Toward Economically Rational Hydrogen Production from Solar Energy: From Battery Versus Hydrogen to Battery × Hydrogen

16

Michihisa Koyama

Contents

Abstract

The use of renewable energy as a main primary energy source can be perceived as a common target of all the countries in the world to reach a sustainable society late in this century. Toward the sustainable goal, the photovoltaic and wind power generations are expected to play important roles in coming decades. To counter the intermittency of their power outputs, economically feasible energy storage measures are necessary. In this chapter, the storage technologies as key technologies for making intermittent renewable energies a main power generation option are discussed focusing on the battery and hydrogen energy systems. The rationality of hydrogen energy as a long-term storage measure is first discussed by a Fermi estimate formula proposed by Hasegawa. Then the rationality of

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integrating battery with hydrogen production from solar energy is discussed. A concrete example of the integrated system optimization is introduced to clearly show that the integration will lead to the realization of an economically viable hydrogen production from solar energy.

16.1 Introduction

Future energy vision cannot be separable from the global warming problems. Until Kyoto protocol agreed in 1997, demand-side energy savings and a reduction of greenhouse gas (GHG) emission associated with electricity generation have been major directions. Early in this century, nuclear power attracted much expectations and new plant constructions have been promoted in many countries, which is called as “Nuclear Renaissance.” Severe accident in Fukushima Daiichi Nuclear Power Plant in March 11, 2011 (hereafter, 3.11) has changed this paradigm drastically. It has become difficult to locate the nuclear power as a major option for the GHG emission reduction and better energy security especially in Japan [1]. This shift can be clearly seen, for example, from the energiewende in Germany [2] and fourth strategic energy plan of Japan published in 2014 [3] as an update of the third published in 2010, before 3.11 [4].

Two major world directions have been published in 2015: sustainable development goals (SDGs) [5] by United Nations in September and The Paris Agreement [6] adopted at the twenty-first Conference of the Parties in December. In Paris Agreement, Japan has promised 26% GHG emission reduction by 2030 compared to 2013 [7]. In 2016, Japan’s cabinet published the Plan for Global Warming Countermeasures [8], in which 80% GHG reduction by 2050 is targeted as a long-term goal. The 2030 target is set on the basis of reasonable bases, and thus, its achievement will be realized by promoting the measures in the course of present trends. However, many recognize 2050 target as unachievable by the extrapolations of present trends. In fact, Japan’s fifth strategic energy plan published in 2018 [9] describes “It is difficult to foresee a long-term perspective of 2050 with a certain rational due to the possibilities and uncertainties of technology innovations as well as a lack of transparencies of geopolitical situations.”

In this chapter, the author would like to discuss the future directions and present the possibilities of hydrogen production from solar energy toward the massive utilization of intermittent renewable energy.

16.2 Trend of Renewable Capacities

Toward the deep decarbonization for the world to meet key climate goals by 2050, we only have three options for primary energy: nuclear energy, renewable energy, and fossil fuels implemented with carbon capture, utilization, and storage (CCUS) measures as illustrated in Fig. 16.1. If we regard a nuclear fusion as a nuclear energy, no other option exists, thus those three options are the

