Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 158 (2019) 3802–3807

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Techno-economic assessment of the residential photovoltaic systems integrated with electric vehicles: A case study of Japanese households towards 2030

Takuro Kobashi[a,*], Masaru Yarime[b,c,d]

[a]*Renewable Energy Institute, Tokyo 105-0003, Japan*
[b]*City University of Hong Kong, Hong Kong SAR, China*
c University College London, United Kingdom
d University of Tokyo, Japan

Abstract

Finding economical and sustainable pathways for the deployment of renewables is critical for the success of decarbonizing energy systems. Because of the variable nature of renewable energy, however, it becomes increasingly costly when the renewable penetration becomes higher. The recent rise of electric vehicles (EVs) provides us with an opportunity to increase self-consumption of solar photovoltaic (PV) at households with substantially less additional costs. In this paper, we conducted an economic assessment of residential PV systems integrated with EVs (V2H: Vehicle to Home) at Japanese households towards 2030, incorporating the cost projections of these technologies in the future. We found that a system that consists of PV and an EV is already cost-competitive with the use of grid electricity and a gasoline vehicle in 2018. By 2030, the combination of PV + EV would substantially improve the energy economics at households in Japan, reducing annual energy costs (electricity and gasoline) by as much as 68 % in 2030 and decarbonizing the household energy system by 92%. We also found that the PV + EV system is much more economical than a PV-only or PV + battery systems, due to the fact that EV's large battery can be utilized with minimum additional costs. To facilitate the deployment of the combination of PV + EV, policy makers should reinforce policies to enhance EV, PV, V2H penetration, which will ultimately allow more renewables to be deployed in a cost-effective way.

* Corresponding author. Tel.: +81-3-6866-1020; fax: +81-3-6866-1021.
E-mail address: t.kobashi@renewable-ei.org

1876-6102 © 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.
10.1016/j.egypro.2019.01.873

Keywords: PV plus EV; electricity; economics, hosehold; Japan; V2H

1. Introduction

Since November 2009, a feed-in tariff (FIT) has been introduced in Japan for solar photovoltaic (PV) at households with \$0.44/kWh for 10 years. Then, wider FITs were introduced from 2012 for wind, mid- to small-size hydro, geothermal, biomass. Since the introduction of the FITs, solar power effectively expanded in Japan from 2.6 GW in 2009 to 38.7 GW in 2016, but with limited successes for other renewables. As a result, the FIT surcharge for electricity consumer expanded to annually \$19.5 billion or \$0.024/kWh [1] that became a political issue creating a debate how much FITs should be used to further expand renewables. In Japan, the costs of renewables remain one of the highest countries in the world [2], partly owing to the earlier lavish FIT prices. Thus, finding economical pathways for renewable expansion without policy supports is increasingly important for Japanese societies at a time when the first FIT starts to phase out in the fall 2019.

Most widely available renewable energies, solar and wind powers, are variable, requiring energy storage [3]. With the expansion of electric vehicles (EVs), battery costs are rapidly declining, enhancing economic viability of residential "PV + battery" systems [3,4]. However, battery system costs (lithium-ion batteries) remain relatively high for the foreseeable future such that the economic viability is limited [4–6]. On the other hand, EVs with a large battery capacity (e.g., Nissan Leaf: 40 kWh) are capable to charge electricity from PV and supply it to home (Vehicle to Home: V2H), incurring minimum additional costs as an energy resource. Only 5% of time of a passenger vehicle is used on average in Japan [7], indicating that EV is available for the V2H for most of the time. Already, 7,000 V2H systems have been adapted in Japan when the EV penetration is less than 1% [8]. We also note that the degradation of the EV battery by the use of V2H is possibly less than that without the V2H if it is properly managed [9,10]. With declining costs of PV and EV [11,12], the residential "PV + EV" system may provide a viable pathway of further renewable penetration.

