Utilization of Energy Storage and Hydrogen in Power and Energy Systems: Viewpoints from Five Aspects

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***Abstract*—Decarbonizing power systems is crucial to mitigating climate change impacts and achieving carbon neutrality. Increasing renewable energy supply can reduce greenhouse gas emissions and accelerate the decarbonization process. However, renewable energy sources (RESs) such as wind and solar power are characterized by intermittency and often non-dispatchability, significantly challenging their high-level integration into power systems. Energy storage is acknowledged as a vital indispensable solution for mitigating the intermittency of renewables such as wind and solar power and boosting the penetrations of renewables. In the CSEE JPES Forum, five well-known experts were invited to give keynote speeches, and the participating experts and scholars had comprehensive exchanges and discussions on energy storage technologies. Specifically, the views on the design, control, performance, and applications of new energy storage technologies, such as the fuel cell vehicle, water electrolysis, and flow battery, in the coordination and operation of power and energy systems were analyzed. The experts also provided experience that could be used to develop energy storage for constructing and decarbonizing new power systems.**

***Index Terms*—Electrolysis, electric vehicle, energy storage, flow battery, fuel cell electric vehicle, hydrogen energy.**

I. INTRODUCTION

WITH the increase of the whole society's electrification level, more carbon emissions are transferred from the terminal energy sector to the power sector and the pressure on the power sector to reduce carbon emissions continues to increase. Thus, accelerating the construction of new power systems with new energy as the main body is an inevitable choice to decarbonize power systems, mitigate climate change effects, and achieve carbon neutrality of the whole society. Although increasing the penetration of renewable energy sources (RESs) can reduce greenhouse gas emissions and accelerate the decarbonization process, the intermittency and non-dispatchability of wind and solar power significantly challenge their high-level integration into power systems [1]. Energy storage is recognized as a vital indispensable solution for facilitating the penetration and increasing the application of RESs such as wind and solar power in power systems.

Take China as an example. By 2021, the installed capacity of energy storage in China has reached 46.1 GW, about 22% of the total installed capacity worldwide, and with a year-on-year increase of 30%. Among them, the installed capacity of the pumped hydro storage is 39.8 GW. The installed capacity of novel energy storage systems, such as the lithium-ion battery storage and compressed air energy storage is about 5.7 GW. In 2021, the annual increase of the installed capacity of energy storage in China has reached 10.5 GW, including 8 GW and 2.4 GW increment in the installed capacity of the pumped hydro storage and novel energy storage respectively. The capacity of the lithium-ion battery storage plant and the compressed air energy storage plant has reached 100 MW among the novel energy storage plants [2].

In order to fully exploit the roles of energy storage in boosting RESs penetration, decarbonizing energy and power systems, and accelerating the carbon neutrality process, the CSEE JPES holds a forum on the *utilization of energy storage and hydrogen in power and energy systems*, which brings together experts and scholars in the fields related to energy storage to share their viewpoints on the design, control, and applications of various energy storage technologies, such as the fuel cell vehicles, water electrolysis, and flow battery.

This work shows the key academic viewpoints in the forum. In Section II, Prof. Mohammad Shahidehpour discussed the operations of fuel cell electric vehicles in coordinated hydrogen-integrated systems. In Section III, Prof. Saifur Rahman introduces some interesting opinions on energy storage and hydrogen in decarbonization. In Section IV, Prof. Nigel Brandon discussed the innovations and challenges in elec-

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Manuscript received November 23, 2022; revised January 5, 2023; accepted January 12, 2023. Date of online publication January 25, 2023; date of current version January 30, 2023. The insights presented in this article are drawn from "CSEE JPES forum on utilization of energy storage and hydrogen in power and energy systems", organized by Professor Xiaoxin Zhou.