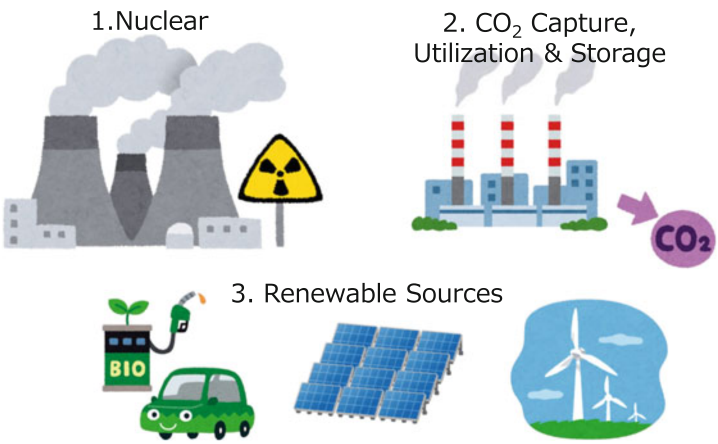

Fig. 16.1 Three primary energy options for future deep decarbonization

first-principles for considering the deep decarbonization. As discussed in the introduction, illustrating a realistic pathway to increase the contribution from nuclear power is difficult especially in developed countries. CCUS is an important and necessary option especially considering the deep decarbonization in chemical and steel-making industries [10–12]. Even if the high cost and low social acceptance outstanding presently as technology challenges are solved in future, this option is associated with fossil fuel depletion. In addition, a present trend of divestment from fossil fuel-based technologies should be recognized as a risk for this option. Therefore, it would be preferable to minimize the dependence on this option as possible. As a result, maximizing the contribution from renewable energy is essentially required for the deep decarbonization as well as massive energy savings at the demand side [13].

Total capacity of renewable energy systems in the world has reached more than 2350 GW in 2018 [14] as shown in Fig. 16.2. Hydropower's capacity is ca. 1172 GW, accounting for approximately half of the total capacity. Those of wind and solar energy are 564 and 486 GW, respectively. When we focus on the increase ratio from 2009 to 2018 rather than the present capacity, rapid increase of solar energy is noticed. Solar increased by ca. 2000%, and wind energy increased by 300%. On the other hand, hydropower increased by ca. 30%. From the projection of this trend, it is expected that wind and solar energies will play central roles in future deep decarbonation. As is well known, wind and solar energies are intermittent by nature and cannot adjust their outputs to the power demand in a timely manner required for the stable operation of the electricity grid system. In addition, due to low capacity ratios of wind and solar energies, total capacities will become much larger than the maximum peak demand when one envisions a fully renewable power supply system [15]. Therefore, storage measures must be massively implemented together with wind and solar energy systems in order to supply a major part of the energy in future.

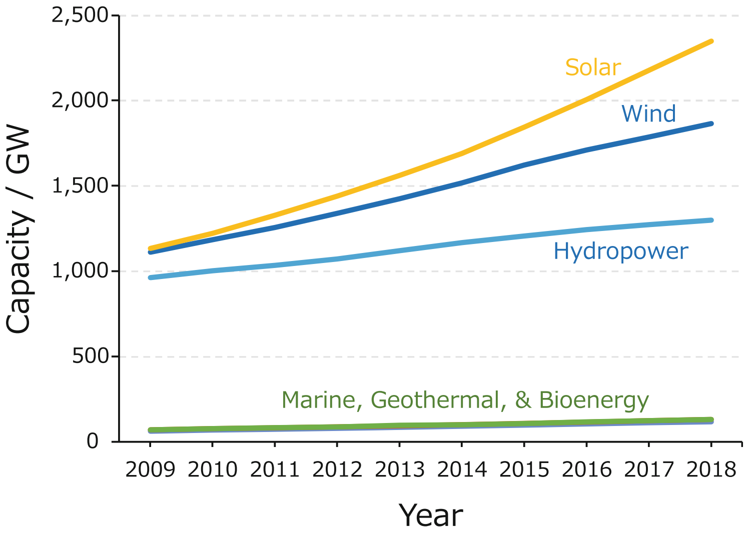

Fig. 16.2 Capacities of renewable energy systems [14]

