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T Kobashi¹ , P Jittrapirom^{1,2}, T Yoshida¹ , Y Hirano³ and Y Yamagata¹¹ Center for Global Environmental Research, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan² Nijmegen School of Management, Radboud University, Heyendaalseweg 141, Nijmegen, Gelderland 6525 AJ, the Netherlands³ Fukushima Branch, National Institute for Environmental Studies, 10-2 Fukasaku, Miharu, Tamura District, Fukushima 963-7700, JapanE-mail: kobashi.takuro@nies.go.jp**Keywords:** photovoltaics, electric vehicles, urban decarbonization, renewable energy, decentralized power systemsSupplementary material for this article is available [online](#)**Abstract**

Cities have become the focus of global climate mitigation efforts because as they are responsible for 60%–70% of energy-related CO₂ emissions. As the world is increasingly urbanized, it is crucial to identify cost-effective pathways to decarbonize and enhance the resilience of cities, which ensure the well-being of their dwellers. Here, we propose a ‘SolarEV City’ concept, in which integrated systems of cities’ roof-top photovoltaics and electric vehicles (EVs) supply affordable and dispatchable CO₂-free electricity to urban dwellers. Our analyses indicate that implementations of the concept can meet 53%–95% of electricity demands in nine major Japanese urban areas by 2030. CO₂ emission from vehicle use and electricity generation in these areas can be reduced by 54%–95% with potential cost savings of 26%–41%. High cost-effectiveness and seasonally stable insolation in low latitudes may imply that the concept may be more effective to decarbonize urban environments in emerging economies in low latitudes. Among several factors, governmental interventions will play a crucial role in realizing such systems, particularly in legislating regulations that enhance penetration of the integrated system of PV and EV and enable formation of decentralized power systems. As bottom-up processes are critical, policy makers, communities, industries, and researchers should work together to build such systems overcoming social and regulatory barriers.

1. Introduction

The global energy sector is undergoing a significant transformation (Gielen *et al* 2019, Cozzi *et al* 2020), driven by phenomena such as peak oil, the rise in gas production, geopolitical tensions, the phasing out of nuclear energy, the plummeting costs of renewable energy technologies (IRENA 2019, Yan *et al* 2019), and the COVID-19 outbreak (Le Quéré *et al* 2020). In parallel, the transport sector is also undergoing significant transition (Nikitas *et al* 2017). The quartet of ‘connectivity’, ‘autonomous’, ‘sharing’, and ‘electrification’ is altering the landscape of mobility services, changing the definitions of mobility and how these services are offered to travelers (Jittrapirom *et al* 2017, Möller *et al* 2019). These so-called ‘disruptions’ have pervasive implications in the energy and environmental aspects (Sprei 2018). Among

these, electrification has the foremost potential in contributing to urban decarbonization (Williams *et al* 2012, Mccollum *et al* 2014). As a majority of transport activities are still fossil fuel-powered contributing to a large proportion of global CO₂ emissions (Friedlingstein *et al* 2019), shifting the sector’s power source to electric is an apparent and cost-effective means to reduce its CO₂ emissions (Needell *et al* 2016).

However, depending on electricity generation, CO₂ emission reductions from electric vehicles (EVs) are limited. In coupling with photovoltaics (PV), EV can be charged by CO₂-free electricity from PV (Kobashi *et al* 2020c), but also using EV as energy storage, affordable CO₂-free PV electricity becomes dispatchable for wide-spread uses within cities and beyond toward full-electrification (Kobashi *et al* 2020a, Kobashi *et al* 2020c).

Urban environments draw particular attention as 60%–70% of greenhouse gasses are emitted from cities (United Nations Human Settlements Programme 2011). Many co-benefits exist on urban decarbonization, such as air pollution, noises, cost-saving, and job creation (Kammen and Sunter 2016, Jacobson *et al* 2018). Previously, urban decarbonization concepts such as ‘Solar City’ with rooftop PV have been proposed (Byrne *et al* 2015, Hosseini 2019). However, the effectiveness of PV to reduce emissions is limited by the large variability of PV electricity without batteries (IRENA 2019). As stand-alone battery remains expensive, many studies investigated the use of EVs as batteries for grid services or virtual power plant through vehicle-to-grid (V2G) (Kester *et al* 2018, Pearre and Ribberink 2019). Recently, Kobashi *et al* conducted an analysis for Kyoto City, in which rooftop PV systems are combined with EVs as storage (Kobashi *et al* 2020c). The PV + EV system is capable of supplying ~70% of electricity with hourly demand-supply matching (Kobashi *et al* 2020c). The city-scale PV + EV system also has the potentials to enhance the resilience of urban energy supply systems at the time of disaster (Yamagata *et al* 2016, Kobashi *et al* 2020c). As the cost-effectiveness of the two components significantly increases by coupling, the diffusion of these sustainable urban solutions can also be accelerated.

In this study, we hypothetically applied the concept to address the variability of urban systems in eight Japanese cities, namely, Niigata, Okayama, Koriyama, Sendai, Hiroshima, Kyoto, Sapporo, and Kawasaki in addition to special wards of Tokyo (figure 1). These cases were chosen for their variations in socio-demographic characteristics such as population, density, rate of motorization, the availability of their annual power demand data (table 1 and figure S1 (available online at stacks.iop.org/ERL/16/024042/mmedia)). In the next section (section 2), we introduce the basic statistics of these cities and our methodology and assumptions. In section 3, we explain the results with economic and environmental indices. We discuss further the implications of our findings and limitations in section 4 and conclude the study in section 5.

2. Data and methods

2.1. Eight cities and special districts of Tokyo in Japan

The descriptive statistics of our nine case studies are presented in table 1. There are apparent differences in the urban structures of these major Japanese urban agglomerations. Although these municipalities are major urban areas in Japan, the urban structures are profoundly different. In this set, the special wards of Tokyo have the largest population, 9.4 million, and the highest population density (16 100 people km⁻²). It is characterized by tall

buildings and well-developed public transport systems. In contrast, Koriyama City in Fukushima prefecture has a population of 0.33 million with a much lower population density (4800 people km⁻²), a larger city area, and a higher number of private vehicles per capita.

Highly urbanized areas such as Tokyo also have a relatively small rooftop area per capita (RAPC) than others. On the other hand, rural cities (e.g. Koriyama, Niigata, and Okayama) have a larger rooftop area and a higher number of vehicles per capita, which are important factors for economic and CO₂ emission reduction potentials of ‘PV + EV’ systems. There is a significant correlation ($r = 0.95$; $p < 0.01$) between the RAPC and the number of vehicles per capita (figure 2). Sapporo and Niigata have high snowfalls during winter, thus have lower PV capacity factors with average CO₂ emissions per capita of 7.3 ton yr⁻¹. Certain cities, such as Kawasaki, have a higher CO₂ emission per capita than others due to their active industrial activities. The average CO₂ emission per capita is 7.3 ± 4.8 ton yr⁻¹ for these cities. CO₂ emissions per capita are strongly linked with CO₂ emissions of the industry sector in these cities ($r = 0.94$; $p < 0.01$).

