

Article

Urban Energy Transition Toward 2050 Through Gradual Diffusion of PV, EV, and V2H: A Scenario-Based Assessment in Suita, Japan

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Abstract

Achieving carbon neutrality toward 2050 requires not only the adoption of renewable energy technologies but also long-term planning based on their gradual integration into urban systems. This study presents a novel scenario-based framework that quantifies year-by-year impacts of deploying rooftop photovoltaics (PVs), electric vehicles (EVs), and Vehicle to Home (V2H) systems from 2018 through 2050. Five key dimensions are assessed: CO₂ emission reduction, cost savings, self-consumption, energy sufficiency, and self-sufficiency. Using Suita City, Japan, as a case study, we analyzed two diffusion scenarios, “baseline (current growth case)” and “accelerated deployment case”. The results indicate that despite high initial investment, an accelerated scenario can achieve up to a 60% CO₂ emission reduction and over 25% cost savings by 2050. Importantly, the integrated deployment of PVs, EVs, and V2H surpasses PV-only systems in overall effectiveness from around 2035 onward. By capturing the dynamic evolution of technology impacts over time, this study provides unique and actionable insights for designing data-driven policies supporting long-term urban decarbonization.

Keywords: renewable energy; future scenarios; gradual diffusion of technology; techno-economic analysis; multidimensional assessment; future design

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1. Introduction

1.1. Climate Change and Urban Decarbonization

With the emergence of climate change and various other challenges in recent years, the importance of sustainability has been widely recognized internationally [1,2]. In connection with this issue, the concept of “planetary boundaries” has attracted considerable attention, demonstrating that for “climate change,” as well as “phosphorus–nitrogen cycles” and “rate of biodiversity loss,” the tipping point has already been passed [3]. To meet the goal of limiting global temperature rise since the Industrial Revolution to 1.5 °C, it is vital to achieve net-zero emissions of greenhouse gases (GHGs) worldwide by 2050 [4]. It is therefore vital to mitigate climate change by reducing CO₂ emissions as quickly

as possible. A roadmap and measures to achieve carbon neutrality by 2050 have been discussed [5], and a radical transformation of the energy system is required [6].

A wide variety of efforts are being made to achieve carbon neutrality globally [7]. One example is the development of renewable energy-related technologies [8,9]. These efforts include the improvement of promising technologies such as wind and solar power generation, the development of new technological “seeds” based on electrocatalysts, and the development of storage batteries for electric power generation systems [10–13]. In Japan, there are also initiatives aimed at reducing CO₂ emissions through the use of existing regional resources, such as small-scale hydroelectric power generation plants in rural areas [14].

It is important that R&D on these technologies include evaluations of their long-term impact when they have diffused to the level of local governments, in terms of GHG reduction and technical and economic benefits. Given that cities account for 60–70% of energy-related CO₂ emissions [15] and are expected to account for an even higher proportion of CO₂ emissions in the coming years, the decarbonization of cities is an urgent challenge [16]. However, due to the limited amount of land available in urban areas, it is difficult to use technologies such as wind power, which require large amounts of space. This makes it necessary to use technologies that enable efficient electric power generation in limited spaces.

Two promising technologies that fit this description are photovoltaics (PVs) and electric vehicles (EVs) [17]. PVs have the advantage that PV devices can be installed on the roofs of buildings anywhere, making them well suited to urban areas with very limited amounts of vacant land [18]. Additionally, since EVs do not emit any CO₂ in operation, they are being promoted worldwide as an alternative to gasoline-powered vehicles [19]. The Ministry of Economy, Trade and Industry (METI), Japan, has set the goal of achieving 100% EVs on Japan’s roads by 2050 [20]. Another promising technology is Vehicle to Home (V2H), which aims at a synergy of PVs and EVs [21]. V2H works by storing the surplus power generated by PV devices during the day in EVs and making that power available for use in the home at night; that is, it enables bidirectional power transmission between homes and EVs [22]. V2H is attracting interest for three main reasons: it provides PV systems (which lack energy storage) with an energy storage function; it enables a transition from selling power to the grid to self-consumption and energy storage as the price of electricity drops significantly [23]; and it has the potential to promote vehicle electrification along with the development of autonomous driving [24,25].

1.2. Future Design and Policy Implementation

It is essential to envision the future state of society and discuss how to diffuse such promising technologies in cities from the viewpoint of policy design for carbon neutrality. Various studies and practices aimed at envisioning a sustainable future society and addressing relevant technologies have been conducted [26–29]. On the other hand, it is important to evaluate the effects of the diffusion of such technologies from a long-term perspective in order to rationally design policies toward an envisioned future society. To achieve a decarbonized society in 2050, it is important to build consensus among stakeholders to discuss how to solve the socio-economic and technical challenges of the process of transition [5]. It is of vital importance to identify promising renewable technologies and build consensus among various stakeholders on the priority of adopting these technologies in the process of transition, while accounting for possible impacts and relevant costs associated with the adoption of technologies. In such discussions and in relevant policy design, provision of objective information about the long-term effects of diffusing renewable energy technologies is very useful as a reference. In particular, analysis of the effects of their gradual diffusion would be of use when making decisions on policies.

Notably, climate change is an intergenerational issue, making it indispensable to take into account the benefits to future generations when designing policy measures toward carbon neutrality. In recent years, Future Design, which is the design and praxis of generating futurability of people and society considering the benefits to future generations, has been studied and practiced [30,31]. One of the promising methods to introduce the perspective of future generations and activate futurability is the use of “imaginary future generations (IFGs),” who are tasked with representing future generations in decision-making and negotiations. The IGF method has been adopted in various public policy fields, such as city planning, environmental planning, water environmental problems, facilitation of renewable energy installations, and technology assessment (e.g., [32]). It has also been applied to the policy design for carbon neutrality by 2050 [33]. However, the discussion and decisions in the practice were made without simulated data on the impact of renewable energy penetration by 2050. If the expected future benefits and impacts of PVs, EVs, and V2H can be quantitatively demonstrated, it is likely that local governments will set specific adoption targets and promote these technologies more effectively and strategically in such Future Design practices [34]. Thus, it is important to develop a method to forecast and evaluate the impact of the future diffusion of PVs, EVs, and V2H in terms of techno-economic analysis and CO₂ emission reductions at the local government level.

1.3. Urban Decarbonization Through Rooftop PVs and EVs

Several studies on evaluating the adoption of promising renewable energy technologies have been performed [35–38]. Rooftop PVs are expected to play a substantial role in decarbonizing urban environments, particularly in lower latitudes with their abundant solar energy and the increasingly lower costs of rooftop PVs [39]. However, solar power is limited in its use owing to variability. It has been shown that, by coupling with EV batteries, rooftop PV systems can improve their economic and decarbonization potential [17,24]. A nationwide analysis of all 1741 Japanese municipalities estimated that integrating rooftop photovoltaics with electric vehicles as mobile batteries could supply approximately 85% of hourly electricity demand, while reducing carbon emissions by 87% and total costs by 33% [17]. They showed that rooftop PVs + EVs can cut 54–95% of CO₂ emissions from electricity generation and driving in these areas with potential 26–41% energy cost savings, which they call the “SolarEV City Concept”. As the effects of rooftop PV integrated with EV systems on urban decarbonization differ by climate, urban structures, electricity tariff, etc., various global cities have been analyzed, including South Korean cities [40]. They found that rooftop PVs integrated with EVs is a highly cost-effective measure.

This study builds upon the earlier studies. Reference [24] evaluated the CO₂ emission reduction and technical/economic benefits in 2030 of adopting V2H and other technologies. Compared with other previous studies, that study was unique in three aspects: its focus of analysis was a local government; it investigated the synergistic effect of multiple energy technologies rather than looking at just a single technology; and it examined the impact of technology penetration according to five different indicators. However, there were two issues that the study [24] did not address. Firstly, it only covered the period up to 2030 instead of 2050, the target year for achieving carbon neutrality, so it was not a long-term evaluation. Secondly, it did not consider gradual diffusion of products. To gain further insight into the effects of the diffusion of these renewable energy technologies, it is essential to extend the timeframe to 2050 and to assess the impact of gradual diffusion of the technologies.

In accordance with the above, the present study developed a methodology to evaluate the impact of diffusion of renewable energy technologies up to 2050, taking 2018 as

the starting year. By overcoming the limitation of System Advisor Model (SAM) [41], which is not applicable to assess gradual diffusion of renewable energy technologies, we developed a method for multidimensionally evaluating the effects of gradual diffusion of PV, EV, and V2H while taking into account the aspect of product life cycle, with reference to [17]. Taking Suita City, Osaka Prefecture, in Japan as a case study, we conducted a quantitative assessment of the impact and limitations of gradual diffusion of PVs, EVs, and V2H based on two diffusion scenarios (continuation at the current growth rate and accelerated deployment), taking account of deregulation, technological development, and social conditions.

This study aims to contribute to the development of a methodological basis for the multidimensional evaluation of the long-term impact of technological diffusion up to 2050, as well as to policy formulation by local and national government bodies for promoting the adoption of renewable energy technologies toward carbon neutrality. We argue that such a method will be useful when designing pathways toward a carbon-neutral society. Importantly, the proposed assessment methodology and the results of the case study have significant implications for international policy discussions on carbon neutrality.

To guide this analysis, we address the following research questions:

- (1) How will the year-by-year integration of PV, EV, and V2H technologies affect urban CO₂ emissions and energy sufficiency through 2050?
- (2) What are the long-term techno-economic trade-offs between deploying PV systems alone versus integrating PV, EV, and V2H?
- (3) How can scenario-based evaluations of gradual technology diffusion inform local energy policies aligned with carbon neutrality goals?