16.3 Trend of the Levelized Cost of Electricity

World trend of the levelized cost of electricity (LCOE) is summarized in the LAZARD's report [16]. Unsubsidized mean LCOE's of coal are 0.111 and 0.102 US $/kWh, in 2009 and 2018, respectively, and those of gas combined cycle are, respectively, 0.083 and 0.058 US $/kWh. Mean LCOE of nuclear decreased from 0.123 US $/kWh in 2009 to 0.095 US $/kWh in 2011, then increased to 0.151 US $/kWh in 2018, from which one can see the shift of paradigm from Nuclear Renaissance to Safety-first after 3.11. Those of crystalline photovoltaic (PV) and wind power plants decrease from 0.359 to 0.043, and from 0.135 to 0.042 US $/kWh, respectively, during the same period. To see more closely the trend, the author summarized the LCOE of selected power generation options focusing on Japan as shown in Fig. 16.3 [17–22]. Horizontal and vertical axes of the figure correspond to the LCOE associated with plant and fuel, respectively. Vertical axis value of nuclear includes the front end, reprocessing, back end costs. That for LNG and Coal consists of fuel and GHG countermeasure costs. From the figure, nuclear increases its LCOE associated with the power plant, especially after 3.11. General trends in Coal and LNG are the increase in LCOE associated with fuel, in line with the future prospects of current and new policy scenarios of IEA [23]. Note that recent sustainable development scenario of IEA [23] may influence those estimates. Compared to other countries in the world, the LCOE of the PV is much higher in Japan. The deployment of PV in Japan is accelerated by Feed-in Tariff actuated in July 2012, leading to a rapid decrease of its LCOE from 2013 to 2017. The value of 2040 is estimated to be 3.7 JPY/kWh. Crossover with nuclear, coal, LNG is expected to

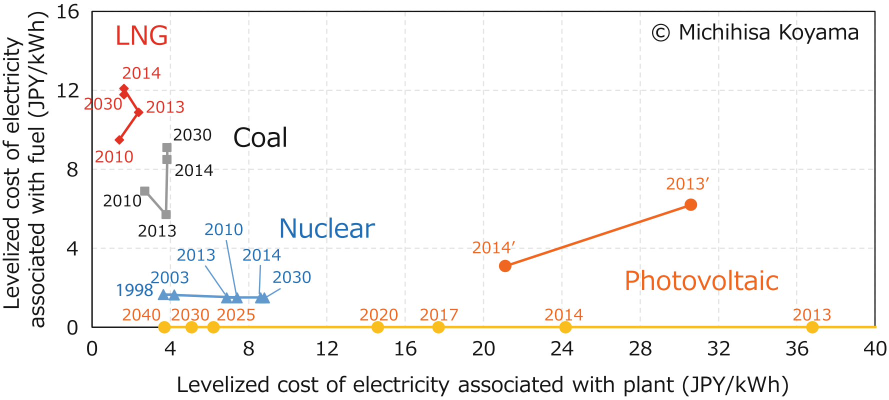

Fig. 16.3 Levelized cost of electricity of representative power generation options in Japan. The LCOE's of nuclear power plants estimated for 1998 [17], 2003 [18], 2010 [19], 2013 [20], 2014 [21], 2030 [21], coal and LNG combustion power plants for 2010 [19], 2013 [20], 2014 [21], 2030 [21], and non-residential photovoltaic power plants for 2013 [20], 2014 [21], 2017 [22], 2025 [22], 2030 [22], 2040 [22]. 2013′ and 2014′ for photovoltaic are the different plots of 2013 and 2014. In references [20, 21], the unsubsidized LCOE and the procurement price of Feed-in Tariff scheme are explicitly considered. The latter is a policy-incentive cost corresponding to internal rate of return, which is proportional to the electricity generated. This policy-incentive is assigned to horizontal axis values for 2013 and 2014 while it is assigned to vertical axis values for 2013′ and 2014′. (This policy-incentive is not explicitly described in reference [22].) Copyright retained by the author

occur between 2020 and 2025. The LCOE of renewable technologies under Feed-in Tariff is controversial. In Fig. 16.3, the plot of setting the policy incentive corresponding to the internal ratio of return as the vertical value of the PV with the unsubsidized LCOE as the horizontal axis is also shown. From Fig. 16.3, three distinct trends are clearly seen. One is the horizontally increasing trend of the nuclear. The second is the vertically increasing trend of the Coal and LNG, and the third is horizontally decreasing trend of the PV. Under the trend of the nuclear, one may assume a background paradigm: No incentive to increase the conversion efficiency; high incentive to increase the capacity ratio for easier capital investment recovery. Actually, no increase in efficiency is found in references [17–21]. The trend of the coal and LNG will evoke a different background paradigm: High incentive to increase the conversion efficiency even with some increased capital investment costs; the simultaneous importance of energy savings at the demand side to reduce the total GHG emission because the increase in supply capacity will result in the increase in the total GHG emission, also accepting the decrease in the capacity ratio to a certain extent. A future paradigm expected from the trend of the PV's LCOE in Fig. 16.3 can be free from all of the above. Energy savings may not be important after massive deployment and decreased LCOE of PV in future, especially during a sunny daytime. This means that measures with lower thermal or exergy efficiency but with better economic rationality may increase their importance in future.