2.2. Technoeconomic analysis

An evaluation of any renewable energy projects should take into account variability of generated electricity, costs of technologies, PV and battery capacities, demand variability, tariff structures including feed-in-tariff (FiT), local insolation, temperature, combinations of technologies, project period, discount rate, maintenance cost, degradation, electricity losses, and management of systems (Short *et al* 1995, Hoppmann *et al* 2014). For EVs to be part of the system, EV battery capacity, EV usage pattern, energy costs, EV additional costs relative to internal combustion engine vehicles (ICEs), and V2G system costs need to be considered (Kobashi *et al* 2020a) (table S1). A techno-economic analysis integrates these parameters and assesses if proposed projects are economically viable by comparing the above factors with the costs of existing energy systems (e.g. the use of grid electricity and ICEs) (Hoppmann *et al* 2014, Kobashi *et al* 2020c).

We conducted the techno-economic analysis to examine the feasibility of the SolarEV City concept in the cities under three main scenarios in an hourly time scale. We consider only private passenger vehicles in cities for the analysis. The first scenario is the implementation of ‘PV-only’ with 2018 pricing, and the second scenario is the implementation of ‘PV-only’ but with the projected pricing in 2030. In the third and final scenario, the ‘PV + EV’ implementation with the projected pricing in 2030 is analyzed. This last scenario assumes that all passenger vehicles in the cities are converted to EVs, and half of the battery capacities are utilized as electricity storage for PV

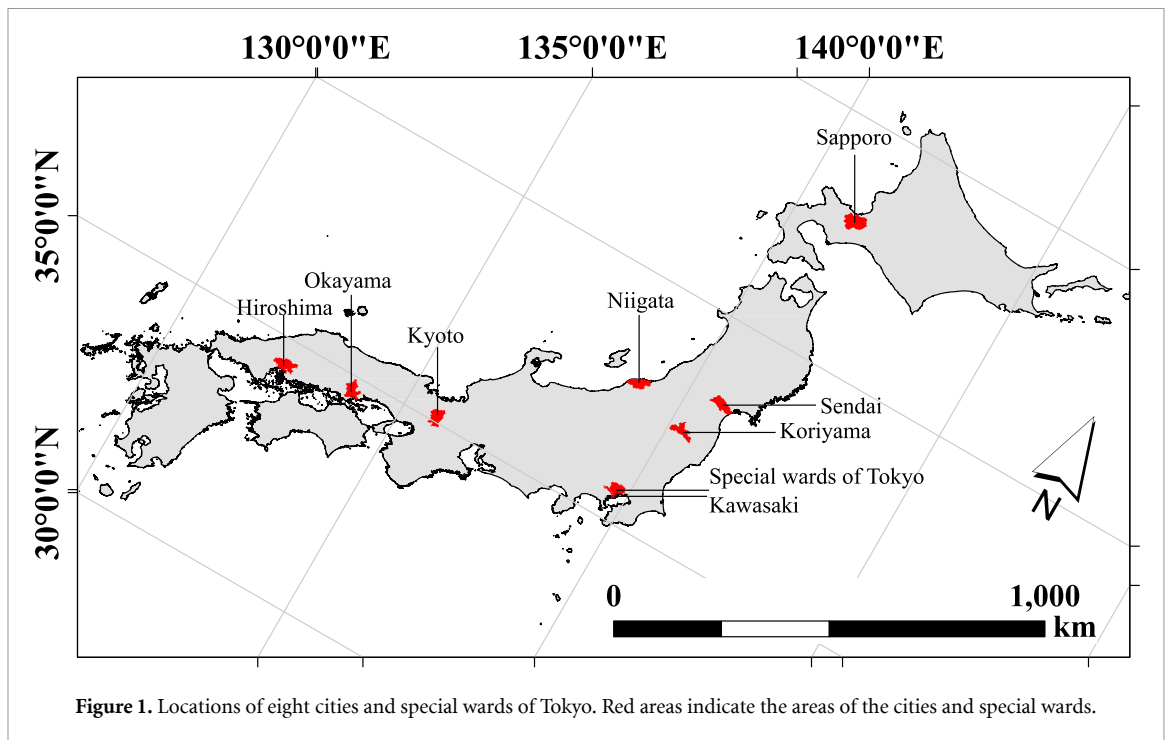


Figure 1. Locations of eight cities and special wards of Tokyo. Red areas indicate the areas of the cities and special wards.

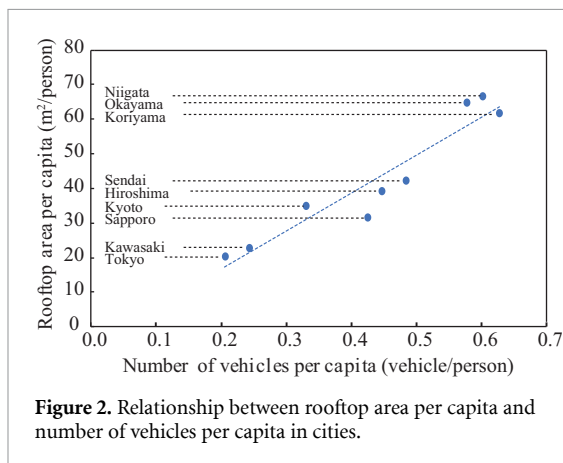


Figure 2. Relationship between rooftop area per capita and number of vehicles per capita in cities.

(appendix A). Additional costs of EVs to the cost of ICEs are considered in the analysis as people purchase EVs at the time of replacement of ICEs (appendix A). Economically optimal PV capacities are identified by parametric analysis with the maximum capacities defined by the available rooftop spaces (Blair *et al* 2018). We did not examine the ‘PV + battery’ system here as our earlier studies concluded that stand-alone batteries barely add any economic value to PV systems even in 2030, due to the high battery prices in Japan (Kobashi *et al* 2020c). A project period of 25 years and a discount rate of 3% were applied to the calculation, which are commonly used assumptions for PV projects in Japan (Kobashi *et al* 2020a).

Constant electricity tariff (0.18 \$ kWh⁻¹), a mixture of high and low voltage prices, is assumed for the analyses over the project period (appendix A) and examined two variations of FiTs: with minimum FiT near wholesale prices of 0.08 \$ kWh⁻¹ and without FiT cases (appendix A). As the daily vehicle operation

rate in urban areas of Japan is minimal (out of home duration is about 30 min per day on average) (MLIT 2015, Kobashi *et al* 2020c), for the rest of the time EVs are available as storage for PV electricity. Therefore, we consider that EV charging happens at home. For the ‘PV + EV’ scenarios, we assumed all the vehicles (ICEs) are replaced by EVs in cities in the 2030 scenario. Although it is not likely that all the ICEs are converted to EVs in Japan by 2030, we analyze the potentials of the SolarEV City (‘PV + EV’ systems) using the cost estimates for 2030 such that the real economic potential of the system after 2030 is likely larger than our estimates.

