INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (XXXX) XXX

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Toward a hydrogen society: Hydrogen and smart grid integration

*Rong-Heng Lin**, *Ying-Ying Zhao*, *Bu-Dan Wu***

State Key Laboratory of Networking & Switching Technology, Beijing University of Posts and Telecommunications, Beijing, 100876, China

HIGHLIGHTS

- The integration of Hydrogen and Smart Grid is a trend.
- The integration will help boost new economy and form hydrogen society.
- Four different viewpoints include grid, vehicle, economy and system models.
- More than 100 publications are reviewed for the integration.

ARTICLE INFO

Article history:
Received 27 August 2019
Received in revised form
24 December 2019
Accepted 7 January 2020
Available online xxx

Keywords:
Hydrogen
Smart grids
Renewable energy
Hydrogen fuel cell
Hydrogen economy
Energy system

ABSTRACT

Hydrogen has an important role as a smart solution for Smart Grid, as it can play as an energy vector, a storage medium, and a clean fuel cell. The integration of Hydrogen and Smart Grid can minimize the impact on the environment while maximizing sustainability, which indicates that we are developing toward a hydrogen society. There have been already many studies on different aspects of this topic. For a better understanding of the related work, this paper proposed a comprehensive overview of the related work on the integration of Hydrogen and Smart Grid. Related literature is organized and analyzed from four categories, including Hydrogen energy in smart grids, Hydrogen fuel cell electric vehicles, Hydrogen economy in smart grids, and Models for energy system in smart grids. And each subject has been introduced more carefully. What's more, for a clear understanding for readers, we provide overall scenario views for the organization of the related work.

Introduction

Hydrogen, called the ultimate energy of the 21st century, can play an important role on providing electricity, industry, transport and energy storage for a green energy system. The growing public interests and policy supports for hydrogen technologies around the world have been fully displayed [1]. In a broader sense, the so-called "hydrogen society" refers to the use of hydrogen in social daily life and economic industry activities. And many countries have adopted "hydrogen society" as a strategic goal nowadays.

The transitions to environmental energy system of some successful cases are studied, including the factors and policies. And an investigation provided references and the basis for determining a stable, low-carbon energy system in Japan [2].

* *Corresponding author.*
** *Corresponding author.*
E-mail addresses: rhlin@bupt.edu.cn (R.-H. Lin), wubudan@bupt.edu.cn (B.-D. Wu).
https://doi.org/10.1016/j.ijhydene.2020.01.047

What's more, the Japanese government is carrying out the development of a full-scale hydrogen energy infrastructure [3].

Itaoka et al. [4] conducted a public investigation into the awareness of hydrogen infrastructure and fuel cell vehicle in Japan. The results showed that people's support for developing hydrogen society is increasing, but they are also more cautious about the related risks.

For now, the decarbonization of the electricity sector is the main part of the reduction of the greenhouse effect today. Moreover, the main features of smart grids include the energy management systems and storage technologies, where hydrogen can be the key element for a low-carbon target as described in the beginning. Therefore, research on smart grid and hydrogen energy integration are necessary and also an important factor in the development of hydrogen society.

Bennoua et al. [5] evaluated the effects of the integration of hydrogen systems and electricity systems. The experiments in French context demonstrated the economic benefits and balance mechanism of this coupling.

Lazarou and Makridis [6] emphasized that the integration of hydrogen and smart grids can greatly contribute to climate change mitigation, which can help reduce carbon emissions. Santacana et al. [7] noted that to minimize the impact on the environment in smart grids, meet customer demand by combining energy from different sources, which can also maximize sustainability.

Smart grids can support not only centralized, but distributed energy sources, where hydrogen dominates in the energy system. What's more, different energy sources, such as renewable energy and fossil fuels, all can produce hydrogen, which is the key advantage of hydrogen. Thus, the integration of hydrogen and Smart Grid can be a worth studying topic.

Dincer and Acar [8] illustrated that the wide-ranging application of the technologies of hydrogen provides massive benefits to the environment, energy security, and the economy. And in order to serve renewable electricity, hydrogen can be an energy storage medium, and provide electricity at peak demand.

Lund et al. [9] explained that smart grids can be seen as part of smart energy systems that combine renewable sources and hydrogen to achieve a sustainable future. And Kabalci [10] investigated the integration of the transmission, distribution and customer appliances in smart grids, such as the interaction of hydrogen-based microgrid and electric vehicles. Andújar et al. [11] proposed a real smart grid with distributed generation, which integrates renewables with hydrogen as backups.

The proposed grids, including an energy management system for power balance and hydrogen management strategy, has been implemented physically to verify the feasibility.

Therefore, the integration of Hydrogen and Smart Grid is a vital research topic in current hydrogen society. Four major subjects on the integration of Hydrogen and Smart Grid will be focused in this paper, including hydrogen energy in Smart Grid, Hydrogen fuel cell electric vehicles, Hydrogen economy in smart grids and Models for energy systems in smart grids, as shown in Fig. 1.

Energy-saving and emission reduction are also known as the major features of current smart grids, where hydrogen technology plays an essential role in power generation, energy management, energy storage, fuel cells and so on. In Hydrogen energy in smart grid, we mainly described the literature from the perspective of hydrogen energy use in the structure of smart grids. Furthermore, many pieces of researches are proposed for developing fuel cell electric vehicles (FCEV) in Hydrogen fuel cell electric vehicles.

Related work on the hydrogen economy in smart grids can be introduced from the electricity market and demand side response, including some energic economic considerations in Hydrogen economy in smart grids. Finally, the literature about the specific models and algorithms related to the energy system in smart grids is focused on in Models for energy system in smart grids.

Overall, in this paper, we organized over 100 works of literature, as shown in Table 1. And the overall integration diagram is shown in Fig. 2.

Hydrogen energy in smart grid

Nowadays, renewable energy sources are integrated into smart grids ubiquitously, such as energy storages (battery, thermal, and hydrogen) in the main grids. And they are highly influential parts in smart grids.

Recently, most research are about renewable energy in smart grids. We will introduce the related works on hydrogen energy usage in smart grids from three aspects in this section. Firstly, the studies on renewable energy and hydrogen in smart grids are illustrated. Secondly, some related works on microgrids and hydrogen storage are introduced. Finally, we organized the literature on energy management for Smart Grid.

Renewable energy and hydrogen

In the current state of extreme resource shortage, replacing fossil fuels and nuclear fuels with renewable energy fuels, that is, applying clean energy carriers such as hydrogen, is the most urgent and important issue. What's more, the demand of applying renewable energy in smart grids increase, due to the concerns on the environment and high prices of fossil fuels. Hydrogen can define a sustainable and cleaner energy system comparing with other fossil fuels, which can solve environmental problems [12]. Thus, research on renewable energy in smart grids is a topic worthy of further study. And a schematic diagram of related issues and solutions summarized in this subsection is shown in Fig. 3.

It is noted that the instability of renewable energy sources will impact the grids, causing voltage fluctuation, flash and frequency change, which will reduce the quality of service of electricity. Thus, the renewable energy penetration into smart grids is currently facing various problems and challenges [13]. As a solution, the renewable energy can be accessed reliably in the smart grids with monitoring system, sensor system, and communicating system [14]. Kolhe [15] put forward a power system network for future smart grids, which can link the distribution network and higher-capacity power generators by serving for the bidirectional energy flows. Additionally, energy storage system, which is the vital part of the future smart grids, can solve intermittent problems of renewable resources [16].