The remainder of the paper is organized as follows. Section 2 presents the methods, focusing particularly on the assessment of the impacts of gradual diffusion of PVs, EVs, and V2H in terms of five indicators. Section 3 summarizes the assessment results under two diffusion scenarios: “current growth case” and “accelerated deployment case”. Section 4 discusses the main findings and implications, followed by conclusions and policy implications.

2. Methods

In this study, we multidimensionally evaluated the impact of the gradual diffusion of PVs, EVs, and V2H within a municipality using future projections. This study builds upon previous techno-economic analyses that estimated the cost savings attained by introducing renewable technologies, such as PV and EVs, relative to using existing systems over a certain period [17,24]. Using techno-economic analysis, we can evaluate the viability of the renewable energy project by considering the electricity tariff, the costs of technologies, degradation, variability of insolation and demand, etc. [24]. Here, after introducing the case study area, we explain how we overcame the limitations of SAM to express gradual diffusion of these technologies in Section 2.2. We then explain the methods for evaluating the effects of gradual diffusion of these technologies in the case study area in terms of CO₂ reduction, cost saving, self-consumption, energy sufficiency, and self-sufficiency, based on [17]. Note that details of relevant data used in the evaluation is shown in Appendix A.

2.1. Case Study Area

In this study, our aim was to evaluate the impact of diffusion of PV, EV, and V2H in a single municipality. Our case study focused on Suita City. The city is the first “New Town” developed in Japan and is an urban center in the northern part of Osaka Prefecture with a population of about 380,000.

The primary characteristics that led to Suita City being selected were as follows: (1) the city's potential for the installation of rooftop PV systems due to the city's unique characteristics, as described below; (2) the city's commitment to achieving zero GHG emissions by 2050, as stated in the "Joint Climate Emergency Declaration of Toyonaka City and Suita City" issued on 10 February 2021; and (3) its proximity to the university where the authors work and the willing collaboration of the local government.

Suita City has developed into a residential suburban district through the construction of Senri New Town and land readjustment projects. More specifically, Suita serves as a "bedroom community" of Osaka Prefecture, with large concentrations of buildings used by individuals and households. This concentration implies that the deployment of PV systems should be reasonably effective here.

Table 1 shows some basic information about Suita City, and Figure 1 shows a map of Suita City obtained using QGIS (3.20.3) (a software application released in 2009 for analyzing geospatial information data) [42].

Table 1. Basic information about Suita City.

Characteristic	Value
Urban area [km ²]	36.1
Latitude [°]	35.45
Longitude [°]	135.31
Population [-]	371,753



Figure 1. Aerial photograph of Suita City created using the QGIS software.

2.2. Preparation for the Assessment

2.2.1. Analysis Tools (Software)

To analyze the impact of technology diffusion, we used System Advisor Model (SAM) (Version 2020-2-29) [43]. This software, used for decision-making in the renewable energy industry, is provided by the National Renewable Energy Laboratory, a U.S. research institute. The software automatically computes the quantity of energy that can be generated and its cost for different types of renewable energy technologies, based on the various data entered for analysis at an hourly resolution (i.e., techno-economic analysis) [24]. A special feature of SAM is its ability to simultaneously analyze two or more tech-

nologies. For this study, the two technologies we selected were PVs and the Li-ion batteries used in EVs.

2.2.2. Correction Methods for PV and EV Degradation over Time and Analysis Process

A study [17] analyzed the impact of the penetration of EVs in individual years from 2019 to 2030 using multiple indicators. By entering the various data for specific (single) years necessary for calculating evaluation indicator parameters such as CO₂ emission reduction and techno-economic assessments into SAM, we were able to output the data necessary for evaluation. However, this study aimed to analyze multiple years simultaneously. Due to its limitations, SAM is only capable of generating outputs for technological seeds deployed at one point in time. For these reasons, we could not obtain the data we desired by simply entering data into SAM. In other words, we were unable to deploy renewable energy technologies such as PV across multiple different years and analyze the effects simultaneously. For example, we could not run a simultaneous analysis of PVs installed in 2018 and PVs installed in 2019. This is because the performance degradation rates of the PVs installed in 2018 and the PVs installed in 2019 are different, and SAM does not allow the input of multiple performance degradation rates. Thus, in order to analyze PVs installed in different years at the same time, it is indispensable to devise a way to incorporate corrections for performance degradation as shown in the flowchart in Figure 2.

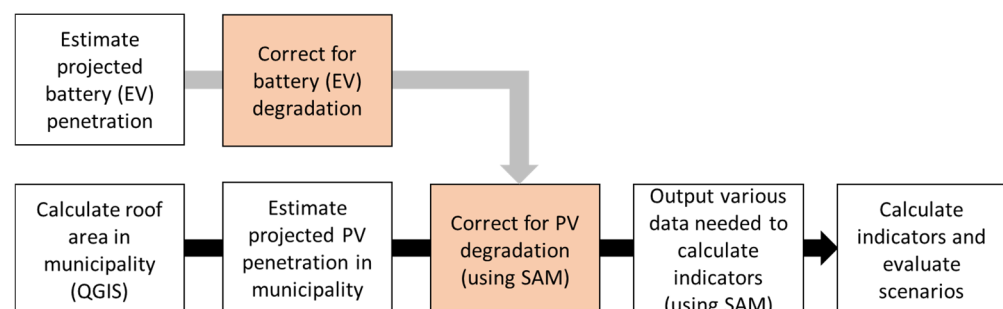


Figure 2. Research flowchart for this study.

For this study, we substituted the reduction in power generation due to performance degradation with a reduction in power generation due to a change in PV panel area, based on the assumption that all PVs installed across multiple years have the same degree of degradation. Here, we present the specific methods of correction used to account for the degradation in EVs and PVs. Other parts of the analysis process are described in Section 2.3.

First, we present the correction method used to account for the degradation of EVs over time, shown in Figure 3.

1. Based on the EV penetration rate of 2018 and EV penetration targets for Japan, we calculated the projected EV penetration (explained in Section 2.3) and increase in the number of EVs for each year.
2. We multiplied the number of EVs added in 2018 by the battery capacity and output per EV to calculate the increase in battery capacity and output in 1 year. For our calculations, we also assumed a battery degradation rate of 1% per year (monotonic decrease) and a useful EV life of 15 years (since EVs are treated as batteries in our analysis; 15 years is the typical life of storage batteries) [44,45]. We also calculated battery capacity and output up to 2033.
3. The process described in step 2 was performed for all years from 2019 to 2050.

4. We summed up the battery capacity and output determined in step 3 and summed them up for all years of the study period to compute total battery capacity and output, taking into account the yearly degradation rate.

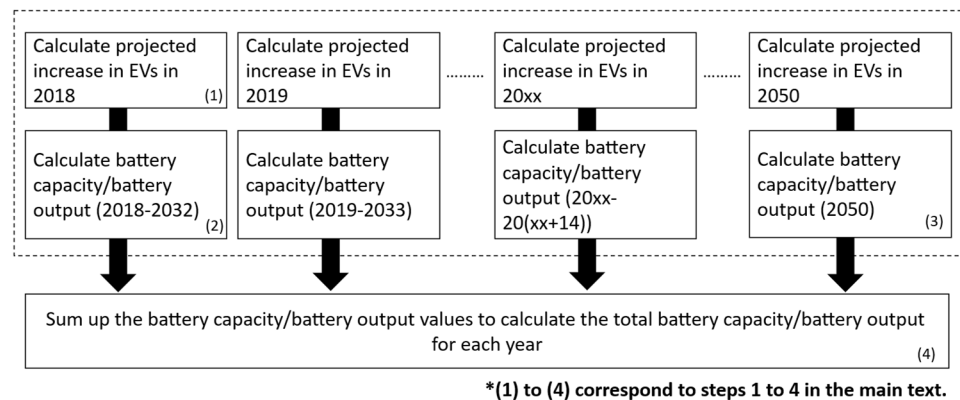


Figure 3. Procedure to correct for EV degradation.

Next, we describe the method used to correct for PV degradation. This is different from the correction method used for EVs. Since SAM allows detailed settings for different modules and inverters, we used SAM to correct for PV degradation over time.

The procedure is described below, where Figure 4 shows the correction procedure:

1. We entered various data inputs into SAM, including PV panel sizes and panel installation costs for PVs installed in 2018 (explained in Section 2.3), to obtain as output their total annual power generation. Since we also entered the degree of PV degradation and the number of years until disposal into SAM, the total annual power generation for each year until PVs are disposed of (20 years for PVs installed in 2018) could be output automatically.
2. The process described in step 1 was repeated for every year from 2019 to 2050.
3. We summed up all the values determined in step 2 to calculate total annual PV power generation for each year with performance degradation taken into account.
4. From the total annual power generation calculated in step 3 using SAM, we back-calculated PV panel size in the converted state (i.e., the corrected PV installed capacity).

