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Techno-economic assessment on PV systems integrated with batteries and electric vehicles in residential area and urban district in Japan

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ABSTRACT

With declining cost of renewable energy technologies, new form of urban energy systems can be established in a cost-effective way. Urban environments consist of various areas such as residential area and urban district with different energy consumption patterns and building structures. Cost effectiveness of the technologies can be different in different parts of urban environments and different time. To evaluate these differences, we performed techno-economic analyses of renewable energy technologies (PV, battery, and EV) for a residential area in Shinchi, Fukushima and a central district of Kyoto, Japan. We found that high electricity demands in the central Kyoto provide higher cost reduction through renewable energy than that of the residential area in Shinchi in 2018. PV only system has the highest cost reduction in 2018. By 2030, "PV + EV" provides the highest cost reduction for both environments, but the Shinchi area with relatively larger number of EVs exhibits the higher cost reduction than that of Kyoto. These differences have important implications for strategies of urban decarbonization for coming decades.

Keywords: renewable energy resources, photovoltaics, electric vehicles, battery, urban decarbonization, techno-economic analysis.

NONMENCLATURE

Abbreviations	
EV	Electric Vehicles
FITs	Feed-in-tariffs
HVAC	Heating and ventilation, and air conditioning
PV	Photovoltaics
SAM	System Advisor Model
V2C	Vehicle to Community
V2H	Vehicle to Home
3D	3 Dimensions

1. INTRODUCTION

Effective ways to decarbonize urban energy system are constantly changing with new development of technologies and changes in the costs. For the next 10 years, it is expected that costs of PV and battery keep declining and the number of EVs will increase substantially in cities [1]. This environment will create unprecedented opportunities to build cost-effective decentralized energy systems in cities with a consequence of rapid decarbonization [2]. In our earlier studies, we found that a household in Kyoto can benefit from having a PV system integrated with EVs with substantial cost saving by 2030 [3]. As a whole city, Kyoto can also save around 30% of energy costs by applying PV on 70% of rooftops of Kyoto City and using EVs as storage [2]. However, it was not clear how and where we can start building such systems in urban environments before 2030 considering the best cost opportunities.

Cities are not homogenous but have a wide variety of structures from the central area to its periphery. Depending on the area, energy demand patterns such as electricity and car usages are highly variable owing to various kinds of social activity. In addition, building structures, materials, usages, and layouts affect heating and cooling demands and PV electricity generation by shading, energy balance, etc. [4,5]. These factors need to be considered to adequately evaluate viability of renewable energy projects.

Recent developments of 3D building energy modeling tools can be used to evaluate these aspects [6]. "Rhinoceros 3D" is a program to model 3D building structures from GIS data (Fig 1 and 2). Using "Grasshopper", a plug-in for the Rhinoceros 3D, radiation amounts on the surface of the building can be evaluated [7]. In addition, energy consumptions in building can be estimated using other plug-ins (ladybug, honeybee, etc), which utilize a widely used energy model, "EnergyPlus".

Estimated hourly radiation amounts and energy consumptions from these programs are used to conduct techno-economic analyses for renewable technologies for the central district in Kyoto and residential area in Shinchi, Fukushima for 2018 and 2030.

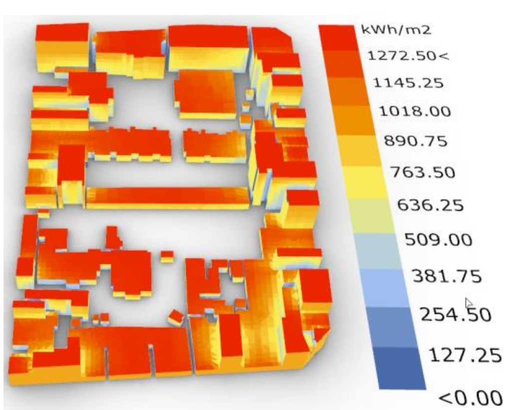

Fig 1 Central district of Kyoto City. Colours indicate annual radiation amounts. Colour bar indicats rdiation amounts with axis pointing toward north.

2. METHODS AND MATERAIS

2.1 Central district in Kyoto and residential area in Shinchi, Fukushima

In this study, we analyzed two different areas for comparison. One is a central commercial area of Kyoto City (Fig. 1), and the other is a residential area of Shinchi, Fukushima (Fig. 2). Kyoto City (35.0°N, 135.7°W) has annual average temperature of around 16 °C. Minimum winter and summer monthly average temperatures are around 28 °C and 5 °C, respectively. Shinchi, Fukushima (38.0°N, 140.6°W) is located north of the main island of Japan facing Pacific Ocean. Mean annual temperature is around 12°C. Minimum winter and summer monthly average temperatures are around 24 °C and 2 °C, respectively. Both regions have limited snow in winter.