Also, one can see the transition of relative locations of the PV, nuclear, coal, and LNG power generation systems in the context of energy security, environmental protection, and economic efficiency (3E). The nuclear was favorable in all aspects of 3E. The coal was the worst in terms of environmental protection, while it was the second better choice from the other two aspects. The PV was too unfavorable to consider in terms of economic efficiency. After 3.11, 3E and Safety (3E + S) was set as a new paradigm of the energy systems. This makes the nuclear less favorable economically, but still favorable compared to the coal and LNG partly due to the increase in the fossil fuel prices. Focusing on 2030, most economically favorable option is expected to be the PV, followed by the nuclear, coal, and LNG in this order. It is needless to mention that the PV is also favorable in terms of the energy security, environmental protection, and safety. Therefore, one may imagine a future humanity freed by the economically efficient future PV from the depletion and geopolitical risks associated with fossil fuels, which have often been a cause of wars historically. Of course, one may point out a serious concern of the intermittency of PV, which is not explicitly considered in the values shown in Fig. 16.3. Therefore, I would like to discuss the storage options and their integration with PV in the subsequent sections.

16.4 Fermi Estimate for Energy Storage Options

Only studying the future investment costs of storage measures is insufficient because the levelized cost of storage depends on the role of storage. A system integration of storage measures to counter the intermittency of renewable energies has been intensively studied [24–29]. Schmidt et al. investigated the levelized costs of storage and showed valuable global map for technology options suitable for specific existing application targets [24]. When we assume the existing application targets, deep understanding of the present system and paradigm is important. By contrast, it is important to consider the system configuration itself, free from a priori assumptions when designing future systems that do not exist in the course extrapolated from the present trends and paradigm. However, it should be noted that even when we design future energy systems, one should place a highest priority on economic rationality. Therefore, it is ideal attitude to consider the economic rationality of future energy systems even early in the conceptual design phase.

Hasegawa has proposed a Fermi estimate formula to calculate the crossover storage time at a given set of costs related to technologies considered [30]. Fermi estimate means the estimate of approximate values, which cannot be easily investigated, based on a certain clues and logics, named after Enrico Fermi's estimate of the strength of the atomic bomb [31]. Such an approach is also known as an order estimate or a back-of-the-envelope calculation.

Hasegawa focused on the hydrogen energy-based and lithium ion battery (LIB)-based energy storage system (ESS) for renewable electricity in his first study [30]. The LIB is an electrochemical device that stores electrical energy as chemical energy through the charge-transfer reaction at the interface between the active material and electrolyte. Therefore, the LIB itself is equipped with functions of

Table 16.1 Comparison between LIB and hydrogen ESS [30]

	LIB ESS	Hydrogen ESS
Energy conversion cost Cost per power ($/kW)	Low *A* (≡0)	High *C*
Energy storage cost Cost per storage ($/kWh)	High *B*	Low *D*

both energy conversion and storage. On the contrary, a high-pressure tank for hydrogen storage only has a function of energy storage. Therefore, energy conversion functions, i.e., to convert electricity to hydrogen and vice versa, are needed externally to the tank. He assumed a set of water electrolyzer and fuel cell (FC) systems. Because the storage function is independent from the energy conversion function in the hydrogen ESS, the system's economic rationality is determined by the cost for storage, i.e., the high-pressure tank when the stockpile is infinitely large. Oppositely, the economic rationality is determined by the cost for energy conversions when the stockpile is small. In the case of LIB, the cost is apparently proportional to the storage.