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DOI: 10.17775/CSEEJPES.2022.08320

trolyzers and flow batteries for longer term energy storage. In Section V, Prof. Kai Strunz analyzed stakeholder roles and interactions considering the integration of electric vehicles. In Section VI Prof. Yonghua Song discussed the control strategy and implementations of battery storage and water electrolysis in power systems for frequency regulation. In conclusion of this work, Section VII summarizes the main ideas of the experts.

II. PROF. MOHAMMAD SHAHIDEHPOUR: FUEL CELL ELECTRIC VEHICLE OPERATIONS IN COORDINATED HYDROGEN-INTEGRATED URBAN TRANSPORTATION AND POWER DISTRIBUTION NETWORKS

Hydrogen has been advocated as a promising energy carrier to achieve low-carbon integration of the urban transportation network (UTN) and power distribution network (PDN) [3], [4]. Grid-connected hydrogen production can mitigate the variations of renewables, making renewable energy even more valuable for energy production. The hydrogen fuel cell electric vehicle (HFCEV) can immensely reduce carbon emissions in the transportation sector [4]. After introducing the benefits of HFCEV utilization, such as the vehicle-to-grid, vehicle-to-vehicle, and transactive energy trading for managing the duck curve, Prof. Mohammad Shahidehpour presented three control models of HFCEV infrastructure. With the popularization of HFCEVs, hydrogen-integrated UTN and PDN were coupled tightly. The traveling and refueling behaviors of massive HFCEVs will impact the traffic flow of arcs and the hydrogen demand of hydrogen refueling stations (HRSs) in UTN [5]. To minimize the overall emissions in both the UTN and PDN, with the role of HFCEV considered, Prof. Mohammad Shahidehpour presented an application and operation strategy of HFCEVs in the two coupled networks, as shown in Fig. 1.

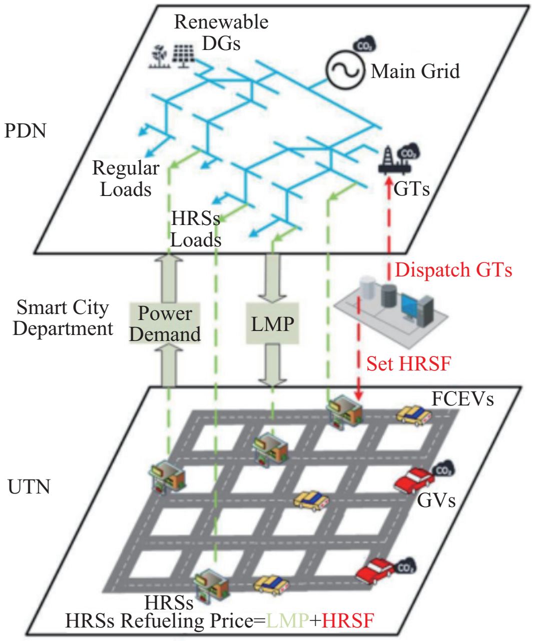


Fig. 1. Coordinated operation framework of hydrogen-integrated UTN and PDN based on HRSFs [6].

There are two decision levels in Fig. 1. At the smart city department level, the operation conditions of the coupled system are carefully monitored. Then, a smart city department will adjust the HRSF to guide HFCEVs to select HRSs to minimize the total cost. At the PDN and UTN operators level, the locational marginal price (LMP) decided by the PDN operator will be sent to UTN as the initial hydrogen refueling price of HRS. Then, the smart city department can adjust HRSF based on the operation conditions of UTN and PDN. The final hydrogen refueling price of the HRS includes the LMP and HRSF. The network equilibrium is reached when both the UTN and PDN cannot reduce their cost [6]. The hydrogen sold to HFCEVs is produced by water electrolysis in the on-site HRSs at the current or previous time intervals, which need to purchase electricity from PDN. Correspondingly, a coordinated operation model with hydrogen refueling service fees (HRSF) control is established to minimize the total UTN travel cost, PDN operation cost, and environmental cost, while the nodal carbon intensity restriction, the uncertainties of renewable distributed generators output, and origin-destination traffic demand are also taken into account. The developed model is decoupled and solved in a decentralized way based on the alternative direction method of multipliers (ADMM). The model is verified by applying to Sioux Falls which is the hydrogen-integrated UTN and PDN [6]. Numerical results and applications indicate that the popularization of HFCEVs contributes to emission reduction, and the coordinated operation between the UTN and PDN with HRSFs control can not only reduce emission and improve operation efficiency but also promote renewable energy accommodation.