The economic viability of the "PV +" systems depends on various parameters such as prices and sizes [3,4,13] of PV and battery (type and operation) [13,14], EV [15], degradation [5,9,10,13], tariff structure (e.g., retail and wholesale) [3,14,16], availability of FIT [13], finance [3], solar insolation [3,14], load profiles [17], system configuration (e.g., inverter) [3]. However, a comprehensive economic assessment of such integrated systems with EV for households has not been conducted enough, particularly by incorporating the rapid decline in the cost of PV and EVs to be expected in the coming decades. In this paper, we investigate the economic viability of integrating residential PV systems with/without EVs or batteries by considering the case of Japanese households towards 2030.

2. Methods

To examine the economic viability of the residential "PV only", "PV + battery", "PV + EV" systems, we generally followed the methodology developed by Hoppmann et al. [3]. As the economics of the PV + battery systems highly depend on the sizes of PV and battery, we calculated the largest net present values for given prices of PV, battery, and electricity by running the model with various PV and battery capacities, and compare the results with a reference case of no PVs, batteries, and EV [3]. We used a conversion rate of Japanese ¥110 per US\$1 throughout the paper. We used a typical discount rate of 3% applied for a PV project in Japan [18] with 25 years of project time (PV module lifetime) [3].

Residential PV and battery system costs: In Japan, the average cost of building a PV system (crystalline silicon) for residential sector (<10kW PV) was \$2.66/W at the end of FY2016 [19]. For the future projection, BNEF estimates that when the global PV market matures the cost of small scale PV would converge globally to around \$1/W by 2025 [11]. Then, the cost declines further to \$0.64/W by 2040. For our analyses, we set average PV system costs declining annually by 10% from the value of \$2.66/W in 2016 to \$1/W in 2025 [11] (Fig. 1a). Then, the cost continues to decline annually by 3% from 2025, leading to \$0.64/W at 2040. The battery system cost (lithium-ion battery) for residential sector has been high in Japan, costing \$2,009/kWh on average for FY2015 [20]. However, new entrances from oversea are expected to introduce much cheaper battery systems as low as \$609/kWh near future (e.g., Tesla Powerwall2). In our analyses, we used cost estimates of future battery system by BNEF from 2016 to

2025 (Fig. 1a) [21]. To extend the estimate to 2030 that are not available on the BNEF estimates, we extrapolated annual declining rate (4%) from 2024 to 2025 in the BNEF [21] to 2030 (Fig. 1a).

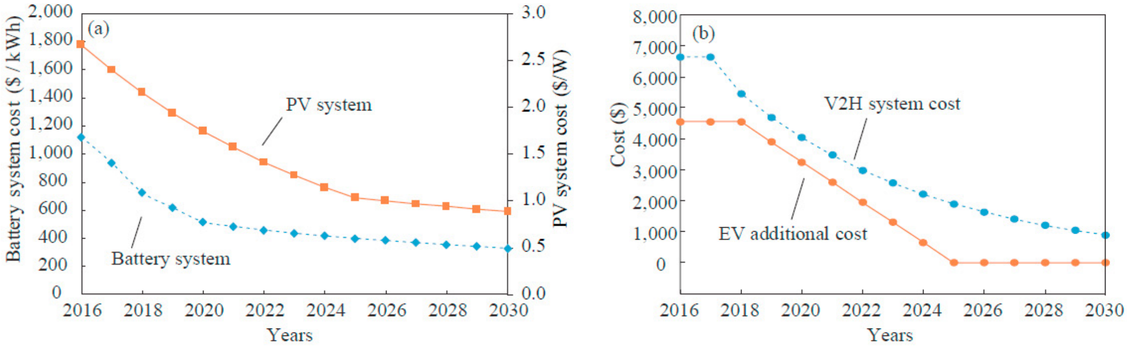

Figure 1. Cost estimates from 2016 to 2030. (a) Battery system and PV system, (b) V2H system and EV additional cost.