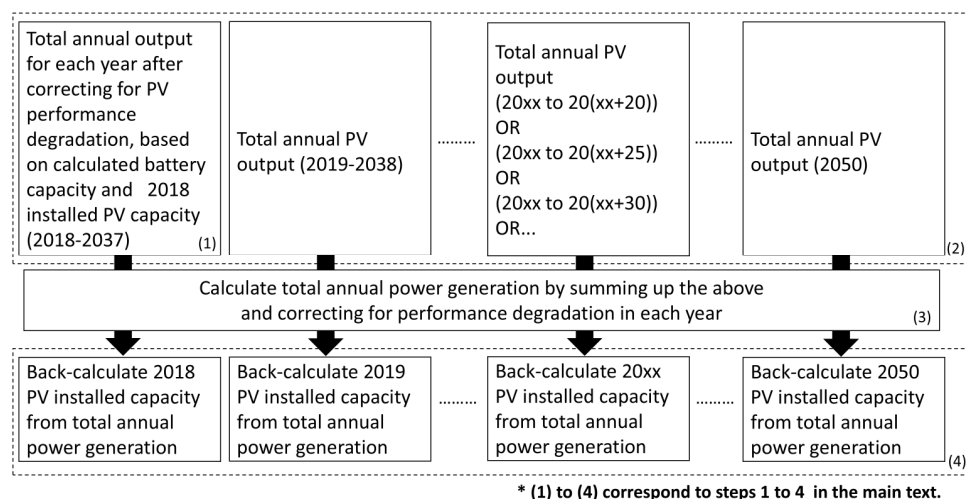


Figure 4. Procedure to correct for PV degradation.

2.3. Calculating EV and PV Diffusion and Cost Projections

Here we discuss the EV and PV diffusion projections used in the analysis described in Section 2.2.2. As shown in Figure 5, we calculated EV diffusion projections using a polynomial approximation based on three points: the EV penetration rate in Japan in 2018, and the EV penetration targets for 2030 and 2050 announced by the Ministry of Economy, Trade and Industry (METI) and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (i.e., 30% in 2030, 100% in 2050) [20]. The annual increase in the number of EVs for each year was then computed based on the total number of vehicles in Suita City in 2018.

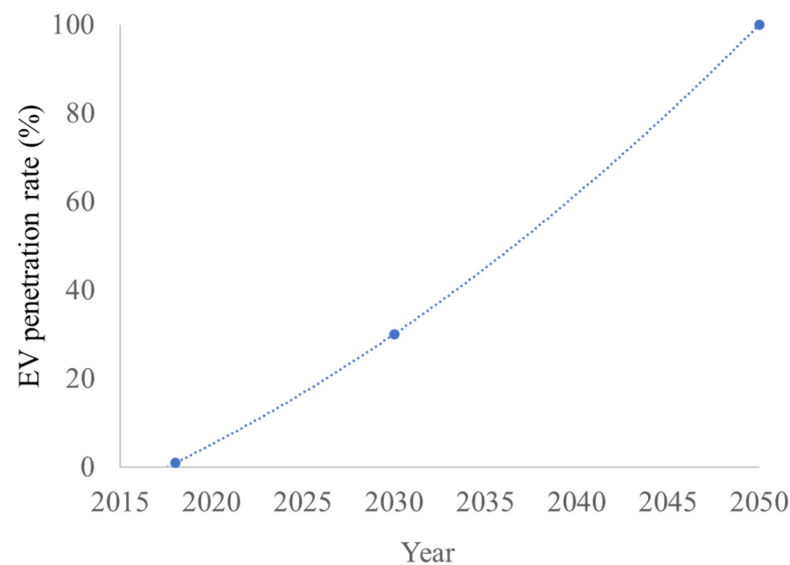


Figure 5. Projection for EV penetration.

We calculated EV cost projections based on U.S. EV cost trends provided by Bloomberg New Energy Finance (NEF) and actual EV prices in Japan. The mean EV cost in the U.S. in 2018 ranged from \$35,000 to \$40,000 [46]. For this study, we also used data from Nissan Motor Co., Ltd.'s Leaf (model) EV. The purchase price of a Nissan Leaf in 2018 in Japan was \$33,720 to \$38,020, based on an exchange rate of 110 JPY/USD. This indicates that EV prices in the U.S. and Japan were quite similar. We calculated the cost trend of a Nissan Leaf up to 2030 using BloombergNEF data and the purchase price of a Nissan Leaf.

The projected size and installation cost of PV panels installed in Suita City were calculated using panel diffusion and disposal projections and installation cost projections for Japan, provided by RTS Corporation [47]. Since these forecast data applied to Japan as a whole, it was necessary to adapt them to the characteristics of Suita City.

Specifically, it was necessary to reduce the PV panel installation size projection to the scale of Suita City. In this study, the following procedure was used to reduce the scale of installation: (1) the theoretical total available roof area of Suita City was calculated from the aerial photograph of Suita City shown in Figure 1 using the QGIS software; (2) it was assumed that the total effective roof area on which PV systems can be installed was 70% of this total theoretical roof area, due to shade and other factors relating to the positions of buildings; (3) using SAM, we calculated the total PV capacity when PV systems are installed on all effective roof space; and (4) we divided the calculated PV capacity by the PV capacity in 2050 in the data obtained from RTS Corporation [47] to compute the reduction rate. According to the QGIS computation results, the total roof area of Suita City is 7.07 km². We calculated the total PV capacity when PV systems are installed on 70% of this total roof area to be 1 GW. In comparison, according to the forecast of RTS Corpora-

tion, total PV capacity in Japan in 2050 will be 486 GW, resulting in a reduction rate of 1/486 (for scaling down data to Suita City).

PV installation costs also needed to be adapted according to the housing patterns of the case study area, Suita City, Osaka Prefecture. The PV installation cost projections of RTS Corporation [47] were divided into four cost categories based on the scale of installed capacity: residential PV systems, small-scale PV systems, medium-scale PV systems, and large-scale PV systems. Interviews with Suita City officials regarding the patterns of housing in Suita City revealed that the ratio of detached homes to apartment buildings was 3:7, indicating that apartment buildings account for a large proportion of homes. Consequently, we applied the following calculation formulas in this study using cost projection for residential PV and small-scale PV systems.

$$\begin{aligned} [\text{Installed cost projection}] &= [\text{Residential PV system cost projection}] \times 0.3 \\ &+ [“\text{Small-scale}” \text{ PV system cost projection}] \times 0.7 \end{aligned} \quad (1)$$

2.4. Evaluation Indicators and Calculation Methods

To evaluate the impact of technology diffusion in this study, we followed [17] by using the following five indicators: CO₂ emission reduction, cost saving, self-consumption, self-sufficiency, and energy sufficiency. Detailed explanations of these five indicators are given below.

2.4.1. CO₂ Emission Reduction

CO₂ emission reduction is the most important indicator for local governments when making policy decisions aimed at carbon neutrality. In this study, this indicator specifically refers to the CO₂ emission reduction rate when PV or V2H systems are deployed in Suita City, relative to the 2018 level. This CO₂ emission reduction rate is calculated as follows:

$$[\text{CO}_2 \text{ emission reduction rate}] = \frac{A - B}{A} \quad (2)$$

where A and B are, respectively, CO₂ emissions from electric power generation in 2018 and after system deployment. For A, we refer to the annual power consumption of Suita City in 2018. On the other hand, B is affected by several factors, but for this study, we made use of a concept known as “Scope 1, 2, and 3 emissions” [48]. “Scope 1” refers to the direct emissions from a company’s own processes, such as its direct use of fuel; “Scope 2” refers to indirect emissions from the company’s use of electricity and heat supplied by other companies; and “Scope 3” refers to all other emissions (apart from Scope 1 and Scope 2) when the company’s supply chains and product life cycles (LC) are taken into account. In this study, we consider CO₂ emissions generated within Suita City and outside Suita City separately; that is, we consider two cases: only “Scope 1 and 2” emissions and all emissions (i.e., “Scope 1, 2, and 3” emissions). Firstly, the life cycle for motor vehicles is assumed to be as shown in Figure 6. The factors that are assumed to influence CO₂ emissions for EVs and gasoline vehicles are shown in orange. These two factors are defined as follows:

C: Emissions from gasoline use (while driving) (Scope 1)

D: Difference in emissions from raw material mining, smelting, and manufacturing processes (Scope 3)

C was calculated by multiplying the CO₂ emissions from motor vehicles in 2018 by the future proportion of gasoline vehicles. D was calculated by multiplying the difference in CO₂ emissions between the production of one EV and one gasoline vehicle by the projected number of future EVs. In this study, we used data for the LEAF, an EV produced

by Nissan Motor Co., Ltd. The LEAF is classified as a compact vehicle. Manufacturing one compact EV emits approximately 6.7 t more CO₂ than manufacturing a gasoline vehicle of the same size, and 6.3 t of extra CO₂ is also emitted during maintenance due to battery replacement (Nissan's standard replacement period is 8 years) [49]. Although the amount of CO₂ emissions generated in EV production is expected to fall over the coming decades, we assumed this difference to remain constant throughout our calculation period. Furthermore, in our analysis, we calculated the CO₂ emitted in the process of motor vehicle manufacturing using the number of vehicles in operation in the particular year, not the number manufactured that year. There are two reasons for this: the transition in the penetration of vehicles manufactured before 2018 is unknown; and there is thought to be a strong correlation between the number of vehicles in circulation and the number of vehicles manufactured because the number of products manufactured is optimized to meet market demand. For PV systems, we assumed the LC shown in Figure 7. The orange-colored boxes in the figure are the processes that would emit CO₂. The total emissions over their life cycle are estimated to be between 17 and 48 CO₂/kWh, and since installation and maintenance are performed by humans, such as suppliers, it can be said that most of the emissions are related to Scope 3 [50]. For this study, we used the maximum value of this range, 48 g-CO₂/kWh, to calculate total emissions E. Additionally, the amount of CO₂ emissions generated by power producers, F, changes when PV power generation is used. To calculate the amount F, we multiplied the amount of electricity generated obtained as output from SAM by the amount of CO₂ emitted per unit of generated power, a statistic published by every power producer (Scope 2). Then B is calculated as follows:

$$B = C + F \text{ (Scope 1 and 2 emissions)} \quad (3)$$

$$B = C + D + E + F \text{ (Scope 1, 2, and 3 emissions)} \quad (4)$$

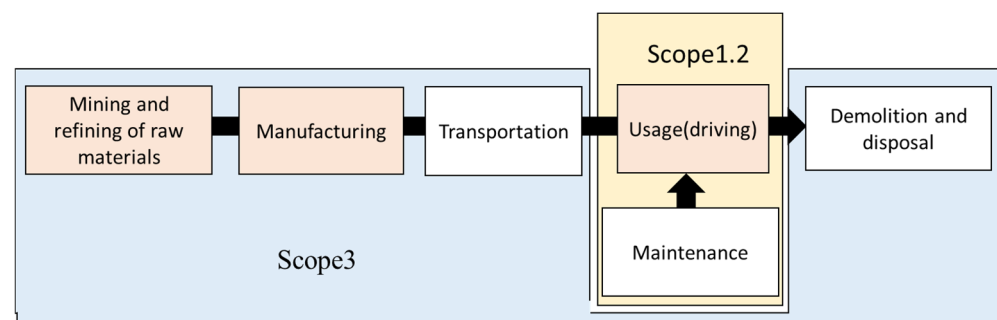


Figure 6. Vehicles' life cycle.

