



Facilitating a carbon neutral transition in Kyoto: Initiatives on rooftop photovoltaics integrated with electric vehicles

Takuro Kobashi^{a,*}, Eric Zusman^b, Makoto Taniguchi^c, Masaru Yarime^d

^a Graduate School of Environmental Studies, Tohoku University, 468-1, Aoba, Aramaki, Aoba-ku, Sendai, Miyagi, 980-2259, Japan

^b Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan

^c Research Institute for Humanity and Nature, Kyoto, Kyoto, Japan

^d Division of Public Policy and Division of Environment and Sustainability, The Hong Kong University of Science and Technology, Hong Kong SAR

ARTICLE INFO

Keywords:

Urban decarbonization
Rooftop photovoltaics
Electric vehicles
Energy transition
PV + EV

ABSTRACT

With nearly 70 % of the global population expected to live in urban areas by 2050, cities will need to manage energy transitions to achieve ambitious carbon neutrality goals. As the current rate of decarbonization in cities is too slow to achieve these ambitious goals, feasible pathways toward deep decarbonization are becoming increasingly urgent. This paper synthesizes a technical and economic analysis with more qualitative methods (transition theory, thick description, and action research) to examine the potential for a key set of niche technologies to drive carbon neutral transitions in Kyoto, Japan: rooftop photovoltaics (PVs) integrated with electric vehicles (EVs) as batteries at the city scale ("SolarEV City Concept"). The article examines the opportunities and challenges of using the Kyoto Miraimon Project to establish a community-scale "PV + EV" system that can inject momentum into transitions in Kyoto. The platform accelerated transitions by supporting the adoption of innovative technologies and aligning key stakeholder interests around regime-level government climate goals. With increasing EV penetration globally and the rapid uptake of PV technologies, the windows of opportunities for deep decarbonization of cities through rooftop PVs integrated with EVs are gradually opening.

1. Introduction

The evidence is incontrovertible: climate change poses an existential threat to the planet and its people [1–3]. To avert a climate crisis, holding global temperatures below 1.5 °C and reaching carbon neutrality goals by 2050 is critical [4]. While national governments are increasingly heeding this warning, the achievement of net zero goals will often depend on cities. Simply stated, cities will determine whether net zero is aspirational rhetoric or an achievable reality. The pivotal role of cities is evident in estimates that suggest 68 % of the global population will be urban by 2050; this growth is a marked increase from 55 % of the population who lived in cities in 2018 [5]. The centrality of cities is similarly apparent in research showing national governments frequently lack the context-specific knowledge and multi-stakeholder connections required to reach all segments of society and steer transitions alone [6–8]. Finally, the need for urban action is clear in previous studies that suggest that cities and other subnational governments often prove more flexible and innovative in crafting climate solutions than national governments [9–13]. The importance of cities has made its way

into high-level policy statements: the 2023 G7 Hiroshima Leaders' Communiqué, for instance, underlined "the transformative power of cities as drivers for every aspect of sustainable development" [14].

To some degree, how cities harness this transformative power is likely to vary across countries and contexts. More concretely, Japanese cities may face hurdles that differ from more studied European or American cities. Many of these differences can be traced to rapidly declining and aging populations as well as limited land area in Japan [15]. From this perspective, these constraints set Japan apart from other countries. There is indeed no question that Japan's population is shrinking faster than much of the world. A similar claim can be made about the availability of land in Japan. In fact, Japan's efforts to harness renewables for green hydrogen fuels have often focused on investments in Southeast Asia due to limited land. However, when viewed from another perspective, Japan is not as unique as it seems on the surface. For example, many other countries are also adopting bold net zero targets and fashioning multi-level power-sharing arrangements to help cities decarbonize energy systems. One needs to look no further than the G7 to see examples of the growing emphasis on devolution of

* Corresponding author.

E-mail address: takuro.kobashi.e5@tohoku.ac.jp (T. Kobashi).

<https://doi.org/10.1016/j.techsoc.2024.102774>

Received 19 September 2023; Received in revised form 24 November 2024; Accepted 25 November 2024

Available online 26 November 2024

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decision-making authority when it comes to climate policy.

To cite a relevant example of how cities in many countries are moving forward, a core feature of the United States Inflation Reduction Act is that cities and other local governments are expected to apply for fiscal transfers to help reach ambitious national and subnational targets. A similar pattern is also evident in Japan, wherein the national government unveiled plans about five years ago to reach carbon neutrality by 2050 and then followed that up with a sixth basic energy plan that stipulated that greenhouse gas (GHG) emissions should be reduced by 46 % in 2030 from 2013 levels [16]. Japan's renewable energy target for 2030 increased from 22–24 % to 36–38 % in recent years, again underlining the heightened attention to shifting development pathways [16]. Importantly, these policy changes had a significant impact on local governments; many began to develop strategies that would help them achieve carbon neutrality goals in their wake [16–19]. In a slightly different variant on the same theme, some countries have also placed the onus on high-profile cities to set the example for other cities to follow [20]. Paris, for instance, is being held up as a model exemplar in France (and other countries) on how a subnational government can orchestrate a low-carbon transition. In Japan, too, the national government has selected more than 100 leading areas for decarbonization to showcase how frontrunner cities with requisite capacities and additional back-stopping support can move a transition forward [21]. The hope is that a critical mass of lighthouse cities can lead the way and spur replication effects for other cities to follow in many countries [22].

There are also important parallels in the opportunities and challenges to decarbonization in cities across countries [23]. Some of these commonalities relate to the technical and economic feasibility of renewable technologies [19,24,25]. For example, many cities may lack charging stations required to spread electric vehicles or the financing models required to drive down the costs of renewables [26]. These possibly shared constraints on transitions require a deeper understanding of not simply the technical or economic but also the social and institutional feasibility of transformative change [27]. Although techno-economic analyses provide the least-cost pathways [19], they may not be feasible due to real-world factors that are not easily captured in modeling such as social acceptance and multi-stakeholder cooperation [27,28].

In fact, a sizable body of literature has shed light on these factors that are often relegated to the margins of models to demonstrate the potential and constraints on socio-technical transitions. Among the most illuminating of these studies is the work of Geels and others who have developed a multi-level perspective (MLP) [29]. The MLP perspective suggests that transitions require looking at three levels of analysis to understand the drivers and barriers to transforming socio-technical systems: the innovative niche (a technology), the regime (policies/institutions and business patterns), and the exogenous landscape (outside shifts in markets and/or norms) [27]. When actions or changes within these three levels are well-aligned and mutually reinforcing, a window of opportunity could open, allowing a radical shift socio-technical systems.

One of the strengths of this multi-level perspective is its generalizability. That is, it can shed light on not only the technical and economic but also the social and institutional dimensions of transitions in a variety of contexts [27,30]. Another virtue of this perspective is it underlines that starting and sustaining transitions is not easy. Several mutually reinforcing inertias within and across energy, urban, policymaking, and other socio-economic systems can prevent new technologies from breaking through and gaining ground. Yet a third reason that the MLP (and similarly motivated work on strategic niche management) is illuminating is that it suggests the possibility of overcoming these barriers when their mutually supportive pressures are at the lower niche and regime levels. To foreshadow the case study in this paper, those pressures could be created by setting up a platform that helps align the interests of different stakeholders around the installation and spread of rooftop PV systems integrated with EVs as batteries ("PV + EV" or

"SolarEV City Concept"), which is highly efficient technologies for deep urban decarbonization [18,19]. This could begin with a demonstration project that opens a niche for "PV + EV" and then expands further as the platform builds trust and mutual understanding across actors. It could grow even further as broader policy and governance reforms help strengthen that platform and bring the funding and regulatory reforms needed to spread that innovative technology.

While the work on MLP [30–32] and strategic niche management [33–35] have much to offer in illustrating the potential and challenges to transitions, there have been relatively few studies to use those insights in Japanese cities [33]. In fact, the vast majority of work on transitions is concentrated in the Netherlands, where this line of thought originated, as well as other countries in Europe [33]. Though this regional concentration may be partially attributable to some of the unique characteristics of Japan, such as the aging of society and limits on land, the case featured in this article, decentralized renewable-based "PV + EV" energy systems, is selected precisely because it offers a useful way to potentially expand opportunities [18] and overcome some of these challenges in a non-European context. Further, as the article will also show, the case of the renewable-based "PV + EV" system in Kyoto can also shed light on some of the opportunities and impediments to developing a niche technology and then working with different policy frameworks and institutions and multi-stakeholder platforms to support the spread of that socio-technical solution. The insights gathered from such a deep-dive case study are, therefore, likely to have implications for Japan and other cities. The present study, therefore, draws upon the above rationales to answer the following questions.

1. What are the opportunities and challenges for cities with falling populations and limited land, such as Japan, to transition to decentralized renewable-based "PV + EV" energy systems?
2. How can researchers, industry, NGOs, and local government collaborate to open and expand a niche for renewable-based "PV + EV" systems?
3. What kinds of policy frameworks and governance arrangements can strengthen this multi-stakeholder collaboration and help spread niche-level "PV + EV" innovations and move forward transitions?

2. Methods

This research employs a case study approach to understand the opportunities and barriers to initiating and scaling up rooftop PV systems integrated with EVs ("PV + EV") in Kyoto. Building upon our previous study on the energy-financial model analysis of the "PV + EV" system in Kyoto [19] (Fig. 1), this study utilizes several commonly employed case study research methods, including socio-technical transition and policy analysis [36–38], to provide those insights. The initial phase of this research involves a relatively standard economic and technical assessment of the feasibility of "PV + EV" [19], which underscores the significant potential for niche development around this particular solution in Kyoto. That analysis is further supported by a brief technical overview of CO₂ emission trends in Kyoto.