We calculated the rooftop areas in eight cities and the special wards of Tokyo using the official building footprint data (table 1) (Geospatial Information Authority of Japan 2018). We assumed 70% of the rooftop areas in the cities to be available for PV installation, but did not consider parking lots or roadway spaces as potential locations for PV installation, making our estimations conservative. The aggregated PV capacities for cities are estimated, based on assumed PV panel efficiency of 20% (table 1). In comparison, Google’s estimations for the available rooftop area ratios for PV installation in six cities in Japan reported that 71% of the total rooftop area in Kyoto City, 77% in Matsuyama City, 71% in Odawara City, 71% in Yokohama City, 56% in Shinagawa Ward, Tokyo, and 62% in Saitama City are available for PV installation. The estimation considered shades from neighboring buildings and rooftop segment sizes, etc using a 3D model derived from areal imagery (Google 2020).

Our assumption is consistent with Google’s and indicate that densely populated areas with many tall buildings such as Shibuya have smaller usable rooftop

Table 1. Statistics of eight cities and special wards of Tokyo in Japan. Latitudes and longitudes are for the locations of municipal buildings and are used as a location for local weather data for each city. Urbanization control areas are designated areas for urbanization by governments excluding forests. Population density was calculated using the urbanization control areas. Passenger vehicles include general, small, and light (Ket) private passenger cars. CO₂ emissions from industry (%) are the percentages among four sectors (households, commercial, transport, industry). Urbanization control areas were obtained from (MLIT 2014). Population, number of vehicles, and CO₂ emissions from cities are available from municipal government homepages. The rooftop area for each city was calculated using geospatial data (Geospatial Information Authority of Japan 2018). PV capacity factors are observed average values for prefectures where the cities are located (Information for solar power 2019). The data are mostly for 2018. When data for 2018 were not available, the latest data were utilized. Annual average temperatures are from the weather files used for SAM, which are originally from MERRA-2 (Gelaro *et al* 2017).

Prefecture City	Okayama Okayama	Hiroshima Hiroshima	Kanagawa Kawasaki	Miyagi Sendai	Niigata Niigata	Hokkaido Sapporo	Fukushima Koriyama	Kyoto Kyoto	Tokyo Special wards
Population (millions)	0.71	1.2	1.52	1.09	0.79	1.97	0.33	1.47	9.4
Latitude	34.7° N	34.4° N	35.5° N	38.3° N	37.9° N	43.0° N	37.4° N, 1	35.0° N	35.7° N
Longitude	133.9° W	132.5° W	139.7° W	140.9° W	139.0° W	141.4° W	40.4° W	135.8° W	139.7° W
Urbanization control area (km ²)	104	160	127	180	129	250	69	150	585
Population density (thousands km ⁻²)	6.8	7.5	11.9	6	6.1	7.9	4.8	9.8	16.1
Passenger vehicles (thousands)	409	534	369	526	476	834	209	485	1928
Vehicles per capita	0.58	0.45	0.24	0.48	0.6	0.42	0.63	0.33	0.21
Rooftop area (km ²)	46	47	35	46	53	62	21	52	194
Rooftop area Per capita (m ²)	65	40	23	43	67	32	62	35	21
PV capacity factor	14.6	13.7	14.5	12.6	12.4	12.2	14.1	13.4	14.4
CO ₂ emissions Per capita (ton)	8.2	6.3	12.1	7.6	8.1	6	8.2	4.3	4.5
CO ₂ emissions from industry (%)	37	21	75	33	25	5	32	13	6
Annual average temperatures (°C)	15.1	14.5	15.8	12	13.9	6.8	11.4	14.4	17

areas for PV. However, if we include the façade of buildings for PV installation, the areas with tall buildings have higher PV potentials than the areas with lower buildings (Zhu *et al* 2020). Although at present the costs of installing PV on the façade of a building are too high for wide-spread applications, they could become more affordable in the mid to long term. Considering these points and future technological advances such as higher efficiency of PV, we believe that usage of 70% of the usable rooftop areas in major cities in Japan can be justified for the long-term application. We believe that urban buildings would need to utilize physically maximum roof-top areas for PV to establish sustainable urban systems.

We used Nissan Leaf (40 kWh) as a model EV for the analysis as it is the bestselling EV in Japan. The price of a Nissan Leaf (40 kWh) is ranged between \$30 000 and \$38 000 in Japan (January 2020). A similar model of an ICE, such as the Nissan Sylphy, is priced between \$18 500 and \$25 000. We assumed here that government subsidies approximately 50% of the difference (Kobashi *et al* 2020a). It is also assumed that the difference will be negligible by 2025, and for the price of EVs to be 10% cheaper than the similar models of ICE vehicles by 2030 (BNEF 2018). The unit cost of the V2H system is \$5500 in 2018, and reduce to \$2900 in 2030 (Kobashi *et al* 2020c). Therefore, the additional costs of EV including the V2H system are estimated to be \$10 000/vehicle (or 250 \$ kWh⁻¹) in 2018 and 900 \$/vehicle (or 22 \$ kWh⁻¹) in 2030 (Kobashi *et al* 2020c). The 'PV + EV' system in 2018 have negative cost-saving owing to high prices of PV and EV (not shown). It is noted that we did not consider the difference in maintenance and operating costs between ICEs and EVs and also the potential benefits of using EV for ancillary services for the grid. Inclusions of these factors could further enhance the financial benefits of implementing the SolarEV City concept.

We compared the cities across various scales using RAPC and evaluated the impact of the system using five indices: (a) energy sufficiency, (b) self-sufficiency, (c) self-consumption, (d) cost-saving, and (e) CO₂ emission reduction (appendix A, figures 3 and 4). We define 'Energy sufficiency' as to how electricity production of PV in the cities compares to demand in terms of annual energy (figures 3(a) and 4(a)). As PV generation and demands are variable, a higher 'energy sufficiency' does not immediately indicate that the generated PV electricity can be used for the city's demands. Instead, 'Self-sufficiency' indicates how much electricity demand of the cities can be supplied by locally generated PV electricity (figures 3(b) and 4(b)). This also directly relates to CO₂ emission reduction from grid electricity. Also, a higher 'self-sufficiency' means that the system can supply energy to the cities at the time of blackout or disaster for a longer period. 'Self-consumption'

indicates how much electricity generated by PV is consumed within the cities (figures 3(c) and 4(c)). A higher (lower) 'self-consumption' indicates that less (more) grid infrastructure is required to bring in/out electricity to/from the cities associated with PV generation often leading to less (more) curtailments.

