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Potentials of Rooftop Photovoltaics Combined with Electric Vehicles for Decarbonization in Korean Cities

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ABSTRACT

The major objective of this research is to support future-proof applications of rooftop photovoltaics (PV) and electric vehicles (EV) as batteries for urban decarbonization. Although extensive research has been conducted, the feasible pathways have often been limited due to the complexity of analyzing interdependencies of energy, environment, and cost effects as well as a lack of sectoral analysis for cities which could offer stepwise application strategies. Therefore, this research conducted techno-economic analyses for rooftop PV + EV with respect to multiple cities in South Korea using System Advisory Model (SAM), and different building sectors in Seoul using MATLAB. The results showed that CO_2 emissions can be reduced about 49% when applying rooftop PV combined with EV in Seoul in 2030. The results also indicate that the investment of PV and EV in residential buildings should be prioritized in Seoul. This research will contribute to providing decarbonization pathways for Korean cities, and ultimately alleviating global warming.

Keywords: decarbonization, techno-economic analyses, solar energy, electric vehicle, vehicle to building, civil infrastructure systems

NONMENCLATURE

Abbreviations	
BIPV	Building Integrated PV
CO_2	Carbon Dioxide
PV	Photovoltaic
LIRE	Least Invasive Renewable Energy
EV	Electric Vehicles
FIT	Feed in Tariff
NPV	Net Present Value
ICE	Internal Combustion Engine
V2B	Vehicle to Building
IRR	Internal Rate of Return

1. INTRODUCTION

As energy demand and energy-related CO_2 emissions are increasing, energy systems have to transition to renewable energy-based systems. Solar Photovoltaic (PV), one of promising renewable sources, has penetrated existing buildings and cities as affordable and sustainable technologies. Renewable energy often requires large lands to collect widely dispersed energy, sacrificing large natural lands. However, rooftop PVs are installed on unused spaces on the top of buildings [1] and considered as the least invasive renewable energy (LIRE), thus their applications should be prioritized.

Meanwhile, the transportation sector where 95% depend on petroleum-based fuels, accounts for about 15% of global greenhouse gas emissions [2]. For both energy saving and environmental protection, electric vehicles (EVs) have been promoted [3]. With the progress of EV technology, low noise, and no pollution, applications of EV become essential for the sustainable development [3,4].

The rooftop PV can be integrated with electric vehicles (EV) through bi-directional charging of EV battery. The concept of solar EV City was proposed to use the rooftop PV + EV system on a city scale. Previous

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studies subjected to Japanese cities were found that up to 95% of electricity can be supplied with 20-40 % energy cost reduction [5,6].

This study intends to analyze the feasibility of the PV+EV system in Korean cities. In 2020, the government of the Republic of Korea formally announced the commitment in the carbon neutrality plan by 2050 [7]. Over the last 60 years, with exerting economic growth [8], urbanization and large-scale land development have occurred in the country [7]. The nation has faced with palpable impacts from the climate change. For example, the average temperature in the nation has risen 1.8°C and annual rainfall has increased by nearly 160mm [7]. The changes often cause extreme weather events such as heatwaves, snowstorms, and typhoons, etc. [7], threaten natural habitats, and affect human health and wellbeing. Therefore, action plans for cities in South Korea need to be taken to alleviate global warming and protect living environments. In particular, building-integrated PV (BIPV) and EV adoptions have been proposed for transitions in cities' infrastructure and energy systems [9].

This research intends to propose decarbonization strategies in cities by supporting decisions of applying rooftop PV and EVs. The feasibility of the PV + EV transitions were investigated in the four areas in South Korea including three cities of Seoul, Incheon, SeJong City, and one province of Jeju-do. In particular, to identify suitable investment strategies in Seoul, the largest and capital city of South Korea, PV+EV transitions by different building types were investigated. The analyses will underpin forthcoming transitions in both building and transportation sectors for the future smart and connected cities achieving net zero CO_2 emission society.

2. RESEARCH METHODOLOGY

To analyze potentials of rooftop PV + EV systems for Korean city's decarbonization, we used techno-economic analyses. The techno-economic analyses can evaluate the viability of renewable energy projects by comparing it with existing energy systems such as grid electricity and/or gasoline cars, considering electricity tariffs, cost of technologies, maintenance cost, solar radiation, project period, degradation, discount rate, etc. The analyses were conducted for 2019 and 2030 with declining cost of rooftop PV systems and EV. The basic methodology follows Kobashi et al. [5].