However, because the scope of this research extends beyond merely assessing technical and economic potential, the study also draws upon socio-technical transition studies and qualitative methods commonly used in case study research [38], such as thick description and process tracing [39,40]. These methods enable a more detailed exploration of non-technical factors that could facilitate or hinder a "PV + EV"-centered transition in Kyoto (Fig. 1). Those methods are helpful because they can shed light on how key agents and interests interacts with policies and institutional frameworks at the regime level, and thus offers a more nuanced assessment of the feasibility of change within a carefully delineated case study. To complement the qualitative methods, the study also incorporates action-oriented research involving the Kyoto Miraimon Project, a stakeholder platform supporting "PV + EV" in Kyoto (Fig. 1). This connection to real-world initiative illustrates how

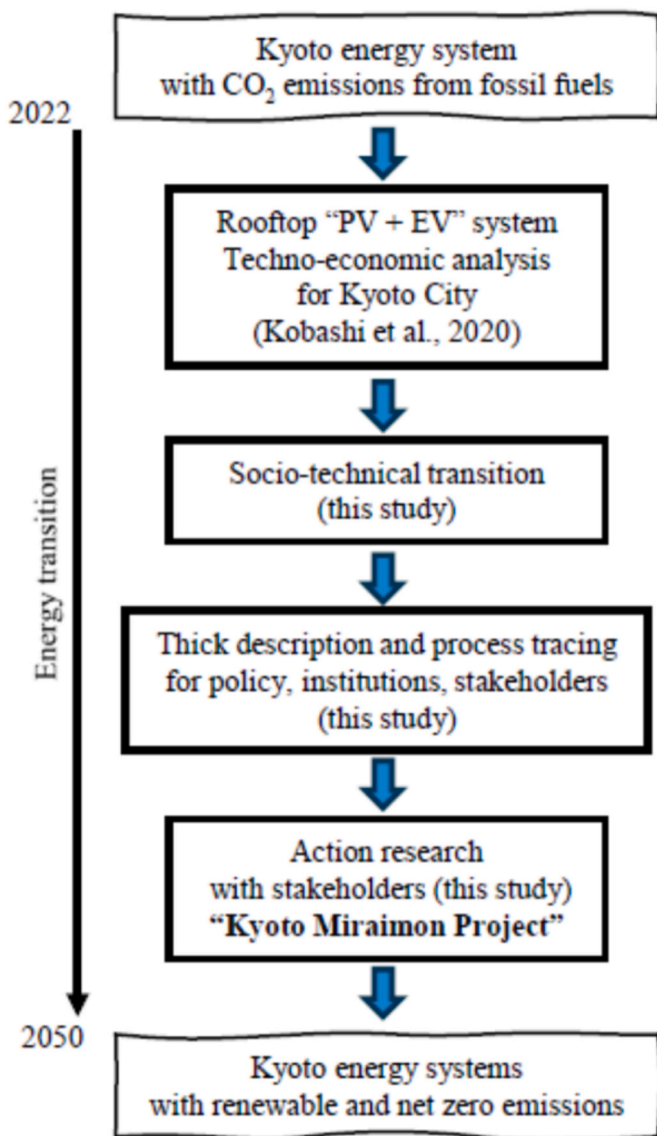


Fig. 1. A flow chart of this research. A techno-economic analysis of “PV + EV” identified as an important technology for Kyoto’s decarbonization [19]. This study examines the socio-technical transition of niche technology, policy, institution, and stakeholders in Kyoto to scale up the system. Action research provides hands-on experiences for harnessing the “PV + EV” technology.

researchers can actively contribute to facilitating change on the ground. Thick description, process tracing, and action-oriented research have been applied in various areas of transitions and policy research to illuminate social and institutional barriers to change and can also provide useful insights for the research in Kyoto [41–44].

3. Case study background

The starting point for this case study is the niche technology—that is, decentralized renewable-based “PV + EV” energy systems. To understand the technical potential of this technical solution, it merits underlining that PV outputs are greatly variable as they only work during the daytime, and thus require energy storage for deep decarbonization. Against this backdrop, the “SolarEV City Concept” has been introduced to mitigate the problems of variable PV outputs and to decarbonize the transport sector as well as the building sector [18]. This is done by integrating EVs as batteries at the city scale [45–47]. The concept uses V2H (vehicle-to-home) and/or V2B (vehicle-to-building) systems, which

allow bi-directional charging of EVs from rooftop PV [48].

As the costs of PV and EV are expected to continue to decline in subsequent decades, the systems can provide affordable and dispatchable electricity to cities [49,50]. V2H systems have been commercialized in Japan since 2012 following the Fukushima disaster. More than 20,000 V2H units have been sold by the end of March 2023 in Japan [51]—though other countries still lack well-developed V2H markets. Thus, Japan is well positioned as a leading country to build the SolarEV City. Finding suitable locations for renewable energy (e.g., solar or wind) is difficult due to limited land areas and high population densities [18]. Given this situation, using rooftops for the installation of PV is a priority. The SolarEV City Concept was first proposed for Kyoto in 2020 as a way to allow the maximum utilization of rooftop areas for PV in an economically efficient manner [45]. It was assumed that 70 % of the rooftop area of the city was utilized for rooftop PV, that all the vehicles were converted to EVs in the city, and that 50 % of the EV battery capacities of all the vehicles were used as energy storage. Following this calculation, it was found that the “PV + EV” systems could supply up to 70 % of electricity demand, including EV demand, and CO₂ emissions from electricity and driving would decrease by 60–74 %. The energy costs would also fall by 22–37 % in Kyoto [45]. Further analyses of other urban areas in Japan (Hiroshima, Kawasaki, Koriyama, Kyoto, Niigata, Okayama, Sapporo, Sendai, and Tokyo special districts) and other countries suggested that the niche technology, rooftop PV system combined with EV as a battery (“PV + EV” system), could serve as a cost-effective way to decarbonize urban energy systems [25,52–56].

The potential of integrated “PV + EV” systems in facilitating a transition towards carbon neutrality is also based on other potentially supportive trends. Since a national feed-in-tariff (FIT) began in 2012, large-scale PV has been installed on many optimal lands. In 2020, the cumulative installed PV capacity reached 72 GW (third in the world after China and the U.S.), and the PV capacity per flat land area, 470 (kW/km²), was the largest among major countries [57]. However, owing to falling FIT rates, high PV installation costs, and limited land area, annual PV installation stagnated at around 7 GW since 2016—a figure that needs to be much larger to reach carbon neutrality by 2050. The use of rooftop space and agricultural lands has received increasing attention in recent years in an effort to increase annual PV installation and reach 2030 CO₂ emission reduction targets. For example, the Tokyo metropolitan and Kawasaki City governments mandated rooftop PV be installed on newly built houses for large homemakers starting in 2025; other local governments will likely follow suit.

Another way in which cities like Kyoto can decarbonize involves accelerating the spread of EVs. The rapid increase in EVs [58] cannot only help reduce CO₂ emissions from transport but also from other energy-related activities. This is because bi-directional EV charging makes it possible for EVs to use batteries to store surplus electricity from rooftop PV [59]. This multi-functional potential is sizable in Kyoto. Although individual technologies are already commercially available, for these technologies to work on a city scale, new technologies that maximize PV utilization on rooftops such as peer-to-peer (P2P), virtual power plant (VPP), and microgrids need to be developed [60,61].

There are other reasons these technologies could feasibly grow and spread in Kyoto. Most notably, relatively small, decentralized energy technologies can develop and penetrate more rapidly than larger centralized technologies, facilitating the decarbonization of energy systems [62]. In addition, the quick development of ICT, AI, and digital technologies could help build a new power system as part of smart city development. The growing use and purchase of EVs could further ease and accelerate these trends. Simultaneous developments of technologies from various directions can converge to build momentum behind rapid decarbonization.

The above suggests that a “PV + EV” system is technically and economically feasible and could serve as a niche for larger energy transition. However, Kyoto currently has introduced 148 MW of PV. Unfortunately, this only accounts for 2 % of the expected 7 GW rooftop

solar (if 70 % of the rooftop area in Kyoto City is used for PV with 20 % efficiency) [63]. A critical question is why has rooftop solar and complementary technologies not gotten more traction. As illustrated in Fig. 2, the answer to this question may lie in the fact that managing and then bringing that niche to scale depends on factors beyond the technological solution itself. Rather, it necessitates the combination of pressures at different levels and strategic management with stakeholders around the specific solution. The next section will offer a detailed description of some of the additional factors that could help or hinder the advancement of a niche built around “PV + EV” in Kyoto, beginning with an overview of the city’s emissions.

4. CO₂ emissions in Kyoto

Kyoto, the eighth largest city in Japan, has a population of 1.46 million in 2022 and is located in the mid-latitude of 35.0°N, 135.8°W with large seasonal variations in temperatures and weather patterns. The minimum and maximum daily temperatures are 2 °C in January and 33 °C in August, incurring space heating in winter and cooling in summer, respectively [45]. CO₂ emissions from energy use in Kyoto (direct emissions in the city plus emissions from electricity consumption) were 5.49 MtonCO₂ in 2020 [65]. About 54 % of the emissions originate from electricity consumption, 18 % from city gas consumption, and 28 % from fossil fuels (e.g., gasoline) [66]. Looking across different sectors, households emit the largest amount (32 %), followed by the commercial (29 %), transport (26 %), and industry sectors (13 %) (Table 1). The relatively smaller share of the industry compared to an average value of 45 % of Japan in 2020 suggests there is potential for electrification, energy efficiency improvement, and renewable energy to decarbonize Kyoto’s energy systems [45].