'Cost-saving' indicates how much energy costs can be saved by the installation of technologies (i.e. 'PV only' or 'PV + EV' systems) over the project period of 25 years. We also considered capital and maintenance costs, in comparison to the cost of existing systems (grid electricity and gasoline vehicles) (figures 3(d) and 4(d)) (Kobashi *et al* 2020c). 'CO₂ emission reduction' indicates associated changes in CO₂ emissions in each case (figures 3(e) and 4(e)). The interdependencies between these factors are highly complexed, for example, 'PV capacity per capita' is an important index for urban decarbonization as it increases when the cost of PV reduces or with FiT, and indicates the optimization point for NPV. However, a higher PV capacity does not translate to higher self-sufficiency or CO₂ reduction owing to the variable PV generation. However, with more energy storage, higher PV penetration can lead to higher CO₂ reduction.

3. Results: enhanced cost-saving and CO₂ emissions reduction by 'PV + EV'

Our analyses indicate the energy sufficiency of rooftop PV systems in our case studies is confined to a limited range of around 30% in 2018 (figures 3(a) and 4(a)). The relatively higher price of renewable energy technologies in 2018 keeps the optimum PV capacities low (figures 3(f) and 4(f)). In 2030, with FiT, the optimum PV capacities grow to the maximum with energy sufficiency reaching up to 200% for larger RAPC cities, indicating a future possibility that aging rural cities with diminishing population can obtain additional resources by selling electricity to industrial or metropolitan areas (figure 3(a)). 'PV + EV' depicts slightly lower energy sufficiency owing to energy losses in the battery (figure 3(a)). Without FiT, energy sufficiency increases 15% for 'PV only', and 50% for 'PV + EV' in 2030 from 2018 (figure 4(a)), which is much smaller than that with FiT (figure 3(a)).

The 'PV only' system has limited self-sufficiency of about 25% in 2018 (figures 3(b) and 4(b)). With lower costs in 2030, the PV capacities increase, resulting in a higher level of self-sufficiency for the cases. However, the increases in the levels of self-sufficiency are limited by the lack of electricity storage as a large proportion of the generated electricity is exported to the grid for the 'PV only' system. The availability of EVs as energy storage in the 'PV + EV' scenario substantially increases the level of self-sufficiency, particularly for cities with higher RAPC values (up to 83% without FiT and 95% with FiT; figures 3(b) and 4(b);

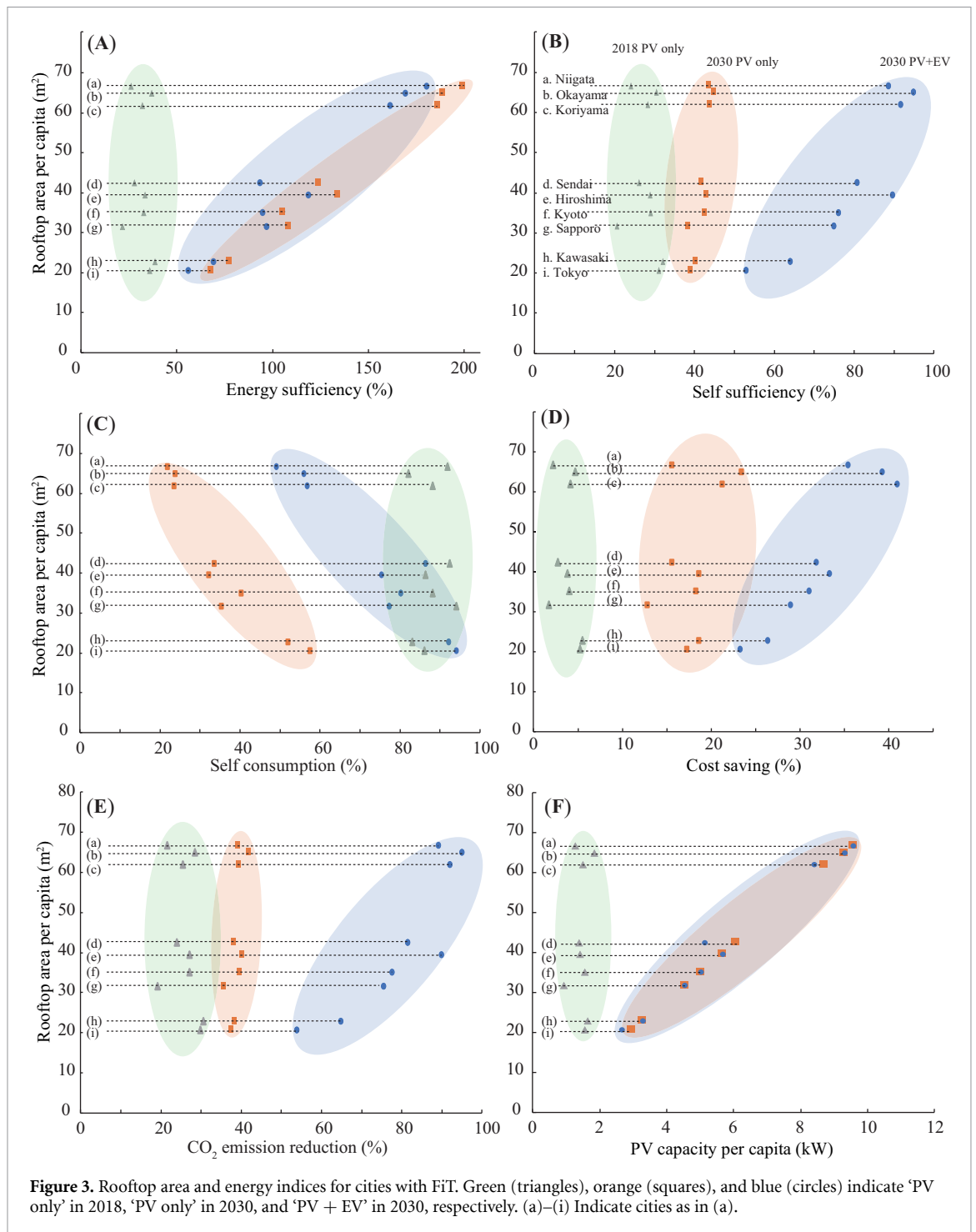
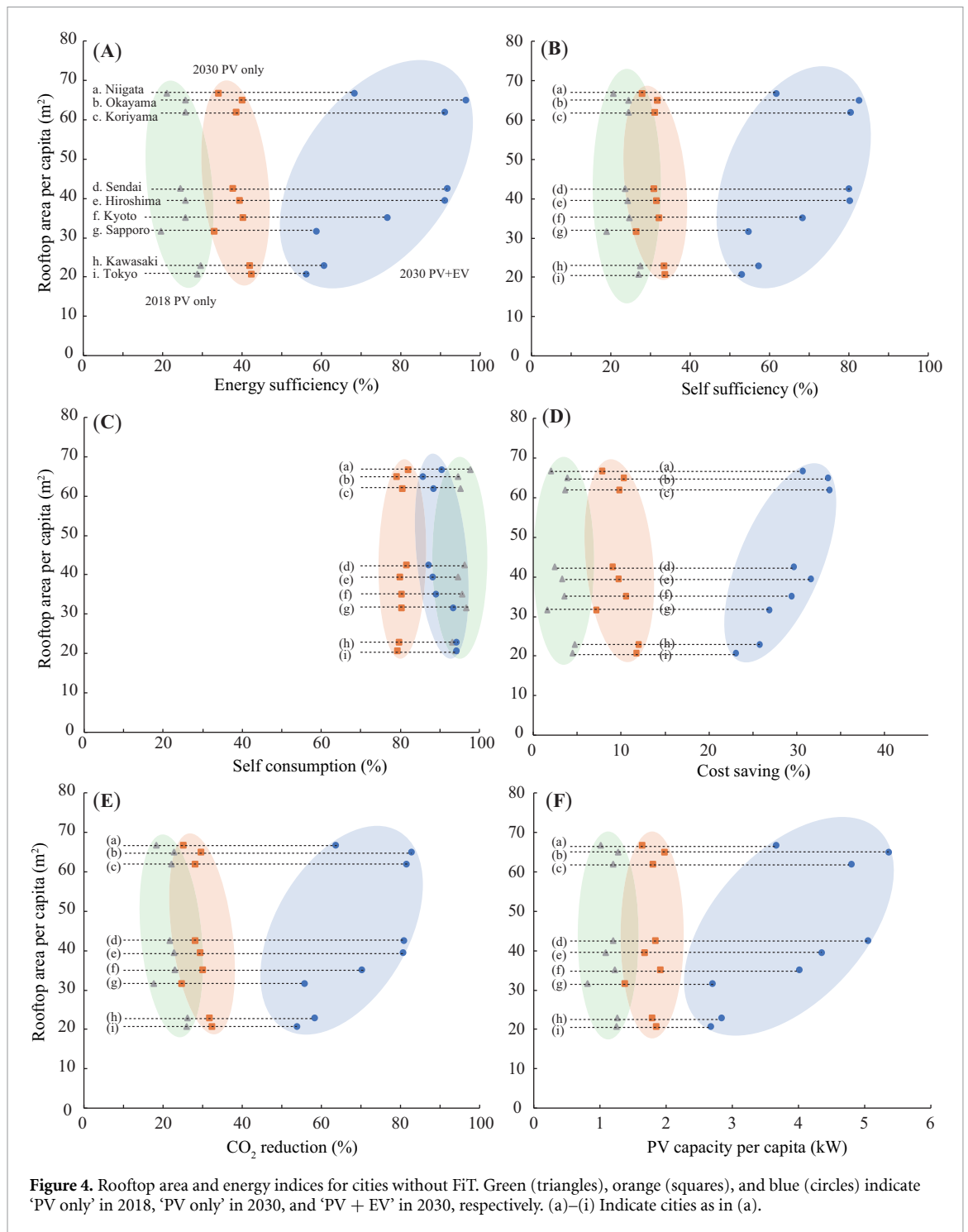


