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To cite this article: Runsen Zhang and Shinichiro Fujimori 2020 *Environ. Res. Lett.* **15** 034019

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LETTER

OPEN ACCESS

RECEIVED
24 May 2019

REVISED
25 December 2019

ACCEPTED FOR PUBLICATION
30 December 2019

PUBLISHED
19 February 2020

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The role of transport electrification in global climate change mitigation scenarios

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Keywords: transport electrification, electric vehicles, cross-sectoral interaction, energy consumption, mitigation cost

Supplementary material for this article is available [online](#)

Abstract

Electrification is widely considered an attractive solution for reducing the oil dependency and environmental impact of road transportation. Many countries have been establishing increasingly stringent and ambitious targets in support of transport electrification. We conducted scenario simulations to depict the role of transport electrification in climate change mitigation and how the transport sector would interact with the energy-supply sector. The results showed that transport electrification without the replacement of fossil-fuel power plants leads to the unfortunate result of increasing emissions instead of achieving a low-carbon transition. While transport electrification alone would not contribute to climate change mitigation, it is interesting to note that switching to electrified road transport under the sustainable shared socioeconomic pathways permitted an optimistic outlook for a low-carbon transition, even in the absence of a decarbonized power sector. Another interesting finding was that the stringent penetration of electric vehicles can reduce the mitigation cost generated by the 2 °C climate stabilization target, implying a positive impact for transport policies on the economic system. With technological innovations such as electrified road transport, climate change mitigation does not have to occur at the expense of economic growth. Because a transport electrification policy closely interacts with energy and economic systems, transport planners, economists, and energy policymakers need to work together to propose policy schemes that consider a cross-sectoral balance for a green sustainable future.

1. Introduction

The transport sector accounts for approximately a quarter of global greenhouse gas (GHG) emissions and is one of the major sectors where emissions are still rising [1–4]. Within the transport sector, road transport is by far the biggest emitter, accounting for more than half of all transport-related GHG emissions. Rapidly growing mobility needs and private vehicle ownership counteract the global efforts to reduce global GHG emissions from transport [5]. Due to society's persistent reliance on fossil fuels, the reduction of global GHG emissions from transport to limit the magnitude or rate of long-term climate change will be more challenging than in other sectors [6, 7]. Low-carbon vehicles, powered by

electricity, offer an alternative to conventional fossil-fuel technologies, and switching to electricity for road transport has been proposed as a significant way to reduce direct CO₂ emissions and ease the imbalance between the supply and demand of oil [8].

Because electric vehicles (EVs) are often considered a promising technology and an attractive solution for low-carbon transport [9, 10], several governments have set goals and timelines for the phase-out of diesel and then gasoline engines by 2050. The European Union aims to be a major force in the EV market, and most European countries have assembled a series of measures that would help them revitalize the automotive industry and provide more high-technology jobs. The United States does not have a

federal policy to boost EV adoption, but several states have set goals to reduce national vehicle emissions to zero by 2050. Japan has set a goal of selling only EVs by 2050. India is one of the few countries that has a concrete strategy for transport electrification and also has committed to end the sale of fossil-fuel powered vehicles by 2030. China is working on a plan to ban the production and sale of vehicles powered solely by fossil fuels and achieve a zero-emissions fleet by 2050. In developing countries there are a range of policies, with some countries embracing the future of electric-powered mobility, while others are skeptical about whether EVs will penetrate the market and have resisted the trend toward transport electrification. Although many countries have proposed bans to prohibit vehicles powered by diesel or gasoline, only a few nations or individual cities have actually legislated against internal combustion engine (ICE) vehicles. Thus, most vehicle bans will not be effective due to the lack of legal enforcement [11].