Cost of EV was calculated as the difference between Internal Combustion Engine (ICE) and EV including the vehicle-to-building (V2B) cost. Net Present value (NPV) was used as a main financial indicator. PV capacities were calculated to maximize the NPV. Rooftop area was calculated from publicly available footprint data of buildings. Then, maximum rooftop PV capacity is defined by the total rooftop area divided by 7 m^2/kWh. We evaluate PV + EV potentials using energy and financial parameters, which include energy sufficiency, self-sufficiency, self-consumption, CO_2 emission reduction, NPV, payback period, and internal rate of return (IRR).

2.1 Application of System Advisor Model (SAM)

This research used System Advisor Model (SAM), an open source software developed by National Renewable Energy Lab (NREL) [10], for the techno-economic analysis [11]. Through the techno-economic analyses, the viability of PV and PV+EV projects were analyzed by 1) collecting data, and 2) modeling and simulating transition scenarios.

2.1.1 Data collection

This research collected the data from publicly available sources in Korea. The building rooftop area [12], the number of vehicle registrations from [13], electricity consumption per hour [14], gasoline cost [15], solar panel installation and maintenance costs [16], FIT (Feed in Tariff) price [17], were obtained from multiple sources such as National Spatial Data Infrastructure Portal by the Ministry of Land, Infrastructure and Transport, Korean Statistical Information Service, International Energy Agency, and Seoul Metropolitan Government.

This research reviewed several cities and selected three cities (Seoul, Incheon, and Sejong City) and one province (Jeju-do). Considering the size of the cities, the degree of urbanization, population size, and the number of cars, the selections are expected to provide useful comparisons of potential energy, environment, and economic impacts of PV and EV adoptions by different urban forms.

2.1.2 Modeling transition scenarios for Korean cities

The SAM was used to model the applications of rooftop PV and EV based on the data collected in 2.1.1. SAM loads data from input parameters such as location, financial and incentive assumptions, equipment type, costs, weather files, etc. The input values for PV and battery capacity that can provide the maximum NPV were identified using the parametric analysis in SAM. We analyzed the effects of renewable energy generation, CO_2 emissions, payback period when applying "rooftop PV only" in 2019 and 2030 and adopting "PV+EV" systems in 2030 for with or without FIT support.

Six (6) scenarios in the below were investigated in each case.

- In 2019,
  - Rooftop PV only with FIT
  - Rooftop PV only without FIT
- In 2030
  - Rooftop PV only with FIT
  - Rooftop PV only without FIT
  - Rooftop PV combined with EV with FIT
  - Rooftop PV combined with EV without FIT

2.2 MATLAB Calculations

MATLAB scripts [6] were employed to make techno-economic analyses on different sectors in Seoul. Summed results of the sectoral analysis were found to agree with the SAM results within 10%. By using the data collected in 2.1.1., vehicle registrations in residential and commercial sectors are given. The number of EV was assigned based on occupancies estimated for each building type. A MATLAB function used the inputs and evaluated self-consumption, self-sufficiency, energy sufficiency, cost saving (%), and CO_2 emission reduction (%) [5] in 2030 when integrating PV on building rooftops, transforming vehicles to EVs, and adopting vehicle-to-building (V2B) utilizing EV battery to charge buildings. The V2B has been presented as a concept of powering buildings by plug-in electric vehicles (PEVs) for peak load [18]. In this research, V2B was used as a concept of using EV for powering buildings when the vehicles are not operated. This research assumed that EVs are operated three trips a day from 7am to 7pm, and EV battery are charged from the grid at midnight when the battery capacity is less than the initial 100% capacity.

3. RESULTS AND FINDINGS

3.1 Potentials of PV+EV for multiple cities in Korea

By comparing the performance of PV+EV in multiple cities, we can investigate the effectiveness of PV+EV application in different urban forms. Table 1 presents economic, energy, environmental impacts of PV+EV applications in 2019 and 2030 for Seoul. This research investigated four cases in Korea: Seoul, Incheon, Sejong City, and Jeju-do. The results of comparing different cities are presented in Fig. 1.

In Table 1, 33% cost saving can be expected when applying PV combined with EV because we can expect saving of ICE gasoline expense and reduction of grid electricity purchase in 2030 by EV battery use. CO_2 emission reduction (%) become nearly double in PV+EV scenario the PV only scenario in 2030 from 20% to 42% without FIT and from 23% to 49% with FIT. Self-sufficiency indicates the urban resilience, the ability to supply electricity during blackouts [5]. The resilience can increase as PV capacity increases in Seoul.

