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COST-OPTIMAL PATHWAYS TO DECARBONIZE URBAN ENERGY SYSTEMS WITH PV, BATTERIES, AND ELECTRIC VEHICLES: A CASE STUDY FOR KYOTO, JAPAN

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ABSTRACT

To minimize the impacts of climate change, it is increasingly clear that global CO_2 emissions should be eliminated by 2050 (IPCC, 2018) and that advanced cities for carbon neutrality should have net zero emissions by 2040. However, the precise pathways by which they can reach such ambitious goals, have not been identified. As the costs of photovoltaics (PV), batteries, and electric vehicles (EV2) likely keep falling, they will play key roles for deep decarbonization. Here, we conduct a techno-economic analysis of a city-scale energy system with PV, batteries, and EVs for the city of Kyoto, Japan. We find that aggressive EV adoption could help PV penetration in the city with substantially lower costs than just deploying PV and batteries alone. CO_2 emissions from vehicle and electricity usages from the city could be reduced by 70-80% in 2030 if 60% of current cars are replaced by EVs, at the same time reducing the costs by 40-50%.

Keywords: renewable energy resources, technoeconomic analysis, PV, EV, urban decarbonization

1. INTRODUCTION

With falling renewable energy costs, existing energy sources around the globe are starting to decarbonize [1]. However, the speed of decarbonization is far from rapid enough to keep the global temperature rise well below 2 °C [1]. Particularly in Japan, renewable energy remains costly [2], making renewable penetration more difficult. Therefore, it is urgently necessary to find economic pathways, through which societies can decarbonize their energy systems.

As their penetration into the grid increases, variable power sources such as PV require energy storage to balance their variability. Although the cost of batteries is rapidly declining, partly through the increasing number of EVs, installation of batteries remains rather costly for the foreseeable future. In an earlier study [3], we found that utilizing batteries in EVs with PV in households (vehicle to home, or V2H) is the most cost-optimal option with the highest potential of reducing CO_2 emission, compared with PV only and PV + battery systems in Tokyo, Japan by 2030. However, it is still not clear how the V2C (Vehicle to Community) system involving pear to pear (P2P) transaction will benefit in a city scale.

In this study, we investigated cost-optimal decarbonization pathways for the city of Kyoto by 2030, using PV, batteries, and EVs. Then, we discuss possible benefits of PV, EV, and V2C penetration policy.

2. MATERIAL AND METHODS

2.1 The city of Kyoto

Kyoto is an old capital of Japan, and the place where the Kyoto Protocol was signed in 1997. In 2018, the population was 1.47 million with about 720,000 households [4]. In FY2016 (fiscal year: April 2016 to March 2017), CO_2 emissions were 7.52 MT_{CO2}, representing a slight reduction (-0.8%) from the previous year [5]. Per-capita CO_2 emissions were about 5.1 T_{CO2} per year. The largest emitting sector is the commercial

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sector (2.38 MT_{CO2}), followed by households (1.98 MT_{CO2}), transport (1.56 MT_{CO2}) and industry (0.86 MT_{CO2}) [5].

In Kyoto, about 40% of total energy consumption (75,833 TJ) is in the form of electricity in FY2016 [5], of which low voltage (*Dento*) for households, etc. is 3.19 TWh [4] and high voltage (*Denryoku*) for industries, etc. is 5.15 TWh [4,5]. We analyzed Dento and Denryoku separately owing to their different electricity prices. Then, two separate results are combined to obtain the estimates for the entire city of Kyoto.

2.2 Model

To conduct technoeconomic analyses for PV, batteries, and EVs, we used the widely-used energy-economic model HOMER (Hybrid Optimization of Multiple Energy Resources) from the U.S. National Renewable Energy Laboratory (NREL) [6]. HOMER analyzes minimum investment and operation costs under the constraints of various technologies, finding optimal generation technology capacities [7]. It also calculates resulting CO_2 emissions. The model has been applied to various scales of energy systems from the household to the urban scale [7]. A currency exchange rate of 110 yen/$ in 2018 was used. A discount rate of 3% and project lifetime of 25 years are applied for all analyses [3].

2.3 Model parameters

The methodology and parameters generally follow our earlier work for a household scale [3], but extends to the entire city scale for Kyoto. We analyzed electricity consumption and the transport sector for 2018, 2024, and 2030 for the city of Kyoto. In Japan, electricity prices can be subdivided into two categories: Dento and Denryoku. In our calculation, we used electricity tariffs of $0.22/kWh and $0.16/kWh which represent the averages from 2007 to 2016 for Dento and Denryoku, respectively [8]. We also set prices of $0.1/kWh (average wholesale price) and $0.06/kWh for selling PV-generated excess electricity to the grid [3], respectively.

Hourly global horizontal irradiance (GHI) and surface temperature data were obtained from the web-based PV generation tool “Renewables.ninja” [9,10] for the city of Kyoto (35.01°N, 135.77°E) by setting the tilt to 0°. Then, the GHI was used for all analyses in HOMER. As the data have been shown to overestimate PV generation [10], we adjusted the capacity factor of PV as 13.4%, which matches the average measured data for Kyoto [11].