Existing studies have identified the potential market for EVs and the key factors affecting EV utilization and benefits, such as vehicle usage behavior, cost, battery weight, charging patterns, battery range limitations, and the lack of public awareness about the availability and practicality of these vehicles, the associated infrastructure, and safety regulations [9, 12, 13]. Different types of EV (battery EVs, hybrid EVs, and plug-in hybrid EVs) have been compared to determine the vehicle technology that is likely to dominate in the coming decades [10]. Because integrated assessment models (IAMs) have been extensively used to explore decarbonizing pathways in the transport sector [2, 3, 14–20], representations of technological advancement, consumer preferences, and increased market shares of EVs have been input to global IAMs [5, 21–23]. Current research clearly indicates the overwhelming importance of the role of transport electrification in a low-carbon transition. However, despite EVs reducing transport-related emissions and these benefits not being substantially affected by changes in travel distances, battery ranges, or charging frequencies [24], it is still very difficult to detect the cross-sectoral effects of transport electrification (e.g. the impact of the deployment of EVs on the CO₂ emitted by the power sector and the impact of EV penetration on mitigation costs). It remains uncertain if EVs will deliver the transition toward a green future.

Unlike ICEs, EVs do not emit carbon dioxide, but the power in their batteries must be sourced from somewhere. A transport electrification policy could produce an additional demand for electricity, which could result in an increase in emissions if the electricity is generated from fossil fuels. It would be problematic to overlook the interaction between the transport sector and other sectors (e.g. the power sector) when the deployment of EVs is implemented. The electrification of the transport sector requires the integration of vehicles into a reliable and efficient clean energy

network. The associated infrastructure, i.e. suitable recharging points, is another determining condition for a fully electrified transport system [25–27]. Although EVs will probably make up a significant portion of our future transport needs due to technological development and decreasing battery costs, it is necessary to investigate whether EVs are as green as they are claimed to be and what overall results transport electrification policies may have.

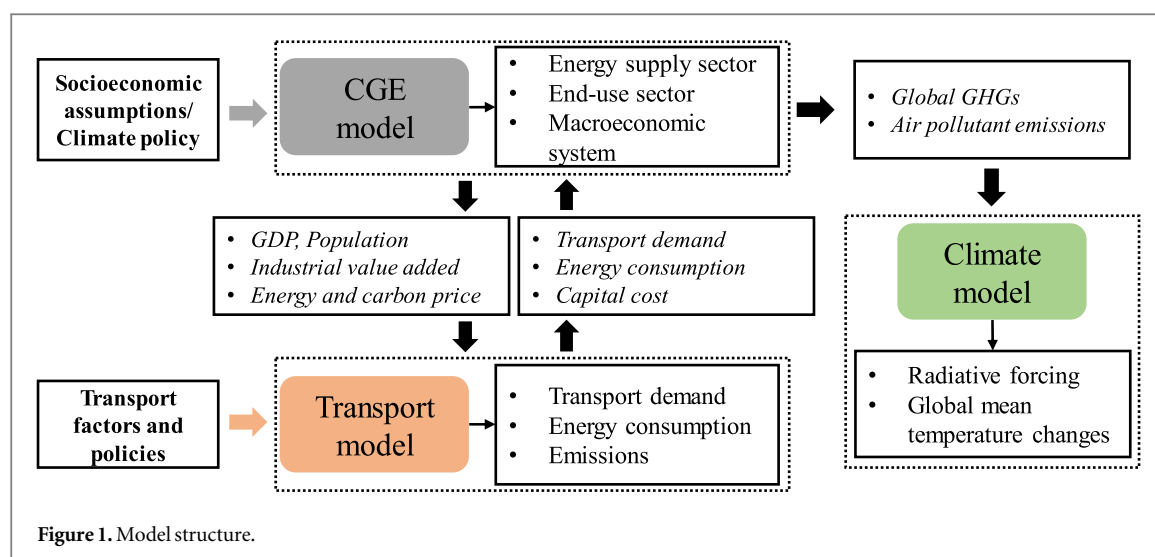
To investigate how transport electrification would impact emission trajectories and climate change, as well as what policies and strategies are needed for emission reduction and climate change mitigation, this study employed a global transport model to project the global transport demand of passengers and freight in terms of the choice of transport mode and its technological details to predict world transport energy use and emissions. The transport model was coupled with a global economic model and a simplified climate model to reveal the interactive mechanisms between transport electrification, economics, energy, and climate change. Such model coupling will enable electrified transport to be represented in an IAM by providing technological or behavioral factors [28]. To explore the combined effects of transport electrification and climate change mitigation efforts, we developed a set of six scenarios according to socioeconomic pathways, transport electrification strategies, and energy policies, such as carbon pricing and a high reliance on renewable energy.