Table 16.1 shows a conceptual comparison of LIB and hydrogen ESS. Because the energy conversion function is inherently equipped with LIB, the cost for energy conversion can be defined to be zero. Energy storage cost of LIB can be regarded to be expensive compared to high-pressure tank because the former needs 1 mol of functional compounds to store 1 mol of electrons while the latter requires vacuum space for hydrogen storage and the metallic alloy or carbon fiber composing high-pressure tank as a shell. The energy conversion cost of hydrogen ESS is expensive compared to that of LIB ESS, which is zero.

Crossover time for storage, at which the costs of LIB and hydrogen ESS's become equal, can then be derived as follows.

$$A \times P + B \times P \times t = C \times P + D \times P \times t \tag{16.1}$$

P and *t* are the rated power of ESS (kW) and storage time (h), respectively. *A* is zero by its definition, and given that *B*, *C*, and *D* are independent from *P*, *t* is expressed as

$$t = C/(B - D). \tag{16.2}$$

For an initial estimate in this chapter, I updated values of *B*, *C*, and *D*, by referring available technology information. The battery cost of 125 $/kWh can be found as United States Department of Energy (US DOE) Project target [32] and 50 $/kWh is indicated as cost of advanced battery in 2030 [33]. Because those are for the battery pack, the doubled cost is assumed for LIB-based ESS cost: i.e., $100–250/kWh for *B*. US DOE's cost target is 53 $/kW for FC power plant, on a condition of 500,000 units annual production of 100 kW-FCs [34]. 50,000 JPY/kW (ca. 455 $/kW) as a cost target of the water electrolyzer plant can be found in the report of CO_2 free hydrogen working group, the Ministry of Economy, Trade, and

Industry, Japan [35]. Considering that a balance of plants cost for integrating FC, electrolyzer, and high-pressure tank is necessary, 1000 \$/kW for *C* is assumed: an approximately doubled cost of the summation of the cost targets of FC and electrolyzer plants. The cost for hydrogen tank is estimated by US DOE's project: 14.8 \$/kWh for 700 bar baseline tank system at a manufacturing volume of 500,000 systems/year [36]. Also, doubled cost is assumed for high-pressure tank, meaning 30 \$/kWh for *D*.

Assigning those values to Eq. (16.2) will give us a crossover time of 4.5 and 14.3 h for the battery cost of 250 and 100 \$/kWh, respectively. If we assume a good advancement of battery and retarded advancement of the FC and electrolyzer, i.e., 100 \$/kWh for *B* and 10,000 \$/kW for *D*, crossover time is calculated to be 143 h, still shorter than a week. Fermi estimates here mean that the crossover time will be in the order of 10^1–10^2 h, and hydrogen ESS will show the economic rationality over LIB ESS for the energy storage period longer than the estimated crossover time. Schmidt et al. assumes that LIB and hydrogen will be major options for energy storage in future [24]. Their detailed estimation of levelized cost of storage showed a crossover time of ca. 30–40 h. One can see how the Fermi estimate formula proposed by Hasegawa works well.

16.5 Integrating Storage Measures to Photovoltaic Power Generation

The discussion in the previous section is to show the rationality of hydrogen energy as a long-term storage measure for renewable electricity. However, a simple combination of hydrogen and PV will not result in the economically feasible system due to the low capacity ratio of the PV, hindering a capital recovery within a reasonable depreciation period. So far, various studies have been conducted under the concept of the Power-to-Gas [37]. Recently, hybridization possibility of the battery with hydrogen production from the PV was discussed by Gillessen et al. [28]. They considered technology options such as the LIB and redox-flow battery with the technology levels around 2030 to conclude that the system without battery is most economically feasible, even assuming an electricity cost of zero. This result is in line with our apparent intuition that the system becomes more expensive by incorporating the expensive battery into the expensive hydrogen production from the PV. Then, is there no solution in this direction, and should one consider different directions to realize a sustainable energy supply system based on the PV?