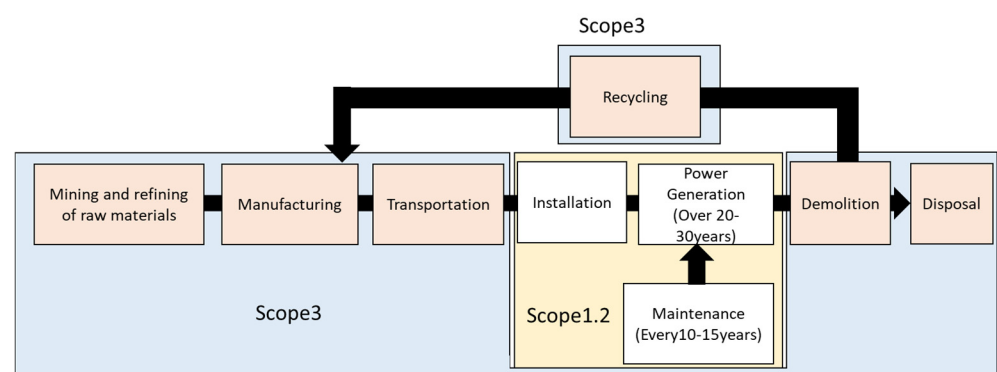


Figure 7. PV system life cycle.

2.4.2. Cost Saving

When measures to promote carbon neutrality are considered, it is also important to look at costs. The cost saving enabled by these technologies is as follows:

$$[\text{Cost saving}] = \frac{G}{H} \quad (5)$$

- G: Relevant cost after system deployment in Suita City
- H: Relevant cost in Suita City (2018)

Here, “relevant cost” refers to the costs associated with generating electric power to supply the electric power consumed within Suita City and the consumption of gasoline by automobiles in Suita City. Next, we can eliminate costs that do not change after the deployment of the system. Let ω be the net change in cost (increase or decrease) that results from the introduction of the system. Then, cost savings can be expressed as follows:

$$[\text{Cost saving}] = 1 - \frac{H + \omega}{H} \quad (6)$$

Here, ω is the sum of all the following cost components:

PV installation cost,

PV removal cost,

Cost due to decrease in electric power generation by power producers $\times (-1)$,

EV cost – gasoline vehicle cost,

Future cost reduction due to not using gasoline $\times (-1)$,

V2H system cost,

V2H construction cost.

Costs with a minus sign are cost reductions. Of the seven costs listed above, the PV installation cost, PV removal cost, and cost due to decrease in electric power generation by power producers are calculated automatically by SAM. We will now describe the calculation methods for the remaining four components. First, we explain the calculation method for the cost difference between gasoline-powered vehicles and EVs. According to BloombergNEF, the cost of EVs is expected to fall below that of gasoline vehicles in 2025 [46]. We therefore assumed the cost of EVs in 2025 to be equal to that of gasoline vehicles. Table 2 shows the cost difference between gasoline vehicles and EVs from 2018 to 2030, based on the EV price trends calculated in Section 2.3. However, from 2030 onward, the cost difference in the analysis was assumed to be constant. For the future cost savings due to not using gasoline, I , we calculated costs using the following formula:

$$I = \frac{J \times K \times L}{M} \quad (7)$$

J: No. of vehicles as of 2018

K: Average driving distance in Japan

L: Gasoline cost/L

M: Vehicle fuel consumption

The costs of V2H systems and construction were calculated by multiplying the system unit cost and construction cost by the projected number of households in the municipality. Because Nichicon Corporation currently has the largest market share for V2H systems in Japan, we took the price of the company’s standard model (¥498,000/unit) as our unit system cost [51]. We set the installation cost at ¥300,000/unit, which factors in the subsidy currently implemented by Japan’s Ministry of the Environment and METI [52].

Table 2. Cost difference between gasoline vehicles and EVs in Japan from 2018.

Year	Cost Difference (USD)
2018	10,174.35
2019	8430.21
2020	6686.07
2021	5287.15
2022	3851.86
2023	2162.96
2024	474.07
2025	0
2026	−474.07
2027	−912.15
2028	−1350.21
2029	−1756.23
2030+	−2162.24

2.4.3. Self-Consumption

The indicator that has drawn the most interest in the field of PV power generation in recent years is “self-consumption” in Japan. This is a measure of the proportion of electricity generated by a PV system that can be consumed onsite. This indicator started to attract attention after the revision of the national feed-in tariff (FIT) scheme. Under the FIT scheme, electric power producers purchased the surplus power generated by PV systems at a generous fixed price. In recent years, however, the price paid for surplus PV power has dropped dramatically, so the benefit to PV system owners of selling their surplus power has evaporated. Therefore, to reduce their surplus power as much as possible, PV system owners have increasingly looked to maximize the self-consumption rate. Whereas self-consumption rate is an indicator that applies to a single building, self-consumption is an indicator that applies more broadly to an entire municipality. Furthermore, self-consumption rate applies to a day, whereas self-consumption applies to a whole year. Self-consumption is calculated as follows:

$$[\text{Self-consumption}] = \frac{(N + O) \times 24 \times 365}{P} \quad (8)$$

N: Quantity of PV-generated electricity that is self-consumed [kW/h]

O: Quantity of electricity stored in EVs by V2H [kW/h]

P: Total annual PV-generated electricity

Note that the values of N, O, and P are the data output by SAM.

2.4.4. Energy Sufficiency

When a municipality implements a policy to install PV systems, it needs to know how much electricity can be generated by installing PV panels on the roofs of buildings in the municipality. “Energy sufficiency” is an indicator that shows how much of the city’s total electricity consumption can be covered by PV power alone. This indicator is calculated as follows:

$$[\text{Energy sufficiency}] = \frac{P}{Q} \quad (9)$$

Q: Quantity of electricity consumed in 2018

If the value of this indicator is 1 or higher, the municipality can potentially provide for 100% of its electricity consumption needs while using only PV power.

2.4.5. Self-Sufficiency

To increase the self-consumption rate, it is necessary to reduce the proportion of electricity generated by PVs that cannot currently be used. The associated indicator is “self-sufficiency,” which represents the efficiency of electric power use. This indicator is the proportion of the total electricity consumed in the municipality that is covered by power supplied from PV generation or EV storage. It is calculated as follows:

$$[\text{Self-sufficiency}] = \frac{[N \times 24 \times 365] + [O \times 24 \times 365]}{Q} \quad (10)$$

The second term in the numerator represents the total annual quantity of PV-generated electricity used to charge EVs. The value of this indicator can never exceed 1, but a higher value indicates that PV-generated electricity is used more efficiently.

3. Results

The results of our evaluation of the impact of the gradual diffusion of V2H in Suita City up to 2050, based on the five indicators explained in Section 2 above, are shown below. These evaluations refer to two diffusion scenarios based on projections provided by RTS Corporation [47]. Scenario (a) is the “current growth case,” under which policies, deregulation, and technological development are extrapolated into the future along their current growth paths. Scenario (b) is the “accelerated deployment case,” under which government ministries and agencies, and prefectural governments implement ambitious policies, along with substantial deregulation and smooth development of various peripheral technologies to accelerate deployment of the technologies. These two scenarios are defined by eight environmental factors and 26 sub-factors. Since V2H is a system that supplements PV systems with an energy storage function (that they usually lack), we also assessed the impact when there is diffusion of only PV systems, enabling us to estimate the difference that EVs and V2H can make.

Figure 8 shows the results for the CO₂ emission reduction scenario that considers only Scope 1 and 2 emissions under Scenarios (a) and (b). Figure 9 shows the results for the CO₂ emission reduction scenario that considers Scope 1, 2, and 3 emissions under both diffusion scenarios. Let us first compare Figures 8a and 9a and Figures 8b and 9b, respectively. The magnitude of the differences between the two figures gradually increases with time, exceeding 10% by 2050. This demonstrates that it is necessary to consider the impact of Scope 3 emissions on total emissions. Next, let us focus on Scenarios (a) and (b) in Figure 9, when indirect emissions are considered. Under both scenarios, the emission reduction is higher for “PV only” than for “PV/EV/V2H” from 2018 to around 2035. This is explained by the fact that more CO₂ emissions are generated in manufacturing EVs than in manufacturing gasoline vehicles. It is also notable that in the case of “PV/EV/V2H,” there is a dip in emissions around 2025. This is due to the CO₂ emissions generated in the manufacture of replacement batteries used during EV maintenance. On the other hand, the emission reduction in the case of “PV/EV/V2H” overtakes that of “PV only” around 2045 under Scenario (a) and around 2038 under Scenario (b). The difference between the two cases then becomes especially large under Scenario (b).