2.2. Electricity demand data

We obtained hourly electricity consumption data from about 70 houses in the Shinchi area. Only data from 24 houses were used because nearly continuously data were available from these houses for 2018. As addresses of the houses are not available for privacy reasons, we picked a random area in Shinchi with 43 houses (Fig. 2). The obtained demand data were used to calibrate modeled demand data.

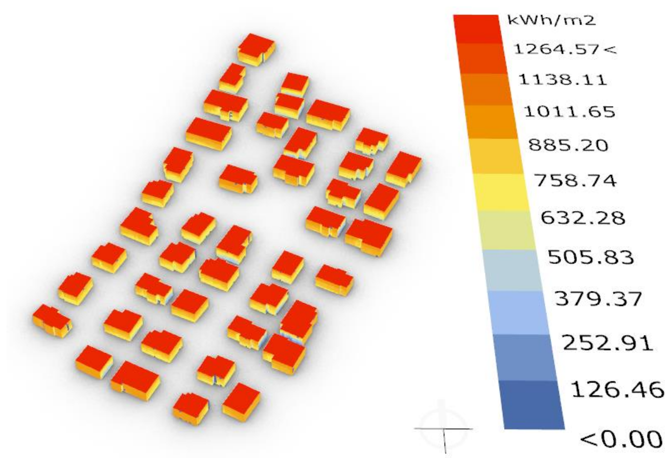

Fig 2 Residential area in Shinchi, Fukushima. Colours indicate annual radiation amounts. Colour bar indicats rdiation amounts with axis pointing toward north.

2.3. Electric vehicles as battery

Vehicle utilization rate is rather low in Japan especially in urban areas. For example, private passenger vehicles are only out of home for less than 30 minutes a day on

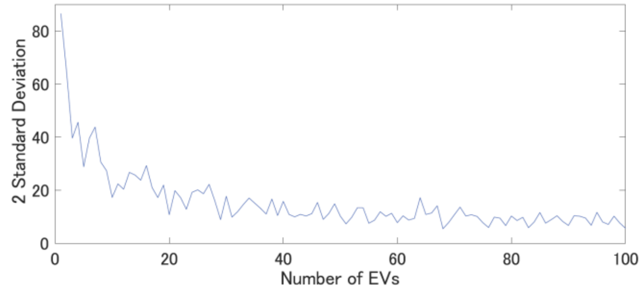

Fig 3 Two standard deviation of available EVs for the system as a battery (%) during daytime (7am-7pm) when EVs are out of home for 3 hours during the period.

average in Kyoto City [2]. By using EV battery as flexibility for PV electricity, high economic values and decarbonization potential can be obtained especially toward 2030 [2,3]. However, the usage pattern of EV can be a bottle neck to maximize the usefulness of "PV + EV" systems for a single home. Sharing of EV battery in a community can effectively increase the stability of the system mitigating the intermittency of EV availability for V2C (Vehicle to Community) (Fig. 3).

If a vehicle is out of home for 3 hours a day from 7am to 7pm (daytime), the vehicle is available as a battery for PV (V2H, Vehicle to home) for 75% of the daytime. Figure 3 shows that if the number of vehicles connected to the system increases to 40 EVs, 55-85 % (2σ bounds) of vehicles are always available for V2C (Fig. 3). In this study, we assumed that 100 EVs are connected to the system for the Kyoto district and 43 EVs are connected for the Shinchi area. With more than 40 EVs are connected to the system, we can assume that the intermittency of EV availability is mitigated and at least half of the total EV battery capacity is available for V2C. We assume that Nissan Leaf as a model EV with a 40 kWh battery. Thus, halves of 1720 kWh and 4,000 kWh of batteries for Shinchi and Kyoto communities are available as in our earlier studies [2].

2.4. Software for 3D analyses for radiation and energy balance for buildings

In cities, neighboring buildings affect energy balance each other depending on their layouts. Solar radiation falls on buildings, which are affected by next buildings through shading, influencing PV generating but also cooling and heating demand on buildings. Therefore, we used a Rhinoceros 3D and associated program, "Grasshopper", which is increasingly used for 3D energy molding for urban environments [6–8]. Using these programs, it is possible to analyze roof-top radiation potentials and energy consumption of buildings with various spatial and temporal resolutions, considering shading of neighboring buildings and energy balance. We created weather files for Kyoto and Shinchi in 2018 using a program "SIREN" that uses reanalysis data, MERRA-2 [9].