Even with this potential and some of the milestones mentioned above, Kyoto has had mixed success navigating the early stages of decarbonization. In Kyoto, annual energy consumption fell from 104,201 TJ in 1997 to 71,820 TJ in 2020, a more than 30 % decrease over 23 years [66]. On the other hand, CO₂ emissions remained relatively flat over the past three decades due to increasing CO₂ emissions from electricity uses in commercial and household sectors and increasing grid emission coefficients (Fig. 3). More recently, CO₂ emissions fell by 24 % from 2013 to 2020 (Fig. 3) due to the reduction in total energy consumption by 9.2 % and lower grid emission coefficients

Table 1
CO₂ emissions (MtonCO₂) from different sectors in Kyoto City. Parentheses indicate emission reductions from the base year 2013 (a base year used in Japan).

Fiscal year	Industry	Transport	Household	Commercial
2019	0.75	1.50	1.56	1.69
2020	0.69 (−33 %)	1.44 (−7.6 %)	1.77 (−16.6 %)	1.59 (−39.1 %)

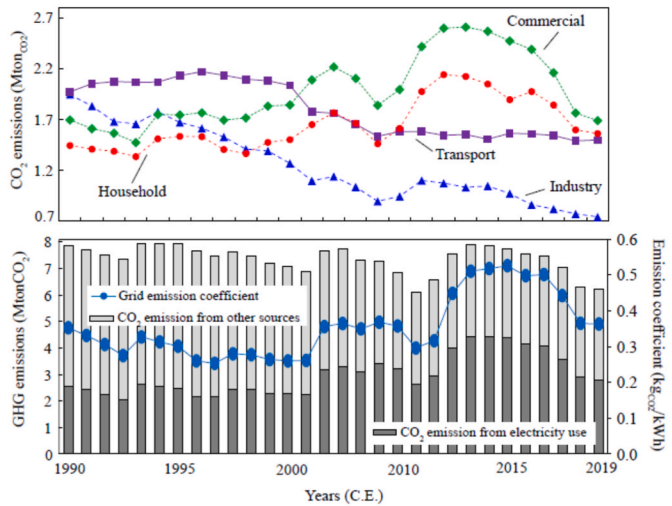


Fig. 3. GHG and CO₂ emissions from Kyoto City [67]. (top) CO₂ emissions from commercial, household, transport, and industry sectors in Kyoto. GHG emissions includes CH₄, N₂O, HCFC, etc. but with small shares in addition to CO₂ [66]. (bottom) GHG emissions separated by CO₂ emissions from electricity use and others. Blue circles are grid emission coefficient [66]. Electricity in Kyoto has been supplied primarily by the Kansai Electric Power Company (KEPCO).

(Fig. 3). After the Fukushima Accident in 2011, all the nuclear power plants in Japan closed for a few years (2012–2015) with increased outputs from fossil fuel power plants during the period. Since 2015, nuclear power plants have gradually reopened, leading to changes in grid CO₂ emission coefficient (Fig. 3). As nearly half of the CO₂ emissions originate from electricity consumption (Fig. 3) and the share is expected to increase from electrification, the supply for affordable CO₂ free electricity from renewables will arguably help make more progress in decarbonizing Kyoto’s energy system.

5. Climate policy institutions in Kyoto

Of course, the potential for “PV + EV” does not solely depend on trends in CO₂ emissions, it also requires an understanding of climate policy institutions and the broader context underlying their development. To explore the prospects for transition in Kyoto, some background on the city is helpful. For more than 1000 years, Kyoto has played a central role in Japan’s historical, cultural, and political development. Kyoto was established as the capital of Japan in 794 by Emperor Kanmu. Japanese emperors (the religious, political, and cultural center in Japanese history) continued to reside in Kyoto until the Meiji Restoration in 1869, when the capital moved to Tokyo. At around the same juncture, the industrial revolution led to a shift to a fossil fuel-based energy system. The industrial revolution fueled Japan and Kyoto’s development for more than a century. Today, the impacts of relying on fossil fuels are increasingly clear: nearly 1.5 million people and 732 thousand households living in Kyoto emit a significant amount of CO₂.

Although the population in Kyoto has remained relatively stable since the 1980s, the number of households has been increasing due to a growing number of single-person households and nuclear families [65].

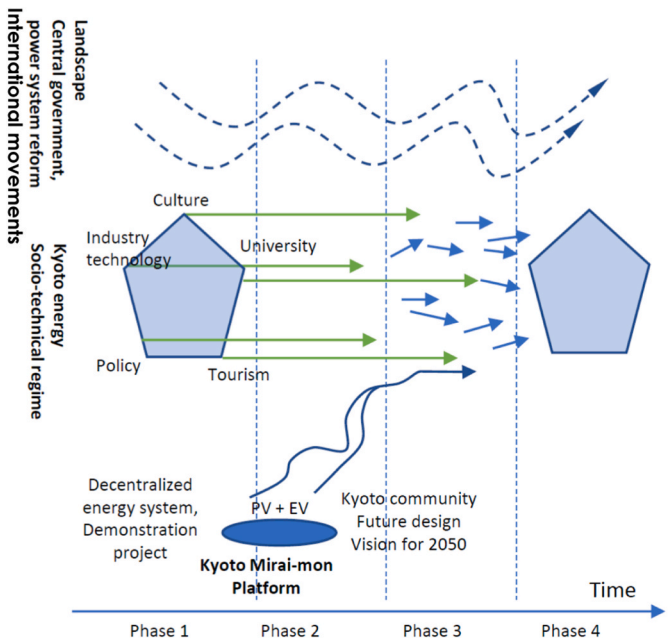


Fig. 2. Socio-technical transition in Kyoto. Adapted from Geels et al. [64].

At the same time, Kyoto has aged and will likely shrink moving forward. More than 28 % of the population is greater than 65 years old, and this proportion is expected to increase, owing to longer life expectancies and declining birth rates [65]. In fact, some projections suggest that the overall population is likely to fall to 1.3 million or experience a 10 % drop from 2021 by 2045 [68]. To some extent, these population declines will help lower the city's CO₂.

Other factors that have arguably kept those emissions down include Kyoto's unique position in the history of international climate negotiations. In 1997, Kyoto hosted the Conference of the Parties 3 (COP3) for the United Nations Framework Convention on Climate Change (UNFCCC) during which the Kyoto Protocol was adopted [69]. The event had substantial impacts on climate awareness in Kyoto [70]. Since 1997, many in the Kyoto government have viewed climate change as a priority and felt the city should lead Japanese and other municipalities abroad as the birthplace of the Kyoto Protocol (Y. Kawai, Pers. Comm.). In 2004, the establishment of a Climate Change Action Ordinance with GHG emission targets by the city marked an important step for Kyoto in demonstrating that leadership. In the years that have followed, subsequent actions based on the ordinance led to wider-scale efforts to address climate change. One of the outcomes was the establishment of a

department for climate change action in the Kyoto government with about 37 officers (as of June 2023).

Another important milestone in Kyoto's effort to address climate change was the creation of Miyako-no Agenda 21 around COP3 in 1997 [71]. This is the local version of Agenda 21, the United Nations sustainable development action plan established in 1992. The Miyako-no Agenda 21 became the basis for the collaboration between Kyoto's government, industries, universities, and NGOs; a platform was formed to strengthen that collaboration known as the Miyako-no Agenda 21 Forum [70]. NGOs also became active around COP3 in Kyoto. The Kiko Network, a major NGO working on climate in Japan, was established in Kyoto in 1998. Although the Kiko Network works throughout Japan, it has played a particularly important role in Kyoto's climate action through the continued involvement with senior personnel in the Kyoto government (K. Taura, Pers. Comm.). The Kiko Network, for instance, contributed to climate change action in Kyoto through the establishment of local community power plants and local power companies [72]. The Kiko Network was also involved in the establishment of Kyoto's ordinance for mandatory renewable energy installation in 2010 and created a project team with Kyoto's stakeholders, including professors at Kyoto University in Miyako-no Agenda 21, to formulate proposals that were

