methods, and the developed prototype is provided in Ref. [44]. In Ref. [47], an overview of the PV and WT generations, system modeling, modeling of backup ESS such as BESS, sizing techniques, optimization objectives, methods, and challenges while developing the system is presented.

In Table 3, a detailed description of various review articles on transportation applications, EV technologies, and development is presented. The main factors considered in different review articles are energy sources of EV technologies, EV control, and management strategies, EV storage availability, and HS application in the transportation section.

Various ESS technologies, development and application are described in Refs. [31,54–59]. In Ref. [31], a detailed study on compressed-air hybrid technology which includes low energy density, low energy efficiency due to losses in the propulsion system, valve and fitting, commercialization of new techniques, and reliability are the key issues for compressed air application. Although regenerative breaking saves energy, hybrid compressed air-based systems are proposed for a cost-effective, reliable, and low-maintenance vehicular system. In Ref. [54], dispatchable PV integrating with the grid along with ES devices is reviewed. A detailed study on the DER integrated grid, a review of different PV-ES models, real/reactive power control, MG control, and monitoring along with issues and challenges are presented. A review of the Flywheel Energy Storage System (FESS) architecture and 3 major components; machine, bearing, and PEI is given in Ref. [55]. A detailed study on thermochemical heat storage (THS) which consists construction, comparison of materials used in solid and liquid absorption, numerical studies, performance evaluation and recent developments are provided in Ref. [56]. In Ref. [57], an overview of the CSP with the combination of coal, gas, biofuels, geothermal, PV and WT, advantages and disadvantages are provided whereas in Ref. [58], an overview of different ESS technologies such as; PV, WT, DG, BESS, and FESS are given along with parameter constraints, performance indices, relative simulation, and analysis. A study on solar closed sorption for refrigeration application is provided in Ref. [59] where a detailed discussion on absorption and adsorption systems, A/C, heating/cooling and refrigeration application, and challenges for the system development are presented.

ESS policy, algorithms, issues, and regulatory regimes are described in Ref. [26]. It is essential for policymakers, stakeholders, and citizens to work together to achieve sustainable and reliable energy generation to effectively decarbonize the power industry. SDGs can be a great measure for addressing these issues. Due to the oil-based economy of Saudi Arabia, the recent developments, energy investments, policies, and trends for reducing GHG emissions in the energy sector from

Table 3 – A detailed discussion of the review articles on transportation applications in the field of hydrogen-based HESS.

Ref	Author and Year	Scope, applicability, and research gaps
[27]	Tie, and Tan (2013)	The environmental impact of EVs, sources of EV technologies, EV control, and EMS strategies are described. The EV storage availability, weather dependency, and the complete dependency of EVs on alternative energy are considered as future suggestions.
[48]	Salvi, and Subramanian, (2015)	The study on HS in the transportation sector considering hydrogen sources, forms, sustainability factors, safety measures, the extraction process, application in the transportation section, economic and policies, and environmental issues on future HS development is described.
[49]	Hemmati, and Saboori, (2016)	The review presented different HESS hybridization principles, and applications, and reviewed various combinations of ESS, system architecture, control, and EMS strategies and challenges.
[50]	Mendez et al. (2014)	The study includes prototypes, FC stacks, types of storage systems, and comparative studies.
[51]	Shaukat et al. (2018)	An overview of the impacts of Transportation electrification in smart grid scenarios such as; voltage and frequency regulations, spinning reserve, and load capacity along with V2G technology is given. Moreover, charging technologies. ES technologies in EV sector and present challenges are also mentioned.
[52]	Sinigaglia et al. (2017)	A study on ESS, production, and socio-economic impacts of hydrogen is presented
[53]	Walker, and Roser, (2015)	The review includes various powertrain configurations, modelling, and impacts of drive cycle designing, and the result concluded that hybrid vehicles have better fuel economy obtained but are less cost-efficient.

fossil fuel-based energy to clean energy are stated in Ref. [32]. Various researchers have reviewed different factors considering the environmental aspects described in Refs. [63–65]. The Life Cycle Assessment (LCA) in environmental aspects consisting of LCA modelling, inventories, and GHG emission of various electricity generation technologies are presented in Ref. [63]. The article concludes that RES and Nuclear power (NP) have the lowest environmental impact, using storage leads to lower CO2 emission and biomass has moderate co-benefits. A detailed review of producing biofuel from microalgae includes microalgae origin, the process of producing chemical energy from light energy, existing methods, environmental impacts, and future direction [64]. In Ref. [65], seven different themes of Sustainable Development of Energy (SDE) were identified and a detailed discussion including advancement, issues, and challenges is provided.

The review of various MG applications for both grid-connected and isolated modes all around the world using the HOMER software is provided in Refs. [60–62]. A detailed review of the stages of HOMER such as; load profiling, component selection, grid mode, and sensitivity analysis for MG optimization provided for obtaining the lowest COE is provided in Ref. [60]. Techno-economic review and analysis using HOMER for Myanmar [61] and Saudi Arabia [62] is presented where the review includes The detailed review and comparison of HOMER-based HRES optimization in Myanmar are presented which includes variance in COE, NPC, number of PV panels, and converter used, types of batteries used, sensitivity analysis, a lifetime in different load scenarios.

The Scopus database is used to extract the top articles based on the highest usage count in the field of hydrogen-based HESS. Among the top selected articles, 67 articles are technical articles where various modelling and optimization methods are developed by various researchers in the corresponding field of research. A detailed evaluation of the developed methodologies is presented in section 4.4. The use of hydrogen-based HESS instead of fossil fuel-based energy generation or transportation applications has gotten great attention due to the benefits regarding sustainability and reliability. Although the technology is not mature enough to replace the BESS. Several countries have implemented plans to shift to hydrogen energy and the hydrogen economy, which leads to an overall cleaner environment.

Results and analytical discussion

The HESS has a great possibility to reduce grid dependency. The hybrid systems can operate both grid-connected and isolated modes and are mainly constructed using the RES which makes them more environmentally friendly. The hydrogen-based HESS has got huge consideration recently due to the high energy density and high storage capability of hydrogen compared to the battery or other fossil fuels. The article focused on identifying and reviewing the articles based on user count in the field of hydrogen-based HESS.

Comparative analysis of usage count with citation analysis

The distribution of the selected top 100 articles over the year 2012–2021 is shown in Fig. 3 (a) and the comparison of the article's usage count and times of citation is presented in Fig. 3 (b). From the analysis, it can be observed that the highest number of articles were published in the year 2015 (16) followed by 2018 (15). A total of 86% of articles published within the year 2013–2018 have shown a continuous growth of research interest in the field of hydrogen-based hybrid ESS. Fig. 3 (a) shows that the number of citations is vastly dependent on the year of publication. While considering the highly cited articles, 73% of articles from the highly cited article in the field