III. PROF. SAIFUR RAHMAN: ROLE OF ENERGY STORAGE AND HYDROGEN IN DECARBONIZATION

Professor Saifur Rahman introduced the global warming potential (GWP) of greenhouse gases over a 100-year timescale. When compared to CO_2, the GWP of methane, nitrous oxide, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), were 28, 265, 138, 6630, and 23500, respectively. He summarized the decarbonization targets of various countries in the world and pointed out that a third way for the decarbonization debate between industrialized economies and emerging economies is to use diverse solutions [7], [8], including six main priorities [9]. They are energy efficiency applications, carbon capture systems, renewable energy integration, hydrogen and storage solutions, cross-border energy transfer, and advanced nuclear technologies. Prof. Saifur Rahman considered hydrogen and storage as one of the most promising solutions. He also compared the characteristics and advantages of different types of storage, including electrochemical energy storage technologies, mechanical energy storage technologies, and other energy storage technologies. Battery energy storage system is the most representative electrochemical storage, which can use lithium-ion, lead acid, lithium iron, or other battery technologies for storing electricity. The mechanical energy storage technologies which Prof. Saifur Rahman focused on consisted of pumped storage hydropower, flywheel, compressed air energy storage

(CAES), gravity energy storage (GES) and many more. Each has specific advantages in duration, reaction time, round-trip efficiency, and unique geographic requirements. Regarding the other energy storage technologies, Prof. Saifur Rahman highlighted thermal energy storage (TES), supercapacitors, and superconducting magnetic energy storage (SMES), as promising solutions. For example, if paired with electrochemical devices, supercapacitors can improve the efficiency and lifetime of the battery components. Prof. Saifur Rahman also considered hydrogen storage as one of the most promising ESSs, which can provide various services. He believed that hydrogen is currently unable to compete with electrochemical energy storage like lithium-ion batteries for shorter duration services on a cost-basis. However, it shows very high potential, especially in the air and ground transportation sector. Finally, he presented some examples of deployments or pilot projects worldwide. He summarized the ecosystem of energy storage technologies and services regarding the average duration and suitability for distributed or bulk power systems of various storage technologies. Fig. 2 illustrates the ecosystem of energy storage technologies and services.