In this section, let me consider the system configuration free from a priori assumptions or background knowledge. An extreme of the free electricity assumed in [28] does not provide a solution because it does not directly solve the difficulty of the capital recovery due to the low capacity ratio. Therefore, another extreme of battery cost of zero, i.e., sufficiently low cost in a practical context, will be discussed. When we do not need any investment to install a battery system, sufficiently large capacity of battery can be installed to PV system. In this extreme end, all the

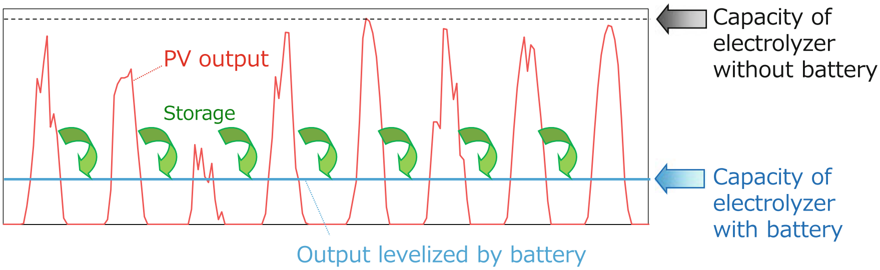

Fig. 16.4 Schematic of the power generation profile of PV and electrolyzer capacity with sufficiently large capacity of battery

electricity generated by the PV is once charged to the battery, then discharged to the electrolyzer with a constant output power as schematically illustrated in Fig. 16.4. When the battery is not installed, the capacity of the electrolyzer is determined by referring the capacity of PV, leading to a low capacity ratio of the electrolyzer. On the contrary, the capacity of the electrolyzer is designed to the discharge output of the battery in the extreme case discussed here. In addition, the capacity ratio becomes 100% meaning much easier capital recovery. Assuming that the capacity ratio of 12% for PV and the battery charge/discharge efficiency of 100%, the discharge output will become 12% of the PV capacity, then the capacity of the electrolyzer can be 12%, ca. one-eighth, compared to that without battery. From this estimate, one can understand that the battery installation is economically beneficial when the investment cost of the battery is smaller than the benefit by decreasing the investment cost and increasing the capacity ratio of the electrolyzer. Here, let's assume the reference system of 1 kW of PV equipped with 1 kW of electrolyzer. When the electrolyzer cost is 500 $/kW, the reference system requires 500$ to install the electrolyzer of 1 kW capacity. On the other hand, the necessary electrolyzer capacity is 120 W when the sufficiently large capacity of the battery is installed, meaning that the necessary investment for the electrolyzer is only 60 $. The difference, 440 $, can be used to invest for the battery. When the battery cost is 100 $/kWh, 4.4 kWh can be installed. The question will be the expected increase of the capacity ratio by installing the 4.4 kWh battery, which can only be estimated by referring the actual power generation profile of PV.

Kikuchi et al. have optimized the system integration of the PV, battery, and electrolyzer [27]. Figure 16.5 shows a schematic system configuration of a battery-assisted hydrogen production from solar energy. The electricity generated by PV is transferred to the energy management system (EMS). The EMS determines the appropriate operation mode from the options of direct input to the electrolyzer, charging excess electricity to the battery, discharging from the battery to meet the electricity deficiency, and rejecting the electricity. When the costs of the PV, battery, and electrolyzer, as well as a solar irradiance profile are given, an operational mode and capacities (ratio) of the PV, battery, and electrolyzer, minimizing the levelized cost of hydrogen (LCOH$_2$), can be determined.

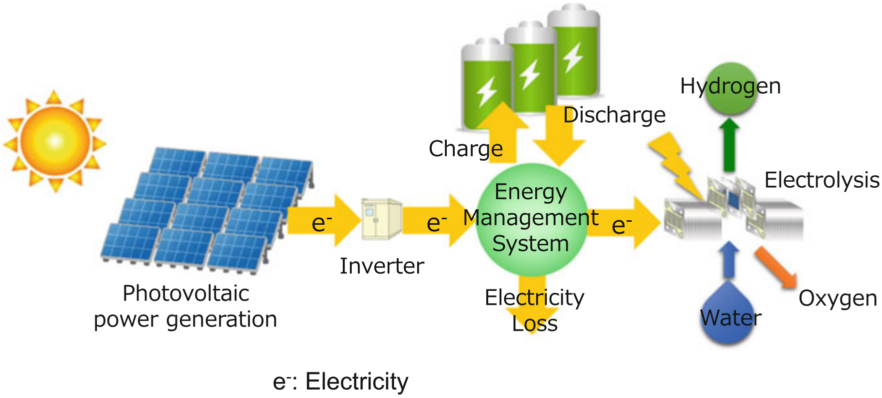

Fig. 16.5 Schematic system configuration of a battery-assisted hydrogen production from solar energy [38]