V2H system: We assume the Nissan LEAF 2017 as a model car for our calculation. The price of the Nissan LEAF is about $9,091 higher than similar gasoline vehicles. However, with a government subsidy, an additional cost of purchasing EV (EV additional cost; Fig. 1b) instead of a gasoline vehicle is about $4,545 in 2016-2018. BNEF estimates that EV prices will decline owing to the decreasing cost of battery, and reach a parity with gasoline vehicles around 2025 (Fig. 1b) [12]. With regard to V2H systems, for general households, a standard type of V2H system is available from Nichicon, for example, with the cost of $5,272 and installation cost of $909 to $1,818. Therefore, we set that V2H system at 2016 and 2017 to be $6,636. For the future V2H pricing, a power conditioning system for EV or battery is expected to merge into a combined power system with that of PV [22]. Thus, the V2H cost is assumed to be similar to the cost of the present home charging systems of around $909 by 2030 (Fig 1b).

Electricity tariff: Average electricity tariff in Japan for the residential sector is $0.23/kWh for the period between 2004 and 2015 ranging from $0.19/kWh to $0.29/kWh [23]. The future electricity tariff is highly uncertain although it is expected that electricity tariff will rise for the foreseeable future, owing to the increasing fuel costs, increasing surcharge for the feed-in-tariffs, and reestablishing distribution lines for the new power systems. We treat this uncertainty by calculating four different sets of the tariffs following a similar study by Hoppmann et al. [3]. We first consider two cases, a constant tariff of $0.23/kWh for 25 years and another annually 1% increase of tariff starting from $0.23/kWh in 2016 (Table 1). Then, we consider other two cases for excess PV electricity to sell to grid by $0.1/kWh (a wholesale price) or zero (Table 1).

Model: We used a publicly available model, "System Advisor Model (SAM)" developed by NREL [14]. The model has a hourly resolution of PV electricity generation, load, and storage including financial metrics (e.g., net present value), various degradation processes, and energy losses, such that the model can realistically evaluate the performance of renewable projects [14]. Calculation is conducted to maximize the net present value of projects with variables in PV and battery capacities with a range 2 kW ≤ PV ≤ 10 kW and 2 kWh ≤ battery ≤ 20 kWh in steps of 2 kW and 2 kWh, respectively. Hourly meteorological data for a year are obtained for an area near Tokyo (Hyakuri, 36.18 °N, 140.42 °E) through the SAM, and hourly PV power generation is calculated, which was used repeatedly for whole analytic periods of 25 years. Hourly load for a household is calculated by SAM taking into account temperature variation, given monthly average household electricity consumption for 3 residents in Tokyo (annual sum of 4,980 kWh) [24]. Battery is replaced when the capacity degrades to 50% of the initial capacity. Battery is dispatched to maximize the self-consumption of PV generated electricity [3], and charged only from PV. We consider that EV battery is available for V2H, except Saturday and Sunday afternoon (12 pm to 12 am). In the model, we assume that a house hold drives a vehicle annually 10,000 km, which is near the annual average driving distance (8,409 km) of passenger cars for FY2016 in Japan [25]. The electricity consumption efficiency of an EV: Nissan Leaf is ~7 km/kWh. Therefore, monthly EV consumption of 119 kWh is added to the household monthly electricity consumption for V2H scenarios. Only half (20 kWh) of the EV battery is assumed to be available for the V2H so that EV is capable for a shorter trip at any time. The degradation of the EV battery is also considered, but it is not replaced during the project as it only reduces to 73 % of the original capacity after 25 years. Gasoline retail price of \$1.09/L is used, which is a lower end in the range from \$0.93 to \$1.47 over the past 5 years in Japan. Average gasoline car's fuel economy of 14 km/L is used for the analyses [26]. CO_2 emissions from the use of gasoline and grid electricity (TEPCO: 0.486 kg-CO_2/kWh for FY2016)[27] are considered, and PV electricity is considered to be zero emission.

3. Results

We analyzed twelve scenarios with two sets of annual tariff increase of 0% (S1, 2, 5, 6, 9, 10) and 1% (S3, 4, 7, 8, 11, 12) for Japanese households (Table 1). We show only six scenarios of annual tariff 0% increase owing to the limited space of this paper. However, we note that scenarios with an increasing tariff annually by 1% slightly improve the economics of "PV + battery" or "PV + EV" more than the case of the constant tariff scenario, which is consistent with earlier studies [3]. S1 and S2 are "PV only" scenarios, S5 and S6 are "PV + battery" scenarios, and S9 and S10 are "PV + EV" scenarios, with and without excess electricity to sell to grid, respectively (Table 1).