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

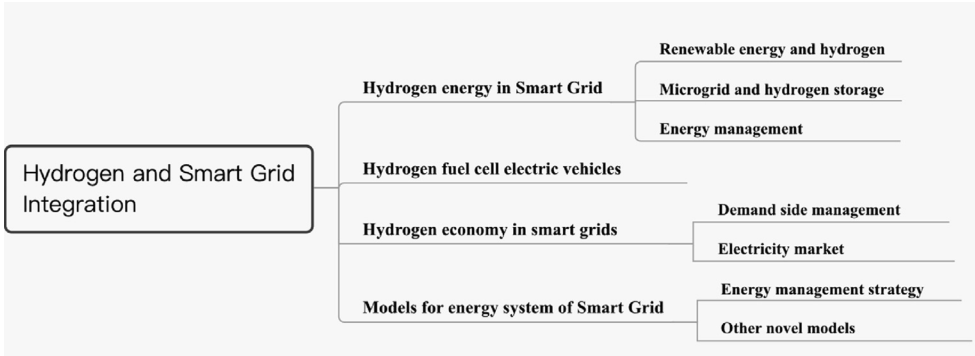

Fig. 1 – The organization of subjects on Hydrogen and Smart Grid integration.

So, what is the role of hydrogen? We can store different sources of energy in the form of hydrogen when renewable energies are excess. Thus, it can be applied to satisfy the users' needs on peak usage. What's more, natural gas and biogas, these hydrogen and hydrogen-rich fuels, can be used to provide clean, efficient electricity and heat in various transportation, fixed and portable power applications [8]. Moreover, hydrogen can be produced through Power-to-gas technology and renewable sources [17]. Hydrogen can also be used as an energy storage medium for unstable and unpredictable renewable energy [18].

Uyar and Beikci [19] confirmed that in terms of achieving the 100% renewable energy target, hydrogen energy technologies are important.

Another challenge is integrating more renewable energy sources into smart grids. It is a feasible solution, that is, applying Power-To-Gas through the medium of renewable production of hydrogen, which is due to that hydrogen can be a fuel as well as an energy storage medium [20].

Furthermore, the strategy for storing hydrogen is also studied. Hakimi and Moghaddas-Tafreshi [21] proposed a novel residential smart system controller for heating/cooling with smart grid function, which can decrease the size of generators of renewable energy, along with increasing the amount of hydrogen that is stored in the hydrogen tank by managing power consumption. Bornapour et al. [22] proposed a stochastic model in microgrids, in order to coordinate the scheduling of the renewable and thermal units with consideration of the strategy to store hydrogen.

Microgrids (MGs) and hydrogen storage

Microgrids (MG) refers to the small power systems consisting of local generations, storage systems and load demands [23], which play an important role in the future Smart Grid. And the microgrids can provide high reliability supply and comprehensive auxiliary services for local loads [24]. Each microgrid can consist of a solar panel, a hydrogen fuel cell stack, and a hydrogen storage tank. Using the reaction of hydrogen fuel cell stack to provide electricity without emission are environmentally friendly.

Additionally, as shown in Fig. 4, microgrids can be stand-alone or grid-tied. Li et al. [25] proposed a stand-alone microgrid with consideration of hydrogen consumption, which used a unit commitment algorithm to determine the optimal components size and operation for the grids. Zhang [26] evaluated the performance and advantages of grid-tied microgrids which include hydrogen fuel cell stack and the hydrogen storage. Konstantinopoulos et al. [27] proved that the application of hydrogen storage system plays an important role in balancing uncertainty in grid-tied microgrids. It can also reduce the uncertainty costs.

In terms of economic considerations of the microgrids, Valverde et al. [28] proposed a model predictive control algorithm by fuel cell technologies, which can help reduce the operation cost in a grid-tied microgrid. Maroufmashat et al. [29] developed a renewable hydrogen powered microgrid considering different renewable-energy-based technologies, along with deciding the optimum size of different energy sources with economic criteria.

Venayagamoorthy et al. [30] presented a new control strategy to optimize and manage microgrids. The experimental results in the laboratory-scale microgrid showed that it can reduce the operating cost and more join hydrogen storage systems to maintain battery backup.

By a storage unit of hydrogen, Mariama et al. [31] solved the intermittent production and out of sync between the production and consumption in microgrids with renewable energy sources. Velarde et al. [32] designed and applied three predictive controllers in a hydrogen-based microgrid. What's more, the comparison of the performance and drawback of the above three controllers are conducted to get a valid criterion for choosing the most proper predictive method.

As for energy storage elements, they are critical in adjusting the fluctuation of power generation due to the integration of renewable energy in smart grids. Colbertaldo et al. [33] simulated the balance of electricity system under extremely permeability of renewable energy.

The proposed study uses hydrogen as the main storage element for large-scale balance of both energy supply and demand sides. Melaina and Eichman [34] proposed that hydrogen storage systems can improve the economics of energy supply systems underlying the smart grids.

The current governments around the world also focus on sustainable energy storage technologies. However, hydrogen energy storage develops into the indispensable component of the energy markets. We can store hydrogen in gas, liquid or

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

Table 1 – Literature summary table.

Hydrogen energy in Smart Grid			Hydrogen fuel cell electric vehicles	Hydrogen economy in smart grids		Models for energy system in smart grids	
Renewable energy and hydrogen	Microgrid and hydrogen storage	Energy management		Demand side management	Electricity market	Energy management strategy	Other novel works
Dincer and Acar [8]	Zhang et al. [23]	Logenthiran et al. [36]	Ehret and Bonhoff [54]	Paulus and Borggrefe [75]	Shi et al. [82]	Valverde et al. [91]	Jaramillo and Weidlich [101]
Nicoletti et al. [12]	Suryanarayanan et al. [24]	Pivovar et al. [43]	Fang et al. [55]	Diamantoulakis et al. [76]	Xiao et al. [83]	Pereira et al. [92]	Eltamaly et al. [102]
Eltigani and Masri [13]	Li et al. [25]	Lund et al. [44]	Gago et al. [56]	Wang et al. [77]	Reichelstein [84]	Nasri et al. [93]	Minciardi and Sacile [103]
Li and Yao [14]	Zhang [26]	Mathiesen et al. [45]	Shaukat et al. [57]	Goulden et al. [78]	Eichman et al. [85]	Cau et al. [94]	Bicer et al. [104]
Kolhe [15]	Konstantinopoulos et al. [27]	Orecchini and Santiangeli [46]	Robledo et al. [58]	Finn and Fitzpatrick [79]	Nojavan et al. [86]	Cau et al. [95]	Tascikaraoglu et al. [105]
Guney and Tepe [16]	Valverde et al. [28]	Bose [47]	Robledo et al. [59]	Nojavan and Aalami [80]	Nojavan et al. [87]	Maroufmashat et al. [96]	Sami et al., [106]
Reiter and Lindorfer [17]	Maroufmashat et al. [29]	Fonseca et al. [48]	Alavi et al. [60]	Ghalelou et al. [81]	Nojavan and Zare [88]	Jarrah et al. [97]	González et al. [107]
Kyriakopoulo and Arabatzis [18]	Venayagamoorthy et al. [30]	Abdin et al. [49]	De et al. [61]		Nojavan et al. [89]	Thomas et al. [98]	Hwangbo et al. [108]
Uyar and Beikci [19]	Mariama et al. [31]	Aki et al. [50]	Felgenhauer et al. [62]		Kho jasteh and Jadid [90]	Mehrjerdi et al. [99]	Saniei and Mashhour [109]
Nastasi and Lo Basso [20]	Velarde et al. [32]	Chen et al. [51]	Xiao et al. [63]			Zhou et al. [100]	Farahani et al. [110]
Hakimi and Moghaddas Tafreshi [21]	Colbertaldo et al. [33]	Kanchev et al. [52]	Kendall [64]				Jarrah et al. [111]
Bornapour et al. [22]	Melaina and Eichman [34]	Jannati and Nazarpour [53]	Sun and Li [65]				Mosaad and Ramadan [112]
	Andújar et al. [35]		Chan et al. [66]				
	Logenthira and Srinivasan [36]		Bernstein et al. [67]				
	Abate et al. [37]		Wilberforce et al. [68]				
	González et al. [38]						
	Zhang et al. [39]						
	Mohd et al. [40]						
	Becherif et al. [41]						
	Groppi et al. [42]						