We can observe that a higher PV capacity per capita is translated to higher self-sufficiency, CO_2 reduction (%), and cost saving (%) in Fig. 1, which is also seen in the Japanese cities [5]. Comparing the cases, we can expect the urban resilience (self-sufficiency) in Jeju-do which is more than double (75%) that of other cities (33% in Seoul and Incheon, and 32% in Sejong City) when applying PV with EV in 2030 without FIT.

Table 1. PV and PV combined with EV scenarios in Seoul

(a) 2019	**PV only: FIT**	**PV only: no FIT**
Payback period(yrs.)	14.2	14.1
PV capacity (GW)	9.3	6.7
Annualized NPV (Million $)	10.4	8.3
Cost saving (%)	0	0.12
Self-sufficiency (%)	23	17
Total CO_2 emission (Million ton)	15.4	16.6
CO_2 reduction (%)	18	15
(b) 2030	**PV only: FIT**	**PV only: no FIT**
Payback period(yrs.)	10.2	10.5
PV capacity (GW)	14.0	9.5
Annualized NPV (Million $)	192.9	122.3
Cost saving (%)	2	2
Self-sufficiency (%)	30	24
Total CO_2 emission (Million ton)	14.0	15.3
CO_2 reduction (%)	23	20
(c) 2030	**PV+EV: FIT**	**PV+EV: no FIT**
Payback period(yrs.)	14.2	14.2
PV capacity (GW)	14.0	14.0
Annualized NPV (Million $)	125.7	125.6
Cost saving (%)	33	23
Self-sufficiency (%)	33	33
Total CO_2 emission (Million ton)	13.4	13.4
CO_2 reduction (%)	49	42

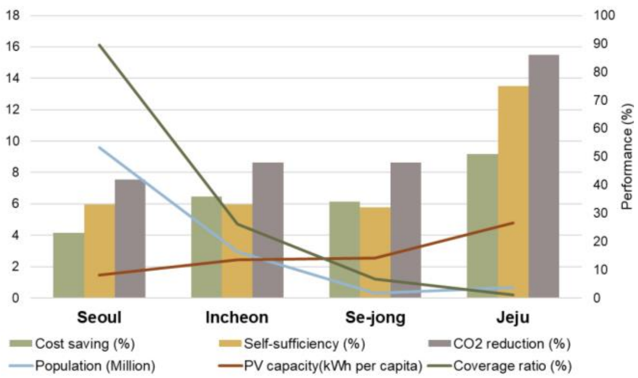

Fig. 1. Four cases in Korea (PV+EV in 2030 without FIT)

3.2 Potentials of PV+EV by buildings types in Seoul

Analyses of different building types in Seoul allow us to identify the most feasible strategies for investing in PV+EV, considering energy supplied by decentralized PV generation, cost saving, and CO_2 emission reduction (Fig. 2). The cost saving shows how much energy costs can be saved by installing the technologies over the period in comparison to existing energy systems (e.g., grid electricity and gasoline) [5]. CO_2 emission reduction presents changes in CO_2 emission compared to the existing energy system (in this case, 2019).

The investment of PV+EV for residential buildings will be the most feasible for self- sufficiency, cost saving, and CO_2 emission reduction. The office buildings are the least effective to implement PV+EV considering energy, economic, and environment.

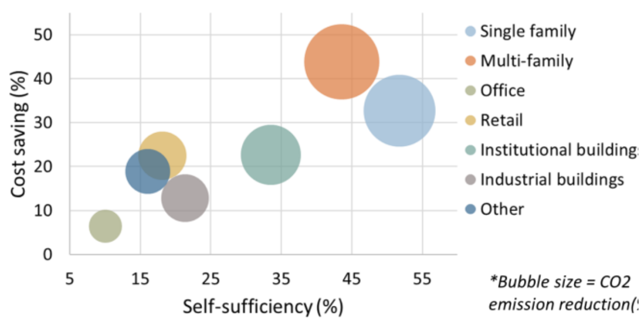

Fig. 2. Performance comparison of different building types in Seoul when applying PV+EV in 2030 without FiT

4. DISCUSSION AND CONCLUSIONS

Currently, the countermeasures for the increase in carbon emissions are mainly carried out in two ways: physical and non-physical. However, most of them are passive responses such as the movement to reduce plastic and to encourage the use of electric vehicles. However, the Solar EV city proposed in this study is an urban infrastructure element that can be applied to all residents who can install solar panels and is expected to be an active physical response nationally. In addition, by 2030, the combination of solar power and electric vehicles is expected to reduce carbon emissions by about 50% in Seoul. Also, in terms of cost, it is expected that a reduction rate of about 30% or more will be derived as a result in this study. If the Solar EV city is prevalent worldwide, it can contribute to reducing the temperature rise and damage caused by global warming.