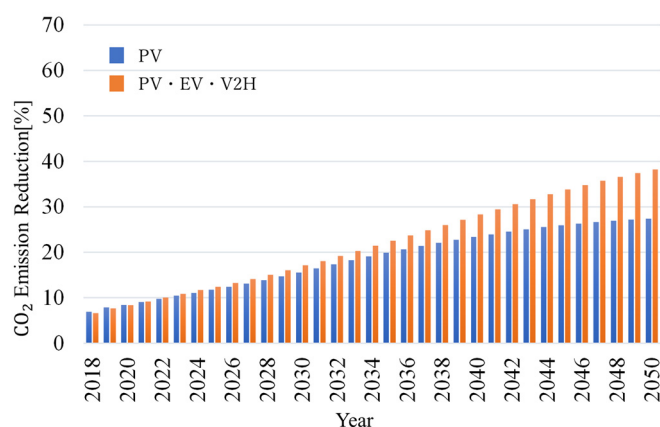
Figure 10 shows the cost-saving results under both diffusion scenarios. Let us first focus on the “PV only” case. The cost saving increases at an approximately constant rate until around 2030, but then its rate of increase gradually drops off, finally flattening out at about 10% under Scenario (a) and 12% under Scenario (b). The reason for this is that although the installed capacity of PVs and total power production both keep increasing, without an energy storage system, the quantity of usable electricity does not change. Next, we turn our attention to the case of “PV/EV/V2H.” Initially, the cost saving rate is not just lower than that of the “PV only” case, but also negative. This is due to the high initial cost

of installing V2H systems. The cost of a single V2H system (Nichicon Corporation's standard model) assumed for this scenario is approximately ¥800,000, including installation costs, which is more than the cost saving achieved by the system. However, as the years progress, the cost saving exceeds the initial system cost and turns positive around 2025 under both diffusion scenarios. By 2050, the year of carbon neutrality, the cost savings with "PV/EV/V2H" are more than 25% in the accelerated diffusion scenario (Figure 10b) and are much higher than those from "PV only." Thus, in terms of cost saving, the adoption of complete PV, EV, and V2H systems offers a better long-term impact.

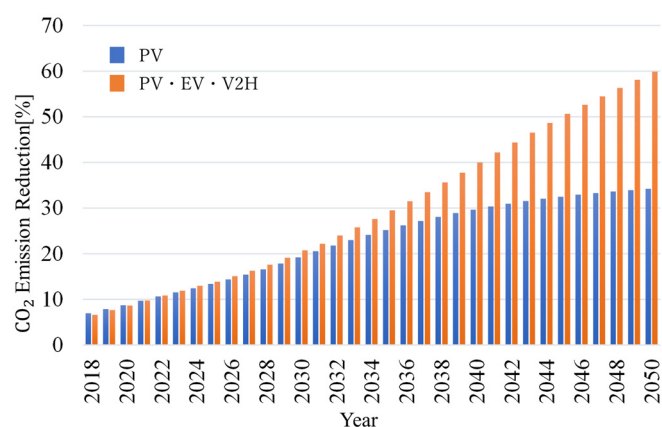
Figure 11 shows the results of self-consumption under both penetration scenarios. Two sudden changes in self-consumption occur in the "PV/EV/V2H" case. This is because 2025 and 2030 are years when PV panels are replaced. Note also that the value of self-consumption should essentially be 100% to begin with, and it should be higher in the case of "PV/EV/V2H" than in the case of "PV only." However, the graph shows that until around 2040, self-consumption is higher for "PV only" than for "PV/EV/V2H." The reason is that, in our analysis of the "PV/EV/V2H" case, the power consumed when a V2H system is used (i.e., power for storage and discharge) is not included in the calculated power consumption. The same phenomenon can be observed with the following two indicators (energy sufficiency and self-sufficiency) too, for the same reason. In the figure, we see that self-consumption initially remains approximately constant, but in the case of "PV only," it gradually starts declining at around 2030. The rate of decline is particularly dramatic under Scenario (b). The reason is that, since there are no EVs to serve as storage batteries, surplus electricity that is generated during the day cannot be consumed, thereby driving down the self-consumption rate.

Figure 12 shows the results for energy sufficiency under both diffusion scenarios. Since this indicator represents the total quantity of electricity generated by PV systems in the whole municipality, EVs (storage batteries) do not make any real impact. Consequently, the values of energy sufficiency for the "PV only" and "PV/EV/V2H" cases are almost identical. The difference between the two scenarios is the rate at which the power generation capacity increases. Under Scenario (a), energy sufficiency reaches around 35%, whereas under Scenario (b), it reaches around 60%. This means that even if PV panels were to be installed on all available roof space in Suita City under Scenario (b), with progressive deregulation and development of peripheral technologies, the remaining 40% of electricity would still need to be generated in other ways.

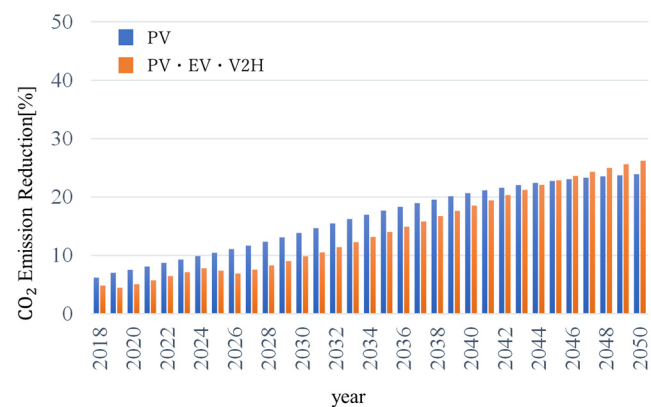
Figure 13 shows the results of self-sufficiency under both diffusion scenarios. We can see that for the "PV only" case, the rate of increase in self-sufficiency gradually decreases from the beginning. In contrast, in the case of "PV/EV/V2H," the rate of increase in self-sufficiency does not change significantly under either of the two diffusion scenarios. For "PV/EV/V2H," the power generated by PV can be used to charge EVs, which means that the power utilization rate remains high, even as the installed capacity of PV systems increases. Accordingly, if self-sufficiency can be increased while keeping the energy sufficiency value high, the power generated by all PV panels in the municipality can be used efficiently, and the self-consumption value described in Section 2.4.3 can be kept high.



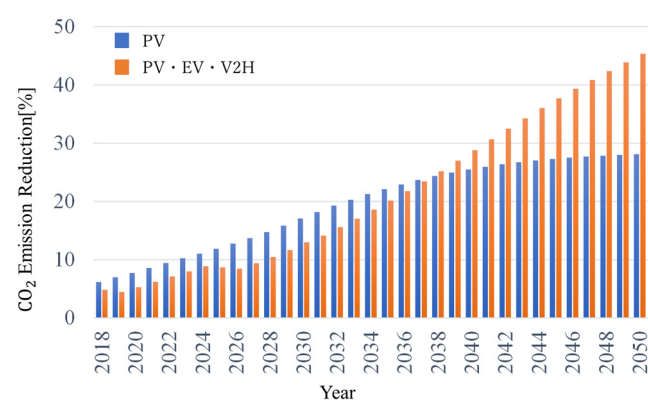
(a) Current growth case



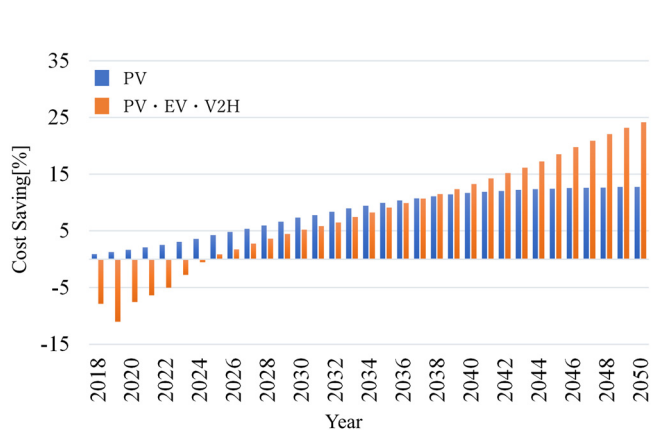
(b) Accelerated deployment case

Figure 8. CO₂ emissions reduction (Scope 1 and 2).