IV. Prof. Nigel Brandon: Innovations in Electrolyzers and Flow Batteries for Longer Term Energy Storage

By analyzing the daily UK total gas, all liquid transport fuels, and electrical demand, Prof. Nigel Brandon demonstrated that as the energy system shifts to renewable power as its main input, longer-term electrical energy storage for periods ranging from 10–12 hours to days or weeks will be increasingly needed. He considered that hydrogen can deal with prolonged lower/no wind periods and effectively enhance energy systems' resilience. He analyzed that 1 million tons of hydrogen stored is the equivalent of 33TWh of energy which is more than the capacity of 3600 pumped hydro facilities such as Dinorwig in the UK. Hydrogen is also currently stored in large-scale in salt caverns in the world, supporting chemical plants and oil refineries [11]. The largest single store in USA can hold over 100 GWh of hydrogen. Taking the UK as an example, Prof. Nigel Brandon reported that the potential for hydrogen storage exceeds 64 million tons, providing 2150TWh of storage capacity. Given this background, he introduced the major components of the hydrogen energy storage system (HESS) and their underlying technologies [12]. There are three major components of a HESS, i.e., the charging system, discharging system, and storage system. The charging system includes electrolyzer modules, balance of plant (BOP), water-handing units, mass flow controllers, electrolyzer management system, compressor, and rectifier. The discharging system comprises stationary fuel cell modules, BOP, gas-handling units, blowers, mass flow controllers, fuel cell management systems, and inverters. The storage system typically includes pipes or caverns. After comparing the costs by components for a 100 MW, 10-hour HESS system, Prof. Nigel Brandon also introduced the alkaline electrolyzer, proton exchange membrane (PEM) electrolyzer, and high temperature solid oxide electrolyzer [13]. Prof. Nigel Brandon also introduced his team's metal-supported solid oxide fuel cell (SOFC) core patent and the hydrogen-manganese hybrid flow battery, which can be ideally suited to integrating with hydrogen infrastructure [14]. The hydrogen-manganese hybrid flow battery has high round-trip efficiency and high power density, operates over a wide temperature range, and has a non-toxic electrolyte. Its schematic diagram is shown in Fig. 3. Prof. Nigel Brandon concluded that flow batteries, liquid air, compressed air, and

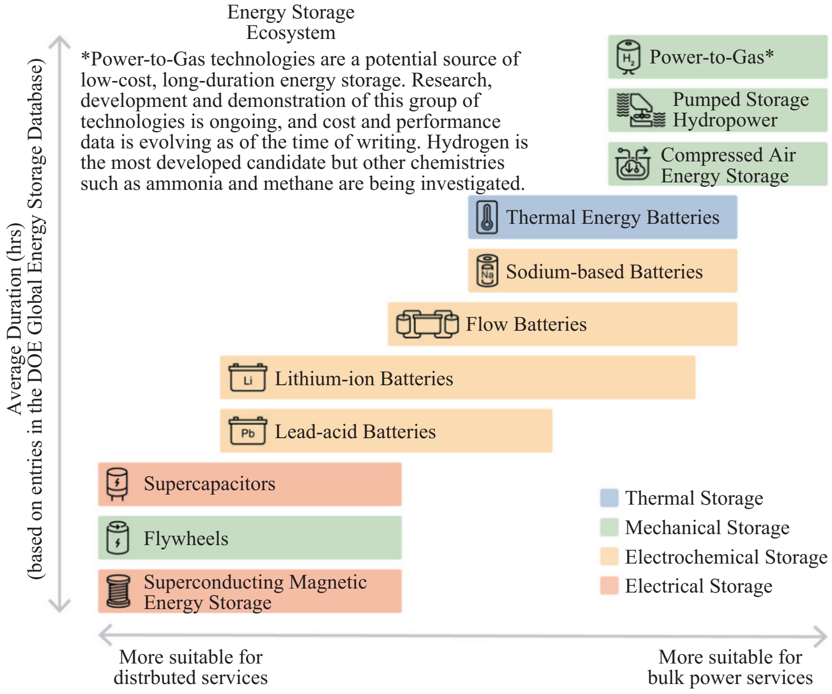


Fig. 2. Ecosystem of energy storage technologies and services [10].

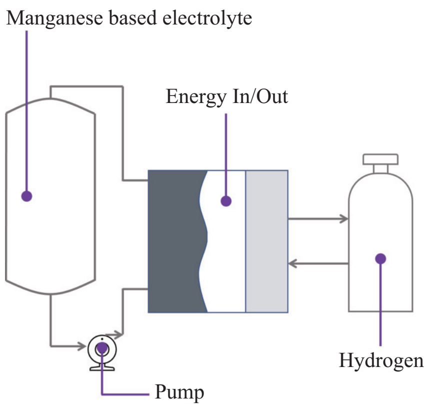


Fig. 3. A schematic diagram for the hydrogen-manganese hybrid flow battery.

potentially reversible electrolyzer/fuel cells that can achieve 10–12 hours or longer energy storage offer a good solution to wind and photovoltaic (PV) energy integration and decreasing variable renewable energy curtailments, but a market mechanism is needed to allow these longer-term energy storage solutions to be valued and incentivized.