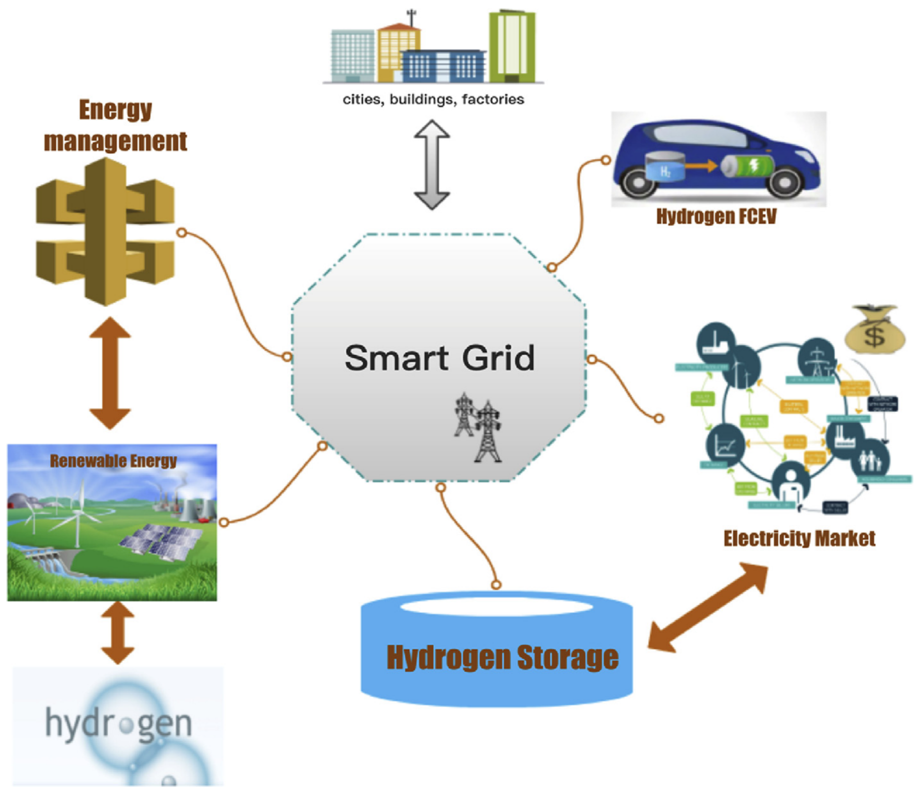

Fig. 2 – The integration of hydrogen and smart grids.

carbon-based form, and it can be produced by chemical reaction along with providing electricity [35,36]. Abate et al. [37] analyzed the advantages of the conversion of sustainable chemical energy for smart grids, especially that technique of hydrogen storage can play an important role in off-grid applications.

However, hydrogen storage technology is still in the developing stage. There are some challenges and problems on the integration of hydrogen storage in smart girds, such as long-term storage, integration strategy and so on.

González et al. [38] introduced that the main challenge of integrating renewable energy into smart grids is the electricity storage from different renewable energy sources. Moreover, they evaluated a hydrogen storage system by some parameters for energy with the presence of a power plant of renewable energy. Zhang et al. [39] investigated the key technology

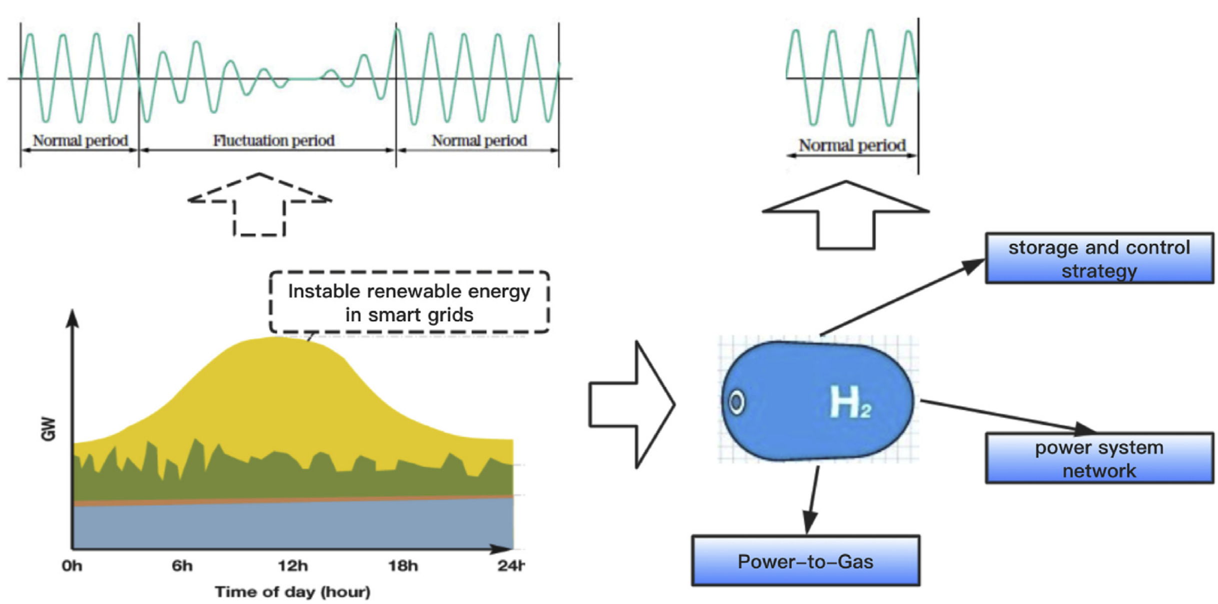

Fig. 3 – Renewable energy in smart grids and the role of hydrogen.

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

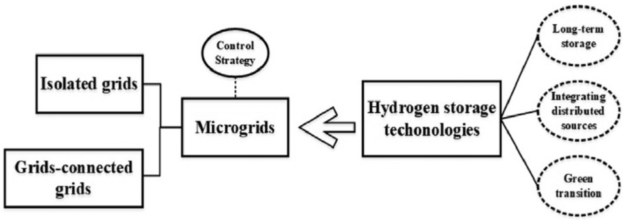

Fig. 4 – Microgrids and hydrogen storage.

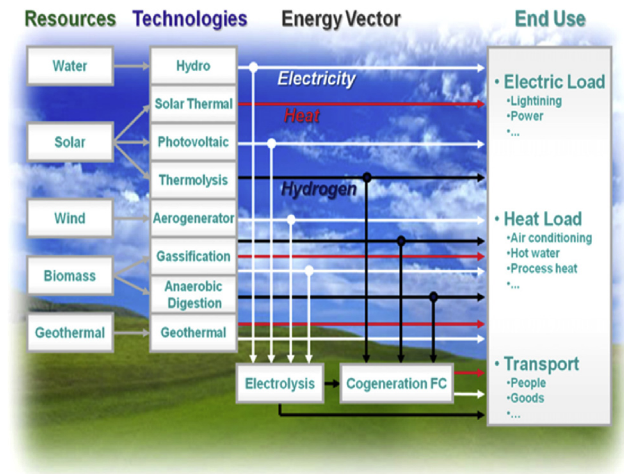

Fig. 5 – Energy system design with renewable energy sources [46].

for hydrogen energy storage along with the hydrogen electricity generation technology.

Mohd et al. [40] analyzed how to integrate the distributed energy storage, including the hydrogen storage, into future Smart Grid. Zhang et al. [23] proposed a flexible metric with a given weighting factor to evaluate the performance of microgrids, considering the electricity price, emission, and service quality. They conducted an analysis of the proposed metric with fluctuation of stored hydrogen.