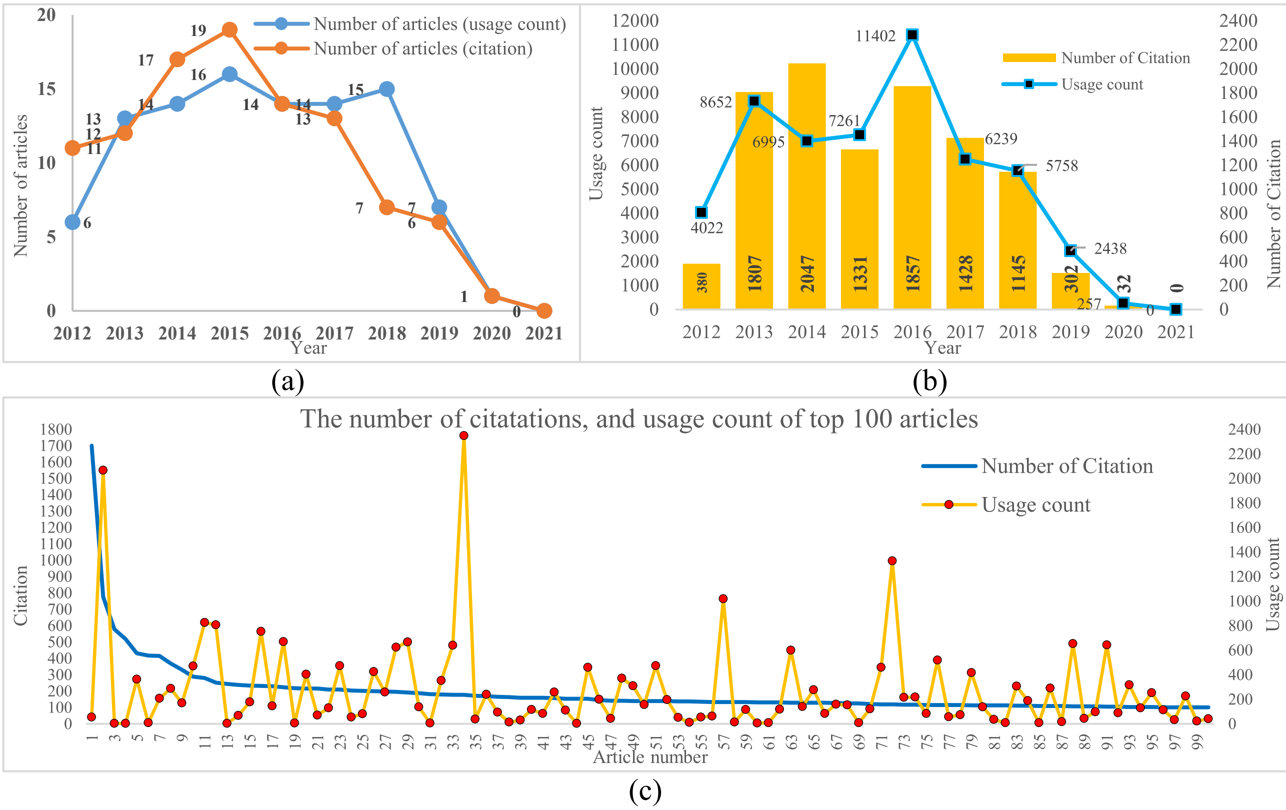

Fig. 3 – Distribution of the selected top 100 articles according to the (a) number of articles per year (usage count and citation) and (b) the total number of usage count and citation per year (c) the number of citations, and usage counts of each article from the selected database.

of hydrogen-based HESS were published within the year 2012–2016 whereas only 27% of articles were published in the last 5 years and only 7% in the last 3 years. For the top 100 articles with the highest usage count in the same field of research, 37% of articles are considered within the year 2017–2021 which is 10% more than the highly cited articles. In the year 2018, 15 articles were considered for the usage count analysis whereas only 7 articles are considered for the citation analysis. In Fig. 3 (b), it can be seen that the usage count is not dependent on the article number or citation. The highest number of articles were published in 2015 although the highest overall usage count was found in the year 2016 when only 14 articles were published. In Fig. 3 (c), the individual usage count and citation of the selected top 100 articles based on user count are shown. It can be observed that the usage count is not dependent on the citation of the article. The highest cited article in the field of hydrogen-based HESS with a citation of 1700 has a usage count value of 52 whereas the article with the highest usage count (2346) ranked 34th among the highly cited article database. It can be concluded from Fig. 3 that the usage count is an individual and powerful indicator that is independent of year and citation and have great potential to identify the recent research trends, research gaps, and development of a particular field of research. Moreover, a few advantages of usage count over citation analysis such as; recentness, time lag reduction, year, type, and domain independence can provide necessary evidence regarding the great potential for considering the usage count as an indicator for future research.

Keyword co-occurrence network analysis and evaluation

The keyword co-occurrence network (KCN) analysis depicts the relationships between distinct terms, as well as their weight and frequency of occurrence, and gives insight into the broader area of study in the related field [66]. In Fig. 3 (a), the KCN analysis of the selected top 100 articles with the highest usage count is shown where the size of the tag of each keyword is denoted as the weight whereas the colour of the same keywords belongs to the same clusters. The VOSViewer is used for the initial construction of Fig. 4. According to VOSViewer, a total of 111 keywords are classified into four different clusters such as; black, blue, orange, and green. The green cluster consists of the highest 39 members followed by blue with 32 members and orange and black have 26 and 14 members respectively. “Renewable energy resources” has the highest occurrence followed by “energy storage” and “hybrid system”. The members of the same clusters are having a strong correlation with each other. A strong correlation is observed between “energy storage”, “electrical power transmission network”, “fuel storage”, “electric batteries” and “hybrid vehicles” which belong to the green cluster. The orange cluster is more related to energy policy and sustainable development where a strong correlation is found between “electric energy storage”, “cost analysis”, “energy planning”, “energy efficiency” and “sustainable development”. The blue cluster is mainly focused on the ESS technologies and optimization techniques whereas the black cluster is focused on the RES-integrated MG. The “hybrid

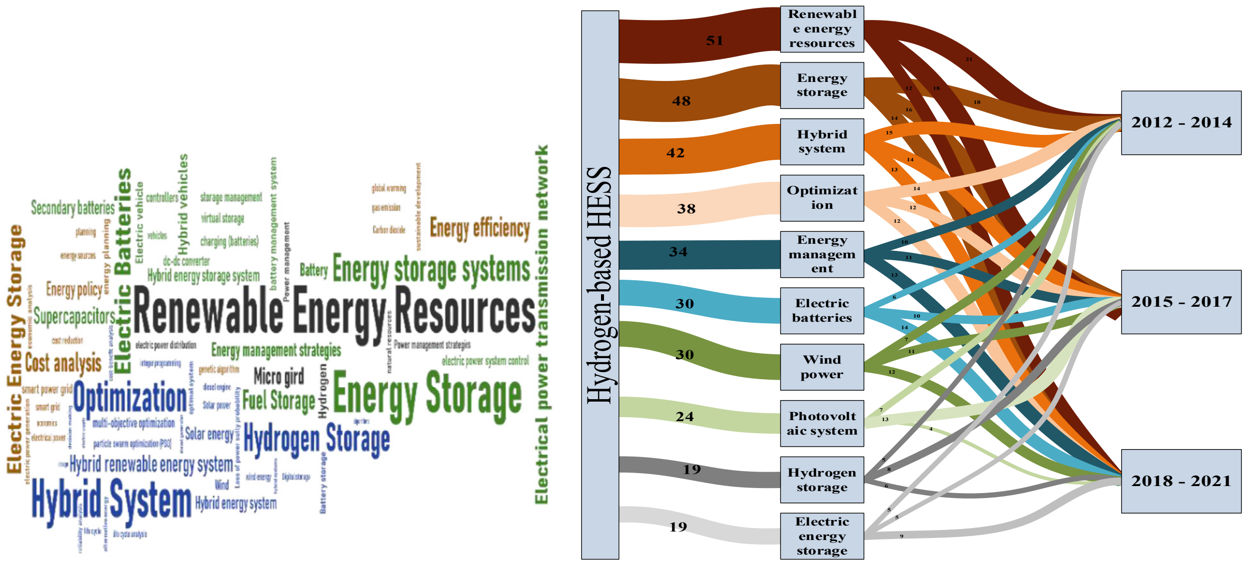

Fig. 4 – The analysis of the chosen articles (a) KCN analysis with keyword mapping (b) diagram of the keyword evaluation over time.

system", "optimization", "hydrogen storage", "PSO", and "multi-objective optimization" belong to the blue cluster, and "Renewable energy resources", "MG", and "power management strategies" belong to the black cluster.

In Fig. 4 (b), the evaluation of the top 15 keywords over different periods is presented using MS excel and MS Visio. The periods are divided into 3 phases, the early research phase (2012-2014), the middle phase (2015-2017), and the recent research phase (2018-2021). The weight of each line is denoted as the total number of occurrences of the keyword. It can be observed that the most used keyword is "Renewable energy resources" followed by "energy storage which is used mostly in the early phase. Most recently used keywords include energy storage (14), electric batteries (14) hybrid systems (13), energy management (13), and optimization (12). Finding from Figs. 4(a) and 3(b) can be summarized as follows.

- Instead of theoretical modelling of the HESS system, researchers are now concentrating on developing optimization and sizing methodologies.
- Research in the field of developing EMS techniques for both MG and EV applications is rapidly increasing.
- The research on hydrogen-based HESS is becoming increasingly popular because of the advantages of hydrogen storage like high energy density and sustainability.
- Through the KCN analysis, future researchers can find an overview of the current research trends and future research aspects.

Distribution of articles over various subject categories

The shortlisted articles are classified into several subject areas in Table 4 to provide a better picture of the present interests of researchers in the field of hydrogen-based HESS. Among the selected overall list of articles, 36% of articles are review articles and 64% of articles are technical articles. The review articles include recent developments in the ESS and HS field, system modelling and optimization, energy policies,

Table 4 – Articles are classified into several subject areas.