V. PROF. KAI STRUNZ: ANALYSIS OF STAKEHOLDER ROLES AND INTERACTIONS IN THE CONTEXT OF ENERGY MARKET AND POWER SYSTEM INTEGRATION OF ELECTRIC VEHICLES

The electrification of the transport sector is accompanied by substantial challenges regarding the supply of additional user-dependent energy demand of electric vehicles and respective infrastructures [15], [16]. Developments in energy market structure and novel mobility concepts require a holistic approach for integrating electric vehicles into power systems and energy markets. An energy market actor generally may hold various roles and has access to particular data yielding a mutual influence between participating energy market actors. In order to develop interaction schemes that generate economic and ecological benefits on all sides among the participating energy market actors and facilitate a sustainable joint mobility and energy transition, Prof. Kai Strunz has been engaged in analyzing the sophisticated interactions between various stakeholders and designing effective methods to represent them, as shown in Fig. 4. Moreover, to make distribution systems with electric vehicles more predictable, observable, and controllable, Prof. Kai Strunz investigated the aggregation and coordination of various distributed energy resources (DERs) including electric vehicles in the form of the virtual power plant (VPP) in the energy market [17]. He believed that the economically and ecologically efficient energy market and power system integration of electric vehicles calls for an in-depth consideration of stakeholders' roles, goals, and available data. To achieve this target, he analyzed the stakeholders' roles in the energy market communication and the interactions involved in the energy supply of electric vehicles. It becomes apparent that individual electric vehicle (EV) owners as actors do not have direct access to electricity market platforms as the latter require bids to be of sizes that cannot be met by individual EVs. But even if there would not be such a size limit, EV owners are likely not inclined to engage in daily bidding processes.

Given these backgrounds, VPPs as actors offer opportunities for leveraging synergies among EV owners, decentralized RESs, and other actors. VPP operators can provide energy services at variable prices, utilize the flexibility potential of electric vehicles, and take over roles necessary to participate in the energy market [18]. Compared to direct participation in the market, VPPs reduce the price risk of energy end users, providing them with a convenient solution in accessing renewable power. According to Prof. Kai Strunz, for the participation of electric vehicles in VPP operations, interaction schemes and role distributions among stakeholders should