Becherif et al. [41] introduced the latest technologies of the production and storage of hydrogen, and it is affordable to use these technologies for storing electricity in long-term.

Groppi et al. [42] investigated the green transition of combination with hydrogen and batteries storage with the island of Favignana (Italy) as a case study. The results show that the proposed hybrid storage system can be a superior solution with consideration of both economic and environmental indicators.

Energy management

From the point of energy view, it's emphasized that a full set of energy forms in smart grids, such as electricity, heat and hydrogen, also need smart management.

Pivovar et al. [43] highlighted the importance of the electrochemistry in energy system, for the clean and efficient conversion of chemical and electrical energy of hydrogen. It showed that hydrogen also has the flexibility to integrate with some research challenge into the energy system.

Generally, the term "smart energy system" refers to the control management systems, which is more widely used beyond the smart grid applications [44]. Mathiesen.

et al. [45] presented the development and design and smart energy system with integration of coherent 100% renewables, which can enable the sustainability and feasibility of more energy sources. Nowadays, designing the energy system with renewable energy sources need an integral well-design set of energy sources and carriers, which focus on smart energy networks as shown in Fig. 5 [46].

It is a superior solution of using a hydrogen-like energy vector to converse the electrical energy to chemical energy in energy management in smart grids [47]. Fonseca et al. [48] reviewed the related literature of designing distributed energy systems with hydrogen energy vector. Abdin et al. [49] introduced the demonstration projects for off-grid power supply, which also use hydrogen as energy vector. That is, hydrogen can be stored in the form of gas or metal hydride, and when needed, it can also be used to generate electricity in fuel cells.

A lot of effort has been paid to establish smart energy management to meet the various demand of the smart grids.

Aki et al. [50] proposed a hydrogen energy network for interchanging energy such as hydrogen in residential areas. The analysis results showed that the proposed interchange network can not only reduce the home cost but also the mitigation. To satisfy demand of the distributed storage system in short-term, Logenthiran and Srinivasan [36] proposed a smart energy management system in smart grids.

Chen et al. [51] discussed the actively used superconducting magnetic energy storage (SMES) technology in smart grids, in which hydrogen and electricity can mixed with energy transfer. It can not only serve hydrogen for the fuel cells, but also can be used as the refrigeration fluids for cooling SMES equipment.

To serve business customers, Kanchev et al. [52] introduced the summary and application of several energy management methods in microgrids, along with an intelligent energy management system. As for hydrogen storage systems, Jannati and Nazarpour [53] studied the optimal energy management of intelligent parking lots for electric vehicles under the demand response program.

Hydrogen fuel cell electric vehicles

Hydrogen and fuel cell technologies can support the green energy transformation, and it is demonstrated with powering electric vehicles and providing energy storage service [54]. Nowadays, fuel cell electric vehicles.

(FCEVs) are developing vigorously, and this is also a major application direction of hydrogen energy. An FCEV is essentially a zero-emission vehicle. The fuel cell

has no combustion process. If pure hydrogen is used as fuel, FCEVs power their motor by transforming the chemical energy of hydrogen energy into electricity. And most FCEVs refer to hydrogen FCEVs.

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

Fang et al. [55] mentioned that, due to the widespread use and deployment of electric vehicles (EV), two concepts have come out, which are Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) respectively. V2G-enabled electric vehicles can provide electricity to smart grids when parked while connected to the nearby grids, which offers a novel way to store and power as shown in Fig. 6. Gago et al. [56] a fast charging system allowing G2V and V2G operation, which can enable fast charging while reducing power quality impact when connecting to the grids.

What's more, Shaukat et al. [57] reviewed the technology of V2G and the challenges for implementation, including the energy storage technologies for EVs in smart grids. It demonstrates that these deployments will bring economic and environmental benefits. Robledo et al. [58] designed a carpark with a local hydrogen network for FCEVs.

The most valuable characteristic of hydrogen fuel cell electric vehicles is low-carbon emissions. Robledo et al. [59] presented a demonstration project, including a hydrogen FCEV for combining mobility and generating power. Their study aims at achieving a zero-energy target for residential building. Because of the instability of renewable energy sources, Alavi et al. [60] proposed an original community microgrid, including FCEVs that can provide vehicle-to-grid electricity when lacking.

De et al. [61] introduced the technology to develop plug-in city bus with electric-hydrogen fuel cells, and this project has advantages in terms of batteries and the hydrogen energy.

Besides, Felgenhauer et al. [62] analyzed comprehensively to determine the total cost and carbon dioxide emissions of two of in the southern communities of Germany when deploying hydrogen FCEVs. And Xiao et al. [63] also designed a hydrogen filling station for FCEV, which can produce hydrogen by electrolysis of water. Similarly, New Energy Vehicles (NEV) are developing rapidly in China [64,65].

Chan et al. [66] reviewed the researches of Singapore institutions and companies on the areas of fuel cells and related hydrogen technologies. It demonstrated that related activities are slow but continue to increase.

Bernstein et al. [67] studied the operating of PEM fuel cell systems in the smart grids, along with optimizing the operation point. Wilberforce et al. [68] explored the design specifications and progress on electric cars, especially on the challenges of replacing the internal combustion engines to fuel cell devices. And a better and efficient settings of hydrogen fuel cell vehicles are studied for low cost, and the new control strategy can solve the technical challenges of developing hydrogen FCEVs [69].

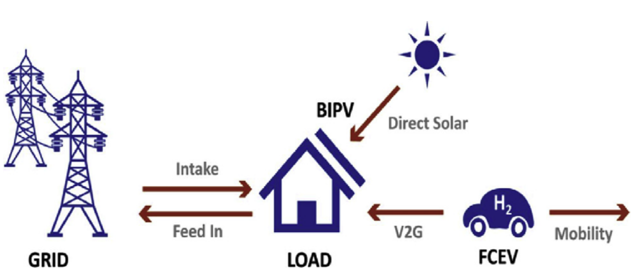

Fig. 6 – An example of V2G [55].

Hydrogen economy in smart grids

The hydrogen economy is a future economic structure that uses hydrogen as a medium (storage, transportation, and conversion) and was proposed in the 1970s. What's more, hydrogen economy has become a hot topic as a result of the sustainable development of hydrogen fuel cells and other products of hydrogen in various industries [70,71].

Hydrogen allows more renewable energy to penetrate smart grids while delivering energy to all sectors in the energy system, that is, there is no need to build expensive additional grid capacity. The potential of hydrogen in all economic fields should be achieved by the cooperation with industry and academia [72].

Marbán and Valdés-Solís [73] focused on the implementation of hydrogen economy by converting the current energy sources into cleaner energy productions with some potential methods. They evaluated the potential exploitation of both renewable and non-renewable energy sources with consideration of their availability and the efficiency to produce hydrogen. Alanne and Cao [74] introduced "zero-energy hydrogen economy" (ZEH2E) concept, where hydrogen is used as the main energy vector.

The introduction of the literature of hydrogen economy in smart grids will be divided into two categories, demand-side management (DSM) and electricity market in this section. The overall description structure of this section is shown in Fig. 7.

Demand side management (DSM)

Demand side management (DSM) refers to the management of the electricity market by the electrical supply and demand sides for achieving the purpose of improving power supply reliability, reducing energy consumption for both the supply and demand sides. Besides, due to the intermittent nature of renewable energy sources including hydrogen, balancing the supply and demand sides in smart grids are required for better service quality.

For better balance management for the above situation, Paulus and Borggrefe [75] aimed at offering demand side management to balance electricity markets through 2030 by investigating the potential of technology and economy in energy-intensive industries. Diamantoulakis et al. [76] introduced big data analysis for dynamic energy management which deployed by predicting renewables and loads in smart grids. This study highlights the necessity and efficiency of big data technologies for optimizing smart grid management.