Subject Category	Including Articles	Publication Frequency (%)	Range of usage count
HS research and implementation	[42,44,48,50,52,62,67–81]	21	214–668
ESS research and implementation	[26,27,31,38,39,45,46,50,51,55–57,61,71–73,82–86]	21	228–2346
Cost optimization and economic evaluation	[25,26,29,30,42,51,53,61,63,70,78,79,81,87–93]	20	213–2410
PV research, and development	[27,33,34,44,47,54,74–76,78,81,93–100]	19	210–2066
EMS and Control strategy development	[33,38,42,68,75,80,91,96,99–108]	18	214–1033
RE research and implementation	[28,29,35,36,39,40,45–47,49,72,73,84,85,89]	17	210–1708
BESS research and implementation	[33,47,58,62,72–76,81,84,91,96,100,105,109]	16	210–1033
Wind power research and development	[29,33,47,62,69,74,78,81,84,87,99,105,110,111]	16	210–1327
Optimal allocation and sizing of HESS	[34,40,47,67,74,97,98,105,111–116]	14	210–1016
Transportation application (EV)	[27,48–51,90,98,101,107,117–119]	12	225–2066
Environmental aspects	[26,27,32,48,63,64,86,89,99,118]	10	228–2346
MG application	[25,43,54,60,94,105,107,109,120]	9	232–2410

application of HRES, and techno-economic analysis. Most of the researchers have focused on modelling the various HRES system consisting of both RES and ES components. The highest 21% of articles are focused on developing the HS-integrated HESS system modelling and optimization and the "ESS research and implementation" field. Some of the key issues of developing an efficient HESS system are cost, size of the system, and energy management strategies. A total of 20% of the article focused on cost optimization and economic evaluation, 18% of articles on defining EMS and control strategies, and 14% of articles on optimal sizing of the HESS system. The key motivation for developing an HRES system is to ensure reliability and environment friendliness. Although, only 10% of the selected articles are considered "environmental aspects" and the rate of GHG emission and CO2 emission reduction is mentioned.

Evaluation of the developed methodologies

Various researchers have modelled grid-connected/standalone HRES consisting of different combinations of dispatchable and non-dispatchable RES along with storage technologies and converters. In Table 5, the combination of components presented by different researchers from the selected articles is shown. The dispatchable resources are denoted as the sources, which can be dispatched on demand and controlled such as DG, Biomass whereas non-dispatchable resources are environmentally friendly but neither controllable nor consistent such as solar, wind, or hydro energy. The converters transform AC to DC or DC to AC according to the necessity whereas the electrolyzer is used to produce hydrogen through electrolyzing water. The BESS, hydrogen tank, and PHSS are mostly used as backup power and act like ESS. In the hydrogen-based HRES, the electrolyzer acts as a converter whereas the hydrogen tank act as an ES. Table 5 shows that PV (96.3%) is the most common source used by the researchers followed by BESS (81.5%). HS is used in 62.9% of the articles from the selected database. The resources that can be used to model an efficient HRES system are dependent on various factors such as; location, environmental conditions, availability of the components, and suitable transportation system [121]. Table 5 can be helpful for the future researcher to understand various kinds of combinations of resources and help to select the suitable combination for future improvement in the field of HESS development.

Several researchers have proposed optimization approaches in the recent decade to meet a variety of goals such as reliability, fast processing and reaction time, optimal sizing, and environmental friendliness. The developed models and optimization approaches can be divided into two separate groups, such as single objective (SO) and multi-objective optimization problem (MOP). Researchers mostly focused on developing different combinations of components and finding out the optimal sizing of the system with minimum overall cost. It is observed in Table 5 that most of the articles have SO optimization problems and most of the optimization methods are focused on minimizing the overall cost of the system.

Fig. 5 depicts the energy generation sources explored in the 100 publications. The number of times each of the sources is used as a dispatchable/non-dispatchable/ES is shown in Fig. 5. According to Fig. 5, PV has been used in the highest number of articles (38) followed by BESS (35). The WT and HS are used 29 and 28 times, respectively. The researchers mostly modelled a combination of PV-WT-BESS-HS-based HRES to find out the optimal sizing of the combination of components with the lowest possible COE. The DG, BESS, and HS are often used as backup power, and the excess energy obtained from PV/WT is used to charge BESS or used for hydrogen production, or in an electrolyzer for reforming hydrogen. The trends show HS as a potential source to replace BESS but more research is needed regarding cost reduction, safety issues consideration, and optimal sizing.

The essential qualities of an efficient HESS system are, quick reaction time, reliability, flexibility, improved power quality, less voltage, and frequency deviation, and environmental friendliness. Tables 4 and 5 showed that in recent years, researchers are focused more on developing cost and size optimization along with some EMS control strategies. Various models and methods have been introduced by different researchers to solve the above-mentioned issues are shown in Fig. 6. It can be observed from Fig. 6 that the FLC (9) is the highest used method for optimization. HOMER software is another popular simulation tool used by researchers to optimize the size and cost of the system, which is used in 8 articles whereas GA and PSO are used in 6 and 5 articles, respectively.

The selected database shows that FLC is the most common method used in several articles [34,38,69,72,74,96,102,104,106,112]. In Ref. [96], a grid-connected PV-HS-BESS is designed and the power flow control strategy between each system component is determined using the dynamic modelling (DM), Elman Neural Network (ENN)-based controller, Takagi-Sugeno-Kang based fuzzy gain tuner and Virtual Flux Oriented Control (VFOC). A general FLC-based control system has three steps; initial steps, processing steps, and final steps. In the initial steps, the mapping of the inputs is computed along with the suitable membership functions whereas in the processing steps, some rules are defined for computation. In the final step, the aggregated result is converted back into a detailed control output value [96].

In [102], the open-circuit voltage of SC VSC, demand P_{demand}, and charging rate of battery C rate is considered as the input of FLC, and the membership function equation is denoted as;

$$\propto_0 = \frac{P_{bat\_demand}}{P_{demand}}, P_{cap\_demand} = P_{demand} - P_{bat_{demand}} \quad (1)$$

When VSC and P_{demand} are higher, SC tends to deliver more power, whereas VSC and P_{demand} are lower, the battery tends to deplete. The result shows a 23% reduction in LCC by using the FLC in the SC-based system instead of a battery-only system. In Ref. [104], trapezoidal-type and singleton-type membership functions are utilized and the SOC limitation for battery from 20% to 80% and SMES from 5% to 95% are stated. The objective function is levelling the power fluctuation of WT output and a comparative analysis between FL and FL-based GA (FLGA) is presented. The results show that grid-connected SMES and BESS-integrated WT with FLGA control strategies can reduce power fluctuation effectively. Tascikaraoglu et al. in Ref. [69] modelled a WT-FC-BESS-based system where FL is used for battery SOC control whereas ANN is used for wind speed

Table 5 – Combination of dispatchable and non-dispatchable resources along with storage and converters.

Ref.	Optimization approach	Objective function	Non-dispatchable resources			Dispatchable resources			Converters		Storage		
			PV	WT	MHP	DG	Grid	Biomass	Conv.	Electrolyzer	BESS	HS	PHSS
[33]	DSM	LPSP	✓	-	-	✓	-	-	✓	-	✓	-	-
[34]	FLC- based DEA	NPC, LPSP	✓	✓	-	✓	-	-	-	✓	✓	✓	-
[112]	FLC	Charging strategies	✓	✓	-	-	✓	-	-	✓	✓	✓	-
[109]	Simulation using LABDER	Minimize cost	✓	✓	-	✓		✓	-	✓	✓	✓	-
[67]	SDO + LP	Minimize cost	✓	✓	-	-	✓	-	-	✓	✓	✓	-
[88]	HOMER	LCOE	✓	-	-	-	-	-	-	-	✓	-	-
[114]	CS	DR, Minimize cost	✓	✓	-	-	-	-	✓	-	✓	-	-
[89]	CCaLC software	Minimize CO2 emission	✓	-	-	-	✓	-	✓	-	✓	-	-
[94]	GNN + wavelet transform	Designing EMS with controller and DR	✓	-	-	-	-	-	-	-	-	-	✓
[70]	MATLAB simulation	Minimize cost	✓	✓	-	-	-	-	-	✓	✓	✓	-
[71]	HOMER	COE	✓	✓	-	-	✓	-	✓	✓	-	✓	-
[96]	ENN + VFOC-based neuro-fuzzy gain turner	PV tracking and power flow control	✓	-	-	-	✓	-	✓	✓	✓	✓	-
[74]	PSO-based FLC	Minimize cost, LPSP	✓	✓	-	-	-	-	-	✓	✓	✓	-
[111]	PSO	LCOE	✓	✓	-	✓	-	-	✓	-	✓	-	-
[75]	SDO	Minimize cost	✓	-	-	-	-	-	-	✓	✓	✓	-
[78]	FPA	NPC, LOLE, LOEE	✓	✓	-	-	-	-	-	✓	-	✓	-
[62]	HOMER	NPC, COE	✓	✓	-	-	-	-	✓	-	✓	-	-
[85]	HOMER	NPC, COE	✓	✓	-	-	-	-	-	✓	✓	✓	-
[105]	MOSaDE	COE, LPSP, RF	✓	✓	-	✓	✓	-	✓	-	✓	-	-
[99]	Modelling using Excel/VBA	COE	✓	✓	✓	-	-	-	✓	-	-	-	-
[80]	GA	Minimize cost	✓	-	-	✓	-	-	-	✓	✓	✓	-
[106]	FLC	EMS control strategies	-	✓	-	-	-	-	✓	-	✓	-	-
[81]	HOMER	COE	✓	✓	-	✓	-	-	✓	✓	✓	✓	-

DG: Diesel generator; PHSS: Pumped hydro storage systems; DSM: Demand side management; FLC: Fuzzy logic controller; LPSP: Loss of power supply probability; DEA: Differential evolution algorithm; WT: Wind turbine; HT: hydrogen tank; NPC: net present cost; PSO: Particle swarm optimization; LP: Linear Programming; DER: Distributed energy resources; EG: Energy generation; ED: Energy demand; SDO: Simulink Design Optimization; DR: Demand response; ENN: Elman Neural Network; VFOC: Virtual Flux Oriented Control; FPA: Flower pollination algorithm; LOEE: Loss of energy expected; LOLE: Loss of load expected; RF: Renewable Factor; GA: Genetic Algorithm.