table S2). Higher self-sufficiency is vital for urban resilience as electricity can be supplied during black-outs/disasters for a longer period by the system.

In the 2018 scenario, most of the generated electricity (82%–98%) is consumed in the cities as their PV capacity is limited (figures 3(c) and 4(c)). In 2030, a lower cost of PV systems leads to the maximum extent of PV capacity with FiTs which produce ample electricity to be exported outside of the cities (figure 3(c)). The ‘PV only’ system has a self-consumption as low as 22% in large RAPC cities (figure 3(c)). The availability of EV

battery significantly increases the self-consumption with an additional 40% up from the ‘PV only’ system in 2030. A higher self-consumption is essential as low self-consumption (i.e. high export) may induce large curtailments owing to limited grid capacity.

The cost-savings of the ‘PV only’ system in 2018 are already positive for the case studies, indicating that the rooftop PV system has already reached grid parity by 2018 (figures 3(d) and 4(d)). In 2030, the cost-saving of ‘PV only’ systems increase by an additional 10% from the 2018 case, although a larger



RAPC plays a minute role in increasing profitability (figures 3(d) and 4(d)). On the other hand, the cost-saving of 'PV + EV' reaches 30% on average (figures 3(d) and 4(d)). Cities with a larger RAPC have larger cost-savings up to 41% with FiTs (figure 3(d)).

The reductions in CO₂ emission of the cases occur when the consumption of grid electricity or gasoline is replaced with PV electricity. Therefore, it shows a similar trend with self-sufficiency (figures 3(b), 3(e), 4(b), and 4(e)). In the 2018 case, the CO₂ emission reduction is about 25%, and it

increases to about 30%–40% in 2030 for 'PV only'. For the 'PV + EV' case, the CO₂ emission reduction reaches 70% and 80% on average without and with FiTs, respectively. Notably, cities with a higher RAPC have a high CO₂ emission reduction of up to 95% (figures 3(e) and 4(e)).

These analyses indicate that by combining rooftop PV with EVs, all the indices significantly improve compared with the 'PV only' system. This becomes even clearer when 'PV + EV' is compared with 'PV & EV' which means PV and EV are separately introduced into the city (EV charging only) (table 2).

Table 2. Comparisons ‘PV + EV’ with ‘PV & EV’ (not combined) and ‘PV only’ for Kyoto in 2030. ‘PV & EV’ means PV and EV are separately introduced into the city.

Kyoto in 2030	With FiT			Without FiT		
	PV + EV	PV & EV	PV only	PV + EV	PV & EV	PV only
PV capacity (kWh/per capita)	5	5	5	4	2	2
Self-consumption (%)	80	41	40	89	80	80
Self-sufficiency (%)	76	43	43	68	33	32
Energy sufficiency (%)	95	104	106	77	41	40
Cost saving (%)	31	24	18	29	17	11
CO ₂ emission reduction (%)	78	46	40	70	37	30

Indices for ‘PV & EV’ are generally similar to ‘PV only’ with cost saving and CO₂ emission reduction slightly higher than those of ‘PV only’ (table 2). CO₂ emission reduction of ‘PV + EV’ is nearly double and cost savings increase by 22% to 43%, compared with ‘PV & EV’ (table 2).

Therefore, the effectiveness of the rooftop PV system in these cities can be highly enhanced in terms of its economics as well as the CO₂ emission reduction by using EV as storage. However, realizing such a system faces numerous hurdles, such as regulation, user acceptance, implementation resistance, and also behavior changes. Several of these challenges can be overcome with active involvements of stakeholders in implementation and should be considered in the subsequent studies (Kobashi *et al* 2020c).

4. Discussion

4.1. Implementation challenges for SolarEV City toward net-zero CO₂ emitting cities

Grid infrastructure can be an important constraint for the development of the SolarEV City, if large capacity of PVs and number of EVs are employed without proper managements (Verzijlbergh *et al* 2012, Marra *et al* 2014). As the SolarEV City aims to increase self-consumption of the PV system by coupling with EV batteries, the grid constraints are generally minimized in the local and inter-regional scales with high PV penetration. However, smart EV charging/discharging will be critical to minimize grid investments (Tang *et al* 2019). Aggregation of EV charging/discharging also could play roles in contributing as a virtual power plant (Abbasi *et al* 2019) or provide ancillary services to grids (Deforest *et al* 2018), which may provide additional benefits to EV owners (Bishop *et al* 2016, Uttamrao *et al* 2020).