Wang et al. [77] proposed a novel DSM mechanism including a distributed energy storage program. The simulating results revealed its superiority in reducing peaks and reducing total cost.

Goulden et al. [78] presented two contrasting visions of smart grids. It demonstrated that the design of smart grids must go beyond simply the technology, the importance of the smart users in demand side management, which actively participate in energy, should be recognized for future development.

Finn and Fitzpatrick [79] introduced that, by increasing the proportion of wind power generation by shifting demand to

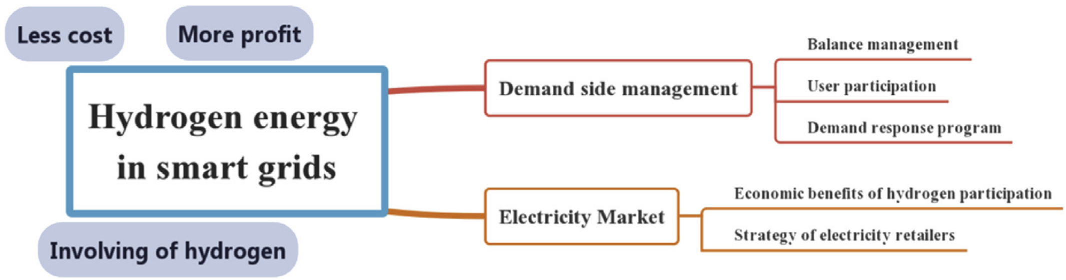

Fig. 7 – The overall description structure of hydrogen economy in smart grids.

low prices of industrial consumers, the possibility for implementing demand response considering price can be analyzed.

The electricity demand response program (DSP) is the main solutions for DSM. In restructured power markets, Nojavan and Aalami [80], in view of the impact of demand response planning and energy storage systems, proposed a stochastic procurement issue of energy for large-scale power consumers with multiple sources of energy procurement. Besides, Ghalelou et al. [81] proposed a random self-scheduling program of renewable energy in smart grids, which can minimize the operation cost by considering compressing air energy storage in a DSP.

Electricity market

The electricity market refers to a mechanism for the change of electricity prices under the influence of supply, demand, sales and purchase of the overall electricity.

With the participation of hydrogen energy in the electricity market, Shi et al. [82] have conducted the economic sensitivity analysis to illustrate the degree of adaptation of hydrogen-based electrical energy storage with hydrogen valence and hydrogen storage capacity, which is based on the high price volatility of Danish electricity market. Furthermore, a energy market framework is established locally with trade of electricity and hydrogen, which is demonstrated to improves local combination of renewable energy and lowers peak demand by case studies [83].

Based on the fluctuating prices of electricity and electricity generation of intermittent renewables, Glenk and Reichelstein [84] considered the integration of renewable energy and power-to-gas facility to optimize the available capacity more economically.

Eichman et al. [85] quantified the value for hydrogen energy storage and demand response systems to participate in. Hydrogen systems can present a positive value proposition for current markets by three main findings in this article.

Within the last decade of restructuring of the electricity market, an electricity retailer is an enterprise that is approved to purchase electricity from the electricity market and retail electricity directly to end-users. Therefore, electricity retailers can maximize the expected profit by determining the retail price for different kinds of consumers, along with managing price fluctuations and achieving robust scheduling [86–89].

Nojavan et al. [86,87] proposed methods to determine the selling price in the smart grids that is with the hydrogen storage system. It also showed that the model increases the expected profit of electricity retailers. Nojavan and Zare [88] modeled the uncertain pool market price by proposing an interval optimization approach, to increase the average profit of electricity retailers. Nojavan et al. [89] proposed a robust optimization method for the pool market, which can solve the retailer's optimal bidding strategy for more profit.

Turn to the electricity retailers that manage self-generation facilities to satisfy customers' needs for various energy sources, including hydrogen, a strategy of bi-level stochastic energy acquisition is proposed [90], and the main point in this paper is to simulate customers' conversion behaviors, considering the uncertainty of the retailers' strategy of the competitors and wholesale price.

Models for energy system in smart grids

The section will mainly focus on the literature about specific models and algorithms related to the energy system in smart grids.

Energy management strategy (EMS)

To ensure the electricity plant in the optimal operation state, a suitable energy management strategy (EMS) need to be applied in highly integrated power systems. Several papers show experimental results of different aspects of application and improvement on EMS, which will be introduced in the following.

Valverde et al. [91] have studied through both theoretical and experimental aspects, to obtain the role of EMSs in hydrogen microgrids. Additionally, Pereira et al. [92] applied a model predictive control for the management of a laboratory-scale microgrid in an economical manner. Moreover, by comparing different control strategies, it demonstrated that the controller is robust and stable with considering constraints and the changing operation points. Nasri et al. [93] proposed the EMS for managing a hybrid power system with renewable energy and hydrogen conversion to provide electricity for remote areas.

From real meteorological data, Cau et al. [94] studied the behaviour of the system in two different weather conditions for three different logics. And the results evaluated the best strategy to effectively meet user needs and optimize the efficiency of the whole system.

Cau et al. [95] presented a novel energy management strategy to manage isolated microgrids. Especially to evaluate the uncertainties with a stochastic approach in such a strategy.

As for energy management, Maroufmashat et al. [96] developed a general mathematical model for communities to obtain optimal energy management with hydrogen energy vector.

Jarrah et al. [97] proposed a three-level stratification optimization approach, which minimizes daily power costs by maximizing the percentage of renewable energy use with addresses scalability. Thomas et al. [98] investigated the cooperative evaluation of an energy management strategy operation by applying a proposed mixed-integer linear programming framework-based model.

Mehrjerdi et al. [99] proposed a home energy management model, which optimizes the cogeneration of wind, solar, and battery storage units to charge for hydrogen and electric vehicles with less pollution. And Zhou et al. [100] studied smart home energy management system. Besides, the usage of renewable energy, as well as various scheduling strategies for reducing the cost of residential electricity and increasing the efficiency of power generation facilities, are also investigated.

Other novel models

There are also some other novel solutions for other issues. including problem modeling, optimization models, artificial intelligence algorithms and some simulated programs.

Firstly, as for the problem modeling, in Ref. [101], a model of multi-objective mixed-integer linear programming is proposed for optimizing the schedules for the operation of components of a grid-tied microgrid. Eltamaly et al. [102] studied the best size of hybrid renewable energy systems to provide highly reliable power supply for remote areas at the lowest cost.

Minciardi and Sacile [103] proposed a model method for achieving the optimal decisions in a cooperative grid. The experimental results show that the application can gain enhancements in the direct connections between microgrids.

With the current trend of artificial intelligence, a method based on artificial neural networks is incorporated in smart grids that integrated with proton exchange membrane fuel cell [104].

What's more, many other related models were applied to real projects. Tascikaraoglu et al. [105] introduced an experimental project of smart home with storage systems for different renewable energy sources, which includes the management for home energy. Sami et al. also proposed a prototype of a smart home with continuous power supply [106].

González et al. [107] presented a remote monitoring platform for monitoring the smart microgrids, which integrates renewable energy and hydrogen.

Hwangbo et al. [108] proposed a deep-learning-based model, called HySIREN, to build a self-sustaining energy system with integrated hydrogen production process design. The experimental results showed it is beneficial for sustainable development.

Saniei and Mashhour [109] provide a novel multi-slack optimization model based on multiple models, which considers both the electrical and thermal loads for the management of operating the energy hub in smart grids.

Farahani et al. [110] proposed a technical, analytical and economic framework for Car as Power Plan concept, including integrating hydrogen storage and studying hydrogen FCEVs. Jarrah et al. [111] modeled and simulated the different components of clean smart grids to determine the exact design with the best low-carbon power generation. Besides, the optimization simulations on a novel fuel cell with new renewable energies are conducted to control the voltage in grids [112].