Table 1. Twelve scenarios for the future development of energy economics at Japanese households till 2030. Note that two scenarios in one column indicate annual tariff increases by 0 or 1%.

	S1, S3	S2, S4	S5, S7	S6, S8	S9, S11	S10, S12
Combination	PV	PV	PV + battery	PV + battery	PV + EV	PV + EV
Excess electricity sell to grid (\$/kWh)	0	0.1	0	0.1	0	0.1
Annual tariff increase (%)	0, 1	0, 1	0, 1	0, 1	0, 1	0, 1

Figure 2a shows household yearly expenses (reference expense – annualized net present values) for the use of electricity and gasoline, compared with the reference scenario (S0) of constant electricity tariff of \$0.23/kWh and gasoline price (\$1.09/L). Our analyses show that the "PV only" with sell (S2), "PV + EV" with and without sell (S9, S10) in 2016 are already more economical than the reference, and by 2020 all the scenarios become more economical than the reference case. It is noteworthy that in the early years of "PV + EV" scenarios of S9 or S10 are not much different from "EV charge only" (no V2H) from grid (Fig. 2a). This is because changing to an EV from a gasoline car reduces household expenses by price difference between gasoline and electricity, but additional costs of V2H and EV in the early years largely cancel the fuel benefits.

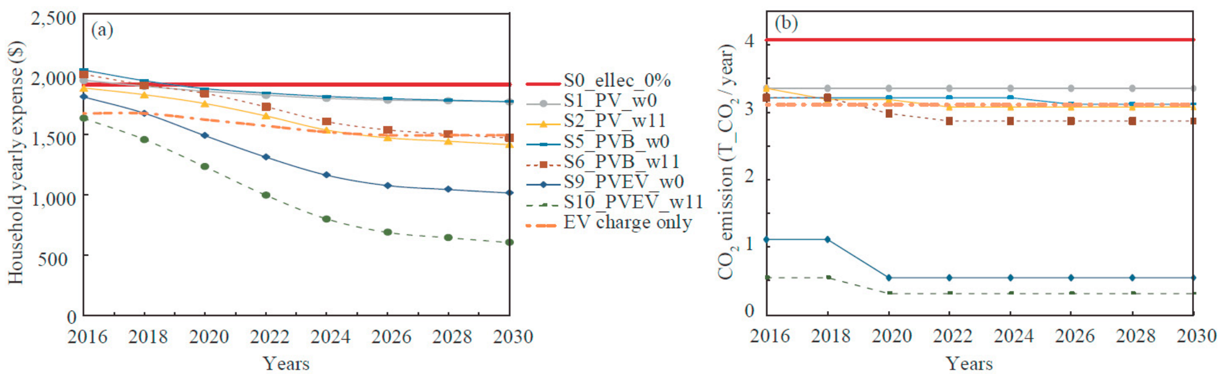

Figure 2. (a) Household yearly expenses and (b) CO_2 emission from the use of vehicles and electricity.

Declining costs of PV, battery, EV, and V2H substantially improve the energy economy at households, especially, for the next 10 years (Fig. 2a). The most economical scenario is the "PV + EV" with excess electricity to be sold with \$0.1/kWh (S10). The maximum net present value is obtained with the PV capacity of 10 kWh in 2030, which is the maximum possible value. The reduction in energy expense is estimated to be 68% from the reference scenario in