2. Methods

2.1. Transport model

A global transport model was employed to provide spatially flexible and temporally dynamic simulations of transport demand, energy use, and emissions with consideration given to various technological factors such as device cost, speed, travel time, load factor, and preferences. The transport model was developed as a one-year interval, recursive-type transport choice model, which is described in detail in Zhang *et al* (2018) [29]. A summary of the model structure and its equations is provided in the supplementary information, available online at stacks.iop.org/ERL/15/034019/mmedia. The model considered different distances, modes, sizes, and technologies for the global projection of passenger and freight transport demand in 17 regions around the world (see supplementary figure S1 and table S1). Global passenger and freight transport demand was distinguished between short- and long-distance travel, and different modes, vehicle sizes, and technologies (see supplementary table S2). Energy use and CO₂ emissions from transport can be estimated according to technology-wise transport demand.

The passenger and freight transport demand was calculated by GDP, industrial value added, population, and generalized transport cost. Then, discrete choice models were used to compute the shares of



different distances, modes, sizes, and technologies based on the generalized transport cost, which includes the fuel cost, device cost, infrastructure cost, time cost, and carbon price. Fuel cost was calculated by fuel price and vehicle energy efficiency. Device cost was the annualized purchase cost for the vehicle device. The cost of travel time was estimated by the wage rate and vehicle speed. Infrastructure cost was the expense related to the infrastructure upgrades required at filling stations and EV charging stations. Technological improvements in EVs were incorporated into the process of technology selection. Technology selection parameters for EVs (cars, buses, two-wheelers, and small trucks) in future years aligned with different scenarios would increase gradually, accompanied by the implementation of transport electrification policies. The transport and energy data from 17 regions that were used for parameter estimation and calibration were collected from the Asia-Pacific Integrated Model database. The detailed data sources used in the transport model are listed in supplementary table S3.

2.2. Model coupling with a global economic model

The transport model was coupled with a global economic model and climate model to capture the interactions and tradeoffs between the transport sector, energy, emissions, macroeconomy, and climate change (figure 1). The frameworks of the computable general equilibrium (CGE) model and the Model for the Assessment of Greenhouse-gas Induced Climate Change were employed for global economic and climate modeling. The CGE model was developed for 17 regions, which was consistent with the transport model. The CGE model is classified as a multi-regional, multi-sectoral model that covers all economic goods, while considering production factor interactions [30]. An iterative procedure was used to obtain the convergence of the coupled model. The economic model passed the macroeconomic variables

to the transport model to project the transport demand, with consideration given to the modal structure and technology shares. Then, the transport demand, energy consumption from transport, and transport device cost from the transport model were fed back to the economic model to re-estimate the parameters. This loop continued until the energy consumption from transport calculated in the economic model and the transport model were equal. Next, global GHGs and other air pollutant emissions were passed to the climate model to generate climate outcomes, such as radiative forcing and global mean temperature changes. The mitigation costs, such as carbon price and economic losses were estimated by the CGE model according to the emission constraints given by a Dynamic Integrated Climate—Economy—type intertemporal model.

2.3. Scenario settings

Scenario simulations were developed not only to prove the positive effects of the deployment of EVs on transport decarbonization and emission reduction but also to detect how transport electrification policies interact with the power sector. A set of scenarios was created to investigate the long-term (to year 2100) impacts under various EV technology assumptions and energy policy schemes. These scenarios were defined according to two dimensions covering the model assumptions of transport electrification and energy policies, respectively. Transport electrification is designed based on the technological preferences for EVs, including cars, buses, two-wheelers, and small trucks, which reflect the key behavioral factors influencing consumers' willingness to purchase or select EVs. It was assumed that 100% EV market share will be achieved around the world by 2050 due to the EV policy incentives in the HiEV scenarios, while no stringent EV policy would be considered in the LoEV scenarios. In the HiEV scenarios, the parameters of the technological preferences for ICE vehicles were

Table 1. Scenario settings.

Scenario	Description
LoEV_BaU	No EV policy, with no climate efforts
LoEV_2D	No EV policy, with carbon pricing for the 2 °C target
LoEV_Renew	No EV policy, with a high preference for renewable energy
HiEV_BaU	100% EV market share by 2050, with no climate efforts
HiEV_2D	100% EV market share by 2050, with carbon pricing for the 2 °C target
HiEV_Renew	100% EV market share by 2050, with a high preference for renewable energy

exogenously set to zero by 2050, while higher preference parameters were given in relation to consumer's purchasing decisions regarding EVs to achieve the target of 100% market share.