2.5. System advisor model (SAM) for technoeconomic analysis

Estimated radiation potentials of roof-tops and hourly estimates of energy consumptions of each building are used to conduct technoeconomic analyses of PV, battery, and EV as storage for 2018 and 2030. We

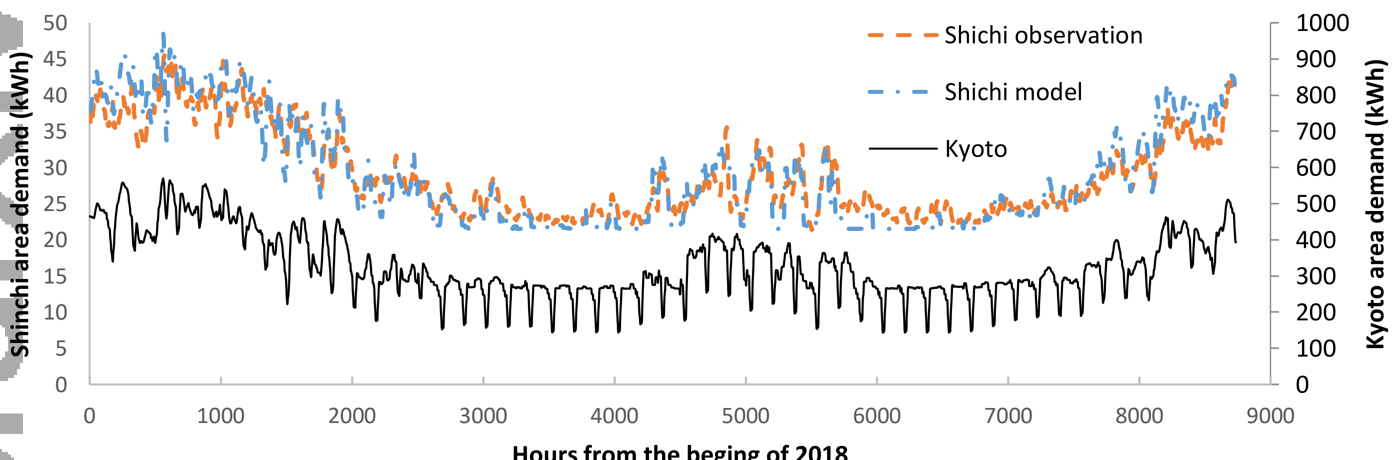

Fig 4 Hourly Kyoto and Shinchi total demands with 24-hour running means. Note that Shinchi has both observed and modeled data.

used System Advisor Model (SAM), which evaluates renewable energy projects [10]. For methodology and parameters for the techno-economic analysis, we generally followed our earlier analyses [2,3]. PV and battery capacities are determined for the maximum net present values (NPVs) of the projects by parametric analyses. Costs of PV, battery, and EV are also used from our earlier studies [2,3] based primarily from Bloomberg Energy Finance (BNEF) [1]. For example, PV system costs are 2.16 and 0.89 $/W for 2018 and 2030, respectively. Battery system costs are 726 and 330 $/kWh for 2018 and 2030, respectively. EV additional costs are 250 and 22 $/kWh for 2018 and 2030, respectively [2]. The project period and discount rate are set to 25 years and 3%, respectively.

3. RESULTS

3.1. Scenarios

We analyzed four technology combinations, "PV only", "PV + battery", "PV + EV", and "EV charge only" for 2018 and 2030. Electricity tariffs, $0.18/kWh for Kyoto commercial area (mix of high and low voltage prices) [2], $0.22/kWh for Shinchi residential area (low voltage price) are used for the analysis. We also considered two scenarios with/without FITs (feed-in-tariffs) ($0.08/kWh for Kyoto and $0.09/kWh for Shinchi).

3.2. Buildings and radiation

We identify 114 buildings for the Kyoto district in an aera of 47,900 m^2 and 43 houses for the Shinchi area in an area of 26,200 m^2 (Fig. 1 and 2). Annual radiation amounts are similar for the both area (Fig 1. and 2.). Roof-top areas are calculated to be 26,952 m^2 and 6,600 m^2, which corresponds to 56 % and 25 % of the total area for Kyoto and Shinchi, respectively. For Shinchi, neighboring houses do not affect PV generation. The Kyoto central district has denser and taller buildings than those of Shinchi. In the Kyoto district, the rooftop area with little shading from neighboring buildings (>95% of full radiation) is 47% of the total rooftop area. Rooftop area receiving >70% of full radiation is 84% of the total rooftop area. We assume that 70 % of roof-top areas are available for the maximum PV capacities for Kyoto and Shinchi, which correspond to 3,252 kW and 943 kW, respectively.