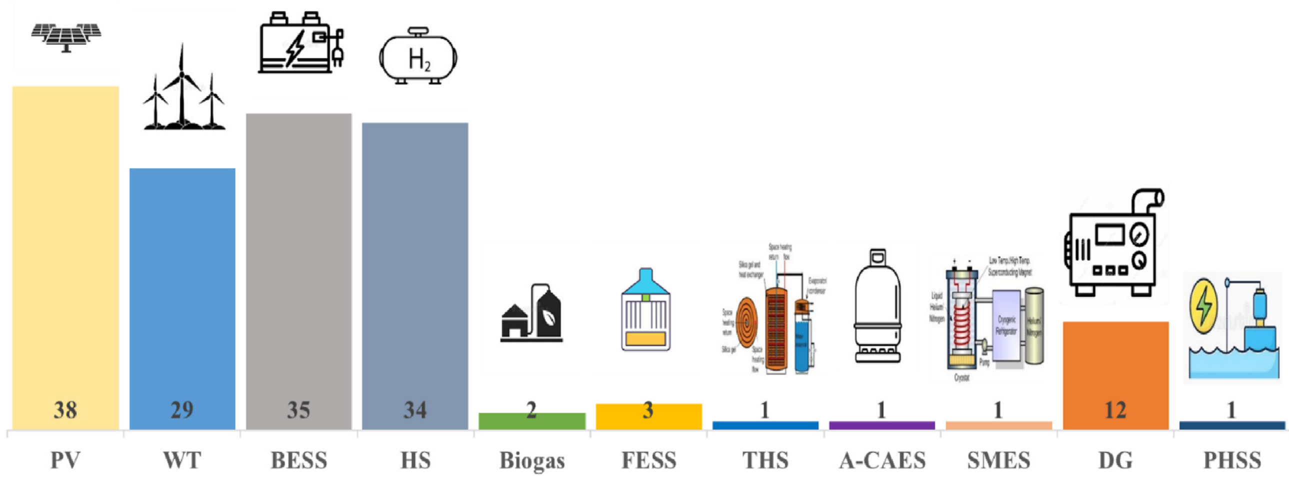

Fig. 5 – Types of energy generation sources used in the selected articles.

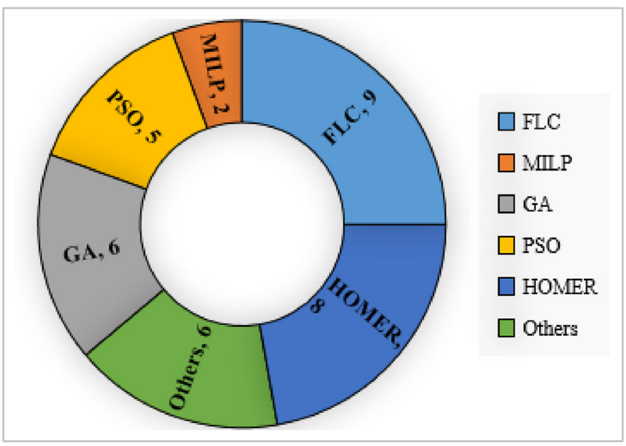

Fig. 6 – Different methods that are applied by various researchers from the selected database.

prediction. The article aims to reduce the use of hydrogen in FC by applying short-term wind power and the result shows 17% less use of hydrogen.

GA is a metaheuristic approach which is used by various researchers in the selected article database [29,80,86,97,115,116]. In Table 6, a comparative analysis of various GA-based approaches is presented. In Ref. [29], GA is used for determining the optimal sizing of an HPS system consisting of hydro turbines (HT), WT, and reservoirs. A MOP is used where both sizes of each component and LOCE is considered as the objective function. Mellouk et al. in Ref. [115] have introduced the P-GA-PSO algorithm to obtain the optimal size of the system and ensure its reliability of the system by meeting the power demand. In Ref. [80], a novel GA-based control strategy is presented along with a comparative analysis with the conventional manually tuned integral controller.

The PSO is another popular optimization approach among researchers where the objective function is just necessary,

Table 6 – Comparative analysis of various articles using GA.

Ref	Methods and System	Scope, applicability, and research gap
[29]	Maximization of return of the HPS investment, RES penetration, and cost optimization using GA	From an economic, initial investment, and performance perspective the design is highly dependent on WT which may cause issues with the system reliability because of the weather dependency on wind energy.
[80]	GA for optimization	DSTS-DG-FC-HS-BESS-based HESS is modelled, I, PI, and PID controllers are optimized using GA and comparative analysis is presented. The result shows GA-PID as the best performer.
[86]	GA based optimization	PCM-integrated ITES is demonstrated and analyzed in energy, exergy, environmental and economic perspectives for A/C application, and the OFs are TCR and energy efficiency
[97]	GA-based optimization	PV-WT is the main source and a combination of DG, VRFB, LIB, and LAB is used combinedly or separately to find out the optimal system. The result shows that PV-WT-VRB has the lowest COE with a range of 0.34 €/kWh to 0.65 €/kWh.
[115]	Optimal Sizing and EMS using P-GA-PSO	A hybrid WT-PV-CPV-SST-based HRES is designed and the main OF is the size of the system components. The COE of the system is 0.17 US$/kWh with 50% fossil fuel substitution.

PI: Proportional plus integral; PID: proportional integral derivative; DSTS: Dish-Stirling solar thermal system; VRFB: Vanadium redox flow battery; VRB: Vanadium redox battery.

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Table 7 – Comparative analysis of various articles using HOMER.

Ref.	Year	Location	COE (US$/kWh)	NPC (US$)	Sensitivity analysis
[61]	2018	Myanmar	0.193	344,304	Fuel price and average load
[71]	2015	Turkey	0.103	2343,611	Wind speed and solar radiance
[72]	2019	Nigeria	0.459–0.562	10,733–17123	Wind speed and hub height
[73]	2013	Brazil	1.351	102,323	FC and electrolyzer purchase price
[84]	2015	Malaysia	0.199	77, 019	Wind speed and solar radiance, fuel price, capacity shortage, and RF
[62]	2017	Saudi Arabia	0.609	38,523	Wind speed and solar radiance
[81]	2017	China	0.178 (BESS) 0.212 (HS)	101 million (BESS) 125 million (HS)	–

which is independent of the gradient or any differential form [74,82,98,111,115]. Various researchers have applied the PSO algorithm to optimize the cost [111] and size of the components [82] or modified PSO to optimize the cost and sizing of the components [74,115]. In Ref. [82], and [74], the cost is considered the main objective function. In Ref. [74], PSO-based FLC is used to optimize cost and LPSP. The FLC is used for HGPS controlling and the input variable for FLC are net power flow, SOC, and power set point (P*). The control strategies include the HS where P* is considered positive the fuel cell ingests hydrogen whereas when P* is negative hydrogen production starts in the electrolyzer. The result shows that applying the PSO-based FLC improves the battery SOC by 6.18% whereas the increase the hydrogen tank capacity by 13.53%. In Ref. [111], the main objective function is LCOE which is denoted as;

$$LCOE_j = \frac{CC_j + OC_j + MC_j + RC_j + SC_j + OC_{U_j} - SV_j}{\sum_{n=1}^{N_p} \frac{Q_n}{(1+r)^n}} \tag{2}$$

where, $CC_j, OC_j, MC_j, RC_j, SC_j, OC_{U_j}$ and SV_j are the capital cost, operation cost, maintenance cost, replacement cost, social cost, utility outage cost, and salvage value. The constraints are battery SOC, reliability constraints, and active generator and battery units. The battery SOC and the active generator and battery units are denoted as follows:

$$SOC_{min} \le SOC \le SOC_{max} \tag{3}$$

$$N_{DGmin} \le N_{DG} \le N_{DGmax} \tag{4}$$

$$N_{PVmin} \le N_{PV} \le N_{PVmax} \tag{5}$$

$$N_{WTGmin} \le N_{WTG} \le N_{WTGmax} \tag{6}$$

$$ad_{min} \le N_B \le N_{Bmax} \tag{7}$$

The result shows that the optimum configurations include a PV-WT-BESS-based system with the lowest possible COE. In Ref. [82], the ε-constraint method and PSO-based optimization approach are introduced for a MOP where the objectives are LLP, CO2 emission, and cost. The PV-WT-BESS-DG-HS-based system configuration is modelled and the proposed system's key advantages are simplicity and efficiency, whereas load shifting and source availability are considered.