Scenarios for energy policies included carbon pricing and a preference for renewable energy. The carbon pricing scenarios considered corresponded to a 2 °C climate stabilization target versus no climate action. The 'BaU' scenario assumed no climate mitigation efforts, whereas the '2D' scenario imposed a price on carbon, which was consistent with the 2 °C target, with the global mean temperature increase peaking at 1.82 °C in 2090 and settling at 1.8 °C in 2100. The radiative forcing level associated with the 2 °C target was around 2.8 W m⁻² in 2100. The radiative forcing for the BaU and 2D targets is provided in supplementary figure S2. The renewable energy preference scenarios examined the sensitivity of high preferences on renewable energies. In the CGE model, a factor for representing renewable energy preference determined the share parameter as a logit function, which accelerated the usage of renewable energies, such as wind and solar, when a high value was used.

Such scenario settings, considering the different model assumptions of the transport and power sectors, were structured to analyze cross-sectoral relations and tradeoffs, while also assessing mitigation pathways associated with the deployment of EVs (table 1). The default values of the underlying socioeconomic conditions, other than road transport-related parameters (e.g. GDP and population), were based on Shared Socioeconomic Pathway 2 (SSP2) [31].

3. Results

3.1. Energy use and emissions from transport

The energy use in the transport sector indicated that the transport sector would consume more electricity if the targets for the implementation of electric road transport were achieved through scenarios HiEV_BaU, HiEV_2D, and HiEV_Renew, regardless of whether energy policies were established (figure 2(a)). However, the global consumption of oil and biomass was lower with the deployment of EVs, implying that transport electrification could reduce oil dependency and the moderate demand for biofuels. Figure 2(b) shows the CO₂ emissions by transport mode. Without ambitious transport electrification goals, cars and trucks were

major contributors to CO₂ emissions, whereas with the policy goal of 100% EVs, emissions from road transport, including cars, buses, two-wheelers, and small trucks, decreased to zero. In all the transport electrification scenarios, transport modes such as large trucks, aviation, and navigation, which are currently difficult to electrify without breakthrough efforts and technological changes, are expected to emit most emissions in the future. Moreover, the deployment of EVs (HiEV_BaU) was more effective at reducing emissions than carbon pricing without the introduction of EVs (LoEV_2D), because road transport cannot achieve zero emissions by the implementation of carbon pricing alone. A high preference for renewable energies did not have direct positive effects on emission reduction in the transport sector. Time series results of energy use and mode-wise emission trajectories are provided in supplementary figures S3 and S4, respectively.

Despite the powerful and effective impact of transport electrification on reducing direct CO₂ emissions from the transport sector, it is unwise to reach an overly optimistic conclusion by ignoring the indirect CO₂ emissions from the electricity generation that energizes EVs. As displayed in figure 3, the deployment of EVs increases emissions from electricity production. A comparison of HiEV_BaU with LoEV_BaU shows an increase in indirect emissions, although direct emissions decrease with the stringent penetration of EVs during 2005–2100. Thus, without decarbonization of the future power supply by means of energy policies, instead of a low-carbon transition, electrified transport would lead to an increase in total emissions. A high preference for renewable energy would reduce the indirect emissions to some extent, whereas a significant emission reduction could be achieved by carbon pricing.

3.2. Emissions from the power sector

Figure 4(a) presents a more detailed analysis of CO₂ emissions from the energy-supply sector. Without the ambitious climate change mitigation efforts in the power sector, the deployment of EVs resulted in increased emissions from energy production. Such increases in energy-supply-related emissions can be interpreted as a globally growing demand for the electricity required as a result of deploying more EVs. The emission trajectories of LoEV_2D and HiEV_2D showed that carbon pricing could significantly reduce