Figure 16.6a shows the breakdown of the optimized $LCOH_2$ when the LCOE of the PV and electrolyte investment cost is 7 JPY/kWh and 50,000 JPY/kW, respectively. When the battery unit cost is 20,000 JPY/kWh, $LCOH_2$ becomes ca. 50 JPY/Nm^3, indicating that the system will be economically viable against the present gasoline price. One can see that the PV electricity occupies the large part of the cost, followed by the electrolyzer including investment, operation and maintenance. As the unit cost of the battery becomes cheaper down from 20,000 JPY/kWh, the ratio of the battery cost in the total cost increases. Below the unit cost of around 14,000 JPY/kWh, the ratio of the battery cost decreases as the unit cost decreases. To see more details, the ratio of the battery and electrolyzer capacities is plotted against the battery unit cost in Fig. 16.7. When the unit cost of the electrolyzer ($CAPEX_{ely}$ in the figure) is 50,000 JPY/kW, the relative battery capacity increases steadily as the battery unit cost decreases from 20,000 JPY/kWh. Below 14,000 JPY/kWh, the relative capacity increases only slightly. The cost of the installed battery is given as the product of the unit cost and installed capacity. The increase of the installed capacity explains the increase of the battery cost in Fig. 16.6a even if the unit cost decreases from 20,000 to 14,000 JPY/kWh, while the plateau of installed capacity will explain the decrease of battery cost as the unit cost decrease below down to 14,000 JPY/kWh. Figure 16.6b shows the breakdown of the $LCOH_2$ when the LCOE of PV and the battery unit cost is 2 JPY/kWh and 5000 JPY/kWh, respectively. It can be seen that the $LCOH_2$ is ca. 20 JPY/Nm^3 when the electrolyzer unit cost is 20,000 JPY/kW.

16.6 Summary and Future Perspective

In this chapter, the author introduced the discussion focusing mainly on the storage technologies as key technologies for making intermittent renewable energies a main power generation system of the future. From the trend analysis of LCOE's of the PV,