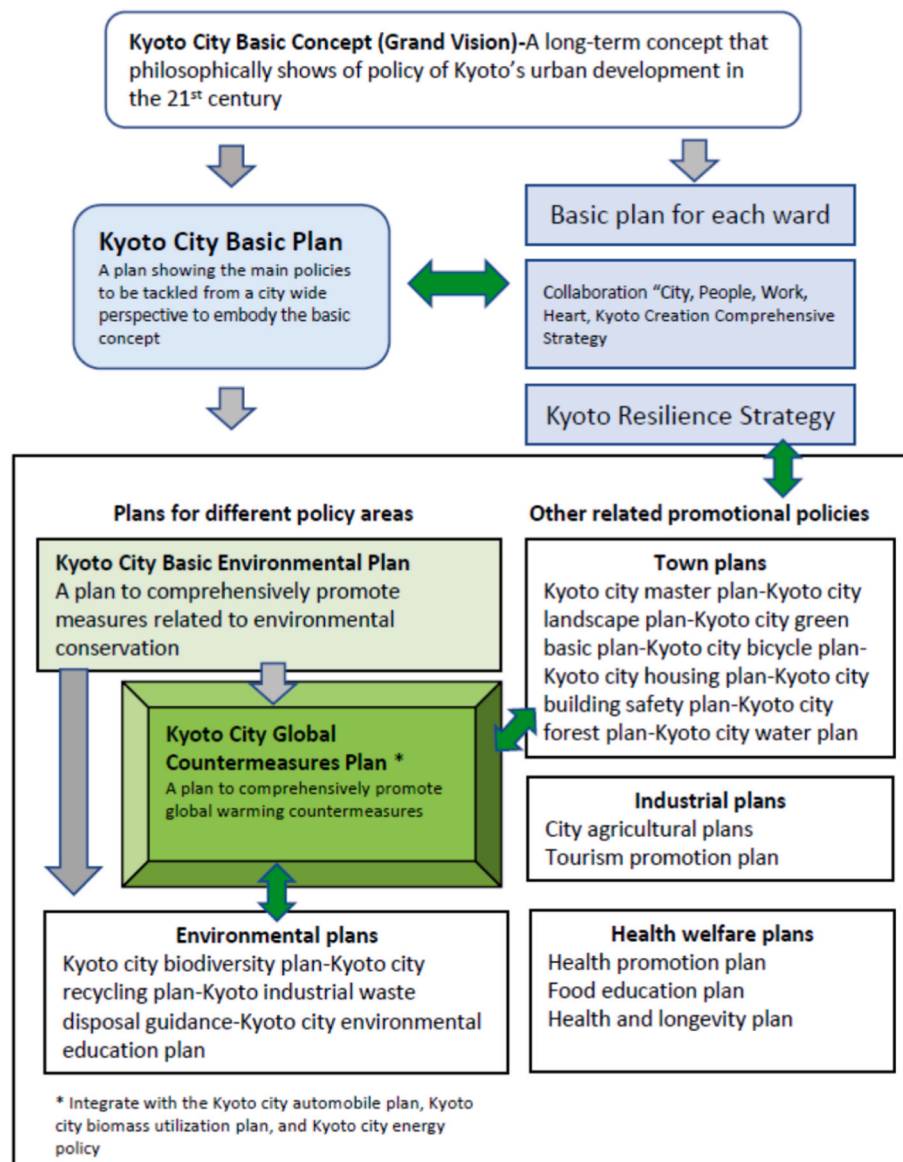


Fig. 4. Relationship between Kyoto climate plans and related policies and plans [76].

successfully included in the final form of the ordinance (K. Taura, Pers. Comm.).

In 2021, Kyoto adopted a mid-term climate change action plan. The plan runs from 2021 to 2030 with some provisions extending to 2050. The plan is the latest in a series of eight such plans; it is also the first version to include emission reduction targets for 2030. For example, the plan includes a GHG emissions reduction target of 46 % off 2013 levels by 2030. Importantly, the plan emphasizes the contributions of solar PV and electric vehicles to achieving emission reduction targets. Solar PV, in particular, occupies a prominent place in the plan. The promotion of EVs is part of the transport strategy, which also includes promoting walking, public transport, and AI-supported innovations in the transport sector.

The plan demonstrates a clear effort to ensure policy coherence—both across sectors and levels (Fig. 4). Cross-sectoral horizontal coherence is reflected in, for instance, the strong links between the energy, transport, waste management, and land use elements of the plan. It is also evident in discussions of how the green recovery from COVID-19 could free up resources from the national to local level to drive changes to energy systems. Another feature of the plan is extensive engagement with different social groups, industrial associations, and other stakeholders. With these policies and plans, Kyoto aims to gradually introduce PVs and EVs to move towards carbon neutrality [73–75]. A critical question is whether the plan and governance arrangements can be effective in scaling up PVs and EVs in the city.

6. Collaboration among stakeholders in university, research institute, and industry

Universities and industries could play a crucial role in facilitating innovation such as “PV + EV” systems for sustainability transitions. Kyoto, in particular, has many universities and key industries for decentralized energy systems. Traditionally, industry-academia-government collaboration has mainly been aimed at technological development in specific areas, and the coevolution of technologies and institutions has been promoted through a relatively limited range of networks. In contrast, the creation of innovations to tackle sustainability challenges such as climate change is characterized by the great diversity of knowledge required and the existence of a wider range of relevant stakeholders [77]. Toward this end, there is significant potential for universities to take the lead in forming platforms with relevant stakeholders and creating innovations through social experiments [78,79]. From this experience, it is possible to identify some elements that can drive implementation through that process. These include proposing and sharing a vision based on scientific knowledge, forming a platform with stakeholders, setting clear and specific goals, collaboration between university researchers and industrial practitioners, active participation of a wide range of stakeholders, development of new technologies and systems through social experiments, feedback to decision-makers, and effective institutional design. It is also critical to maintain transparency and inclusiveness in the process so that the project receives recognition and is viewed as legitimate in society.

On the other hand, there are several challenges that need to be overcome for universities to play an active leading role in facilitating close collaboration among academia, industry, government, and civil society for a sustainability transition. They include communication within a network that covers various stakeholders, organizational resistance of faculties and departments, lack of sufficient incentives for each researcher, and difficulty in evaluating the results of collaborative research between different areas of expertise. A key challenge is to effectively integrate the functions of education, research, and social contributions that universities have been carrying out. Analysis of actual cases under various domains and conditions can contribute to understanding the mechanisms by which universities take the initiative in forming platforms and creating innovations for decarbonization in cooperation with various stakeholders involved. A good example can be

found in the collaboration between the Kyoto government and researchers, which produced a base for mid-term climate action plan using future design method [80].

There are some recent developments in facilitating collaboration among stakeholders in university, research institute, and government. Research Institute for Humanity and Nature (RIHN) and local governments (Kyoto Prefecture and Kyoto City), has launched the Climate Change Adaptation Center in Kyoto in July 2021, together with Kyoto University, Kyoto prefectural University and others. This center as well as several research projects on carbon neutrality in RIHN deal with climate adaptation and mitigation in Kyoto, areas that are usually dealt with separately. In this activity, researchers benefit from the following results of interdisciplinary studies [81]: 1) development of a model in Kyoto which can tell synergy and tradeoff among resources related to carbon neutrality, and 2) development of database on carbon neutrality with water-energy-food nexus for understanding relevant linkages in Kyoto. Local governments, farmers, industrial sectors, and citizen as consumers can also benefit from the results of this research as part of a transdisciplinary study [82], including 1) scenario development for future carbon neutrality plan in Kyoto with stakeholders; and 2) best policy mixes for carbon neutrality with other factors such as water, energy, food, labor, land use and others.

Another networking initiative with academia, industries and governments is the formation of University Coalition in Japan for carbon neutrality. The university coalition in Japan was established on July 2021 with the supports from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), the Ministry of Economy, Trade and Industry, and the Ministry of the Environment (MOE). As of this writing, 203 universities and companies have joined the coalition. The objectives of the university coalition in Japan for carbon neutrality are 1) transfer of the knowledge of carbon neutrality related to the efforts by universities, 2) promotion of the social implementation of carbon neutrality research results and research development according to needs by strengthening cooperation with local governments, companies, etc., and 3) strengthen the ability to communicate domestically and internationally. There are five working groups that exist in the coalition including a) carbon neutrality of university campus, b) carbon neutrality for the local area, c) carbon neutrality innovation, d) human development for carbon neutrality, and e) international collaboration for carbon neutrality. The good examples of the carbon neutrality research such as studies in Kyoto can be shared by this coalition from local to national and international.

To understand the socio-economic dynamics and structures of the society [83] for carbon neutrality in 2050, a case study has been conducted in Kyoto Prefecture (different from Kyoto City). The surrounding municipalities have declared zero carbon in the prefecture to set up a dialogue forum for policy and science and attempt to match policy needs with research seeds. In addition, economic analysis has been conducted on new regional electric power projects in the prefecture to quantitatively analyze the economic effects of decarbonization measures. The transdisciplinary study on carbon neutrality has the benefit of identifying the joint issue between researcher and stakeholder. Researchers also get benefits from this work—namely, to access insights from different sectors such as water, energy, and food, which are usually separated and never have been discussed together. Notably, city officers in Kyoto gave researchers many ideas and information of local knowledge about how human behavior and policies are related to the local culture and why general policies did not work in the traditional and historical city. For instance, there is a tradeoff between renewable energy from solar panels on the rooftop and tourism with landscape regulation in the historical city. This kind of information is useful for making scenarios and best policy mixes for the future and analyzing the tradeoffs and synergy in the transdisciplinary study.

The next section describes some of the early efforts to build and expand a niche for “PV + EV” in Kyoto. It then turns to additional action-oriented steps that can be taken to strengthen collaboration between

universities and industries and related policy and governance reforms that can legitimize the platform and spread the technology.

7. A stakeholder platform for a socio-technical transition: Kyoto Miraimon project

Some initiatives have already started to construct a stakeholder platform that would open the niche for community-scale “PV + EV” in Kyoto. In the Spring of 2020, an action research project was initiated to promote “PV + EV” decarbonization on a community scale (Fig. 5). The research project was named the Kyoto Miraimon project. Miraimon (未来門) literary means “Gate for future”. The Kyoto Miraimon project aimed to build a “PV + EV”-based power system in a community to support urban decarbonization. It was organized around five themes and/or objectives: (1) transition research, (2) design of distributed power generation systems for PV and EVs, (3) development and implementation of power supply business model, (4) collaboration with local universities, (5) development of PV, V2H and V2G, and community energy management system (CEMS) with local companies (Fig. 5).