As the ‘PV + EV’ system cannot provide electricity to all the demands of the cities partly owing to seasonal variability of insolation, it would be necessary to receive deficient electricity from markets. Depending on how electricity in the markets is generated, gas power plant may need to play roles as

flexible generation before, for example, hydrogen systems with storage sufficiently develop to fill the gaps (Staffell *et al* 2019). In addition, coupling with locally available other renewables such as wind, biofuels, and small hydro is critical toward net-zero emission cities (Lund *et al* 2015, Arabzadeh *et al* 2020). Consideration of regional electricity exchanges with various renewable resources toward net-zero emissions require more extensive modeling works, which we leave for future investigations.

In this study, we considered CO₂ emissions from gasoline/diesel combustion and power generation. However, various other processes such as producing/disposing battery, PV panels, ICE, and EV emit CO₂ (Hawkins *et al* 2013, Ludin *et al* 2018). Although EVs are less CO₂ emitting in its life cycle than ICEs with cleaner electricity (Hawkins *et al* 2013), it is necessary that all the processes of producing/disposing PV panels and EVs to be zero emission towards global net-zero emissions.

4.2. Developing ‘PV + EV’ system into a city-wide

The realization of the ‘PV + EV’ system requires the development of decentralized power systems facilitated by peer-to-peer (P2P) electricity trading, which maximizes the self-consumption of PV electricity within cities (Sousa *et al* 2019, Wilkinson *et al* 2020). These systems are radically different from centralized power systems, and require polycentric innovation (Nyangan and Byrne 2018). The P2P market is a consumer-centric and bottom-up system, contrary to the traditional power systems (Morstyn *et al* 2018, Sousa *et al* 2019). Thus, community participation and consideration of socio-technological transition are critical to the successful development of decentralized power systems (Manfren *et al* 2011, Geels *et al* 2017, Kobashi *et al* 2020c).

A promising technology, ‘blockchain’, may provide cheap, secure, and transparent ways of transactions in the future (Ahl *et al* 2019, 2020, Andoni *et al* 2019). Involving granular energy technologies such as PV and EV in the SolarEV City, the decentralized systems likely have a faster diffusion rate

and provide rapid and deep decarbonization pathways (Lovins 1978, Wilson *et al* 2020) through the enhanced economics of the combined 'PV + EV' system (Kobashi *et al* 2020c). Additionally, the concept assumes a prevalent adoption of EV, which may be possible through various incentivized policies and measures to enhance pro-environmental attitudes and encourage hands-on experience (Rezvani *et al* 2015).

Many research and development projects for decentralized power systems with EVs are currently underway around the world (Ahl *et al* 2020, Kobashi *et al* 2020b). For example, Toyota, Trende, and University of Tokyo conducted a demonstration project for autonomous P2P electricity trading between homes and businesses combined with PV and plug-in hybrid vehicle in Susono, Japan (Toyota 2020). Japanese automakers have played a crucial role in this development through a standard-type charger, 'CHAdEMO' that has been the only EV charger capable of bi-directional energy flow (CHAdEMO 2020). However, recently, it was reported that the current bestselling EV, 'Tesla Model3' has a function of inactivated bidirectional energy charging inside of the vehicle, which may be activated by remote software updates (electrek 2020). As new trends are evolving rapidly in future mobility, it is critical that for automakers to play more active roles in building SolarEV City as the next urban power and mobility systems.

To facilitate the development of the decentralized power systems, governments must also take the lead in reforming regulations and related governance practices (Ahl *et al* 2020, Kobashi *et al* 2020c). In the case of Japan, network (consignment) fees for distribution lines need to be changed to correctly reflect the usage of the networks (e.g. the distance between transactions) (Ahl *et al* 2020). Currently, low EV penetration is a key bottleneck for the development of 'PV + EV' system, although it could be changing rapidly in years after COVID-19. Central and local governments should provide higher financial supports for purchasing EVs, tighter CO₂ emission regulation, and setting a target date on ICE ban, etc (Javid and Nejat 2017). Separate PV and EV financial supports could be combined with the support of V2H systems (Kobashi *et al* 2020a)

It would be important to promote communities to act together for energy production and consumption for effective use (Curtius *et al* 2018, Wolske *et al* 2020), which would have many social co-benefits such as peer-pressure or social resilience. Once costs of PV and EV become sufficiently low, it would be necessary to build business models for energy management on a community scale (Fouad *et al* 2020), helping communities to maximize cost-saving potentials in their energy usage (e.g. water and space heating).

A possible business model is a leasing model in which the PVs and EVs owned by a third party. Such an approach may have advantages in certain aspects, such as capital investment and effective management, but can have shortfalls in others (e.g. privacy and accumulation of information). In implementing such a novel concept, a high level of deep uncertainties can be expected. Demonstration projects, living labs, and new planning paradigm that accounted for these uncertainties explicitly (e.g. adaptive dynamic planning) should be considered to enable implementation of these innovative ideas (Jittrapirom *et al* 2018, Hossain *et al* 2019).

4.3. Potentials of 'PV + EV' for other countries

As the seasonal variability of insolation depends on latitudes (Twidell and Weir 2015), the 'PV + EV' system would be less effective for countries in higher latitudes, but more effective in countries in lower latitudes than estimated for Japan. Many countries in lower latitudes have increasing population with rapid urbanization, and they are in an on-going process of developing power systems with increasing energy demands (IEA 2020). The 'PV + EV' system with the high cost effectiveness may play an important role to build clean and affordable urban power systems for these countries. However, available number of EVs and car utilization rate are critical factors for the development of 'PV + EV' systems, which may be lacking in these countries. Further researches are necessary to identify the potential usefulness for other regions.

5. Conclusion

Rapidly declining costs of renewable energy are providing a hope to realize carbon neutrality in many societies (Connolly *et al* 2016, Jacobson *et al* 2017, Esteban *et al* 2018, Child *et al* 2019). However, places like Japan with limited land and no interconnection with other countries struggle to utilize these technologies. Rooftop PVs are the least invasive renewable energy with no use of potential natural land, and have a large potential to supply electricity directly to consumers with minimum loss in distribution process. Therefore, they should be utilized to a physically maximum extent for future urban buildings. In this study, we demonstrated that coupling PV with EV in the SolarEV City concept could be a highly cost-effective strategy to decarbonize the urban energy and transport system. The idea can be a basis for the next urban systems for developed and developing countries alike, and should be further explored by policymakers, researchers, industries, and communities. That should also help to fulfill SDG 7. Particularly, at the time of recovery from COVID-19, our society is in the right moment to get a start in this direction.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

T K designed the study, conducted analyses, and wrote the original paper. P J analyzed mobility change and wrote the original paper. T Y conducted data analysis. Y H collected data. Y Y analyzed mobility data. All the authors participated on the revision.

Conflict of interest

The authors declare no competing interests.