Conclusion

This overview introduces the integration of Hydrogen and Smart Grid from various perspectives. Several of the main subjects are microgrid and hydrogen storage, energy management, FCEV and so on. It shows that hydrogen will be used in a variety of applications of Smart Grid in the future hydrogen society. More than 100 publications provide a broad view of the integration of Hydrogen and Smart Grid, which are selected from recent years. Besides, we provide the chart and table in the introduction of the classification of the literature to give readers a clearer understanding of all aspects of integration.

However, the current integration of Smart Grid and Hydrogen is facing many challenges, such as integration strategy, hydrogen energy monitoring, long-term storage and so on, where more efforts need to devote to providing a more complete integration system for a hydrogen society. In conclusion, the future toward a hydrogen society with such an integration is pretty promising. And the development of Smart Grid will be inseparable from the application of hydrogen energy for a clean and efficient future.

Acknowledgement

This work was supported by the State Grid Corporation of China under the project title: “The Improved Core Analysis Algorithms and Utilities for Smart Grid Big Data” (520940180016).

REFERENCES

[1] Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, Ward KR. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019;12(2):463–91.
[2] Chapman AJ, Itaoka K. Energy transition to a future low-carbon energy society in Japan's liberalizing electricity market: Precedents, policies and factors of successful transition. Renew Sustain Energy Rev 2018;81:2019–27.
[3] Popov S, Baldynov O. The hydrogen energy infrastructure development in Japan. In: E3S Web of conferences. vol. 69. EDP Sciences; 2018, 02001.
[4] Itaoka K, Saito A, Sasaki K. Public perception on hydrogen infrastructure in Japan: influence of rollout of commercial fuel cell vehicles. Int J Hydrogen Energy 2017;42(11):7290–6.
[5] Bennoua S, Le Duigou A, Quéméré MM, Dautremont S. Role of hydrogen in resolving electricity grid issues. Int J Hydrogen Energy 2015;40(23):7231–45.

[6] Lazarou S, Makridis S. Hydrogen storage technologies for smart grid applications. Challenges 2017;8(1):13.
[7] Santacana E, Rackliffe G, Tang L, Feng X. Getting smart. IEEE Power Energy Mag 2010;8(2):41–8.
[8] Dincer I, Acar C. Smart energy solutions with hydrogen options. Int J Hydrogen Energy 2018;43(18):8579–99.
[9] Lund H, Andersen AN, Østergaard PA, Mathiesen BV, Connolly D. From electricity smart grids to smart energy systems–a market operation based approach and understanding. Energy 2012;42(1):96–102.
[10] Kabalci Y. A survey on smart metering and smart grid communication. Renew Sustain Energy Rev 2016;57:302–18.
[11] Andújar JM, Segura F, Martínez MÁ. A renewable sources-based smart grid using hydrogen as backup. Optimization criteria for the energy management. 2017, December. In: Saudi Arabia smart grid (SASG). IEEE; 2017. p. 1–8.
[12] Nicoletti G, Arcuri N, Nicoletti G, Bruno R. A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers Manag 2015;89:205–13.
[13] Eltigani D, Masri S. Challenges of integrating renewable energy sources to smart grids: a review. Renew Sustain Energy Rev 2015;52:770–80.
[14] Li Z, Yao T. Renewable energy basing on smart grid. In: 2010 6th international conference on wireless communications networking and mobile computing (WiCOM). IEEE; 2010, September. p. 1–4.
[15] Kolhe M. Smart grid: charting a new energy future: research, development and demonstration. Electr J 2012;25(2):88–93.
[16] Guney MS, Tepe Y. Classification and assessment of energy storage systems. Renew Sustain Energy Rev 2017;75:1187–97.
[17] Reiter G, Lindorfer J. Global warming potential of hydrogen and methane production from renewable electricity via power-to-gas technology. Int J Life Cycle Assess 2015;20(4):477–89.
[18] Kyriakopoulos GL, Arabatzis G. Electrical energy storage systems in electricity generation: energy policies, innovative technologies, and regulatory regimes. Renew Sustain Energy Rev 2016;56:1044–67.
[19] Uyar TS, Beşikci D. Integration of hydrogen energy systems into renewable energy systems for better design of 100% renewable energy communities. Int J Hydrogen Energy 2017;42(4):2453–6.
[20] Nastasi B, Basso GL. Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems. Energy 2016;110:5–22.
[21] Hakimi SM, Moghaddas-Tafreshi SM. Optimal planning of a smart microgrid including demand response and intermittent renewable energy resources. IEEE Trans Smart Grid 2014;5(6):2889–900.
[22] Bornapour M, Hooshmand RA, Parastegari M. An efficient scenario-based stochastic programming method for optimal scheduling of CHP-PEMFC, WT, PV and hydrogen storage units in micro grids. Renew Energy 2019;130:1049–66.
[23] Zhang L, Gari N, Hmurcik LV. Energy management in a microgrid with distributed energy resources. Energy Convers Manag 2014;78:297–305.
[24] Suryanarayanan S, Mancilla-David F, Mitra J, Li Y. March). Achieving the smart grid through customer-driven microgrids supported by energy storage. In: 2010 IEEE international conference on industrial technology. IEEE; 2010. p. 884–90.
[25] Li B, Roche R, Paire D, Miraoui A. Sizing of a stand-alone microgrid considering electric power, cooling/heating, hydrogen loads and hydrogen storage degradation. Applied energy 2017;205:1244–59.
[26] Zhang L, Xiang J. The performance of a grid-tied microgrid with hydrogen storage and a hydrogen fuel cell stack. Energy Convers Manag 2014;87:421–7.
[27] Konstantinopoulos SA, Anastasiadis AG, Vokas GA, Kondylis GP, Polyzakis A. Optimal management of hydrogen storage in stochastic smart microgrid operation. Int J Hydrogen Energy 2018;43(1):490–9.
[28] Valverde L, Bordons C, Rosa F. Integration of fuel cell technologies in renewable-energy-based microgrids optimizing operational costs and durability. IEEE Trans Ind Electron 2015;63(1):167–77.
[29] Maroufmashat A, Mukherjee U, Ranisau J, Barbouti M, Trainor A, El-Shayeb H, Fowler M. Optimization of renewable powered hydrogen micro-grid; taking in to account economic criteria. In: 2016 IEEE smart energy grid Engineering (SEGE). IEEE; 2016, August. p. 252–6.
[30] Venayagamoorthy GK, Sharma RK, Gautam PK, Ahmadi A. Dynamic energy management system for a smart microgrid. IEEE transactions on neural networks and learning systems 2016;27(8):1643–56.
[31] Mariama SM, Scipioni A, Davat B. Study of a micro-grid with renewable energy sources with hydrogen storage. Int J Innov Appl Stud 2018;24(1):208–19.
[32] Velarde P, Valverde L, Maestre JM, Ocampo-Martínez C, Bordons C. On the comparison of stochastic model predictive control strategies applied to a hydrogen-based microgrid. J Power Sources 2017;343:161–73.
[33] Colbertaldo P, Agustin SB, Campanari S, Brouwer J. Impact of hydrogen energy storage on California electric power system: towards 100% renewable electricity. Int J Hydrogen Energy 2019;44(19):9558–76.
[34] Melaina MW, Eichman J. Hydrogen energy storage: grid and transportation services. Golden, CO: National Renewable Energy Laboratory; 2015.
[35] Andújar JM, Segura F, Domínguez T. November). Study of a renewable energy sources-based smart grid. requirements, targets and solutions. In: 2016 3rd conference on power Engineering and renewable energy (ICPERE). IEEE; 2016. p. 45–50.
[36] Logenthiran T, Srinivasan D. Intelligent management of distributed storage elements in a smart grid. In: 2011 IEEE ninth international conference on power electronics and drive systems. IEEE; 2011, December. p. 855–60.
[37] Abate S, Centi G, Perathoner S. Chemical energy conversion as enabling factor to move to a renewable energy economy. Green 2015;5(1–6):43–54.
[38] González EL, Llerena FI, Pérez MS, Iglesias FR, Macho JG. Energy evaluation of a solar hydrogen storage facility: comparison with other electrical energy storage technologies. Int J Hydrogen Energy 2015;40(15):5518–25.
[39] Zhang F, Zhao P, Niu M, Maddy J. The survey of key technologies in hydrogen energy storage. Int J Hydrogen Energy 2016;41(33):14535–52.
[40] Mohd A, Ortjohann E, Schmelter A, Hamsic N, Morton D. June). Challenges in integrating distributed energy storage systems into future smart grid. In: 2008 IEEE international symposium on industrial electronics. IEEE; 2008. p. 1627–32.
[41] Becherif M, Ramadan HS, Cabaret K, Picard F, Simoncini N, Bethoux O. Hydrogen energy storage: new techno-economic emergence solution analysis. Energy Procedia 2015;74:371–80.
[42] Groppi D, Garcia DA, Basso GL, Cumo F, De Santoli L. Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands. Energy Convers Manag 2018;177:64–76.