2030 (Fig. 2a). The 90% of energy demand from the electricity and car use can be supplied from own PV, and CO_2 emission is reduced by 92% from the reference in 2030 (Fig. 2b). Without the excess-electricity being sold (S9), the PV capacity with the maximum net present value becomes 6 kWh in 2030 (Table 2). The cost, however, still is reduced by 47% compared with the reference, and CO_2 emission can be reduced by 87% (Fig. 2a). "PV only" (S1 and S2) or "PV + battery" (S5 and S6) systems provide smaller economic benefits, compared with "PV + EV" as car fuel expenses cannot be eliminated in these scenarios, but we note that "PV only" with the $0.1/kWh sale of electricity is already economical in 2016 as the upfront cost is minimum (Fig. 2a). Economic assessment of "PV only" or "PV + battery" is heavily dependent on whether the extra electricity can be sold to the grid (Fig. 2a). Additionally, because the electricity tariff is set to $0.23/kWh, we found that "PV + battery" does not find large economic benefits even in 2030, relative to "PV only" owing to the high upfront cost of the battery (Table 3, Fig. 2a). Other studies indicate that "PV + battery" with higher tariff become more economical in earlier timings than that of our study [3]. The CO_2 reductions in S1, 2, 5, 6 are also limited as the CO_2 emission from vehicles cannot be reduced (Fig. 2b).

Table 2. PV capacities (kW) required for maximizing net present values. Ranges are defined from 2 kW to 10 kW.

	Sell ($/kWh)	2016	2018	2020	2022	2024	2026	2028	2030
S1	0	2	2	2	2	2	2	2	2
S2	0.1	2	4	4	10	10	10	10	10
S5	0	2	2	2	2	2	2	2	2
S6	0.1	2	2	4	10	10	10	10	10
S9	0	4	4	6	6	6	6	6	6
S10	0.1	6	6	10	10	10	10	10	10

Table 3. Battery capacities (kWh) required for maximizing net present values. Ranges are defined from 2 kWh to 20 kWh.

	Sell ($/kWh)	2016	2018	2020	2022	2024	2026	2028	2030
S5	0	2	2	2	2	2	4	4	4
S6	0.1	2	2	2	2	2	2	2	2

4. Discussions

Although all the scenarios become economical by 2022 in comparison to the reference, the PV + battery system is not much economical than the PV only system even in 2030 (Fig. 2a). Earlier studies with higher tariff and/or lead acid battery indicated that a battery system is economically viable with a PV in earlier timing [3,4], which indicates that the result could vary regionally. On the other hand, the PV + EV system (V2H) is highly effective means to cut the energy expenses and CO_2 emission, increasingly so toward 2030. The PV + EV system is highly economical, because a large battery in EV is available with a minimum additional cost except at the time of being used as a vehicle. The economic advantage of V2H is likely less reginal specific, but needs further studies to confirm it in different regional contexts. Optimum PV capacity is highly dependent on whether excess electricity can be sold, to such an extent that all the scenarios with the sale of electricity reach the maximum PV capacity of 10 kWh by 2022 (Table 2). Higher PV capacity is critical to increase self-sufficiency and CO_2 emission reduction. Therefore, it is recommended that policy supports for the excess electricity be established to provide certain remuneration (e.g., wholesale price). As this study indicated, the highly economic and relatively simple PV + EV system may expand very rapidly in coming years with a possibility of drastic reduction in demand for power companies. In that case, electricity pricing structures, business models, and the regulatory environment need to be restructured from the perspective of lowering the cost of the entire power system [4,28].

5. Conclusions

EV is now rapidly increasing its number worldwide. At the same time, the price of PV, battery, EV, and V2H systems will drop further toward 2030. We found that the PV + EV system would dramatically reduce energy expenses (electricity and gasoline) of Japanese households by 68% by 2030, reducing as much as 92% of CO_2

emissions from the electricity and vehicle uses. At present, EV and PV penetration policies are performed separately. However, governments should pursue a combined PV + EV penetration policy that is economically, environmentally, highly effective. Future studies should consider a variety of EV use pattern, heat uses, and economic optimizations beyond a household such as in a district.

References

[1] METI. FIT surchage for FY2018 in Japan 2017. http://www.meti.go.jp/press/2016/03/20170314005/20170314005.html (accessed April 10, 2018).

[2] BNEF. 1H 2018 solar LCOE update. 2018.