Appendix A. Supplementary information

A.1. Techno-economic analysis

The methodology generally follows the analysis conducted for Kyoto City (Kobashi *et al* 2020c). In this study, we used the net present value (NPV) as a metric. NPV evaluates the cash flows of projects occurring at different times using discount rates (Say *et al* 2018). We defined the NPV of a project as composed of two components: electricity (NPV_{Electricity}) and gasoline (NPV_{gasoline}). The gasoline part (NPV_{gasoline}) is necessary only for the 'PV + EV' system. NPV_{Electricity} was calculated by a techno-economic model 'System Advisor Model (SAM)' (see below). Then, the two NPVs were added to obtain NPV_{total} as in equation (1). The maximum NPV for a given scenario was calculated using a parametric analysis with various PV capacities (maximum PV capacities were set by 70% of the total rooftop areas as discussed below) (Kobashi *et al* 2020a). The currency exchange rate of 110 yen \$⁻¹ in 2018 was applied for all the analyses.

$$\text{NPV}_{\text{total}} = \text{NPV}_{\text{Electricity}} + \text{NPV}_{\text{gasoline}} \quad (1)$$

where

$$\text{NPV}_{\text{Electricity}}(i, p, b, t) = \sum_N^{n=1} \frac{\text{CashFlow}(i, p, b, n, t)}{(1 + R_d)^n} - \text{SystemCost}(i, p, b, t). \quad (2)$$

i = i th city
 p = PV capacity (kW)
 b = Batter capacity (kWh)

t = Project first year (year)
 N = Project period (year)
 R_d = discount rate
 and

$$\begin{aligned} \text{Cash Flow}(i, p, b, n, t) &= \text{Electricity Cost}_{\text{Base}}(i, n, t) \\ &\quad - \text{Electricity Cost}_{\text{System}}(i, p, b, n, t) \end{aligned} \quad (3)$$

where the subscript 'Base' indicates the electricity cost without PV, battery, or EV. The subscript 'System' indicates the electricity costs of renewable energy systems (grid electricity), including PV operation costs and EV battery replacement costs, if any.

$$\begin{aligned} \text{Electricity Cost}_{\text{Base}}(i, n, t) &= E_{\text{import}}(i, 0, 0, n, t) \cdot T_{\text{import}} \\ &\quad - E_{\text{export}}(i, 0, 0, n, t) \cdot T_{\text{export}} \end{aligned} \quad (4)$$

$$\begin{aligned} \text{Electricity Cost}_{\text{System}}(i, p, b, n, t) &= E_{\text{import}}(i, p, b, n, t) \cdot T_{\text{import}} \\ &\quad - E_{\text{export}}(i, p, b, n, t) \cdot T_{\text{export}} \\ &\quad + p \cdot M_{\text{PV}} + b \cdot R_{\text{battery}}(t) \end{aligned} \quad (5)$$

where

p = PV capacity (kW)
 b = Batter capacity (kWh)
 E_{import} = Electricity imported from grid (kWh yr⁻¹)
 E_{export} = Electricity exported to grid (kWh yr⁻¹)
 T_{import} = Flat-rate electricity usage charges (\$ kWh⁻¹)
 T_{export} = Flat-rate feed-in tariff rebate (\$ kWh⁻¹)
 M_{PV} = PV maintenance cost (\$ kWh⁻¹ yr⁻¹)
 R_{battery} = EV Battery replacement cost (\$ kWh⁻¹) when EV battery capacity degrades to less than 80% of the initial capacity.

System costs are initial investments to install PV and battery systems.

$$\text{System Cost}(i, p, b, t) = p \cdot C_{\text{pv}}(t) + b \cdot C_{\text{battery}}(t) \quad (6)$$

where

$C_{\text{pv}}(t)$ = Cost of PV system (\$ kW⁻¹) in year t
 $C_{\text{battery}}(t)$ = Cost of battery system (\$ kWh⁻¹) in year t

In the 'PV + EV' system, $C_{\text{battery}}(t)$ (\$ kWh⁻¹) was calculated as:

$$C_{\text{battery}}(t) = \text{EV}_{\text{add}}(t) / \nu \quad (7)$$

where

$\text{EV}_{\text{add}}(t)$ = EV additional costs (t) (\$/vehicle)
 ν = EV battery capacity (kWh/vehicle)

and,

$$\text{EV}_{\text{add}}(t) = \text{EV}_{\text{pur}}(t) + C_{\text{V2H}}(t). \quad (8)$$

$EV_{pur}(t)$ = Additional costs of EV purchase relative to ICE (\$/vehicle) in year t
 $C_{V2H}(t)$ = V2H system cost (\$/vehicle) in year t
 $NPV_{gasoline}$ was calculated as:

$$NPV_{gasoline}(i, n, t) = \sum_{n=1}^N \frac{Cash\ Flow_{gasoline}(i, n, t)}{(1 + R_d)^n} \quad (9)$$

where

$$Cash\ Flow_{gasoline}(i, n, t) = t(i) \cdot k(i) \cdot g(i) \cdot u(i).$$

$t(i)$ = Total number of passenger vehicles in the i th city

$k(i)$ = Annual average driving distance (km/vehicle yr^{-1}) in the i th city

g = Gasoline efficiency for ICE ($1\ km^{-1}$)

u = Unit gasoline price ($\$ l^{-1}$)

Energy sufficiency $ES(i, p, b)$, self-sufficiency $SS(i, p, b)$, and self-consumption $SC(i, p, b)$ are defined as follows.

$$ES(i, p, b) = E_{PV}(i, p, b) / E_{load}(i, p, b) \quad (10)$$

$$SS(i, p, b) = (E_{PV-load}(i, p, b) + E_{battery-load}(i, p, b)) / E_{load}(i, p, b) \quad (11)$$

$$SC(i, p, b) = (E_{PV-load}(i, p, b) + E_{battery-load}(i, p, b)) / E_{PV}(i, p, b) \quad (12)$$

where

$E_{PV}(i, p, b)$ = Electricity generated by PV ($kWh\ yr^{-1}$) in the i th city

$E_{load}(i, p, b)$ = Total electricity load ($kWh\ yr^{-1}$) in the i th city

$E_{PV-load}(i, p, b)$ = Electricity ($kWh\ yr^{-1}$) supplied from PV directly to load in the i th city

$E_{battery-load}(i, p, b)$ = Electricity ($kWh\ yr^{-1}$) supplied from battery to load in the i th city

To calculate cost saving, we used the following equation.

$$\left\{ 1 - NPV_{total}(i, p, b, t) / N / \sum_{n=1}^1 Energy\ Cost_{Base}(i, n, t) \right\} \times 100 (\%) \quad (13)$$

A.2. Techno-economic model

We used a publicly available model, ‘System Advisor Model’ (SAM version 2020.29) (Blair et al 2018). More detailed information on the use of SAM for the analysis is given in (Kobashi et al 2020c) and its supplementary data. The model calculates the financial merits of renewable energy projects considering different technology combinations, energy losses, and system degradation (Blair et al 2018). The model requires a weather file for each city with

data for temperature, global horizontal irradiance (GHI) (figure S1), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) to calculate the hourly power generation from PV for a location. To obtain the weather file, we used ‘SIREN’, which calculates these parameters from climate reanalysis data, MERRA-2. Because it is known that the use of reanalysis data overestimates PV generation (Pfenninger and Staffell 2016), we scaled GHI, DNI, and DHI equally to match PV capacity factors with actual observations. We set the tilt angle of the PV module to be 30° , and the azimuth angle to be 180° in SAM.