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

[43] Pivovar B, Rustagi N, Satyapal S. Hydrogen at scale (H2@ Scale): key to a clean, economic, and sustainable energy system. Electrochem Soc Interface 2018;27(1):47–52.
[44] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65.
[45] Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, Hvelplund FK. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy 2015;145:139–54.
[46] Orecchini F, Santiangeli A. Beyond smart grids–The need of intelligent energy networks for a higher global efficiency through energy vectors integration. Int J Hydrogen Energy 2011;36(13):8126–33.
[47] Bose BK. Power electronics, smart grid, and renewable energy systems. In: Proceedings of the IEEE, 105(11), 2011-2018. In 2016 3rd conference on power Engineering and renewable energy (ICPERE). IEEE; 2017 (pp. 45–50).
[48] Fonseca JD, Camargo M, Commenge JM, Falk L, Gil ID. Trends in design of distributed energy systems using hydrogen as energy vector: a systematic literature review. Int J Hydrogen Energy 2019;44(19):9486–504.
[49] Abdin Z, Webb CJ, Gray EM. Solar hydrogen hybrid energy systems for off-grid electricity supply: a critical review. Renew Sustain Energy Rev 2015;52(C):1791–808.
[50] Aki H, Yamamoto S, Kondoh J, Maeda T, Yamaguchi H, Murata A, Ishii I. Fuel cells and energy networks of electricity, heat, and hydrogen in residential areas. Int J Hydrogen Energy 2006;31(8):967–80.
[51] Chen XY, Jin JX, Xin Y, Shu B, Tang CL, Zhu YP, Sun RM. Integrated SMES technology for modern power system and future smart grid. IEEE Trans Appl Supercond 2014;24(5):1–5.
[52] Kanchev H, Lu D, Colas F, Lazarov V, Francois B. Energy management and operational planning of a microgrid with a PV-based active generator for smart grid applications. IEEE Trans Ind Electron 2011;58(10):4583–92.
[53] Jannati J, Nazarpour D. Optimal energy management of the smart parking lot under demand response program in the presence of the electrolyser and fuel cell as hydrogen storage system. Energy Convers Manag 2017;138:659–69.
[54] Ehret O, Bonhoff K. Hydrogen as a fuel and energy storage: Success factors for the German Energiewende. Int J Hydrogen Energy 2015;40(15):5526–33.
[55] Fang X, Misra S, Xue G, Yang D. Smart grid—the new and improved power grid: a survey. IEEE communications surveys & tutorials 2011;14(4):944–80.
[56] Gago RG, Pinto SF, Silva JF. September). G2V and V2G electric vehicle charger for smart grids. In: 2016 IEEE international smart Cities conference (ISC2). IEEE; 2016. p. 1–6.
[57] Shaukat N, Khan B, Ali SM, Mehmood CA, Khan J, Farid U, Ullah Z. A survey on electric vehicle transportation within smart grid system. Renew Sustain Energy Rev 2018;81:1329–49.
[58] Robledo CB, Poorte MJ, Mathijssen HHM, van der Veen RAC, van Wijk AJM. Fuel cell electric vehicle-to-grid feasibility: a technical analysis of Aggregated Units offering frequency Reserves. In: Intelligent integrated energy systems. Cham: Springer; 2019. p. 167–94.
[59] Robledo CB, Oldenbroek V, Abbruzzese F, van Wijk AJ. Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building. Applied energy 2018;215:615–29.
[60] Alavi F, Lee EP, van de Wouw N, De Schutter B, Lukszo Z. Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks. Appl Energy 2017;192:296–304.
[61] De Miranda PEV, Carreira ES, Icardi UA, Nunes GS. Brazilian hybrid electric-hydrogen fuel cell bus: improved on-board energy management system. Int J Hydrogen Energy 2017;42(19):13949–59.
[62] Felgenhauer MF, Pellow MA, Benson SM, Hamacher T. Economic and environmental prospects of battery and fuel cell vehicles for the energy transition in German communities. Energy Procedia 2016;99:380–91.
[63] Xiao W, Cheng Y, Lee WJ, Chen V, Charoensri S. Hydrogen filling station design for fuel cell vehicles. IEEE Trans Ind Appl 2010;47(1):245–51.
[64] Kendall M. Fuel cell development for New Energy Vehicles (NEVs) and clean air in China. Prog Nat Sci: Mat Int 2018;28(2):113–20.
[65] Sun ZY, Li GX. On reliability and flexibility of sustainable energy application route for vehicles in China. Renew Sustain Energy Rev 2015;51:830–46.
[66] Chan SH, Stempien JP, Ding OL, Su PC, Ho HK. Fuel cell and hydrogen technologies research, development and demonstration activities in Singapore–an update. Int J Hydrogen Energy 2016;41(32):13869–78.
[67] Bernstein PA, Heuer M, Wenske M. June). Fuel cell system as a part of the smart grid. In: 2013 IEEE grenoble conference. IEEE; 2013. p. 1–4.
[68] Wilberforce T, El-Hassan Z, Khatib FN, Al Makky A, Baroutaji A, Carton JG, Olabi AG. Developments of electric cars and fuel cell hydrogen electric cars. Int J Hydrogen Energy 2017;42(40):25695–734.
[69] Hames Y, Kaya K, Baltacioglu E, Turksoy A. Analysis of the control strategies for fuel saving in the hydrogen fuel cell vehicles. Int J Hydrogen Energy 2018;43(23):10810–21.
[70] Pelaez-Samaniego MR, Riveros-Godoy G, Torres-Contreras S, Garcia-Perez T, Albornoz-Vintimilla E. Production and use of electrolytic hydrogen in Ecuador towards a low carbon economy. Energy 2014;64:626–31.
[71] Brandon NP, Hajimiragha A, Fowler MW, Canizares CA. Hydrogen economy transition in Ontario–Canada considering the electricity grid constraints. Int J Hydrogen Energy 2009;34(13):5275–93.
[72] Kurban Z. Clean energy and the hydrogen economy. Philos Trans R Soc A Math Phys Eng Sci 2017;375 (2098), 20160400.
[73] Marbán G, Valdés-Solís T. Towards the hydrogen economy? Int J Hydrogen Energy 2007;32(12):1625–37.
[74] Alanne K, Cao S. Zero-energy hydrogen economy (ZEH2E) for buildings and communities including personal mobility. Renew Sustain Energy Rev 2017;71:697–711.
[75] Paulus M, Borggrefe F. The potential of demand-side management in energy-intensive industries for electricity markets in Germany. Appl Energy 2011;88(2):432–41.
[76] Diamantoulakis PD, Kapinas VM, Karagiannidis GK. Big data analytics for dynamic energy management in smart grids. Big Data Research 2015;2(3):94–101.
[77] Wang K, Li H, Maharjan S, Zhang Y, Guo S. Green energy scheduling for demand side management in the smart grid. IEEE Trans Green Commun Net 2018;2(2):596–611.
[78] Goulden M, Bedwell B, Rennick-Egglestone S, Rodden T, Spence A. Smart grids, smart users? The role of the user in demand side management. Energy res social sci 2014;2:21–9.
[79] Finn P, Fitzpatrick C. Demand side management of industrial electricity consumption: promoting the use of renewable energy through real-time pricing. Appl Energy 2014;113:11–21.
[80] Nojavan S, allah Aalami H. Stochastic energy procurement of large electricity consumer considering photovoltaic, wind-turbine, micro-turbines, energy storage system in the presence of demand response program. Energy Convers Manag 2015;103:1008–18.
[81] Ghalelou AN, Fakhri AP, Nojavan S, Majidi M, Hatami H. A stochastic self-scheduling program for compressed air