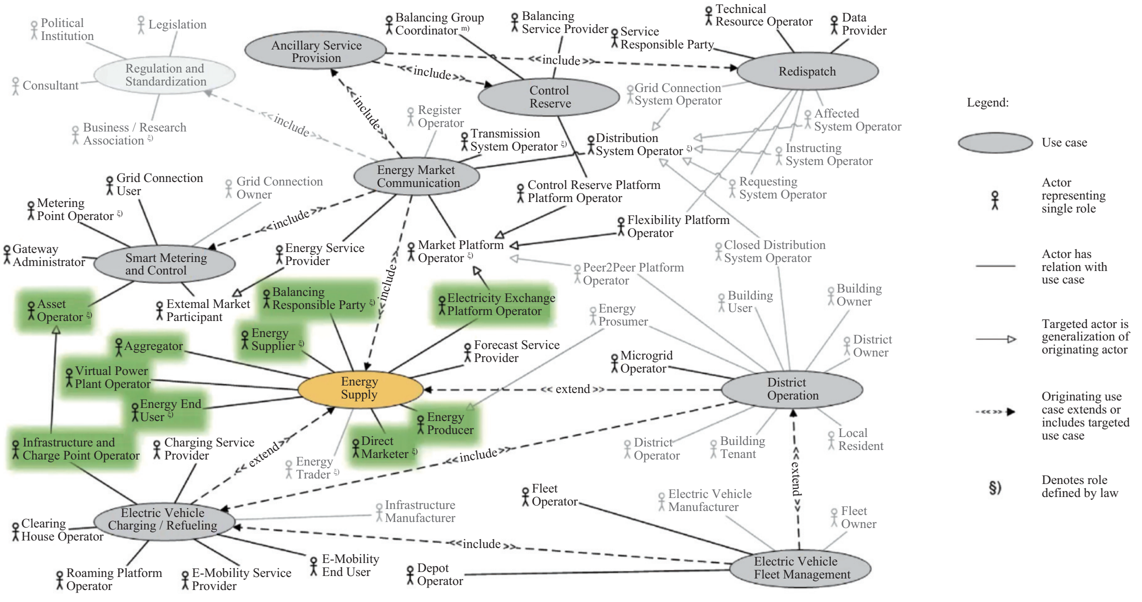
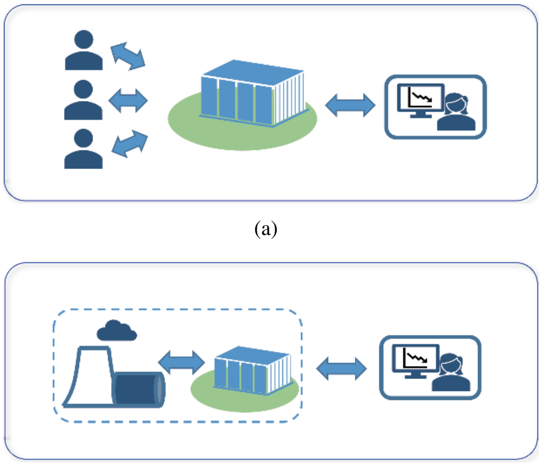


Fig. 4. Analysis and design of the stakeholders' roles and interactions.

be further developed considering various conditions such as the technology solution, user preferences, and infrastructure access.

VI. PROF. YONGHUA SONG: FREQUENCY REGULATION VIA BATTERY STORAGE AND WATER ELECTROLYSIS: CONTROL STRATEGY AND IMPLEMENTATION

The intermittency of renewables significantly challenges the frequency stability of power systems. The battery energy storage system (BESS) and water electrolysis represent two of the most promising technologies for frequency regulation in power systems with high penetration of renewables [19], [20]. Prof. Yonghua Song presented the progress and applications of the control strategy for secondary frequency regulation of the BESS and water electrolysis. Regarding the participation of BESSs in frequency regulation, Prof. Song first introduced the application modes such as the independent mode, sharing mode, and coordinated mode [21]. In the independent mode, the BESS itself is an autonomous entity that independently makes operation decisions. The sharing mode uses a single shared BESS to undertake the primary frequency regulation obligations for multiple RESs and provide commercial automatic generation control (AGC) service in the ancillary market at the same time, as illustrated in Fig. 5(a) [21]. In the coordinated mode, BESSs cooperate with the thermal power plants, enabling the combined system to quickly adjust energy output and sustain energy output for a long time Fig. 5(b). In the presentation, a sharing model is proposed to utilize a large-scale BESS for simultaneous frequency regulation and AGC of a system with multiple RESs. Prof. Song also discussed cooperation patterns of the BESS and thermal power plants are explored and applied in practical projects. Power-to-gas (P2G) is a promising energy storage technology that uses electrolysis devices to convert surplus renewable electricity into hydrogen or other fuels. Fig. 6 shows a coupling system with integrated power and hydrogen. The large-scale grid-connected electrolysis system is expected to become an important support for power grid frequency stability in the future. To ensure the secure and economic operation of the water electrolysis system with a wide power adjusting range, Prof. Song presented a pressure and temperature control strategy for the alkaline electrolysis system to meet the frequency regulation demand of power systems [22]. Furthermore, he demonstrated the potential of cooperative control strategy for large-scale water electrolysis systems to coordinate renewables, by using practical water electrolysis projects and simulations on laboratory platforms [22]. Regarding the future research of the BESS, Prof. Song considered that a more accurate degradation model and real-time control strategies for the shared BESS providing frequency regulation and AGC simultaneously should be considered. Regarding water electrolysis systems, he deemed the power distribution in large-scale systems and the control method for responding more accurately to frequency regulation signals should be considered. In addition, it is also important to consider the operational degradation of the electrolysis system in the bidding and operation of frequency regulation.