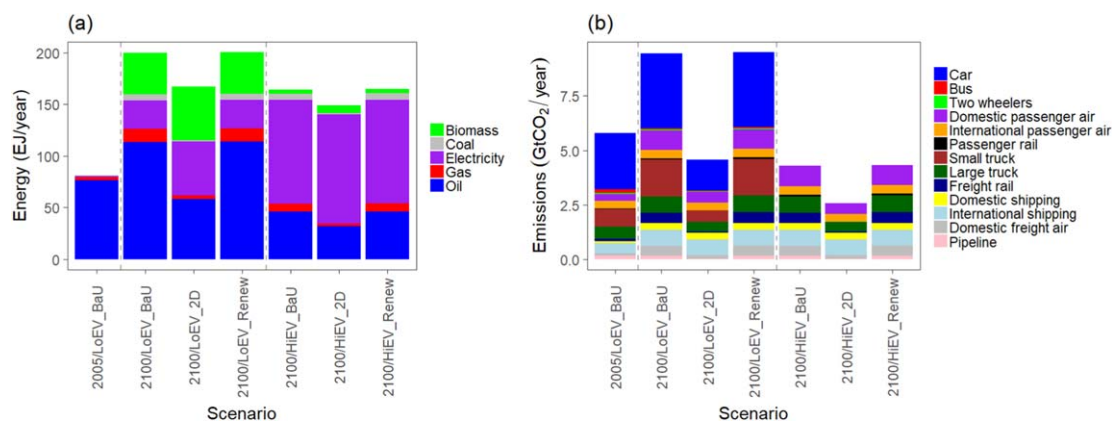


Figure 2. Effects of transport electrification on energy use and CO₂ emissions. Energy use from transport (a) and emissions from transport (b).

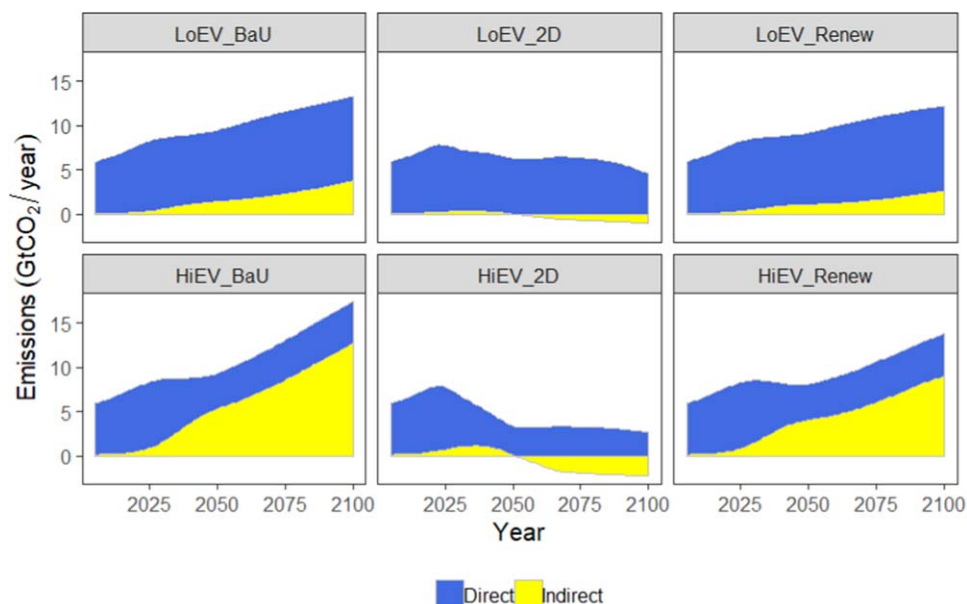


Figure 3. Direct CO₂ emissions from transport and indirect CO₂ emissions from electricity generation that energize electric vehicles (EVs).