Another popular method of optimizing the HRES system is using the HOMER software which has been used in eight different articles from the selected database [60–62,71–73,84], and [81]. The researchers have developed different grid-connected/stand-alone systems for various geographic locations consisting of various components to present the techno-economic analysis using HOMER software. An overview of the optimal planning of the HRES system utilizing HOMER is presented in Ref. [60] considering the COE, NPC, operation and maintenance cost, GHG emission, and sensitivity analysis. The article concluded that the HOMER is more utilized in developing countries rather than in developed countries, the PV is the most used method, and wind speed, hub height, solar radiation, and fuel cost are the most common uncertainty parameters considered by most researchers. Table 7 presents a detailed comparative study of various articles utilizing the HOMER from the selected dataset of articles.

In [61], an HRES is designed for Myanmar considering PV-DG for the base system and LAB and LIB for the backup system, a detailed comparative analysis of the impact of the LAB and LIB is also presented. A PV-WT-FC-BESS-based system is designed in Ref. [71] to present a techno-economic analysis in the Turkey region. The WT-FC-based system is considered the most optimized system with the COE and NPC being $0.103 kWh and $2343611 respectively. Diemuodeke et al. in Ref. [72] designed a PV-WT-DG-BESS-based system in 6 different regions of Nigeria. The COE ranges from US$/kWh 0.459 to 0.562. The result shows that the proposed optimized system can fulfil a household's electrical energy needs of 7.23 kWh per day. Techno-economic analysis of a stand-alone HRES system is presented by Silva et al. in Ref. [73] where the location is selected in Brazil and the system components are PV, FC, and BESS. The purchase price of the FC and electrolyzer affects the overall COE of the system. The sensitivity analysis shows that if the capital cost is reduced by 50% in the upcoming 10 years the COE tends to reduce by 17% which still makes the system less economically feasible compared to the present system with a low COE. In Ref. [62], a PV-WT-BESS-HS-based system is modelled and a techno-economic analysis is presented for seven different regions of Saudi Arabia. The PV-WT-BESS-based system in the Yanbu area has the lowest COE of US$/kWh 0.609 and NPC of US$38,523. The system consisting of HS has automatically increased the overall COE of the system due to the high capital cost of FC and electrolyzer. The COE of the PV-WT-FC-based system ranges from US$/kWh 1.28 to US$/kWh 1.827 which is high compared to the PV-WT-BESS-based system. In Ref. [81], the PV-WT-DG-based system along with BESS and HS is designed and simulated using HOMER. The system lifetime is considered as 20 years and the result demonstrated that the use of BESS is still cheaper that the HS technology as the COE of using HS system

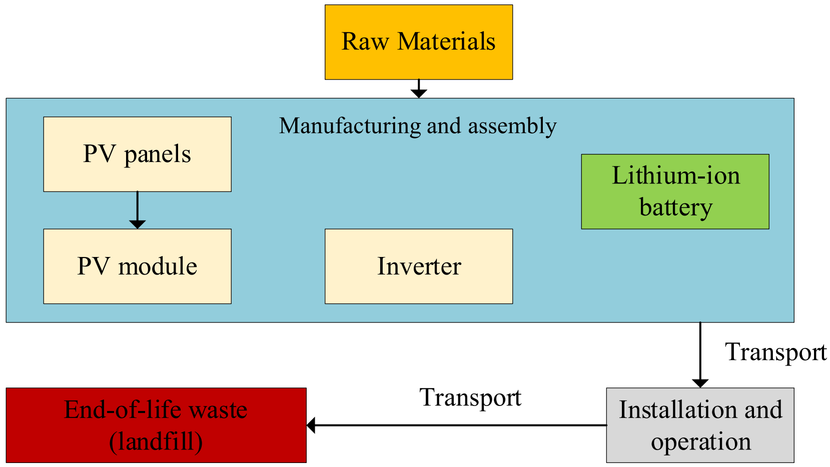

Fig. 7 – Life-cycle stages of a PV-LIB-based domestic HRES [89].

is US$/kWh 0.212 whereas using BESS it reduced to US$/kWh 0.178.

Techno-economic analysis of an isolated HRES for the vineyard is performed in Ref. [77] where PV-BESS-HS-based HRES is designed for vineyards. For hydrogen production, an electrolyzer, compressor, and water purifier are placed. Three types of PV panels; floating, tracking, and fixed are used. The outcome shows 27 tons of equivalent CO2 emission reduction. A case study on the techno-economic analysis of SA-HRES in Egypt is presented in Ref. [85] where A detailed description of the components of the 6 different configurations, configuration models, load profiles, results of the simulation, and comparative study is presented. The result shows that PV-FC has the lowest COE and NPC. Another techno-economic analysis of household HRES is provided [93]. The impact of installing PV and Building-integrated photovoltaic/thermal (BIPV/T) using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM) and Canadian housing stock (CHS) is presented. The BIPV/T system is modelled and simulated and the result shows, that 25%–35% of households are eligible for installation and yearly 227 PJ of energy consumption and 10.85 Mt of CO2 reduction. An HS-integrated PV-WT-BESS-based system is designed and economic analysis is provided in Ref. [79] and the result shows a 60.9% reduction in CO2 emission due to the elimination of the high energy consumption air separation device (HECASD). In Ref. [110], a HESS is modelled which consists of a combination of A-CAES and FESS along with WT where the unbalanced power is dispatched, and the low frequency is passed through adiabatic compressed air energy storage (A-CAES) and high frequency to the FESS and the result shows steady power output and less WT power loss. In Ref. [100], a PV-BESS-SC-based HESS where uncompensated power of BESS is used to improve performance. The main benefits are rapid dc-link voltage restoration and efficient power distribution. Two different HRES systems; WT-DFIG (C1) and WT-DFIG-BESS (C2 or C3) are modelled, and the control strategy is defined in Ref. [91]. The result shows control scheme of C2 performed better in fault conditions.

Lithium-ion battery (LIB) is another popular ESS which is used mostly as a backup power in different HRES configurations [88,89,97,98,119,122]. A design and implementation of FC-LIB-based HESS are presented in Ref. [122]. A 90 kW proton exchange membrane fuel cell (PEFMC) and 19.2 kWh LIB are used as primary and secondary sources respectively. The advantage of the proposed system includes DC-link voltage regulation accuracy and 96.1% power efficiency. A comparative analysis of different LIB storage technologies and LAB is presented for EV application in Ref. [119] and the result shows that, during discharge, LiFePO4 performed better whereas during charging Li[NiCoMn]O_2 performed better. Life-cycle environmental impact (LCEI) assessment using CCaLC software for analyzing the environmental impact is shown in Ref. [89] where PV-LIB-based domestic HRES is modelled to assess the environmental impact where the result shows a significant impact lowering the CO_2 emission 558,000 t CO_2-eq./year compared to the grid. Although feed-in-tariff and incentives for installations are neglected as initial costs. The various life cycle stages that are considered in Ref. [89] are shown in Fig. 7.

The application of hydrogen-based HESS in the transportation sector is increasing rapidly. Various researchers are developing models and EMS control strategies to implement a real-time fuel cell hybrid electric vehicle (FCHEV). In Ref. [123], the impact of HESS in an FCHEV is observed and the optimal EMS strategies are defined, and the main goal is to reduce fuel consumption. Four different control schemes are proposed in Ref. [108] for a stand-alone RES/FC HPS. The batteries and UCs are used for power flow balancing and LF controlling is used for sustaining demand variability due to RES. The AIR-maximum efficiency point tracking/Fuel-load flowing is found to be 3–5% fuel-efficient. Designing and experimental setup of a DC MG for quick charging of EV and plugin hybrid electric vehicle (PHEV) considering EMS and V2G where BGTC is interconnected with 2 DC-DC converters [107]. In Ref. [101], equivalent consumption minimization strategy (ECMS), cascade control loops (CCL), FL, and multiport power converter (MPC)-based 5 different control strategies are given for EMS of hybrid plugin electric vehicle (HPEV). The MPC-based energy dispatching for off-grid PV-WT-HS-Battery-based HRES is modelled in Ref. [68] and the system lifetime is considered as 25 years. While the gird-connected mode where

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Table 8 – Comparative analysis of different approaches.