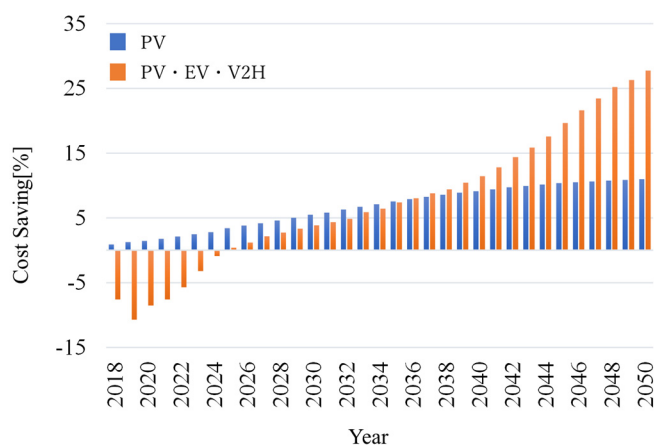
(a) Current growth case



(b) Accelerated deployment case

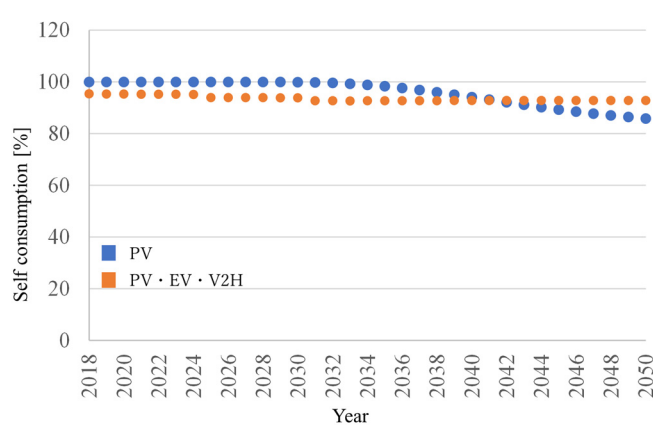
Figure 9. CO₂ emissions reduction (Scope 1, 2, and 3).

(a) Current growth case

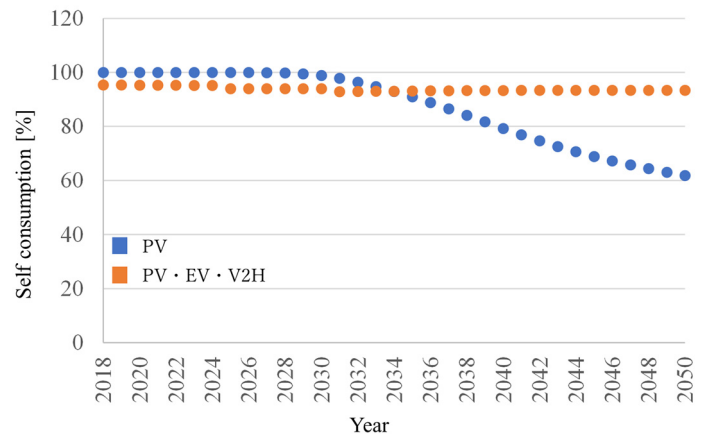


(b) Accelerated deployment case

Figure 10. Cost saving.

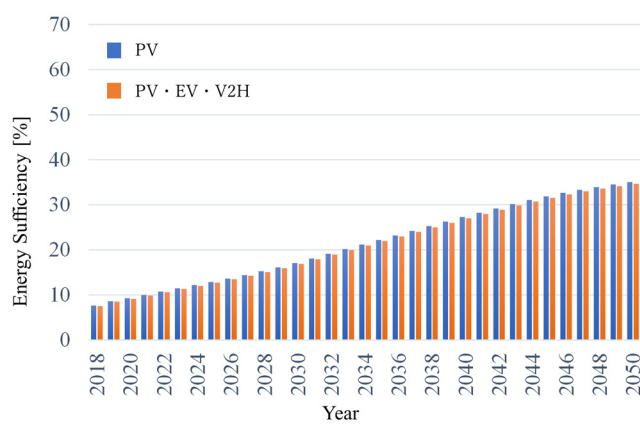


(a) Current growth case

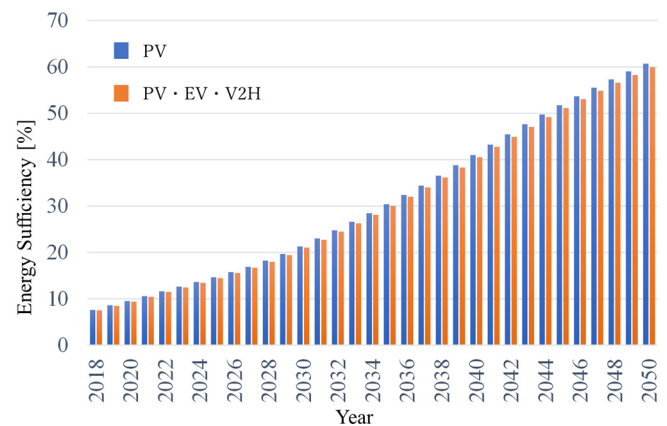


(b) Accelerated deployment case

Figure 11. Self-consumption.

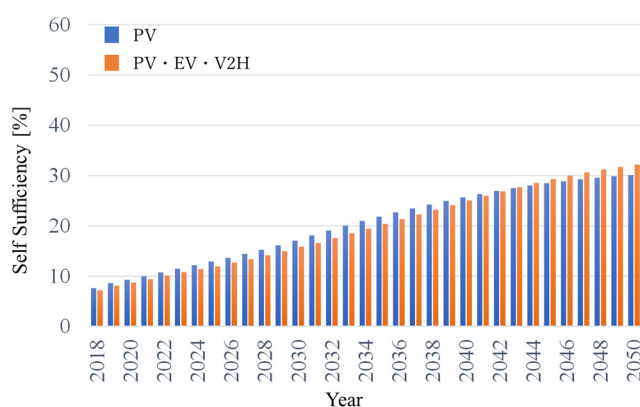


(a) Current growth case

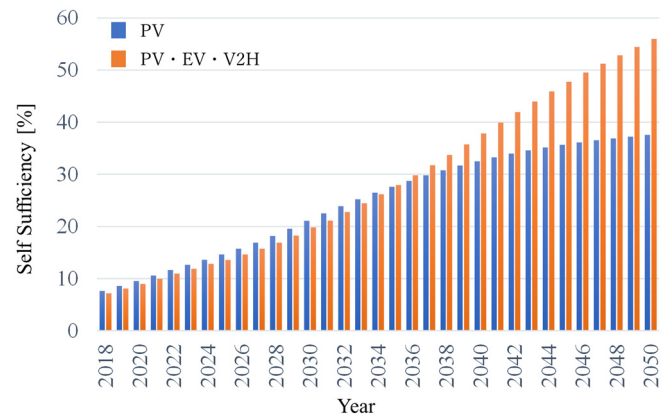


(b) Accelerated deployment case

Figure 12. Energy sufficiency.



(a) Current growth case



(b) Accelerated deployment case

Figure 13. Self-sufficiency.

4. Discussion

We argue that the current challenges of SAM-based techno-economic analysis to be as follows: (1) it has not evaluated the gradual (year-by-year) diffusion of technologies such as PV; (2) it has been limited to mid-term evaluation until around 2030, whereas

long-term evaluation until 2050 is required to address carbon neutrality issues; and (3) the scope of the evaluation needs to be expanded. To address these issues, a case study was conducted in Suita City to increase the applicability of techno-economic evaluations using SAM.

When evaluating the impact of the diffusion of these technologies with a view to the 2050 goal, the results indicate that up to 2030, there was greater benefit in diffusing “PV only” than “PV/EV/V2H” for all indicators except energy sufficiency. On the other hand, from the late 2030s onward, the benefits of “PV/EV/V2H” increase significantly. This indicates the importance of evaluating the benefits of technology implementations using the carbon-neutral target year of 2050, as opposed to only making medium-term projections. More specifically, while the adoption of PV technology can be expected to offer immediate benefits and produce CO₂ emission reductions in the medium term, its contribution to long-term CO₂ emission reductions is low. On the other hand, although the implementation of EVs and V2H, in addition to PVs, requires a large initial investment, once diffusion of systems is achieved, they could offer various future benefits from multiple perspectives, due to synergies between the technologies. A study [24] conducted a techno-economic analysis in Kyoto City and found that PV + EV systems could save energy costs by 22–37% in 2030. However, the analysis is only conducted up to 2030. The fact that we have made a long-term assessment up to the year 2050 is an important contribution of our study.

Furthermore, even if the three energy technologies discussed in this paper were deployed at the maximum rate, it would be impossible for Suita City to achieve a 100% reduction in CO₂ emissions at this time. Therefore, when making policy decisions, local governments need to consider a variety of technologies, mechanisms, and systems, rather than focusing only on the three renewable energy technologies discussed here. We also show that the final CO₂ emission reduction rate that can be achieved is greater than 20%. Under the “current growth” scenario, the reduction amounts to 40%, compared to 60% under the “accelerated deployment” scenario. This means that even if no change is made to the current course of action, CO₂ emissions will be cut by 40%. Therefore, when local governments consider promoting the deployment of these renewable energy technologies for the sake of carbon neutrality, they should adopt flexible measures and actions based on a thorough understanding of the current situation from a broad perspective, taking into consideration not only technological innovation but also deregulation and the development of various peripheral technologies.

Finally, although we focused on Suita City in this study, the shapes and densities of buildings in the many other urban areas of Japan are not significantly different. Nor is there any great variation in daylight hours across Japan by location, due to the small size of the country. We can therefore suppose that our findings for Suita City can be applied with similar long-term impact to most other municipalities in Japan. Thus, the method proposed in this study can be considered to have a certain degree of versatility, provided data on the essential characteristics of the specific municipality, such as roof area, can be obtained. In addition, the long-term projections of the diffusion of promising technologies and the evaluation of their impacts presented in this study can be expected to serve as useful tools for the formulation of policy design aimed at achieving carbon neutrality and taking the interests of future generations into consideration. On the other hand, we expect other municipalities to have different characteristics. We will therefore need to focus on multiple other municipalities to determine the elements necessary for analysis. As explained in the case study results in Section 3, we estimated the approximate total area of Suita City available for the installation of PV systems, but to obtain more accurate analysis results, we need more realistic, fine-grained calculations. Specifically, we need to correctly perform the following three tasks: (1) investigating areas where PV systems cannot be installed, such as rooftop parking lots of commercial facilities, in greater detail; (2) con-

sidering the installation of PV systems on building walls and areas of ground (instead of only roofs, as in this study); and (3) determining the cost of V2H and other technologies more accurately for each of the specific cases of detached houses, apartment buildings, office buildings, and other building types. We will also need to refine the map information and data to calculate the total area for PV installation more accurately.