A.3. Electricity tariffs and cost estimates

Electricity tariffs in Japan can be subdivided into two groups: low voltages (e.g. households and small shops) and high voltages (e.g. industry). For the aggregated analysis on the city scale, we used a weighted average tariff price of $0.18\ \$ kWh^{-1}$. For the FiT price, we used $0.08\ \$ kWh^{-1}$ (table S3). We assumed constant tariffs for the entire analysis period as no significant trends in tariffs were observed for the past 20 years in Japan (Agency for Natural Resources and Energy 2019).

In recent years, the costs of renewable energy have been declining rapidly, and the trend likely continues for the foreseeable future (IRENA 2019). For our analyses, cost estimates of PV and EV systems were obtained primarily from Bloomberg New Energy Finance (BNEF 2016, 2017) with additional domestic sources (Kobashi et al 2020a) and presented in table S4. With the increasing penetration of EVs, the price of batteries is also experiencing a rapid drop (BNEF 2019). As the battery price dominates the current price of EV, the EV’s prices are also decreasing (ICCT 2019). It is estimated that by 2025, EV prices become cheaper than similar models of ICEs, and by 2030 EVs will likely be less expensive than ICEs by 10% (BNEF 2018).

A.4. Assessment of CO₂ emissions from the systems

We considered CO₂ emissions from electricity generation and gasoline burning. CO₂ emissions from the scenarios can be written as:

$$EMI_{Base}(i) = e(j) \cdot E_{imported} + t(i) \cdot k(i) \cdot g \cdot h \quad (14)$$

$$EMI_{System}(i) = e(j) \cdot E_{imported} \quad (15)$$

$$CO_2\ emission\ reduction (\%) = (1 - EMI_{System}/EMI_{Base}) \cdot 100 \quad (16)$$

where

$EMI_{Base}(i)$ = CO₂ emissions in the Base scenario for the i th city

$EMI_{\text{System}}(i)$ = CO₂ emissions in the ‘PV only’ or ‘PV + EV’ scenarios for the i th city
 $e(j)$ = Grid emission factor for the j th power company
 h = Gasoline CO₂ emissions factor (kg_{CO2} l⁻¹)

A.5. Hourly power demand for cities

Data on hourly power demand for cities are generally not available in Japan. Therefore, we estimated the hourly demand for these eight cities and special wards from aggregated demand data of five power utilities (figure S1(A), table S5) (Kobashi *et al* 2020c). TEPCO supplies electricity to the Tokyo region and KEPCO supplies to the Osaka region. HEPCO supplies electricity to Hokkaido, the northern island of Japan. Chugoku and Tohoku supply electricity to the western and northern portion of the main island of Japan (Honshu). Standardized hourly demand data in figure S1(A) exhibit common characteristics of demand curbs from the five power companies. As Hokkaido is located in the north, HEPCO does not show space cooling demand in summer. The space heating demand starts earlier in the fall and ends later in spring than in other regions for HEPCO (figures S1(A) and (B)). Daily average temperatures above 25 °C and below 15 °C induce space cooling and heating demands, respectively (figures S1(A) and (B)). The Hokkaido region (HEPCO) experienced a blackout after a large earthquake on September 6th, 2019, lasting for about 2 d until a 99% recovery of supply (OCCTO 2018) (figure S1(A)).

Although the scale of electricity demands for the five utilities is different in order of magnitude (table S5), normalized daily variations in figure S1(A) exhibit common variability particularly for June and October when cooling and heating demands are absent (figure S1(A)). This indicates that these utility demand curbs are scalable to major cities. Total annual demands for the coverage areas of utilities, prefectures, and cities are available in table S6.

The mixing ratios of industries, households, and commercial sectors affect the aggregated hourly demand curbs as each sector has special demand profiles. We tested how different mixtures of sectors affect the economy and described it in the sensitivity analyses section later in this paper. It is noted that monthly variabilities of utility coverage areas are highly correlated with monthly prefectural demands (table S6), indicating that the seasonal variability of city demands is likely captured in the utility demand data. Therefore, we used scaled utility hourly demands (figure S1(A)) for the cities (tables S5 and S6). For the ‘PV + EV’ scenarios, the annual EV electricity demand $E_{\text{EV}}(i)$ in the i th city was estimated as:

$$E_{\text{EV}}(i) = t(i) \cdot k(i) / EV_{\text{eff}} \quad (17)$$

where

EV_{eff} = EV electricity efficiency (km kWh⁻¹)

This annual EV demand was added to the city’s annual electricity demand, which was used to scale the hourly demand data of utilities.

A.6. Sensitivity analyses

To understand the uncertainties associated with each parameter, we conducted sensitivity analyses using the elementary effects method (Saltelli *et al* 2008, Saltelli and Annoni 2010). The elementary effects method can be used to analyze model sensitivities with a relatively small number of simulations (Saltelli *et al* 2008). Nine parameters were considered with a range of ±20% or estimated ranges when larger ranges were necessary (table S7). The model was run twice for each parameter on the upper and lower bands (table S7). The order ($i = 1, \dots, 18$) of the analyses for 18 inputs were randomly determined. We used a ‘PV + EV for Sendai City’ scenario with FiT and a constant tariff in 2030 as a starting point. The initial value, upper and lower bands for each parameter (table S7) were assigned location numbers of $(l_{i,1}, l_{i,2}, l_{i,3}) = (0, 1, -1)$, respectively. Following the order of the inputs, the parameters were changed one by one to run the model for NPV, leaving the parameter as it is. The elementary effect (EE _{i}) of the i th parameter was calculated as:

$$EE_i = (NPV_i - NPV_{i-1}) / \Delta_i \quad (18)$$

where

Δ_i = the change ($l_i - l_{i-1}$) being made in the location of the i th input from the earlier analysis for the $i-1$ th input.

For example, when the i th input was changed from location number 1 to location number -1, Δ_i became -2. The largest elementary effect (highest sensitivity) was found in the discount rate (table S7). A 2% increase in discount rate results in a 38% decrease in NPV, and vice versa. A 20% increase in electricity tariff induces a 37% increase in NPV and vice versa. An increase in PV costs by 20% results in an NPV decrease by 10%, and vice versa. We also looked at other parameters, including FiT, PV operation costs, EV additional costs, demand, gasoline price, and EV battery capacity (table S7). A change in these parameters induces less than ±10% variations in NPV.

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