The platform consisted of a group of around 10 stakeholders in Kyoto with three divisions (Fig. 6). Every month, a committee meeting was held online or in hybrid form. Six university researchers (social and environmental scientists, engineers, and energy economists) joined the project to form a transition research team (Fig. 6). Two researchers regularly participated in the meeting and acted as meeting leaders. Other researchers served as advisors, occasionally providing relevant knowledge. These researchers helped to assess the progress of the project, advise the committee, and summarize performance in academic papers to disseminate findings.

Participants from industries were Nichicon (V2H system producer), Nissan (automaker), Kyocera (electronics maker), Orix (energy service provider), Tera Energy (a local power retail company founded by Buddhist monks), and other companies in the fiscal year 2021 (Fig. 6). These industry participants formed a team to build a business model for the utilization of “PV + EV” in collaboration with Kyoto and with a researcher specialized in distributed power systems. The team worked with the committee and collaborated with other project members for the establishment of “PV + EV” systems.

Participating NGOs include the Kikko-Network as well as the Kyoto Environmental Activities Association (KEAA: primarily founded by Kyoto City). Higashi Hongan-Ji (a sect of Buddhism in Japan) with a large temple in Kyoto participated since 2021. These organizations have strong ties with local communities and support the project by identifying the community’s needs. Kyoto’s government also participated in the

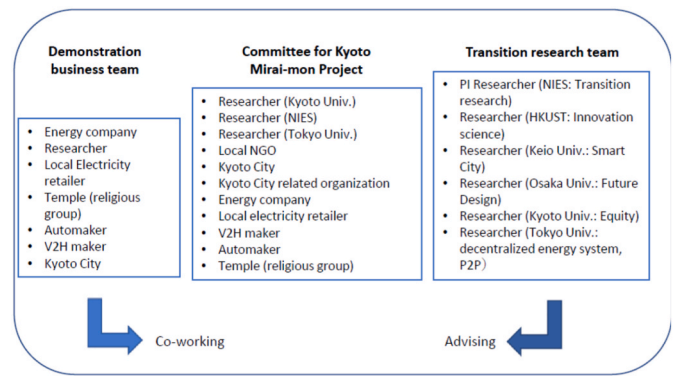


Fig. 6. Organization chart of Kyoto Miraimon project as of 2021.

project since the beginning but as an observer from 2022 (Fig. 6).

In the first year of 2020, those working on this initiative sought to install a rooftop PV and EV project in a district in Kyoto, using subsidies from the Ministry of Environment (MOE) or the Ministry of Economy, Trade, and Industry (METI). Subsidies from these agencies are partial: the ministry provides half or one-third of the necessary cost of the project. Companies must provide the rest of the project money. In addition, the subsidy comes with many requirements that can be difficult to meet in the early stages of a project. For instance, the location of the demonstration project needs to be identified in the proposal before funds are disbursed. Because of these requirements, getting an agreement within the group during the first year proved difficult. It was determined that it would be better to explore an alternative route outside of this scheme in the second year.

In the second year of 2021, it was decided to build off the past experience and rely more on the private sector. As such, ORIX took the lead to form a “PV + EV” project. ORIX, Nissan, and Nichicon collaborated to establish a business model in Kyoto, using “PV + EV” without a subsidy. This helped to reduce some of the challenging requirements encountered in the first year. It also addressed concerns that projects supported by subsidies tend “not” to continue after the subsidy ends. Using the network of Tera energy, the group tried to start a business at Buddhist temples and universities in Kyoto by using carport PV and shared EV schemes. However, reaching an agreement among companies and owners of locations again proved difficult. This may have reflected the importance of a deep understanding of the needs and concerns of communities and demonstrating the benefits of the technology. Moving forward, plans were made to take a different route that would fully

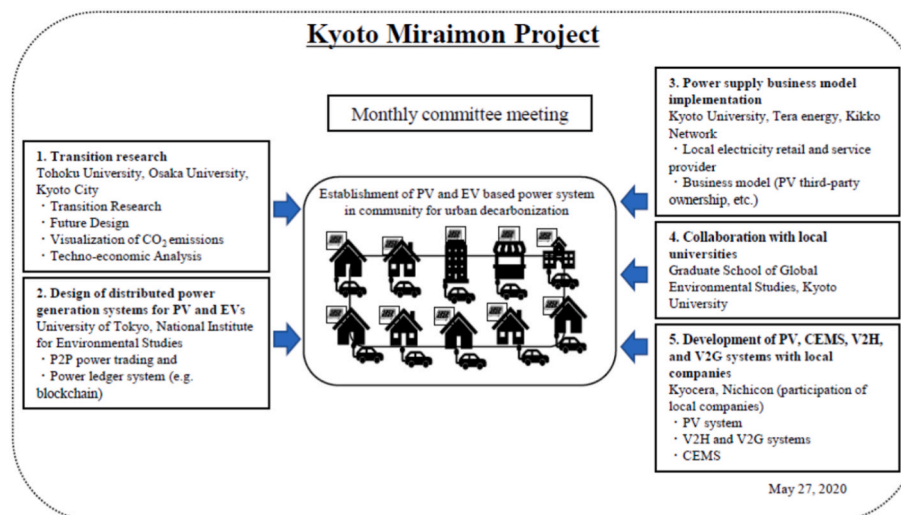


Fig. 5. Kyoto Miraimon project as of May 27, 2020.

understand those needs and concerns.

In the third year of 2022, a decision was made to have researchers work with NGOs to identify communities that were willing and able to collaborate on a “PV + EV” demonstration project. The Kikko Network, KEAA, and Tera Energy led the search as they routinely work with communities on environmental issues. Though the search proved difficult - communities understandably wanted to know if any benefits/subsidies are available from participating in the project - a collaborator in Gion (祇園), Kyoto has been located as a possible demonstration site. Gion is a famous Geisha district with traditional buildings and restaurants. The collaborator owns a café and co-working place in Gion. Both the collaborator and the community have an incentive to participate in the demonstration project because they can help the district gain attention. As of writing this article in July 2024, we were in the process of developing the demonstration project of “PV + EV” in Gion with traditional tile-style PVs as the Kyoto Miraimon projects.

8. Opportunities and challenges in facilitating a socio-technical transition in Kyoto

These experiences—though still ongoing—illustrate some of the challenges and opportunities for creating niche technology “PV + EV” and scaling up collaboration in Kyoto. Several lessons and implications learned warrant consideration in this regard. These lessons begin with the realization that finding a suitable location to initiate a demonstration pilot is a non-trivial undertaking, especially when “PV + EV” is not yet a financially attractive option, and there is underlying uncertainty about to what extent the technology can play an important role in decarbonization. There are understandable questions about the benefits as well as the risks involved in securing the supply of electricity for the local community. These questions need to be answered clearly and convincingly. It also merits noting that benefits are likely to vary greatly from one location to another, especially in the early stages of opening a niche. The benefits may also be intangible, such as demonstrating that a location is a first mover on technology and burnishing those first-mover credentials.

A second point pertains to the challenges of finding a suitable location to install PVs in Kyoto. This includes that many preserved old wooden buildings are too weak to hold PVs and withstand large earthquakes; further, the timing of rebuilding introduces uncertainty over when to install rooftop PV, which is also often discussed for European historical buildings [84]. A related take-home point is a recognition that Kyoto has prohibited the installation of PV panels on many of these old wooden buildings in some protected areas with traditional tiles, Kawara, fearing that they alter and lower the scenic values of the urban landscape. This would necessitate the use of specially designed traditional tile-style PVs, which would incur additional costs but potentially help restore traditional views of the city. In addition, it is now understood that the heights of buildings in cities are not homogeneous, creating shades on the rooftops of lower buildings. A related consideration is that optimal PV capacity is generally calculated using the building’s energy demand, resulting in smaller than optimal uses of rooftop areas, but the integration of EV batteries with PV can substantially increase optimal PV capacity [53].

The third lesson involves the need to identify a sustainable business model for the project in a broader sense. Subsidy schemes may have a short-term appeal but can also include onerous requirements and considerable transaction costs. They may also discourage or crowd out private-sector investment. While initial costs can be high and have prohibited the rapid penetration of rooftop PV thus far [85], increasingly popular third-party models may be the best way to lower these barriers and circumvent some of the obstacles involving direct government funding.

The fourth lesson is that initiating a niche-level project is inherently a learning-by-doing process. The project has generated a considerable amount of interaction among participants; this has helped to refine

goals, disseminate special knowledge of researchers, move past speed bumps, and set those engaged in this work on a more sustainable course. Much of what has been gained would not have been unknowable at the early stages of the project. Many of the learnings involve the various barriers to realizing the potential of “PV + EV”. Viewed from another perspective, however, these challenges may also be turned into opportunities. In this connection, the key is how to strengthen the platform and reform policies and governance arrangements so as to expand those opportunities. Importantly, changing landscapes (advancement of technologies, regulatory reform, and changes in people’s perceptions, etc.) could open the window of opportunities in the future [86].