Ref	Methods and System	Scope, applicability, and research gap
[90]	MILP-based DER-CAM.	EV-connected building EMS is simulated using DER-CAM where cost and CO_2 reduction are considered as OF and the outcome shows that, using stationary storage is reliable and cost-effective instead of using EV storage. Although RES uncertainties are not considered.
[92]	CP	CP is used to solve the optimization problem, adaptive AR for demand forecasting, and EMS strategies to reduce around 18%–30% of the daily operating cost of MG.
[95]	A solar-CLC system is designed and simulated using ASPEN PLUS software	The result shows increased system efficiency of 7% while using solar with CLC, stable operating temperature, 70% solar energy absorption, and 14.25% loss of energy because of re-radiation. The low solar fraction is the main drawback of the system configuration.
[105]	MOSaDE algorithm for MG sizing	PV-WT-DG-BESS-based HMS is designed and the COE and LPSP are the main OFs and RF are the system constraints including the EMS strategies.
[118]	CBA of city buses using the ADVISOR vehicle simulation program	The LCC and cost analysis are presented under the various fleet operation of the hybrid and conventional city buses. Due to less impact on the duty cycle and life cycle cost, plug-in hybrid and electric city buses are more cost-efficient without considering the operative environment.
[120]	MILP-based RHS for MCGS scheme	PV-WT-Biogas-based off-grid MG is designed along with an optimal MCGS scheme for 100% renewable energy and reducing cost. Moreover, overcharging and deep discharging are required to improve battery lifetime.

the RES penetration can affect system reliability parameters has not been considered. A comparative study between the simulation result of both series and parallel connection of MPC on the impact of PFCV is discussed and shows high efficiency in the multi-operating mode [83].

There are a few more approaches also introduced to optimize the size and cost of the system such as; MILP-based distributed Energy Resources Customer Adoption Model (DER-CAM) for cost and CO_2 minimization [90], Convex programming (CP) for demand forecasting and EMS control strategies for MG [92], ASPEN PLUS software to analyze the solar radiation, temperature impact on the system [95], Multi-Objective Self-Adaptive Differential Evolution (MOSaDE) algorithm for PV-WT-DG-BESS-based MG sizing [105], ADVISOR vehicle simulation program for life cycle, and cost analysis [118], and MILP-based RHS for multi-carrier generation scheduling (MCGS) scheme [120], are also presented and discussed in Table 8. In Ref. [90], an EV-connected building EMS is simulated using DER-CAM. The findings demonstrate that the quantity of EVs connected to California commercial buildings is primarily determined by the optimization approach (cost against CO_2) of the building EMS, rather than by battery efficiency factors. A PV-WT-BESS-based MG is designed and a novel CP-based EMS is developed to reduce around 18%–30% of the daily operating cost of MG. A PV-WT-BESS-based MG is developed by Elkazaz et al. in Ref. [92] where CP along with MPC and rolling horizon predictive (RHP) control is used to develop the EMS strategy to minimize the daily operating cost. In Ref. [105], a PV-WT-DG-BESS-based hybrid-microgrid system (HMS) is designed and (MOSaDE) is used for sizing the system components. The main two objective functions are LPSP and cost of energy (COE). The cost-benefit analysis (CBA) of hybrid and electric city buses is provided in Ref. [118], where the article concluded that the plug-in hybrid and electric city buses are more cost-effective without considering the operating environment since they have a lower impact on the duty cycle and LCC. A PV-WT-Biogas-based off-grid MG is modelled in Ref. [120] and the scheduling is done using the MILP-based RHS. The main scheduling objective is cost whereas the system constraints are multi-energy balance constraints, load shedding constraints, battery SOC constraints, battery charging/discharging constraints, digesting temperature constraints, biogas storage constraints and combined heat and power (CHP) unit constraints. All of these strategies and initiatives are an aid to improving the HESS implementation towards a cleaner environment.

In [75,103], dynamic modelling is applied. In Ref. [103], DC/DC converter, DC/AC inverter, and AC/DC rectifier are designed for UPS, PEMFC, and battery which is reliable and cost-efficient including intelligent controller whereas in Ref. [75], PV-HS based FC-BESS based modelling, load profiling and cost analysis of various components and control scheme of BESS and HS level is optimized applying dynamic modelling-based SDO. In Ref. [124], A design and analysis of a dual-source Solar-Assisted-Heat Pump (SAHP) for Domestic Hot Water (DHW) are presented. The overall system is designed and established in Milan and the result shows 15.4% less daily energy consumption than a conventional air-to-water heat pump. Moreover, using "water source" and "air source" increase the system performance by 34%. In Ref. [87], a general algebraic modelling system (GAMS) is used to obtain the highest economic benefit. To maximize the profit of an HRES plant, an optimal operation strategy consists of hourly charging/discharging, and optimal sizing of the storage system. The results have shown certain revenue while using the storage in arbitrage and regulation services. Although few preassumed conditions and parameters such as battery life are not considered while developing. A variable-rate-based dispatching strategy is defined using MATLAB simulation in Ref. [117] where charging rate, and energy efficiency are considered while developing the system consisting of 100 charging points, 25 kW max power, and 1000 vehicles over 8 h of time with the increase of profit and 7% user satisfaction rate. Coelho B. in Ref. [125] configured and analyzed three different CRS various Biogas methods whereas Manandhar et al. in Ref. [100] a HEES is modelled and joint control strategy developed. An FC-BESS-UCs-based system is modelled and simulated where FC acts as a primary and batteries and ultracapacitors (UCs) as secondary sources and operation mode control (OMC) based EMS is defined in Ref. [126]. Therefore, it can be concluded that researchers are focused to develop an efficient, cost-effective, and optimally sized hydrogen-based HESS system for real-time operation.

Application of hydrogen-based HESS

The research on hydrogen-based HESS has increased rapidly in recent years as it is considered the most potential source to replace the fossil fuel-based energy generation system even the batteries. The technology is still not mature enough to replace batteries although there are several key applications of hydrogen-based HESS found which are shown in Fig. 8. Due to the high energy density value (120 MJkg−1) compared to the other existing chemical energy storage system the hydrogen-based ES has gained attention in recent years [127]. The RES is dependent on various environmental conditions. In addition, because of its nature, the RES produces lots of excess energy which is needed to be dumbed. Moreover, high penetration of RE to the grid may cause grid instability. Hydrogen-based ES is environment-independent and controllable, proper utilization of excess energy can be obtained by using the excess energy for hydrogen production and compared to the existing ES technologies such as BESS, PHES, etc. hydrogen has the benefits of having a high energy storage capacity, a prolonged storage time, and adaptability.

Another important application of hydrogen is the power-to-gas application where electric power is utilized to create a gaseous fuel. With efficient storage capability and high energy density, power-to-hydrogen can be applied and can be integrated with the grid as an effective storage solution. Moreover, the average lifespan of power-to-gas projects is 1–3 years, which is significantly shorter than the MG lifespan [4]. Integrating hydrogen-based HESS into the power-to-gas projects efficiently can improve the lifetime of the projects as well as reduce the overall cost of the system. In addition, the excess hydrogen from the MG application can be directly used for industrial applications such as oil refining, ammonia and methanol production [128]. To reduce GHG emission, hydrogen is used instead of coal in the steelmaking and concrete industries [128].

Hydrogen-based ES in the grid-connected MG application can significantly reduce the frequency regulation of the system [129]. The RE-based MG integration with the grid may cause frequency and voltage regulation. Similar to the other ES technologies, HS can be used to mitigate the congestion in the transmission and distribution line and eliminate the frequency and voltage regulation. The integration of HS with the off-grid energy generation system is considered in many areas. In an off-grid system, for a fixed demand, the increase in stored energy does not imply an increase in power providing the HS system more flexibility, expandability, and cons effectiveness. Rizzi et al. in Ref. [130], has presented a PEF FC with the integration of HS and was able to generate 4.8 kWh of electricity, at an average power of 0.76 kW, throughout 6 h. H2One™ is a hydrogen-based autonomous energy supply system developed by Toshiba Corporation [131] which includes a PV capacity of 62 kW, 54 kW of FC output, and an electricity storage capacity of 1.8 MWh. The developed system was installed to supply clean energy to 12 hotel rooms in Japan. A WT-BESS-FC-FESS-based system was installed by Norsk Hydro and Enercon on the Norwegian island of Utsira in 2004 which includes a 55 kW hydrogen engine, 10 kW PEMFC, 50 kWh NiCd battery, and 5 kWh FESS [132]. The Hawaii Hydrogen Power Park (HPP) at Kahua Ranch was established in 2010 consisting of 7.5 kW WT and 9.8 kWp PV, 345 kWh capacity of lead-acid battery, and a 5 kW FC system [4]. A small-scale grid-connected PV-HS-based residential system was