As described in the Introduction, Future Design practices have been conducted in various policy fields. The present study has also been used as a reference for Future Design practices by policymakers in Suita City, the case study area in 2022 [34]. In the future, it is essential to develop assessment methods for renewable technology diffusion, assuming that they will be referred to in actual decision-making and the design of policies for carbon neutrality. We also argue that the proposed assessment methodology and the results of the study should have implications for the international policy discussion on carbon neutrality.

While this study provides a novel year-by-year assessment of PV, EV, and V2H integration in an urban context, several avenues for future research remain. First, the model can be extended to incorporate more granular spatial data, such as building-specific rooftop availability [53], solar radiation, and shading effects, to improve the accuracy of photovoltaic potential assessments [54]. Second, future studies should explore behavioral dynamics, including household adoption rates, charging patterns, and energy consumption changes over time, which can substantially influence the realized benefits of technology deployment [55]. Third, integrating additional technologies, such as stationary batteries, heat pumps, hydrogen, and peer-to-peer electricity trading, would provide a more holistic view of future energy systems [56–58]. Fourth, expanding the analysis to include multiple municipalities with diverse climatic, economic, and demographic profiles would help generalize findings and support regional energy planning. Finally, stronger coupling with participatory planning processes, including deliberative Future Design approaches [33], would enhance the practical value of scenario-based assessments for real-world policy creation.

5. Conclusions

In this study, we developed a method for multidimensional evaluation of the future impacts of the diffusion of energy technologies at the municipal level through 2050, including CO₂ reduction and economic efficiency. We also evaluated these impacts in a case study focused on Suita City, Osaka Prefecture. The results of our scenario evaluations showed that although the deployment of multiple energy technologies for carbon neutrality is subject to high initial costs, significant long-term benefits can be achieved, both in terms of CO₂ reduction and cost savings. We also argue that from around 2035 onward, the deployment of three technologies, PVs, EVs, and V2H, yields greater benefits than the adoption of PVs alone. To help realize a more sustainable society, it is therefore important to promote the deployment of these technologies from a long-term perspective, despite their initial investment costs. This finding suggests that when local governments promote PVs as part of a carbon-neutral policy, it is also important to promote technologies that offer energy storage functions, such as EVs and V2H, to complement PVs. Since the diffusion of EVs is expected to accelerate in the coming years, V2H adoption is likely to grow, even if PV diffusion is sluggish. It is important for local governments to be aware of such current and emerging technological innovations when considering relevant policies. We also showed that even if PV systems were employed on the maximum scale in Suita City, it would still be impossible to generate enough electricity to supply the current level of consumption. Thus, our quantitative evaluation indicates that when local governments are making policy decisions, they need to examine and adopt a variety of technologies, mechanisms, and systems.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The necessary input data were entered into SAM to generate the output data used to generate the diffusion impact as shown in Section 2. The names of the data items, their values, and designations are shown in Table A1. The numerical values for each data item were basically taken from [59]. In SAM, the number of data items to be entered varies depending on the variables considered, for example, the introduction of FIT. Therefore, some variables are not entered into SAM; all variables not included in the table are treated as having the value 0. Next, using the data generated by SAM, we analyzed the five evaluation indicators described in Section 2.4 and created scenarios for predicting the penetration of technologies for promoting carbon neutrality. Table A2 lists the data items output by SAM that were actually used for scenario evaluations. The data items global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) are described below under *1. The data item ground coverage ratio (GCR) is explained under *2.

Table A1. Data entered into SAM.

Item Name	Data Name	Value/Designation
Location and Resource	GHI (2018) to Suita City	*1
	DNI (2018) to Suita City	
	DHI (2018) to Suita City	
Module	PV module	SunPower SPR-X21-335-BLK
Inverter	PV inverter	SMA America:SB3800TL-US-22 [240V]
System Design	Projected size of PV panels installed in Suita City [kWdc]	See Section 2.
	DC/AC conversion ratio [-]	1.2
	Angle of PV installation from horizontal [°]	30
	PV installation direction: South [°]	180
	GCR [%] *2	30
Shading and Layout	PV aspect ratio (width/height)	1.7
Losses	AC/DC conversion loss	Losses due to module malfunction [%].
		Loss with bypass diodes [%]
		Losses due to DC wiring [%]
Battery Storage	Battery capacity [kWh]	See Section 2.

	Projected EV penetration (no. of EVs)	Battery output [kW]
	Capacity when storage battery is fully charged [Ah]	56.3
Lifetime and Degradation	DC annual degradation rate [%]	0.5
System Cost	PV installation cost [USD/Wdc]	See Section 2.
Financial Parameters	No. of years of PV use (2018 to 2025)	20
	No. of years of PV use (2025 to 2030)	25
	No. of years of PV use (2031 to 2050)	30
	PV performance degradation rate (%/year)	3
	Municipal property tax valuation rate (%/year)	100
Electric Load	Scaling factor	12.514

Table A2. Data items used for scenario evaluation in the context of Suita City.

Data Name	Value
Annual electricity consumption in Suita City (2018) [GWh/year]	1845
No. of passenger cars in Suita City (2018)	146,643
Annual CO ₂ emissions in Suita City (2018) [10,000 t-CO ₂]	172
CO ₂ emissions from power producers [t-CO ₂ / kWh].	0.00044
Gasoline cost [USD/L]	1.29
CO ₂ emissions from gasoline consumption [kg-CO ₂ /L]	2.3
Gasoline vehicle fuel consumption [km/L]	12.60
Driving distance (fuel consumption) of EV [km/kWh]	5.3
Average annual driving distance of cars in Japan [km]	2934
Low-voltage rate of power producers [USD]	0.22
High-voltage rate of power producers [USD]	0.15

*1:

GHI, DNI, and DHI are parameters that measure the amount of solar radiation. The amount of solar radiation indicates the amount of heat received per unit area [J/m²]. DNI is the amount of solar radiation per unit area received by a surface that is always perpendicular (normal) to the rays entering in a straight line from the sun. DHI is the amount of solar radiation per unit area that is scattered by molecules and particles in the atmosphere (rather than arriving directly as rays from the sun) and reaches a surface evenly from all directions. Specifically, DHI represents the total quantity of shortwave radiation received from the sky on the ground and on horizontal surfaces, and it can be determined from GHI and DNI. To estimate the quantity of electric power that PVs can generate in a year, SAM uses an Excel file containing annual average values of GHI, DNI, and DHI at hourly intervals.

*2:

GCR (ground coverage ratio) is the ratio of PV module area to site area. The higher the value of GCR, the more densely the PV modules are installed, resulting in a higher level of land utilization. On the other hand, a higher module density also results in greater inter-row shading, which negatively impacts energy yield. When rows of modules are installed close together, the PV panels in one row tend to cast shade on the PV panels in adjoining rows during the early or late hours of the day.

Appendix B. Data for Figures 8–13

CO₂ Emission Reduction: Scope 1 and 2—(a) Current growth case

Year	PV	PV·EV·V2H
2018	6.946	6.611
2019	7.857	7.651
2020	8.445	8.392
2021	9.086	9.191
2022	9.788	10.052
2023	10.448	10.881
2024	11.091	11.699
2025	11.746	12.394
2026	12.431	13.258
2027	13.131	14.140
2028	13.884	15.076
2029	14.689	16.070
2030	15.564	17.139
2031	16.468	18.063
2032	17.384	19.198
2033	18.259	20.318
2034	19.096	21.443
2035	19.895	22.568
2036	20.656	23.704
2037	21.386	24.852
2038	22.090	26.007
2039	22.759	27.168
2040	23.390	28.324
2041	23.976	29.463
2042	24.535	30.595
2043	25.057	31.712
2044	25.533	32.799
2045	25.954	33.826
2046	26.322	34.793
2047	26.652	35.717
2048	26.936	36.587
2049	27.187	37.416
2050	27.415	38.214

CO₂ Emission Reduction: Scope 1 and 2—(b) Accelerated deployment case

Year	PV	PV·EV·V2H
2018	6.946	6.611
2019	7.857	7.651
2020	8.697	8.630
2021	9.657	9.728
2022	10.608	10.823
2023	11.512	11.881
2024	12.414	12.942
2025	13.340	13.877
2026	14.347	15.038

2027	15.399	16.255
2028	16.567	17.599
2029	17.836	19.075
2030	19.195	20.713
2031	20.508	22.176
2032	21.780	23.945
2033	22.967	25.730
2034	24.107	27.597
2035	25.172	29.489
2036	26.193	31.460
2037	27.146	33.485
2038	28.048	35.605
2039	28.872	37.766
2040	29.622	39.968
2041	30.312	42.166
2042	30.939	44.341
2043	31.512	46.502
2044	32.034	48.624
2045	32.494	50.649
2046	32.905	52.598
2047	33.276	54.477
2048	33.612	56.302
2049	33.922	58.111
2050	34.214	59.899

CO₂ Emission Reduction: Scope 1, 2, and 3—(a) Current growth case

Year	PV	PV·EV·V2H
2018	6.180	4.842
2019	6.991	4.480
2020	7.513	5.081
2021	8.084	5.734
2022	8.708	6.442
2023	9.296	7.123
2024	9.868	7.794
2025	10.451	7.395
2026	11.059	6.891
2027	11.682	7.549
2028	12.352	8.257
2029	13.068	9.015
2030	13.845	9.842
2031	14.648	10.518
2032	15.459	11.402
2033	16.231	12.274
2034	16.966	13.151
2035	17.664	14.029
2036	18.323	14.918
2037	18.951	15.819
2038	19.552	16.725
2039	20.119	17.638
2040	20.649	18.547