In addition, to achieve the carbon neutral goal by 2050 [7], the government of the Republic of Korea is promoting green infrastructure, electrification, low-carbon and decentralized energy in industries. The solar EV city concept will align with the government's plan of launching electric vehicles and energy storage system (ESS) to replace conventional energy-intensive industry. This research will also synergize with the government's efforts of collaborating with the industry for optimal energy use by applying future technologies such as hydrogen production/supply/use and CCUS (Carbon Capture, Utilization Storage).

REFERENCE

[1] Quan SJ, Li Q, Augenbroe G, Brown J, Yang PP-J. A GIS-based Energy Balance Modeling System for Urban Solar Buildings. Energy Procedia 2015;75:2946–52. https://doi.org/10.1016/J.EGYPRO.2015.07.598.

[2] U.S. EPA. Global Greenhouse Gas Emissions Data. US Environ Prot Agency 2021. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed August 24, 2021).

[3] Huang X, Ge J. Electric vehicle development in Beijing: An analysis of consumer purchase intention. J Clean Prod 2019;216:361–72. https://doi.org/10.1016/J.JCLEPRO.2019.01.231.

[4] Feng J, Xu SX, Li M. A novel multi-criteria decision-making method for selecting the site of an electric-vehicle charging station from a sustainable perspective. Sustain Cities Soc 2021;65:102623. https://doi.org/10.1016/J.SCS.2020.102623.

[5] Kobashi T, Jittrapirom P, Yoshida T, Hirano Y, Yamagata Y. SolarEV City concept: Building the next urban power and mobility systems. Environ Res Lett 2021;16:024042. https://doi.org/10.1088/1748-9326/abd430.

[6] Kobashi T, Yoshida T, Yamagata Y, Naito K, Pfenninger S, Say K, et al. On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: Techno-economic-social considerations. Appl Energy 2020;275:115419. https://doi.org/10.1016/j.apenergy. 2020.115419.

[7] The Government of the Republic of Korea. 2050

Carbon Neutral Strategy of the Republic of Korea: Towards a sustainable and green society. 2020.
[8] Jeong S-J, Park H, Ho C-H, Kim J. Impact of urbanization on spring and autumn phenology of deciduous trees in the Seoul Capital Area, South Korea. Int J Biometeorol 2018 635 2018;63:627–37. https://doi.org/10.1007/S00484-018-1610-7
[9] Lee S, Jin H, Vecchietti LF, Hong J, Har D. Short-Term Predictive Power Management of PV-Powered Nanogrids. IEEE Access 2020;8:147839–57. https://doi.org/10.1109/ACCESS.2020.3015243.
[10] National Renewable Energy Laboratory. System Advisor Model (SAM). US Dep Commer 2020. https://sam.nrel.gov/ (accessed August 24, 2021).
[11] Fathollahzadeh MH, Speake A, Tabares-Velasco PC, Khademian Z, Fight LL. Renewable energy analysis in indigenous communities using bottom-up demand prediction. Sustain Cities Soc 2021;71:102932. https://doi.org/10.1016/J.SCS.2021.102932.
[12] Ministry of Land Infrastructure and Transport. Building Integrated Information_Master. Korea Natl Spat Data Infrastruct Portal 2020. http://data.nsdi.go.kr/dataset/12623 (accessed August 24, 2021).
[13] STATISTICS KOREA. KOSIS KOrean Statistical Information Service. Stat KOREA 2019. https://kosis.kr/eng/index/index.do (accessed August 24, 2021).
[14] Korea Electric Power Corporation. - KEPCO MAIN | KEPCO -. Korea Electr Power Corp 2019. https://home.kepco.co.kr/kepco/EN/main.do (accessed August 24, 2021).
[15] International Energy Agency. Energy Prices and Taxes for OECD Countries 2019. OECD; 2020. https://doi.org/10.1787/7B080C52-EN.
[16] International Energy Agency & Korea Energy Agency. National Survey Report of PV Power Applications in Korea. 2019.
[17] Kwon H. 2019 Seoul-type solar power generation support (Seoul-type FIT) subsidy announcement plan. Seoul Metrop Gov 2019. https://opengov.seoul.go.kr/sanction/17271219 (accessed August 24, 2021).
[18] Dagdougui H, Ouammi A, Dessaint LA. Peak Load Reduction in a Smart Building Integrating Microgrid and V2B-Based Demand Response Scheme. IEEE Syst J 2019;13:3274–82. https://doi.org/10.1109/JSYST.2018.2880864.