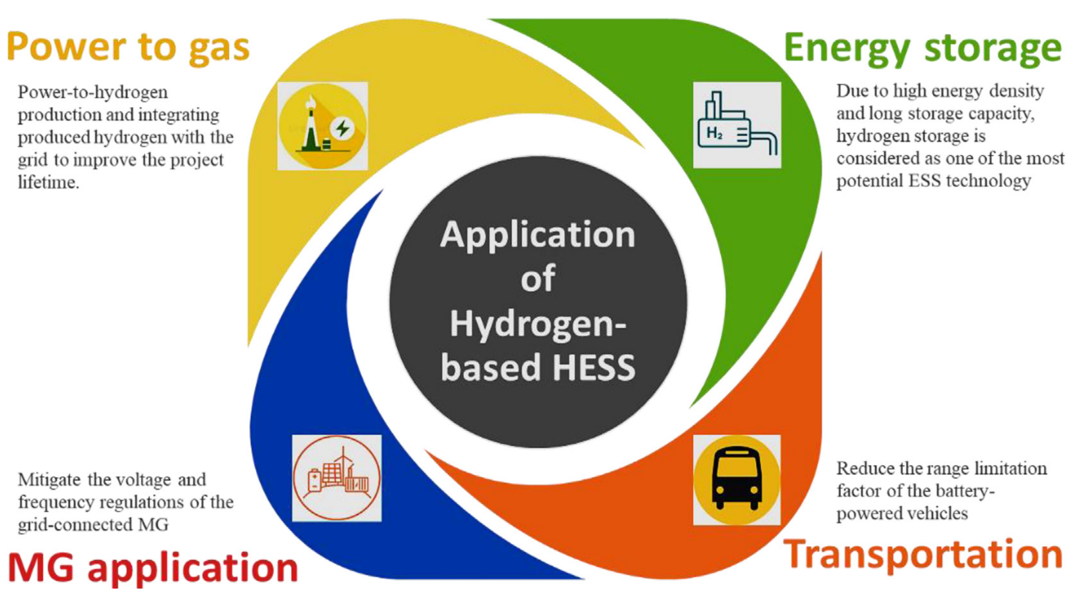

Fig. 8 – The application of hydrogen-based HESS.

installed at the University of California in Irvine which includes a 5 kW PV and 1 kW FC in 2011. A PV-HS-BESS-based hybrid system is developed at the National Institute of Advanced Industrial Science and Technology and Shimizu Corporation in Japan [133] where the main goal is to develop a zero-emission system. The result shows promising performance as a very small power from the grid is needed. During the daytime, the PV can fulfil the required demand as well as charge the battery and produce hydrogen. During the night, HS can provide the necessary power with the help of a grid and battery. The waste heat from the FC can be utilized in the desorption process in the metal hydride tanks which makes the system more energy efficient.

Stationary FC is another popular application of HS where the stationary FC acts like an off-grid MG and supplies the necessary power to the crucial amenities. The two key advantages of stationary FC are; low GHG emission and low space consumption. For example, a 10 MW stationary FC plant can be installed on an acre. Whereas the PV or WT require 10 and 50 acres per MG, respectively which makes it more popular nowadays. According to the Fuel Cell & Hydrogen Energy Association (FCHEA) [134], approximately 550 MW (MW) of stationary FC have already been deployed all across the United States by January 2020 for clean, reliable, distributed power supply.

The application of hydrogen-based HESS in the transportation sector is one of the prominent research fields. Because of the high energy density and long storage capacity, HS can be a great alternative to conventional vehicles even battery-powered vehicles. Battery-powered vehicles are suffering from range limitations. The existing FC vehicles are using high-pressure compressed hydrogen fuel tanks such as Honda's Clarity fuel cell vehicle, Hyundai's NEXO, and Toyota Mirai fuel cell vehicle whereas a liquid hydrogen fuel tank is used in BMW. Although few factors are still needed to be addressed such as; storage occupancy of hydrogen in the FC vehicles, lack of hydrogen refueling infrastructure, initial temperature, types of cylinder, and initial pressure in the tank. In addition, the research shows, that FC vehicles emit 120 g/km of CO_2 over their lifetime which can also affect the environment as well [135]. Moreover, efficient EMS and control strategies are also needed for the effective application of FCEV. Although, due to the possibility of reducing GHG emission at a large scale, long storage capacity, and energy density, hydrogen has a great potential to replace the present energy generation scenario.

Challenges and issues

To reduce the negative environmental impact due to fossil fuel-based global energy production, the world energy revolution is making inroads, aided by the fast development of RE technologies. Hydrogen-based HESS is one of the most potential ESS technologies due to its positive impacts on the environment. Because of the numerous aspects that must be addressed, such as economic feasibility, reliability, power and frequency control, uncertainty, and environmental considerations, developing and establishing hydrogen-based HESS is a tedious process. Nevertheless, such challenges may be solved with an efficient balancing of various technologies, proper planning, and application. The following sections provide a comprehensive overview of these main challenges, as well as specific recommendations.

Economic impact

Economic feasibility analysis of a HESS is one of the key research topics among the researchers. The key concepts of developing an effective HESS are environment friendliness and cost reduction. The overall cost of the system includes capital cost, operation, and maintenance cost, and replacement cost of the components. The capital cost of hydrogen-based HESS includes the capital cost of each component and for hydrogen storage, the capital cost is the summation of each component such as the hydrogen production system, fuel cell system, and reforming hydrogen system. The AELs hydrogen production system costs 1000–1500 Euro/kW whereas FC micro-CHPs (0.3–5 kW) cost 10,000 Euro/kW and AELs hydrogen reforming cost is about 3.2–5.2 Euro/kg [136]. With the development of more matured technology for installation and economic aspects, the capital costs tend to be significantly decreased shortly. Production of hydrogen using water electrolysis is a promising approach, although it is important to consider the amount of electricity consumption. To reduce the electricity generation cost for hydrogen production, the use of RES along with HS can be a promising solution. Although, HS-based HRES installation location, fluctuation of voltage and frequency while connecting to the grid, transmission and distribution cost should be considered while system designing.

Several approaches have been developed by different researchers over the previous decade to minimize the total system's cost [26,28,29,70,74,75,78,82,103,109,113,118,120]. In Ref. [78], a techno-economic optimization of a PV-WT-FC-based system is developed where the objective function is (LCOE) and the defined constraints are loss of energy expected (LOEE) and the loss of load expected (LOLE) using the flower pollination algorithm (FPA).

In [67], a PV-WT-BESS-HS-based HRES is designed and simulated. Moreover, EMS strategies are defined to reduce the operating cost of HS. In Ref. [74], PV-WT-HS-BESS-based HRES is modelled and an optimized FLC is designed for HS using PSO. Another important application of HS is in the transportation sector, A detailed comparative study between FC vehicles and IC engine vehicles is presented in Ref. [48]. The literature shows that, due to more mature technology, the IC engine is more cost-effective than the FC engine. HOMER is also used to present techno-economic analysis where various system configuration is designed as an isolated mode or grid-connected mode [62,81,84]. In Refs. [62,81], a comparative analysis of BESS and HS is presented and the result concluded that BESS is a more mature technology compared to the HS as the configuration consisting of the HS always has higher COE compared to the configuration consisting the BESS due to the high purchasing cost of electrolyzer and FC. Therefore, it can be stated that building an effective, economically viable HS-based HESS for real-time deployment is a difficult and time-consuming task that requires careful consideration of several factors.

Safety issues and efficiency

The present advances in FC and electrolyzer efficiency and safety are still insufficient, and they continue to be obstacles to the successful real-time implementation of HS. While considering safety, within specified limitations, the flammable behaviour of hydrogen and its explosiveness when mixed with air must be considered. Although, hydrogen can be managed securely in industrial applications. For an efficient FC vehicle, hydrogen storage in modest quantities is required. For achieving equivalent quantities of driving range through an FC vehicle compared to the conventional vehicle 5–10 kg of hydrogen has to be stored safely which is considered a great challenge [127]. Some of the effective and safe hydrogen storage technologies include compressed gas, underground storage, liquid hydrogen, and solid hydrogen [136]. At high pressure (up to 700 bar-g) and exceptionally low temperature (−253 °C), hydrogen can be stored and transported [127]. Moreover, the efficiency of the HS production and electrolyzer is needed to improve as well. The efficiency of AEL and PEMEL is 63%–73% and 67%–74% respectively [136]. Another important factor while considering the HS is the electrochemical degradation of FC and electrolyzer. The present electrolyzer system has a lifespan of roughly 40,000 h and the system lifespan of micro-CHP is around 10 years. Various EMS strategies can be applied to improve the lifetime of the overall system which will reduce the system cost as well. Moreover, monitoring the effect of temperature changes on the system is an important factor while system development. In Ref. [76], a PV-WT-HS-PEFMC-BESS-based system is modelled, dead state temperature is defined and the impact of temperature on the system is analyzed. It can be concluded that the safety factors for storage and transportation of hydrogen-based HESS include low temperature, great permeability, low viscosity, flammability limitation, minimizing leakage potential, and embrittlement.