[3] Hoppmann J, Volland J, Schmidt TS, Hoffmann VH. The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model. Renew Sustain Energy Rev 2014;39:1101–18.

[4] Yu HJJ. A prospective economic assessment of residential PV self-consumption with batteries and its systemic effects: The French case in 2030. Energy Policy 2018;113:673–87.

[5] Uddin K, Gough R, Radcliffe J, Marco J, Jennings P. Techno-economic analysis of the viability of residential photovoltaic systems using lithium-ion batteries for energy storage in the United Kingdom. Appl Energy 2017;206:12–21. doi:10.1016/j.apenergy.2017.08.170.

[6] Abdin GC, Noussan M. Electricity storage compared to net metering in residential PV applications. J Clean Prod 2018;176:175–86.

[7] MLIT. people's movement in cities. 2012.

[8] Nissan North America. Smart charging and V2X 2014:17. http://www.energy.ca.gov/research/epic/documents/2014-06-30_workshop/presentations/Nissan_North_America-Smart_Charging_and_V2X.pdf (accessed May 2, 2018).

[9] Uddin K, Jackson T, Widanage WD, Chouchelamane G, Jennings PA, Marco J. On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system. Energy 2017;133:710–22. doi:10.1016/J.ENERGY.2017.04.116.

[10] Uddin K, Dubarry M, Glick MB. The viability of vehicle-to-grid operations from a battery technology and policy perspective. Energy Policy 2018;113:342–7.

[11] BNEF. New Energy Outlook 2016: Long-term projections of the global energy sector (Executive Summary). New Energy Outlook 2016. doi:10.1017/CBO9781107415324.004.

[12] BNEF. Long-term electric vehicle outlook 2017. 2017.

[13] Hesse HC, Martins R, Musilek P, Naumann M, Truong CN, Jossen A. Economic optimization of component sizing for residential battery storage systems. Energies 2017;10. doi:10.3390/en10070835.

[14] DiOrio N, Dobos A, Janzou S. Economic analysis case studies of battery energy storage with SAM. 2015.

[15] Coffman M, Bernstein P, Wee S. Integrating electric vehicles and residential solar PV. Transp Policy 2017;53:30–8.

[16] Parra D, Patel MP. Effect of tariffs on the performance and economic benefits of PV-coupled battery systems. Appl Energy 2016;164:175–87.

[17] Stenzel P, Linssen J, Fleer J. Impact of different load profiles on cost optimal system designs for battery supported PV systems. Energy Procedia 2015;75:1862–8.

[18] Mitsubishi Research Institute (MRI). Basic investigation on new energy promotion on FY28. 2017.

[19] RTS Cooperation (RTS). Chapter 2, Latest information on solar power. Sol Power Inf Sept Issue 2017;27:141.

[20] Mitsubishi Research Institute (MRI). Investigation to increase battery penetration and aggregation services. 2017:167. http://www.meti.go.jp/meti_lib/report/H28FY/000479.pdf (accessed April 11, 2018).

[21] BNEF. 2017 global energy storage forecast. 2017.

[22] BNEF. Cost reductions and residential energy drivers. 2016.

[23] Institute of Energy Economics J. Energy economy statistical review 2017. 2017.

[24] Fukuyo Lab. Residential monthly energy consumption data for more than 2 residents in cities (averages from 2000 to 2004) 2018. http://ds0.cc.yamaguchi-u.ac.jp/~fukuyo/edb001.html (accessed April 18, 2018).

[25] MLIT. Transport related statistics 2018. http://www.mlit.go.jp/k-toukei/index.html (accessed July 4, 2018).

[26] Iwata K, Managi S. Influence of autonomous vehicles on driving distance: Empirical analyses using household finance survey. RIETI Discuss Pap Ser 2018;18-J-005:1–22.

[27] TEPCO. FY2016 TEPCO environmental indicies 2017:2. http://www.tepco.co.jp/about/csr/pdf/csr2016_01.pdf (accessed May 7, 2018).

[28] Rockly Mountain Institute. The economics of load defection. 2015.