(a)

(b)

Fig. 5. Operation modes of the shared BESS. (a) Sharing mode. (b) Coordinated mode.

VII. CONCLUSION

In this article, opinions on the coordination and operation of integrated energy systems, design of electricity markets, and new technologies in the field of hydrogen and energy storage

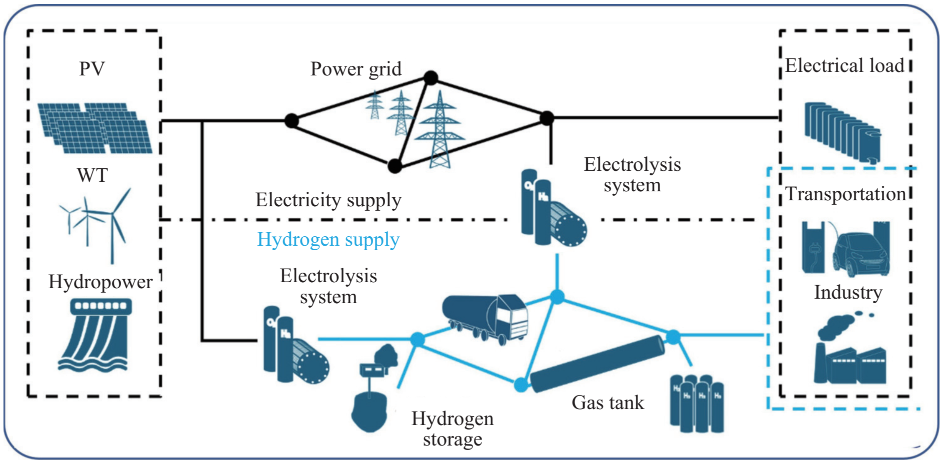


Fig. 6. Illustrative figure of a coupling system with integrated power and hydrogen.

were presented. Specifically, Prof. Mohammad Shahidehpour emphasized the roles of HFCEVs in the coordinated operation of the energy and transportation systems for cost and green gas emission reduction. Prof. Saifur Rahman proposed six priorities for reducing carbon emissions and analyzed the roles of various energy storage technologies. Prof. Nigel Brandon introduced the potential of electrolysis and flow battery devices for the low-carbon energy transition. Prof. Kai Strunz analyzed and recommended stakeholder roles and related interactions for the flexible and sustainable energy supply of electric vehicles. Prof. Yonghua Song presented control strategies for using BESS and electrolysis systems for frequency regulation of power systems with high level of RESs. Experts also elaborated their experiences and viewpoints on using energy storage to facilitate decarbonization of power and energy systems. The major viewpoints of the experts are as follows.

1) HFCEVs can significantly reduce carbon emissions and other harmful air pollutions, and can be used to improve the flexibility of the system and to respond to extreme scenarios, but that requires the coordination of power systems and other infrastructures.

2) Hydrogen and energy storage can play significant roles in decarbonization. It is necessary for future studies to consider the carbon emissions of the whole life cycle in practical engineering applications.

3) Electrolysis and flow battery can achieve longer-term energy storage for power systems. But the market mechanisms should be developed to allow them to be valued and incentivized.

4) VPPs can aggregate and coordinate diverse distributed energy resources including EVs for supportive market participation. Interaction schemes and role distributions among stakeholders should be further developed considering various conditions such as the technology solution, user preferences, and infrastructure access.

5) The BESS and water electrolysis show great potential for frequency regulation. But better accurate degradation models and the real-time control strategies need to be considered for both the BESS and water electrolysis.

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