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047

energy storage (CAES) of renewable energy sources (RESs) based on a demand response mechanism. Energy Convers Manag 2016;120:388–96.
[82] Shi YOU, Junjie HU, Yi ZONG, Jin LIN. Value assessment of hydrogen-based electrical energy storage in view of electricity spot market. Journal of Modern Power Systems and Clean Energy 2016;4(4):626–35.
[83] Xiao Y, Wang X, Pinson P, Wang X. A local energy market for electricity and hydrogen. IEEE Trans Power Syst 2017;33(4):3898–908.
[84] Glenk G, Reichelstein S. Economics of converting renewable power to hydrogen. Nature Energy 2019;4(3):216.
[85] Eichman J, Townsend A, Melaina M. Economic assessment of hydrogen technologies participating in California electricity markets. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2016. No. NREL/TP-5400-65856.
[86] Nojavan S, Zare K, Mohammadi-Ivatloo B. Selling price determination by electricity retailer in the smart grid under demand side management in the presence of the electrolyser and fuel cell as hydrogen storage system. Int J Hydrogen Energy 2017;42(5):3294–308.
[87] Nojavan S, Zare K, Mohammadi-Ivatloo B. Optimal stochastic energy management of retailer based on selling price determination under smart grid environment in the presence of demand response program. Applied energy 2017;187:449–64.
[88] Nojavan S, Zare K. Optimal energy pricing for consumers by electricity retailer. Int J Electr Power Energy Syst 2018;102:401–12.
[89] Nojavan S, Mohammadi-Ivatloo B, Zare K. Robust optimization-based price-taker retailer bidding strategy under pool market price uncertainty. Int J Electr Power Energy Syst 2015;73:955–63.
[90] Khojasteh M, Jadid S. Stochastic risk-constraint pricing strategy of electricity retailers based on Dempster-Shafer evidence theory. Energy strategy reviews 2017;18:260–74.
[91] Valverde L, Rosa F, Bordons C, Guerra J. Energy management strategies in hydrogen smart grids: a laboratory experience. Int J Hydrogen Energy June 2016;1–11.
[92] Pereira M, Limon D, Alamo T, Valverde L, Bordons C. November). Economic model predictive control of a smartgrid with hydrogen storage and PEM fuel cell. In: IECON 2013-39th Annual conference of the IEEE industrial electronics society. IEEE; 2013. p. 7920–5.
[93] Nasri S, Sami BS, Cherif A. Power management strategy for hybrid autonomous power system using hydrogen storage. Int J Hydrogen Energy 2016;41(2):857–65.
[94] Cau G, Cocco D, Petrollese M. Modeling and simulation of an isolated hybrid micro-grid with hydrogen production and storage. Energy Procedia 2014;45:12–21.
[95] Cau G, Cocco D, Petrollese M, Kær SK, Milan C. Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. Energy Convers Manag 2014;87:820–31.
[96] Maroufmashat A, Fowler M, Khavas SS, Elkamel A, Roshandel R, Hajimiragha A. Mixed integer linear programing based approach for optimal planning and operation of a smart urban energy network to support the hydrogen economy. Int J Hydrogen Energy 2016;41(19):7700–16.
[97] Jarrah M, Jaradat M, Jararweh Y, Al-Ayyoub M, Bousselham A. A hierarchical optimization model for energy data flow in smart grid power systems. Inf Syst 2015;53:190–200.
[98] Thomas D, Deblecker O, Ioakimidis CS. Optimal operation of an energy management system for a grid-connected smart building considering photovoltaics' uncertainty and stochastic electric vehicles' driving schedule. Appl Energy 2018;210:1188–206.
[99] Mehrjerdi H, Bornapour M, Hemmati R, Ghiasi SMS. Unified energy management and load control in building equipped with wind-solar-battery incorporating electric and hydrogen vehicles under both connected to the grid and islanding modes. Energy 2019;168:919–30.
[100] Zhou B, Li W, Chan KW, Cao Y, Kuang Y, Liu X, Wang X. Smart home energy management systems: concept, configurations, and scheduling strategies. Renew Sustain Energy Rev 2016;61:30–40.
[101] Jaramillo LB, Weidlich A. Optimal microgrid scheduling with peak load reduction involving an electrolyzer and flexible loads. Appl energy 2016;169:857–65.
[102] Eltamaly AM, Mohamed MA, Al-Saud MS, Alolah AI. Load management as a smart grid concept for sizing and designing of hybrid renewable energy systems. Eng Optim 2017;49(10):1813–28.
[103] Minciardi R, Sacile R. Optimal control in a cooperative network of smart power grids. IEEE Syst J 2011;6(1):126–33.
[104] Bicer Y, Dincer I, Aydin M. Maximizing performance of fuel cell using artificial neural network approach for smart grid applications. Energy 2016;116:1205–17.
[105] Tascikaraoglu A, Boynuegri AR, Uzunoglu M. A demand side management strategy based on forecasting of residential renewable sources: a smart home system in Turkey. Energy Build 2014;80:309–20.
[106] Sami BS, Sihem N, Bassam Z. Design and implementation of an intelligent home energy management system: a realistic autonomous hybrid system using energy storage. Int J Hydrogen Energy 2018;43(42):19352–65.
[107] González I, Calderón AJ, Andújar JM. Novel remote monitoring platform for RES-hydrogen based smart microgrid. Energy Convers Manag 2017;148:489–505.
[108] Hwangbo S, Nam K, Heo S, Yoo C. Hydrogen-based self-sustaining integrated renewable electricity network (HySIREN) using a supply-demand forecasting model and deep-learning algorithms. Energy Convers Manag 2019;185:353–67.
[109] Saniei M, Mashhour E. A multi-slack optimization model for scheduling energy hubs in smart grids. J Power Technol 2018;98(3):294.
[110] Farahani SS, van der Veen R, Oldenbroek V, Alavi F, Lee EHP, van de Wouw N, Lukszo Z. A hydrogen-based integrated energy and transport system: the design and analysis of the car as power plant concept. IEEE Syst Man Cybern Mag 2019;5(1):37–50.
[111] Jarrah M. Modeling and simulation of renewable energy sources in smart grid using DEVS formalism. Procedia Com Sci 2016;83:642–7.
[112] Mosaad MI, Ramadan HS. Power quality enhancement of grid-connected fuel cell using evolutionary computing techniques. Int J Hydrogen Energy 2018;43(25):11568–82.

Please cite this article as: Lin R-H et al., Toward a hydrogen society: Hydrogen and smart grid integration, International Journal of Hydrogen Energy, https://doi.org/10.1016/j.ijhydene.2020.01.047