While the platform development contributes to facilitating a transition, there is still room for further improvement based on the lessons learned on “PV + EV”. One such area involves the mapping and identification of communities with the technical potential to install solar PVs. This mapping could also explore non-technical issues, such as impacts on visibility and less visible community interests. It could, therefore, be accompanied by stakeholder surveys and/or focus groups that could shed light on these issues. Bringing community acceptability into this mapping would help determine not only the technical but also the socio-economic feasibility of “PV + EV”. It would also have positive spillover effects in terms of raising awareness of new technologies. These efforts can be part of larger efforts to strengthen community engagement around the mid-term climate change action plan and its 46 % target. Those efforts will also empower women’s groups and youth movements as part of a sustainable and socially just transition [87].

A second area where current plans and governance arrangements can be strengthened to support a transition involves financing. Though there is likely to be growing financial support for “PV + EV”, a key question is through what channels it is allocated and for what purposes. As noted previously, straight national-level government transfers of resources to cover initial costs would not be an optimal solution. Instead, plans can make strong links to third-party financing models—for instance, opening opportunities for environmental service companies (ESCOs)—that help overcome initial cost barriers by allowing companies to capture cost savings from reduced energy costs over the lifetime of a project. This can also be supported by greater awareness among officials working on investment, transport, and energy. It would also help to bring in local banks that can support debt financing and work with ESCOs to structure financing [88].

There could be scope to use more direct public funding and fiscal transfers to finance the purchase of supportive infrastructure for EVs, including charging stations [89]. This could help accelerate and close gaps between Japan and many other developed countries in the penetration of EVs. Closing this gap is essential for two reasons. The first is that overall, technology penetrates faster when it reaches a critical threshold of 5–10 % of the total share. The second is “PV + EV” technology, rooftop PV and EV need to have relatively high penetration to connect the dots physically for energy sharing. Though the V2H sales have been increasing, reaching nearly 20,000 units in 2023 in Japan [51] (but compare it with 62 million registered passenger vehicles in 2022 in Japan), for “PV + EV” systems, meeting critical thresholds and getting significant price drops will require that essential infrastructure is in place. Similar to the above, greater coordination between divisions working on transport, energy, and urban planning will be helpful in determining the locations of charging stations. This effort could again be paired with work on mapping the social feasibility of PV.

Most of the proposed reforms thus far focus on actions by the local government. At the same time, it will be critical that central governments place more emphasis on EVs. Part of the reason that Japan has lagged relative to other countries on EVs is the lack of purchasing incentives for consumers and price support for manufacturers. This is also arguably attributable to a preference among some ministries and vehicle manufacturers to focus on hybrid or more energy-efficient vehicles. However, the global push for EVs might significantly disadvantage Japan if it continues along this course. Cities like Kyoto can help to

induce national policies in the direction of promoting EVs by demonstrating the benefits of “PV + EV” systems and holding the case up as part of broader national decarbonization efforts. For instance, it could be featured as Kyoto acquires more funds and attention as a leading decarbonization area. For this to achieve maximum impact, it would be necessary to establish mechanisms that provide steady flows of information from the bottom up. Gradually strengthening the vertical connections between Kyoto and the national government could pay dividends for both levels.

A final area involves the style of governance. Some have noted the complexity of managing a transition requires not simply sound institutions and carefully crafted policies but reflexivity. Opening a growing space for innovations to grow will sometimes entail thinking and acting outside the box of established routines and standard operating procedures. For instance, it would be important to think creatively about communicating the benefits of “PV + EV”. It would also be critical to consider new ways of installing PVs in scenic areas or near older buildings. In much the same way the Miraimon platform supported learning by doing, governments will also need to create spaces for the same kinds of processes.

9. Conclusion

For rapid urban decarbonization, decentralized power systems such as rooftop PVs integrated with EVs could play an important role. Many studies have demonstrated that rooftop PVs integrated with EVs as batteries (“PV + EV” systems) is a technically and economically feasible approach to deep decarbonization if it is applied at the city scale (if 70 % of the rooftop area of Kyoto is filled with PVs, the capacity of PVs can reach 7 GW, and the PVs coupled with EVs can supply up to 70 % of electricity to the city.). To build such systems at the city scale, a rapid socio-techno-economic transition needs to occur. Rapid advances in PV technologies combined with a wide penetration of EVs offer a niche technology of “PV + EV” that could make this transition increasingly feasible.

This study offers a first-of-its-kind analysis and discussion of how the “PV + EV” diffusion can gain momentum through collaboration among key stakeholders, including city and national governments, universities, research institutions, business enterprises, and NGOs in Japan. The study also highlights that governance will play a critical role in the penetration of PVs and EVs, and university researchers can provide important future visions of the new technological potentials of decarbonization through techno-economic analysis in Japan. Further, it demonstrates these points by using Kyoto as a thick description case study supplemented by an action-oriented hands-on project, the Kyoto Miraimon Project, with stakeholders in the city to establish a real deep decarbonization pathway. A platform such as this project can facilitate the transition, aligning stakeholders’ goals with local expertise in universities and industries. To establish swift and deep urban decarbonization through “PV + EV”, similar attempts also need to be implemented elsewhere.

While the study offers some useful findings, it also has some limitations. As this study is based on a single case analysis of Kyoto, in order to evaluate to what extent, the experience of this city can be generalized and applicable to other cities, further research would be expected to explore how other cities in Japan and beyond are working on “PV + EV”. That would be helpful to evaluate to what extent the findings based on the experience in Kyoto can be applicable to other contexts with similar constraints on land and aging populations. Comparative case studies of cities that, for instance, would not necessarily have the same level of strong institutional support for climate action would also be useful. Similarly, it is also important to note the uncertainties inherent in work on transitions. While most of the technical and economic assessment of innovative climate solutions could be backed up with relatively robust estimates of mitigation potential and costs, transition studies would lack the same kind of precision. Additional efforts would be required to

integrate insights on social and institutional feasibilities into more conventional assessments of the potential of novel initiatives.

CRedit authorship contribution statement

Takuro Kobashi: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Eric Zusman:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Makoto Taniguchi:** Writing – original draft, Investigation. **Masaru Yarime:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

We thank Yoko Kawai at Kyoto City and Kenro Taura at Kiko Network for providing information on climate action in Kyoto. This project has been supported by research funding through RIHN (Incubation study from October 2018 to March 2019, PI: Takuro Kobashi, Study for energy transition policy and strategy towards RE100 % Asian cities; Feasibility study from April 2019 to March 2020, PI: Takuro Kobashi, Strategic and practical transition research to establish city energy systems sustainable for the next 1000 years) and JSPS KAKEN (23K11520).

Data availability

Data will be made available on request.

References

- [1] IPCC, Climate Change, The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2021, 2021.
- [2] IPCC, Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022.
- [3] IPCC, Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022.
- [4] IPCC, Global warming of 1.5°C, An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in: The Context of Strengthening the Global Response to the Threat of Climate Change, 2018.
- [5] UN DESA, World Urbanization Prospects 2018, 2019. New York.
- [6] A. Hsu, N. Höhne, T. Kuramochi, V. Vilariño, B.K. Sovacool, Beyond states: harnessing sub-national actors for the deep decarbonisation of cities, regions, and businesses, Energy Res. Social Sci. 70 (2020) 101738, <https://doi.org/10.1016/j.erss.2020.101738>.
- [7] S. Linton, A. Clarke, L. Tozer, Technical pathways to deep decarbonization in cities: eight best practice case studies of transformational climate mitigation, Energy Res. Social Sci. 86 (2022) 102422, <https://doi.org/10.1016/j.erss.2021.102422>.
- [8] M. Salvia, D. Reckien, F. Pietrapertosa, P. Eckersley, N.A. Spyridaki, A. Krook-Riekkola, M. Olazabal, S. De Gregorio Hurtado, S.G. Simoes, D. Geneletti, V. Vigiú, P.A. Fokaides, B.I. Ioannou, A. Flamos, M.S. Csete, A. Buzasi, H. Orru, C. de Boer, A. Foley, K. Rižnar, M. Matosović, M.V. Balzan, M. Smigaj, V. Baštáková, E. Streberova, N.B. Šel, L. Coste, L. Tardieu, C. Altenburg, E. K. Lorencová, K. Orru, A. Wejs, E. Feliu, J.M. Church, S. Grafakos, S. Vasilie, I. Paspaldzhiev, O. Heidrich, Will climate mitigation ambitions lead to carbon neutrality? An analysis of the local-level plans of 327 cities in the EU, Renew. Sustain. Energy Rev. 135 (2021) 110253, <https://doi.org/10.1016/j.rser.2020.110253>.
- [9] B.G. Rabe, Beyond Kyoto: climate change policy in multilevel governance systems, Governance 20 (2007) 423–444, <https://doi.org/10.1111/j.1468-0491.2007.00365.x>.