For demand profiles, we used the hourly built-in Community profile of HOMER (peak in 18:00-21:00) for Dento, and Commercial (peak in 8:00-17:00) for Denryoku with annual peak in January [12]. The built-in profiles are randomly perturbed to be more realistic [6]. For the cost of PV, batteries, and EVs towards 2030, we used data from Kobashi and Yarime [3], for which the primary data source is Bloomberg New Energy Finance (BNEF). PV system costs for households decline from $2.16/W in 2018 to $0.89/W in 2030, and small-scale battery system costs (7kWh) decline from $726/kWh in 2018 to $330/kWh in 2030.

2.4 Transition to EVs from internal combustion engine vehicles (ICEs)

EV penetration is relatively slow in Japan, possibly related to less aggressive EV strategies of Japanese automakers. As a result, EV sales including PHEV (Plug-in Hybrid Electric Vehicle) were about 1% of the total car sales in 2017 and 2018 [13], and about half of the sales was NISSAN LEAF [14]. In the city of Kyoto, the total number of registered passenger cars (including small size cars, “Kei”) was 488,342 in FY2017 [4]. The number of EVs including PHEVs was 1,984 in FY2017, although the city has a target of 60,000 EVs by FY2020 [15].

For our analyses, we created two scenarios towards 2030 for EV adoption as a fraction of new car sales: 30% EV sales in 2030 in line with the national target (20-30%), and a more ambitious 100% EV sales in 2030 scenario. We assumed that the total number of cars remains the same in the city, and that the EV sales fraction rises linearly from 2018 to the targets. As a result, the number of EVs reaches 18 % (14,650) and 60% (293,692) for 30% and 100% EV sales in 2030, respectively. We believe that both are plausible as EV prices are expected to reach parity with those of ICEs in the early 2020s [16]. Thereafter, EVs will become cheaper than ICEs.

In the analyses, we assumed all EVs are connected to V2H (or V2C) systems and energy usage is optimized within the city [17]. V2H is an effective means to reduce the variability of renewable energy [18]. The additional costs of EVs plus V2H compared to the use of ICEs is estimated to $250/kWh in 2018 and $22/kWh in 2030 [3]. We assumed NISSAN LEAF as a model EV for the analyses as it is the most popular EV in Japan. Thus, EV battery capacity is 40kWh, and half of the battery is considered to be available for V2H [3]. Compared to a household-scale (V2H) system, EV availability for the community-scale system (V2C) is less problematic, as most of the EVs are connected to the system either at home or the workplace at any given time.

Current annual electricity consumption of Kyoto is 8.1 TWh. Based on our assumptions, in 2030 a 60% EV penetration would increase the consumption by 4%, and a 100% EV penetration would lead to a 7% increase.

3. RESULTS

We created six scenarios (a-f, see Table 1) and compared the results with the base scenario (continued usage of grid electricity and ICEs).

Table 1: Definition of the six scenarios a-f. "Excess sales" is excess PV electricity to be sold to the grid, or not.

	Excess sales	**No excess sales**
PV + Battery	a	b
PV + EV30%	c	d
PV + EV100%	e	f

We found that all the scenarios are already economic in 2018 compared with the base scenario (Fig. 1). As the costs of PV, batteries and EVs decline, in all the cases the costs of the renewable energy systems drop further towards 2030 (Fig. 1).

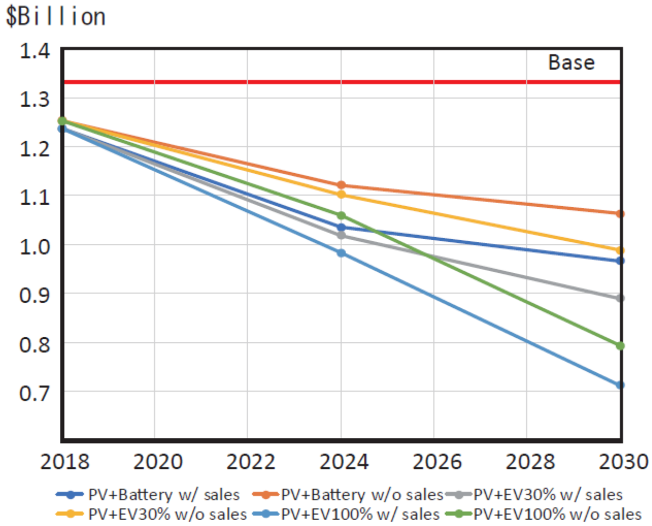

Fig 1 Changes in annualized net present costs for electricity and passenger cars in the Kyoto City for 2018, 2024, and 2030. w/ and w/o are with and without, respectively.