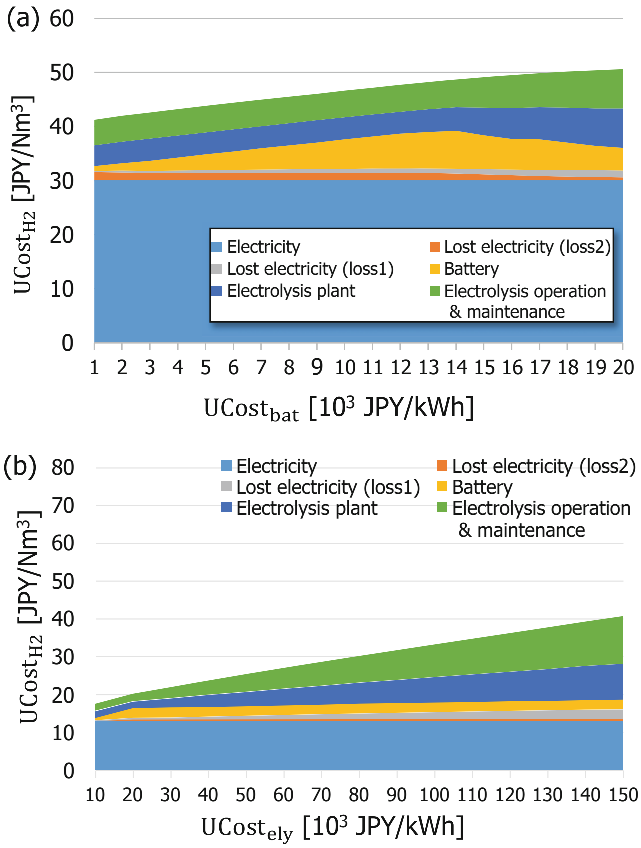

Fig. 16.6 Examples of estimated levelized cost of hydrogen for a battery-assisted hydrogen production from solar energy: (**a**) the LCOE of PV and electrolyzer unit cost is 7 JPY/kWh and 50,000 JPY/kW, respectively, and (**b**) the LCOE of PV and the battery unit cost is 2 JPY/kWh and 5000 JPY/kWh, respectively. (Reprinted from Int. J. Hydrogen Energy, 44/3, Y. Kikuchi, T. Ichikawa, M. Sugiyama, M. Koyama, Battery-assisted low-cost hydrogen production from solar energy: Rational target setting for future technology systems, 1451–1465, Copyright 2019, with permission from Elsevier)

nuclear, coal, and LNG, future paradigm of power generation options was discussed. As an option for long-term storage, rationality of hydrogen against battery was discussed by referring a Fermi estimate formula by Hasegawa. The rationality of integrating battery with hydrogen production from solar energy was discussed. By considering the rationality of the system from scratch, it was derived that the investment cost of the electrolyzer can be one-eighth of the system without the battery. Examples of the system optimization were introduced. By the appropriate integration of the battery into the system, an economic competitiveness of the hydrogen production from the solar energy was clearly shown especially when the future technology costs were assumed.

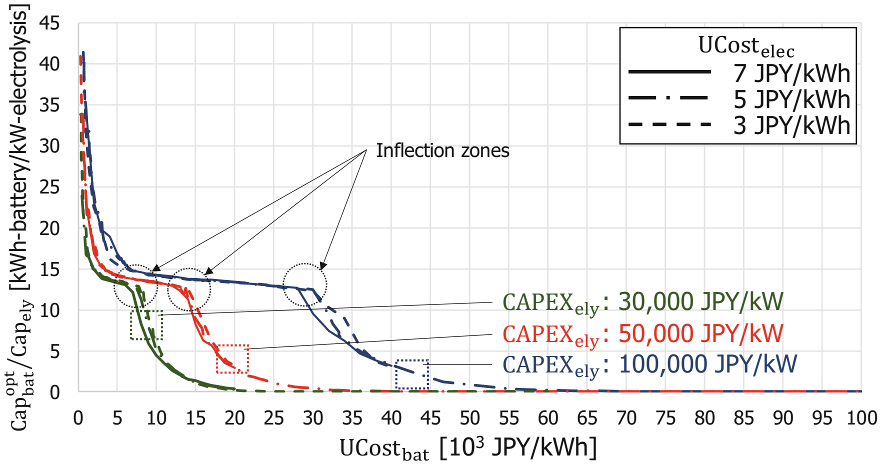

Fig. 16.7 Profiles of ratio of the battery capacity against electrolyzer capacity. (Reprinted from Int. J. Hydrogen Energy, 44/3, Y. Kikuchi, T. Ichikawa, M. Sugiyama, M. Koyama, Battery-assisted low-cost hydrogen production from solar energy: Rational target setting for future technology systems, 1451–1465, Copyright 2019, with permission from Elsevier)

Promoting the research and development to make the PV and electrolyzer cost-competitive toward the economically viable hydrogen production is important beyond controversy. However, one should be reminded that even if the electrolyzer becomes more efficient and less expensive, the issue of a low capacity ratio of the PV, which makes the capital recovery of the electrolyzer difficult, remains outstanding. The investment to the battery may increase the economic rationality of the expensive hydrogen production from the PV. The battery and hydrogen have been often discussed as "battery vs hydrogen," as if they are incompatible competitors. An example discussed in this chapter is a trial of the discussion free from such context. Harmonic integration of battery and hydrogen, i.e., "battery × hydrogen", will be a key toward a renewable energy-centered energy system in future.

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