Environmental impact

The environmental impact of HS is dependent on hydrogen production and storage technologies. Water is an essential component for producing hydrogen through electrolysis. A PEMEL requires 18 L of water and 54 kWh of electricity for the production of 1 kg of hydrogen which can affect the global groundwater reserve while mass production of hydrogen [137]. Integrating seawater for the electrolysis process can be considered as future research to reduce groundwater consumption. Another important factor that can affect the environment is the raw and rare materials used for catalysts and co-catalysts of electrodes. To achieve competitive efficiency, instead of using Nickel-based electro-catalysts, rare materials such as titanium, iridium, ruthenium, palladium, and platinum-based anodes and cathodes are used in PEMEL, PEM, and PEMFC [136,137]. Moreover, after system replacement, the recycling of the materials are also needed to be considered.

There are several forms of hydrogen based on its production process. The production of hydrogen using coal or natural gas is known as “grey hydrogen” which is mostly used for industrial applications. The manufacturing of “grey hydrogen” produces at least 10 kg of CO_2 for each kilo of hydrogen produced [138]. In the “Blue hydrogen,” the production process also includes coal and gas but carbon capture and sequestration (CCS) is applied to reduce the CO_2 emission by 85% [138]. Only the “Yellow hydrogen” production process is a zero-carbon emission process as nuclear energy is used for production. The goal of the hydrogen industry is to replace coal and gas-based hydrogen production with RES, which not only reduces CO_2 emission but also reduces the overall cost of the system. Moreover, due to the leakage of hydrogen from 0.2% to 10% from the overall hydrogen energy storage system, hydrogen emission itself can be regarded as an indirect GHG emission [136].

Effective hydrogen-based hybrid energy storage system development technologies

From the above discussion, it can be concluded that more research is needed to develop an efficient, reliable, cost-effective hydrogen-based HESS. Many factors are needed to be considered for future research. New reliable and leakage-free hydrogen storage and transportation technologies are needed. Recent research includes adding an intumescent paint layer to composite HS tanks to increase their fire resistance [139]. The usage of rare and toxic materials are also needed to be avoided. To reduce the usage of iridium and ruthenium, recently carbon-nanotube-based platinum catalysts are developed [140]. Converters are one of the important elements of the HS system as; DC/DC converters are used to step down the supply voltage for the electrolyzer and step up for the FC. Moreover, DC/AC rectifiers are used while the grid-

Table 9 – Types of challenges and issues considered while developing an efficient hydrogen-based HESS.

Challenges and issues	Key aspects
Economic impact	• Hydrogen production cost reduction • Hydrogen transportation and storage cost reduction • Overall capital, installation, operation and maintenance cost reduction of the Hydrogen-based HESS
Safety issues and efficiency	• Hydrogen storage safety • Hydrogen transportation safety • Minimizing the hydrogen leakage potential
Environmental impact	• Reducing the use of water • Restoring the groundwater reserve • Reducing the grey and blue hydrogen production • Using the RES to produce hydrogen • Replacement and recycling of the hydrogen-based HESS system components
Effective hydrogen-based hybrid energy storage system development technologies	• Reliable and cost-effective system development • Reliable and leakage-free hydrogen-based transportation technology development • Effective integration of RES with HS • Efficiency improvement of the electrolyzer and FC

connected mode of electrolyzer and FC. Suitable, cost-efficient converters with malleable voltage ratios are needed to be applied to improve system performance. The LCA is an effective approach for assessing the possible environmental implications of hydrogen-based ES. In Ref. [63], detailed LCA modelling, inventories, and GHG emission of various electricity generation technologies is presented. The article concludes that RES and NP have the lowest environmental impact, using storage leads to lower CO_2 emission and biomass has moderate co-benefits. Moreover, effective integration of RES with the hydrogen production system can be the ultimate solution to the hydrogen-based HESS development issues. However, generally, HS has several favourable environmental effects, including lower GHG emissions, high energy density, and energy waste protection by storing extra energy. Furthermore, while used as an ES, HS can balance supply and demand disparities, resulting in more dependable and greener energy. In Table 9, a summary of the challenges and issues that are considered while developing an efficient hydrogen-based HESS is provided.

Conclusion and future direction

The study aims to develop a novel approach “usage count” to identify the most impactful articles in the field of hydrogen-based HESS. However, there are a few weaknesses to our study that should be mentioned. Firstly, while selecting the articles, only the Scopus database is considered and manual extraction is conducted while selecting the articles. Secondly, the provided research only includes articles published between 2012 and 2021. More scientific databases such as the “Web of Science” and “Google Scholar” or a combination of these databases can be considered as future suggestions. Thirdly, the articles that are written in “English” are only considered for the study. Finally, the articles within the domain such as; “chemicals”, “electrochemical”, nano-materials”, “electrolysis”, “molecule”, “microbiology”, “geographical” and “genetically” are excluded from the selection process. The articles considering all domains to obtain the top 100 articles with the highest usage count can be suggested as future work.

In the end, the top 100 articles with the highest usage count are extracted and analyzed. A comparative analysis between the usage count and citation analysis is presented. The factors such as; reducing the time lag of research, more focus on recent articles and domain independence make the usage count more expedient over the citation analysis. A detailed keyword analysis is provided for a better understanding of the recent research trends and focuses on the field of hydrogen-based HESS. The state of the art of hydrogen-based HESS followed by a detailed analysis of the selected articles including the methods and system, modelling, optimization objectives, sensitivity analysis, application, and research gaps are provided. Based on the analysis, extensive research on issues and challenges in the hydrogen-based HESS field is also presented. The following are some of the advantages of analyzing the aspects of articles with high usage counts.

- Understanding and acquiring information from highly impactful articles in the field of hydrogen-based HESS analysis can provide future researchers with comprehensive insight.
- Analyzing contemporary research trends, assessing recent advances, and identifying the current research gaps in the field of hydrogen-based HESS will be led to further advancement in the sector.
- The usage count analysis can help future researchers to provide a guideline not only regarding the recently developed methods and system but also the information regarding journals to publish, prominent researchers, and the scope of the research.

The goal of this study is to inform researchers about existing research trends and to better understand the effect and advancements of hydrogen-based HESS, resulting in a greener energy future. From the analysis, the articles presented the research gap between individual articles and overall issues and challenges while developing an efficient system in the hydrogen-based HESS field. Based on the issue and challenges the future recommendations are as follows.

- Availability of the usage count data for the published articles is a major concern while developing usage count analysis in a particular field of research. Publicly available usage count data can be considered as a future recommendation.
- To achieve the SDGs, the RE integration with energy systems and hydrogen production systems instead of coal or natural gas is very much needed. The RE integration not only reduces the overall cost of the system but also provides a cleaner environment.
- Increasing the economic feasibility of HS for large-scale ES applications requires the development of more reliable, efficient, optimized and cost-effective HS methods.
- Electrolysis is a critical step in hydrogen production, and increasing its efficiency could result in more cost-effective and sustainable hydrogen production.
- Effective HS integration with a wide range of RES is needed while the system should be optimized and a control system is needed to develop the most balanced system where produced excess energy is utilized for hydrogen production and the HS will provide necessary power when needed.
- For the storage and transportation application, fully protected, leakage-free, and less space-consuming hydrogen storage system technology is needed to be developed.
- For the transportation sector, the lack of a hydrogen refueling station is observed. Moreover, the refueling time is also very high. An optimized hydrogen refueling station is needed which will be integrated with RES and grid for continuous operation. Furthermore, EMS control strategies are needed to be developed for efficiently refueling the vehicles without compromising grid reliability.
- LCA is a useful method for evaluating the environmental impacts of hydrogen ES. A very few. LCA analysis is provided for the HS integration with MG, which will provide a clear overview of the cost and efficiency of the system.

- To develop large-scale hydrogen storage the corresponding environmental impact such as groundwater level monitoring, hydrogen safety, and yellow hydrogen production are needed to be considered.
- Detailed hydrogen production, storage, and transportation policies are needed to be established for ensuring safety and public acceptance. Moreover, it is necessary to have standardized hardware and operational processes, as well as appropriate codes and standards.

Hydrogen is playing a significant role in assisting large-scale ES applications, particularly in the context of the global energy transition towards decarbonizing. Based on the review, a wide range of advancements is expected nearing the future in the field of hydrogen-based HESS. The study investigated the usage count of hydrogen-based HESS and highlighted some of the technological significant challenges such as; high capital and production cost, lack of efficient and durable electrolyzer and FC system, and proper integration with RES, which are affecting the overall development in the field of hydrogen-based HESS. Research and development for cost reduction, while improving the system reliability and performance and a standardized policy can help deliver hydrogen to today's competitive environment and encourage the development of hydrogen-based HESS. However, with sufficient investment and innovation, hydrogen-based HESS could have a significant impact on shaping the future of energy generation and consumption, and contribute to the development of a more robust and sustainable energy system for future generations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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