- [10] P.H. Koehn, Underneath Kyoto: emerging subnational government initiatives and incipient issue-bundling opportunities in China and the United States, *Global Environ. Polit.* 8 (2008) 53–77, <https://doi.org/10.1162/glep.2008.8.1.53>.
- [11] C.N.H. Doll, J.A.P. de Oliveira, Urbanization and Climate Co-benefits: Implementation of Win-Win Interventions in Cities, Taylor & Francis, 2017.
- [12] R. Bellinson, E. Chu, Learning pathways and the governance of innovations in urban climate change resilience and adaptation, *Journal of Environmental Policy & Planning* 21 (2019) 76–89, <https://doi.org/10.1080/1523908X.2018.1493916>.
- [13] M.M. Betsill, H. Bulkeley, Multilevel governance of global, climate change 12 (2017) 141–159.
- [14] G7, G7 Hiroshima Leaders' Communiqué. https://www.g7hiroshima.go.jp/documents/pdf/Leaders_Communique_01_en.pdf, 2023. (Accessed 6 June 2023).
- [15] N. Tsuya, The Impacts of Population Decline in Japan: Demographic Prospects and Policy Implications, 2014.
- [16] Government of Japan, The sixth basic energy plan of Japan. <https://www.meti.go.jp/press/2021/10/20211022005/20211022005.html>, 2021. (Accessed 19 January 2022).
- [17] IEA, World energy outlook 2022. www.iea.org/t&c/, 2022.
- [18] T. Kobashi, P. Jittrapirom, T. Yoshida, Y. Hirano, Y. Yamagata, SolarEV City concept: building the next urban power and mobility systems, *Environmental Research Letters* 16 (2021), <https://doi.org/10.1088/1748-9326/abd430>.
- [19] T. Kobashi, T. Yoshida, Y. Yamagata, K. Naito, S. Pfenninger, K. Say, Y. Takeda, A. Ahl, M. Yarime, K. Hara, On the potential of "Photovoltaics + Electric vehicles" for deep decarbonization of Kyoto's power systems: techno-economic-social considerations, *Appl Energy* 275 (2020), <https://doi.org/10.1016/j.apenergy.2020.115419>.
- [20] C40, C40 cities. <https://www.c40.org/about>, 2020. (Accessed 19 February 2020).
- [21] National and regional decarbonization meeting, Roadmap for local decarbonization. https://www.cas.go.jp/seisaku/datsutanseo/pdf/20210609_ch_iiki_roadmap.pdf, 2021. (Accessed 29 April 2024).
- [22] European Commission, 100 climate-neutral cities by 2030 – by and for the citizens. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/100-climate-neutral-cities-2030-and-citizens_en, 2020. (Accessed 29 April 2024).
- [23] K. Urrutia-Azcona, M. Tatar, P. Molina-Costa, I. Flores-Abascal, Cities4ZERO: overcoming carbon lock-in in municipalities through smart urban transformation processes, *Sustainability (Switzerland)* 12 (2020), <https://doi.org/10.3390/SU12093590>.
- [24] P. Deroubaix, T. Kobashi, L. Gurriaran, F. Benkhelifa, P. Ciaia, K. Tanaka, SolarEV city concept for Paris, *Appl Energy* 350 (2023), <https://doi.org/10.1016/j.apenergy.2023.121762>.
- [25] R.G. Dewi, U.W.R. Siagian, B. Asmara, S.D. Anggraini, J. Ichihara, T. Kobashi, Equitable, affordable, and deep decarbonization pathways for low-latitude developing cities by rooftop photovoltaics integrated with electric vehicles, *Appl Energy* 332 (2023), <https://doi.org/10.1016/j.apenergy.2022.120507>.
- [26] I. - International Energy Agency, Global EV outlook 2023: catching up with climate ambitions. www.iea.org, 2023.
- [27] F.W. Geels, B.K. Sovacool, T. Schwanen, S. Sorrell, Sociotechnical transitions for deep decarbonization, *Science* 357 (2017) 1242–1244, 1979.
- [28] F.W. Geels, F. Berkhout, D.P. Van Vuuren, Bridging analytical approaches for low-carbon transitions, *Nat Clim Chang* 6 (2016) 576–583, <https://doi.org/10.1038/nclimate2980>.
- [29] F.W. Geels, J. Schot, Typology of sociotechnical transition pathways, *Res Policy* 36 (2007) 399–417, <https://doi.org/10.1016/j.respol.2007.01.003>.
- [30] F.W. Geels, Disruption and low-carbon system transformation: progress and new challenges in socio-technical transitions research and the Multi-Level Perspective, *Energy Res Soc Sci* 37 (2018) 224–231, <https://doi.org/10.1016/j.erss.2017.10.010>.
- [31] F.W. Geels, Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016), *Energy Res Soc Sci* 46 (2018) 86–102, <https://doi.org/10.1016/j.erss.2018.07.008>.
- [32] F.W. Geels, Micro-foundations of the multi-level perspective on socio-technical transitions: developing a multi-dimensional model of agency through crossovers between social constructivism, evolutionary economics and neo-institutional theory, *Technol Forecast Soc Change* 152 (2020), <https://doi.org/10.1016/j.techfore.2019.119894>.
- [33] P. Giganti, P.M. Falcone, Strategic niche management for sustainability: a systematic literature review, *Sustainability (Switzerland)* 14 (2022), <https://doi.org/10.3390/su14031680>.
- [34] J. Schot, F.W. Geels, Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy, *Technol Anal Strateg Manag* 20 (2008) 537–554, <https://doi.org/10.1080/09537320802292651>.
- [35] S. Ruggiero, M. Martiskainen, T. Onkila, Understanding the scaling-up of community energy niches through strategic niche management theory: insights from Finland, *J Clean Prod* 170 (2018) 581–590, <https://doi.org/10.1016/j.jclepro.2017.09.144>.
- [36] I. Argyriou, J. Barry, The political economy of socio-technical transitions: a relational view of the state and bus system decarbonization in the United Kingdom, *Energy Res Soc Sci* 79 (2021), <https://doi.org/10.1016/j.erss.2021.102174>.
- [37] F.W. Geels, V. Johnson, Towards a modular and temporal understanding of system diffusion: adoption models and socio-technical theories applied to Austrian biomass district-heating (1979–2013), *Energy Res Soc Sci* 38 (2018) 138–153, <https://doi.org/10.1016/j.erss.2018.02.010>.
- [38] J. Wachsmuth, P. Warnke, A. Gambhir, S. Giarola, K. Koasidis, S. Mittal, A. Nikas, K. Vaillancourt, H. Doukas, Co-creating socio-technical scenarios for net-zero emission pathways: comparison of five national case studies, *Renewable and Sustainable Energy Transition* 4 (2023), <https://doi.org/10.1016/j.rset.2023.100064>.
- [39] D. Beach, Process tracing methods in the social sciences, in: Oxford Research Encyclopedia of Politics, Oxford University Press, 2017, <https://doi.org/10.1093/acrefore/9780190228637.013.176>.
- [40] F. Rauschmayer, T. Bauler, N. Schöpke, Towards a thick understanding of sustainability transitions - linking transition management, capabilities and social practices, *Ecological Economics* 109 (2015) 211–221, <https://doi.org/10.1016/j.ecolecon.2014.11.018>.
- [41] R. Kemp, J. Rotmans, D. Loorbach, Assessing the Dutch energy transition policy: how does it deal with dilemmas of managing transitions? *Journal of Environmental Policy and Planning* 9 (2007) 315–331, <https://doi.org/10.1080/15239080701622816>.
- [42] J.M. Wittmayer, F. Avelino, F. van Steenberg, D. Loorbach, Actor roles in transition: insights from sociological perspectives, *Environ Innov Soc Transit* 24 (2017) 45–56, <https://doi.org/10.1016/j.eist.2016.10.003>.
- [43] B. van Mierlo, P.J. Beers, Understanding and governing learning in sustainability transitions: a review, *Environ Innov Soc Transit* 34 (2020) 255–269, <https://doi.org/10.1016/j.eist.2018.08.002>.
- [44] D.A. Loorbach, H. Shirokawa, Governance of urban sustainability transitions. <https://doi.org/10.1007/978-4-431-55426-4>, 2016.
- [45] T. Kobashi, P. Jittrapirom, T. Yoshida, Y. Hirano, Y. Yamagata, SolarEV City concept: building the next urban power and mobility systems, *Environmental Research Letters* 16 (2021), <https://doi.org/10.1088/1748-9326/abd430>.
- [46] H. Lund, W. Kempton, Integration of renewable energy into the transport and electricity sectors through V2G, *Energy Policy* 36 (2008) 3578–3587, <https://doi.org/10.1016/j.enpol.2008.06.007>.
- [47] Transport&Environment, BNEF, Hitting the EV Inflection Point, 2021.
- [48] IEA, World energy outlook 2023, Paris, <https://www.iea.org/reports/world-energy-outlook-2023>, 2023. (Accessed 22 March 2024).
- [49] Nichicon, battery and V2H systems by Nichicon: VPP. https://www.meti.go.jp/shingikai/enecho/shoene/shinene/sho_energy/pdf/040_03_00.pdf, 2023. (Accessed 7 June 2023).
- [50] T. Kobashi, P. Jittrapirom, T. Yoshida, Y. Hirano, Y. Yamagata, SolarEV City concept: building the next urban power and mobility systems, *Environmental Research Letters* 16 (2021) 024042, <https://doi.org/10.1088/1748-9326/abd430>.
- [51] T. Kobashi, Y. Choi, Y. Hirano, Y. Yamagata, K. Say, Rapid rise of decarbonization potentials of photovoltaics plus electric vehicles in residential houses over commercial districts, *Appl Energy* 306 (2022), <https://doi.org/10.1016/j.apenergy.2021.118142>.
- [52] S. Chang, J. Cho, J. Heo, J. Kang, T. Kobashi, Energy infrastructure transitions with PV and EV combined systems using techno-economic analyses for decarbonization in cities, *Appl Energy* 319 (2022), <https://doi.org/10.1016/j.apenergy.2022.119254>.
- [53] J. Liu, M. Li, L. Xue, T. Kobashi, A framework to evaluate the energy-environment-economic impacts of developing rooftop photovoltaics integrated with electric vehicles at city level, *Renew Energy* 200 (2022) 647–657, <https://doi.org/10.1016/j.renene.2022.10.011>.
- [54] T. Jittayasotorn, M. Sadidah, T. Yoshida, T. Kobashi, On the adoption of rooftop photovoltaics integrated with electric vehicles toward sustainable bangkok city, Thailand, *Energies (Basel)* 16 (2023), <https://doi.org/10.3390/en16073011>.
- [55] METI, Adequate introduction and management of renewable energy (2022) 49. https://www.meti.go.jp/shingikai/enecho/denryoku/gas/saisei_kano/pdf/041_s_01_00.pdf (accessed January 9, 2023).
- [56] I. Energy Agency, Global EV Outlook 2022 Securing Supplies for an Electric Future, 2022.
- [57] T. Kobashi, K. Say, J. Wang, M. Yarime, D. Wang, T. Yoshida, Y. Yamagata, Techno-economic assessment of photovoltaics plus electric vehicles towards household-sector decarbonization in Kyoto and Shenzhen by the year 2030, *J Clean Prod* 253 (2020) 119933, <https://doi.org/10.1016/j.jclepro.2019.119933>.
- [58] T. Morstyn, N. Farrell, S.J. Darby, M.D. McCulloch, Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants, *Nat Energy* 3 (2018) 94–101, <https://doi.org/10.1038/s41560-017-0075-y>.
- [59] A. Ahl, M. Yarime, M. Goto, S.S. Chopra, N.M. Kumar, K. Tanaka, D. Sagawa, Exploring blockchain for the energy transition: opportunities and challenges based on a case study in Japan, *Renewable and Sustainable Energy Reviews* 117 (2020) 109488, <https://doi.org/10.1016/j.rser.2019.109488>.
- [60] C. Wilson, A. Grubler, N. Bento, S. Healey, S. De Stercke, C. Zimm, Granular technologies to accelerate decarbonization, *Science* 368 (2020) 36–39, <https://doi.org/10.1126/science.aaz8060>, 1979.
- [61] Agency for natural resources and energy, FIT public info webpage. <https://www.fit-portal.go.jp/PublicInfoSummary>, 2022. (Accessed 24 January 2023).
- [62] F.W. Geels, Disruption and low-carbon system transformation: progress and new challenges in socio-technical transitions research and the Multi-Level Perspective, *Energy Res Soc Sci* 37 (2018) 224–231, <https://doi.org/10.1016/j.erss.2017.10.010>.