In the model, we assumed that the central district in Kyoto has all commercial buildings with concrete materials, and Shinchi residential houses are build by wooden materials. Closest options in the program are "supermarket" and "mid-rise apartment" for Kyoto and Shinchi, respectively. According to these specifications, energy demands (e.g., lighting, electric equipment, and HVAC) are calculated for each building consistent with energy balances through building walls for changing radiation and temperatures (Fig. 4).

Total annual electricity demands for the areas in Kyoto and Shinchi are modeled as 2,863,605 (kWh) and 509,807 (kWh), respectively. Compared with the observed data for Shinchi, the modelled data is two times larger possibly owing to house sizes (the second floor is often smaller than the first floor in reality, but they are the same in the model) and differences in activities. Therefore, we divided the Shinchi model demands by two (Fig. 4). Then, the observation and modelled data agree well (Fig. 4). For Kyoto, the modelled data are directly used for the following technoeconomic analyses.

3.3. Technoeconomic analysis

Consistent with our earlier analyses for a house-scale [3] and a city-scale [2], "PV only" projects are already profitable in 2018, indicating grid parity was reached by 2018. "PV + EV" projects show positive cost saving in Kyoto in 2018 but less than "PV only" (Table 1) and they are negative in Shinchi. Battery does not exhibit any additional benefits to "PV only" for all the combinations we considered, and "EV charge only" has limited benefits in 2018 and 2030 (not shown).

Table 1. Results of the technoeconomic analyses for Shinchi and Kyoto in 2018 and 2030.

	With FIT		without FIT	
Shinchi, 2018	**PV only**	**PVEV**	**PV only**	**PVEV**
PV capacity (kW)	60	140	35	140
Cost saving (%)	2.5	-1.6	1.8	-1.6
CO_2 reduction (%)	13.2	63.8	9.7	63.8
Kyoto, 2018				
PV capacity (kW)	1050	1150	850	1150
Cost saving (%)	4.3	0.3	3.7	0.3
CO_2 reduction (%)	37.6	45.9	32.5	45.9
Shinchi, 2030				
PV capacity (kW)	943	943	60	240
Cost saving (%)	20.7	32.7	4.3	19.7
CO_2 reduction (%)	22.6	92.9	13.2	78.6
Kyoto, 2030				
PV capacity (kW)	3252	3252	1300	1650
Cost saving (%)	18.4	21.2	11.2	15.3
CO_2 reduction (%)	55.4	71.2	42.3	57.8

In 2030, "PV+EV" becomes most profitable technology combinations. Particularly, for the scenarios without fit, higher self-consumption brought by EV battery, produces higher cost saving. In addition, relatively larger number of EV in Shinchi suggests that EV batteries with low costs in 2030 play more important role than for Kyoto.

CO_2 emission reduction can be enhanced by combing with EVs, allowing more CO_2-free PV electricity to be consumed by EV and buildings. Shinchi residential area has a relatively large number of EVs in terms of demand size in comparison to the Kyoto district. Therefore, when PV and EV becomes cheaper, the effectiveness of CO_2 emission reduction for "PV + EV" in Shinchi becomes larger than that of the central district in Kyoto in 2030 (Table 1).

4. CONCULUSIONS

We applied 3D modeling of buildings to estimate annual radiation amounts available for PV and energy balance for buildings. Modeling results are utilized to perform technoeconomic analyses for technology combinations of PV, battery, and EV. We applied the method to the urban center in Kyoto and residential area in Shinchi, Fukushima with the cost estimates for 2018 and 2030.

Results show that increasing profitability of "PV + EV" toward 2030 more than other technologies, but the rates are different for Kyoto and Shinchi. The central district in Kyoto with higher demand shows higher cost saving in 2018 than that in Shinchi. However, as rooftop area and the number of EVs are limited in Kyoto, the growth rate of cost saving toward 2030 is limited. On the other hand, Shinchi with larger rooftop area and larger number of EVs relative to its demand has smaller cost saving in 2018, but it grows rapidly toward 2030. These results have important implications on how urban decarbonization should be proceeded in urban areas in coming decades.

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