Scenario "a" (PV + Battery with sales) shows that batteries do not add economic value to the PV system even in 2030, but scenario "b" (PV + battery without sales) shows that PV + batteries become more economic than PV only from 2024. In 2030, the optimum battery capacity becomes 5.2GW (Table 2). In the PV + EV scenarios (c-f), increased EVs add economic value in the PV system as flexibility, reducing energy costs (Fig. 1). At the same time, switching to EVs replaces the use of gasoline for transportation with cheaper electricity. As a result, the higher the EV penetration, the more overall energy costs decline (Fig 1). Therefore, the most economic scenario in 2030 is PV + EV with highest EV penetration with electricity sales to the grid, i.e. scenario "f" (Fig. 1). In this scenario, energy expenditure reduces by 46% compared to the base scenario due to cheap PV electricity as well as increased EV efficiency compared to internal combustion engines.

Table 2. Economically optimal PV and battery capacities in 2030 for Kyoto. Required areas for PV are calculated by multiplying the PV capacity by 7 (m^2/kW) [19]. Battery capacities in (c-f) are predetermined by the number of EVs in the scenarios.

	a	b	c	d	e	f
PV (GW)	7.4	5.1	7.7	5.0	8.8	6.6
Required area (km^2)	52	36	54	35	62	46
Battery (GWh)	0.0	5.2	3.5	3.5	11.7	11.7

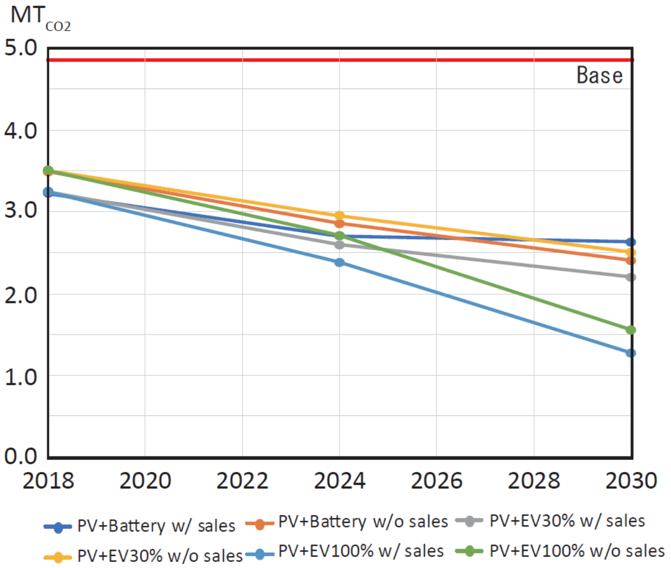

Fig 2 CO_2 emissions from electricity and passenger cars in Kyoto City in the scenarios.

CO_2 emission reductions in Fig. 2 shows similar characteristics as the costs in Fig 1, but with slight differences. In 2018, economically optimal PV capacities are about 3.4 or 2.6 GW, reducing CO_2 emissions by 1.6MT or 1.4MT, depending on whether the sales of excess electricity to grid is allowed or not, respectively. By 2030, most scenarios can more than halve CO_2 emissions compared to the base case (Fig. 2). PV + EV with 100% EV sales in 2030 with excess sales has the highest reduction potential in 2030, reducing CO_2 emissions by 74%. This reduction amount is about half of the CO_2 emission of Kyoto in FY2016. The second highest reduction is realized for PV + EV 100% without sales (Fig 2), indicating that higher EV penetrations are more beneficial both economically and environmentally.

4. DISCUSSION

Economically optimal PV capacities indicate that the amount of PV generated electricity with sales (a, c, e) becomes larger than electricity consumption in 2030 (Table 3). However, a large amount of PV electricity is sold or wasted (Table 3), indicating possibilities to use them to electric heat demand or in future hydrogen or other power-to-gas systems.

Table 3. Ratios (%) for PV generated electricity / consumption, and self-consumed PV electricity / consumption, across the six scenarios. Not that high EV penetration induce high self-consumption.

(%)	a	b	c	d	e	f
PV gen. / cons.	104	72	107	69	118	88
Self-consumption	67	63	71	56	82	72

We calculated the total roof top area of Kyoto as 51.6 km^2 from geospatial data [20], which is consistent with another study for Kyoto [19]. This roof-top area is about one third of the urbanized area of Kyoto (150 km^2). As not all the spaces in roof top can be used for the installation of solar panels, $7m^2/kW$ ($5m^2/kW$ for panels with efficiency of 20%) [19] was used to calculate a technical roof-top PV potential of 7.4GW. PV use of rooftop surfaces depends on various factors such as economics, available spaces, scenery, and building structure. Considering these additional factors can reduce the realistic roof top potential for Kyoto to between 5.8–1.3 GW [19]. Therefore, it is essential for Kyoto to use other available land areas and to cooperate with surrounding regions to supply renewable energy (e.g. from PV, wind, and biofuels) towards net-zero emissions.

5. CONCLUSION

We conducted a techno-economic analysis of PV, battery systems, and EVs for the city of Kyoto, using the HOMER software. We found that increased EV penetration can substantially reduce the costs of energy and CO_2 emissions from the city if it is combined with PV deployment in an integrated vehicle-to-community (V2C) system. Therefore, we conclude that EV penetration policies in Kyoto and Japan more generally should be reinforced, and that these policies should include planning and implementation of EV integration with renewable energy systems.

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