2041	21.137	19.442
2042	21.599	20.332
2043	22.025	21.209
2044	22.412	22.060
2045	22.750	22.859
2046	23.042	23.605
2047	23.303	24.314
2048	23.524	24.977
2049	23.719	25.603
2050	23.893	26.203

CO₂ Emission Reduction: Scope 1, 2, and 3—(b) Accelerated deployment case

Year	PV	PV·EV·V2H
2018	6.180	4.842
2019	6.991	4.480
2020	7.738	5.291
2021	8.592	6.209
2022	9.437	7.124
2023	10.242	8.007
2024	11.045	8.894
2025	11.868	8.704
2026	12.764	8.463
2027	13.699	9.417
2028	14.736	10.485
2029	15.858	11.669
2030	17.053	12.998
2031	18.196	14.146
2032	19.288	15.591
2033	20.294	17.051
2034	21.246	18.584
2035	22.119	20.141
2036	22.940	21.767
2037	23.687	23.442
2038	24.373	25.202
2039	24.975	26.997
2040	25.499	28.831
2041	25.965	30.661
2042	26.371	32.471
2043	26.724	34.269
2044	27.032	36.034
2045	27.290	37.712
2046	27.509	39.325
2047	27.696	40.877
2048	27.854	42.381
2049	27.992	43.874
2050	28.114	45.350

Cost Saving—(a) Current growth case

Year	PV	PV·EV·V2H
2018	0.901	−7.862
2019	1.269	−11.026
2020	1.642	−7.568
2021	2.086	−6.370
2022	2.532	−5.035
2023	3.062	−2.761
2024	3.583	−0.527
2025	4.281	0.858
2026	4.812	1.747
2027	5.362	2.779
2028	5.979	3.631
2029	6.629	4.473
2030	7.338	5.228
2031	7.769	5.828
2032	8.358	6.475
2033	8.946	7.445
2034	9.439	8.256
2035	9.939	9.126
2036	10.374	9.906
2037	10.730	10.697
2038	11.101	11.503
2039	11.435	12.361
2040	11.676	13.266
2041	11.881	14.259
2042	12.059	15.190
2043	12.225	16.145
2044	12.363	17.246
2045	12.424	18.535
2046	12.548	19.783
2047	12.592	20.900
2048	12.629	22.082
2049	12.742	23.188
2050	12.772	24.195

Cost Saving—(b) Accelerated deployment case

Year	PV	PV·EV·V2H
2018	0.901	−7.578
2019	1.269	−10.705
2020	1.459	−8.507
2021	1.766	−7.580
2022	2.114	−5.708
2023	2.470	−3.220
2024	2.823	−0.894
2025	3.426	0.413
2026	3.807	1.195
2027	4.188	2.161
2028	4.605	2.750

2029	5.032	3.345
2030	5.480	3.839
2031	5.817	4.360
2032	6.272	4.869
2033	6.724	5.882
2034	7.116	6.423
2035	7.529	7.405
2036	7.902	8.032
2037	8.264	8.809
2038	8.581	9.404
2039	8.918	10.442
2040	9.130	11.443
2041	9.396	12.821
2042	9.731	14.381
2043	9.933	15.857
2044	10.157	17.577
2045	10.361	19.645
2046	10.503	21.622
2047	10.634	23.461
2048	10.754	25.190
2049	10.866	26.280
2050	10.973	27.731

Self-consumption – (a) Current growth case

Year	PV	PV·EV·V2H
2018	99.997	95.421
2019	99.999	95.373
2020	99.998	95.330
2021	100.000	95.296
2022	100.000	95.263
2023	99.997	95.234
2024	99.998	95.206
2025	100.025	94.003
2026	100.000	93.983
2027	100.001	93.965
2028	99.999	93.945
2029	99.980	93.924
2030	99.925	93.905
2031	99.820	92.741
2032	99.632	92.733
2033	99.351	92.727
2034	98.932	92.731
2035	98.393	92.740
2036	97.703	92.757
2037	96.904	92.777
2038	96.044	92.793
2039	95.121	92.817
2040	94.151	92.828
2041	93.174	92.852
2042	92.191	92.861

2043	91.202	92.872
2044	90.253	92.877
2045	89.364	92.872
2046	88.550	92.863
2047	87.794	92.860
2048	87.109	92.853
2049	86.484	92.840
2050	85.899	92.823

Self-consumption – Accelerated deployment case

Year	PV	PV·EV·V2H
2018	99.997	95.421
2019	99.999	95.373
2020	100.000	95.334
2021	100.000	95.305
2022	99.998	95.276
2023	99.998	95.251
2024	99.998	95.231
2025	99.997	94.035
2026	99.991	94.023
2027	99.938	94.011
2028	99.804	94.008
2029	99.505	94.006
2030	98.872	94.028
2031	97.849	92.918
2032	96.436	92.983
2033	94.814	93.035
2034	92.949	93.102
2035	90.975	93.162
2036	88.840	93.215
2037	86.584	93.255
2038	84.196	93.308
2039	81.747	93.334
2040	79.284	93.364
2041	76.940	93.386
2042	74.727	93.395
2043	72.629	93.406
2044	70.666	93.412
2045	68.897	93.406
2046	67.284	93.409
2047	65.797	93.395
2048	64.414	93.387
2049	63.119	93.410
2050	61.896	93.433

Energy Sufficiency – (a) Current growth case

Year	PV	PV·EV·V2H
2018	7.624	7.512
2019	8.624	8.502

2020	9.269	9.142
2021	9.973	9.841
2022	10.744	10.604
2023	11.469	11.324
2024	12.175	12.024
2025	12.890	12.734
2026	13.645	13.483
2027	14.414	14.246
2028	15.241	15.066
2029	16.128	15.947
2030	17.098	16.909
2031	18.110	17.914
2032	19.154	18.949
2033	20.175	19.961
2034	21.189	20.968
2035	22.196	21.968
2036	23.208	22.971
2037	24.227	23.981
2038	25.249	24.991
2039	26.265	26.000
2040	27.272	26.998
2041	28.249	27.966
2042	29.215	28.922
2043	30.160	29.853
2044	31.058	30.742
2045	31.883	31.558
2046	32.633	32.296
2047	33.326	32.974
2048	33.946	33.584
2049	34.510	34.139
2050	35.036	34.654

Energy Sufficiency – (b) Accelerated deployment case

Year	PV	PV·EV·V2H
2018	7.624	7.512
2019	8.624	8.502
2020	9.546	9.415
2021	10.601	10.458
2022	11.644	11.491
2023	12.637	12.474
2024	13.627	13.455
2025	14.644	14.462
2026	15.750	15.557
2027	16.914	16.709
2028	18.222	18.003
2029	19.677	19.443
2030	21.312	21.060
2031	23.008	22.739
2032	24.793	24.503
2033	26.591	26.282

2034	28.472	28.142
2035	30.375	30.024
2036	32.367	31.993
2037	34.419	34.021
2038	36.571	36.147
2039	38.773	38.322
2040	41.015	40.536
2041	43.250	42.741
2042	45.452	44.915
2043	47.631	47.065
2044	49.765	49.166
2045	51.776	51.151
2046	53.688	53.034
2047	55.521	54.838
2048	57.285	56.569
2049	59.000	58.255
2050	60.682	59.909

Self-Sufficiency—(a) Current growth case

Year	PV	PV·EV·V2H
2018	7.624	7.168
2019	8.624	8.109
2020	9.269	8.715
2021	9.973	9.378
2022	10.744	10.102
2023	11.469	10.784
2024	12.175	11.448
2025	12.894	11.971
2026	13.645	12.672
2027	14.414	13.386
2028	15.241	14.154
2029	16.125	14.978
2030	17.085	15.879
2031	18.077	16.613
2032	19.084	17.572
2033	20.044	18.509
2034	20.963	19.444
2035	21.840	20.373
2036	22.675	21.307
2037	23.477	22.249
2038	24.250	23.190
2039	24.984	24.132
2040	25.677	25.062
2041	26.321	25.967
2042	26.934	26.857
2043	27.507	27.725
2044	28.030	28.553
2045	28.492	29.308
2046	28.896	29.991
2047	29.258	30.620

2048	29.570	31.184
2049	29.846	31.695
2050	30.095	32.167

Self-Sufficiency—(b) Accelerated deployment case

Year	PV	PV·EV·V2H
2018	7.624	7.168
2019	8.624	8.109
2020	9.546	8.976
2021	10.601	9.967
2022	11.644	10.948
2023	12.637	11.882
2024	13.627	12.813
2025	14.643	13.599
2026	15.749	14.627
2027	16.904	15.708
2028	18.186	16.924
2029	19.579	18.278
2030	21.071	19.803
2031	22.513	21.128
2032	23.909	22.784
2033	25.212	24.451
2034	26.465	26.201
2035	27.634	27.971
2036	28.755	29.822
2037	29.801	31.726
2038	30.791	33.728
2039	31.696	35.767
2040	32.519	37.846
2041	33.276	39.914
2042	33.965	41.949
2043	34.594	43.962
2044	35.167	45.927
2045	35.672	47.778
2046	36.123	49.539
2047	36.531	51.216
2048	36.899	52.828
2049	37.240	54.416
2050	37.560	55.975

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