- [65] Kyoto City, Estimated population of Kyoto City (2022) 7. <https://www2.city.kyoto.lg.jp/sogo/toukei/Publish/Analysis/News/132suikei2021.pdf>. (Accessed 12 December 2022).
- [66] Kyoto City, GHG emissions and total energy consumption of Kyoto City in 2020 (2022). <https://www.city.kyoto.lg.jp/kankyo/cmsfiles/contents/0000302/302937/koho.pdf>. (Accessed 13 December 2022).
- [67] Kyoto City, Climate change mitigation of Kyoto City in FY2021 (resource version) (2022) 23. [https://www.city.kyoto.lg.jp/kankyo/cmsfiles/contents/0000024/24419/siryu\(R3\).pdf](https://www.city.kyoto.lg.jp/kankyo/cmsfiles/contents/0000024/24419/siryu(R3).pdf) (accessed January 4, 2023).
- [68] Kyoto city, future population estimate for Kyoto city. <https://www2.city.kyoto.lg.jp/sogo/toukei/Population/Future/>, 2022. (Accessed 12 December 2022).
- [69] M. Fujita, Challenges of koto cities toward 1.5C, in: T. Kobashi (Ed.), *Urban Decarbonization*, Taiga Publishing, 2021, pp. 189–198.
- [70] M. Fujita, Kyoto's challenge on 1.5 C, in: T. Kobashi (Ed.), *Urban Decarbonization*, Taiga Publishing, 2021, pp. 189–198.
- [71] Miyako-no agenda 21 forum, miyako-no agenda 21. <http://ma21f.jp/03archive/ma21/>, 2022. (Accessed 20 January 2023).
- [72] Y. Toyota, The role of NGO on urban decarbonization and regional development, in: T. Kobashi (Ed.), *Urban Decarbonization*, Taiga Publishing, 2021, pp. 151–162.
- [73] H. Li, H. Yi, Multilevel governance and deployment of solar PV panels in U.S. cities, *Energy Policy* 69 (2014) 19–27, <https://doi.org/10.1016/j.enpol.2014.03.006>.
- [74] N. Rietmann, B. Hügl, T. Lieven, Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO₂ emissions, *J Clean Prod* 261 (2020) 121038, <https://doi.org/10.1016/j.jclepro.2020.121038>.
- [75] G. Trencher, A. Taeihagh, M. Yarime, Overcoming barriers to developing and diffusing fuel-cell vehicles: governance strategies and experiences in Japan, *Energy Policy* 142 (2020) 111533, <https://doi.org/10.1016/j.enpol.2020.111533>.
- [76] Kyoto City, Kyoto climate action plan (2021–2030) (2021) 78. <https://www.city.kyoto.lg.jp/kankyo/cmsfiles/contents/0000000/328/keikaku2021-2030.pdf?fbclid=IwAR30vxreo92gnRtJj7qXpEF4gh8SB-y3sBrIC65jTzCxa6DLwXgrvumSdz8> (accessed January 8, 2023).
- [77] M. Yarime, G. Trencher, T. Mino, R.W. Scholz, L. Olsson, B. Ness, N. Frantzeskaki, J. Rotmans, Establishing sustainability science in higher education institutions: towards an integration of academic development, institutionalization, and stakeholder collaborations, *Sustain Sci* 7 (2012) 101–113.
- [78] G. Trencher, M. Yarime, K.B. McCormick, C.N.H. Doll, S.B. Kraines, Beyond the third mission: exploring the emerging university function of co-creation for sustainability, *Sci Public Policy* 41 (2014) 151–179, <https://doi.org/10.1093/scipol/sct044>.
- [79] G. Trencher, X. Bai, J. Evans, K. McCormick, M. Yarime, University partnerships for co-designing and co-producing urban sustainability, *Global Environmental Change* 28 (2014) 153–165, <https://doi.org/10.1016/j.gloenvcha.2014.06.009>.
- [80] K. Hara, Y. Nomaguchi, S. Fukutomi, M. Kuroda, K. Fujita, Y. Kawai, M. Fujita, T. Kobashi, Policy design by “imaginary future generations” with systems thinking: a practice by Kyoto city towards decarbonization in 2050, *Futures* 154 (2023), <https://doi.org/10.1016/j.futures.2023.103272>.
- [81] M. Taniguchi, T. Beer, J. Li, K. Alverson, Asian groundwater perspective for global change and Future Earth, *Global Change and Future Earth* (2018) 179–186.
- [82] OECD, Addressing Societal Challenges using transdisciplinary research, *Policy Papers* (2020) 39–51.
- [83] S.H. Lee, M. Taniguchi, N. Masuhara, R.H. Mohtar, S.H. Yoo, M. Haraguchi, Analysis of industrial water–energy–labor nexus zones for economic and resource-based impact assessment, *Resour Conserv Recycl* 169 (2021) 105483, <https://doi.org/10.1016/j.resconrec.2021.105483>.
- [84] L.F. Cabeza, A. de Gracia, A.L. Pisello, Integration of renewable technologies in historical and heritage buildings: a review, *Energy Build* 177 (2018) 96–111, <https://doi.org/10.1016/j.enbuild.2018.07.058>.
- [85] D.N. yin Mah, G. Wang, K. Lo, M.K.H. Leung, P. Hills, A.Y. Lo, Barriers and policy enablers for solar photovoltaics (PV) in cities: perspectives of potential adopters in Hong Kong, *Renewable and Sustainable Energy Reviews* 92 (2018) 921–936, <https://doi.org/10.1016/j.rser.2018.04.041>.
- [86] B.F.W. Geels, K. Benjamin, T. Schwanen, S. Sorrell, B. Sovacool, T. Schwanen, S. Sorrell, Accelerating innovation is as important as climate policy, *Science* 357 (2017) 4–7, <https://doi.org/10.1126/science.aao3760>, 1979.
- [87] B.K. Sovacool, M. Burke, L. Baker, C.K. Kotikalapudi, H. Wlokas, New frontiers and conceptual frameworks for energy justice, *Energy Policy* 105 (2017) 677–691, <https://doi.org/10.1016/j.enpol.2017.03.005>.
- [88] Jama, Four-wheel vehicles (2024). https://www.jama.or.jp/statistics/facts/four_wheeled/index.html#:~:text=2022%E5%B9%B412%E6%9C%88%E6%9C%AB%E7%8F%BE%E5%9C%A8,7%E5%8D%83%E5%8F%B0%E3%81%A7%E3%81%97%E3%81%9F%E3%80%82 (accessed July 7, 2024).
- [89] Z.Z. Mutiara, D. Krishnadianty, B. Setiawan, J.T. Haryanto, Climate budget tagging: amplifying sub-national government's role in climate planning and financing in Indonesia, in: *Climate Change Research, Policy and Actions in Indonesia*, Springer, 2021, pp. 265–280.