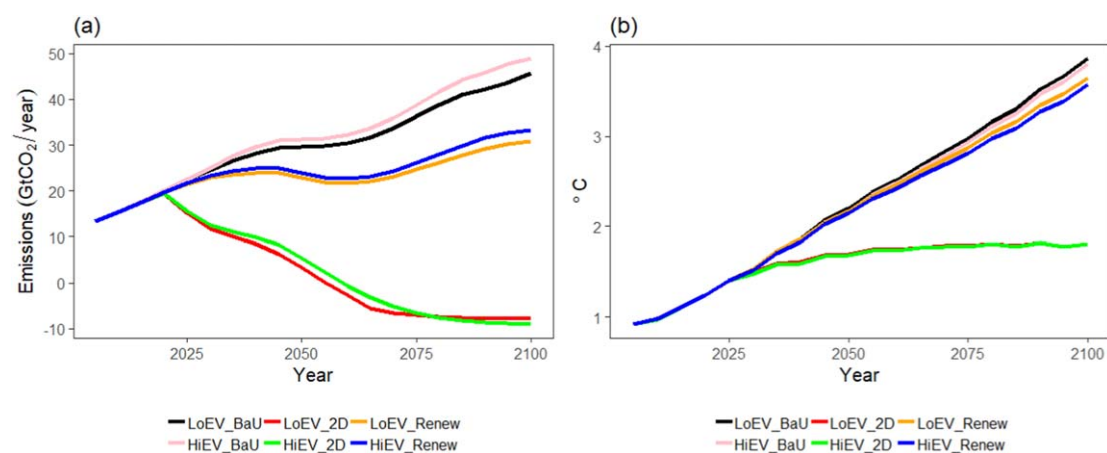


Figure 4. CO₂ emissions from the energy sector (a), and global mean temperature increase above pre-industrial levels (b).

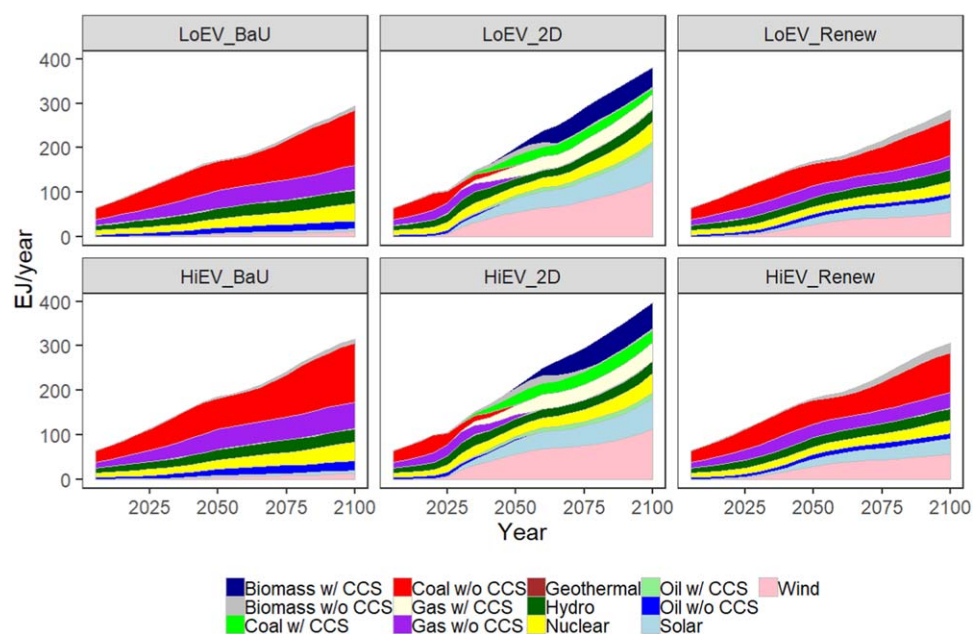


Figure 5. Global energy supply for electricity generation.

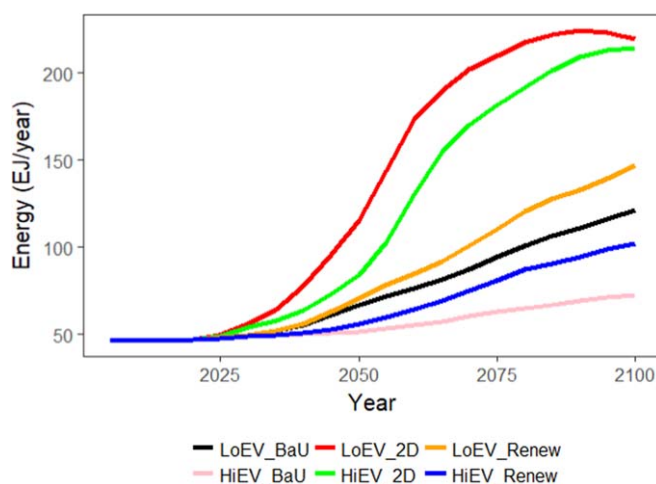


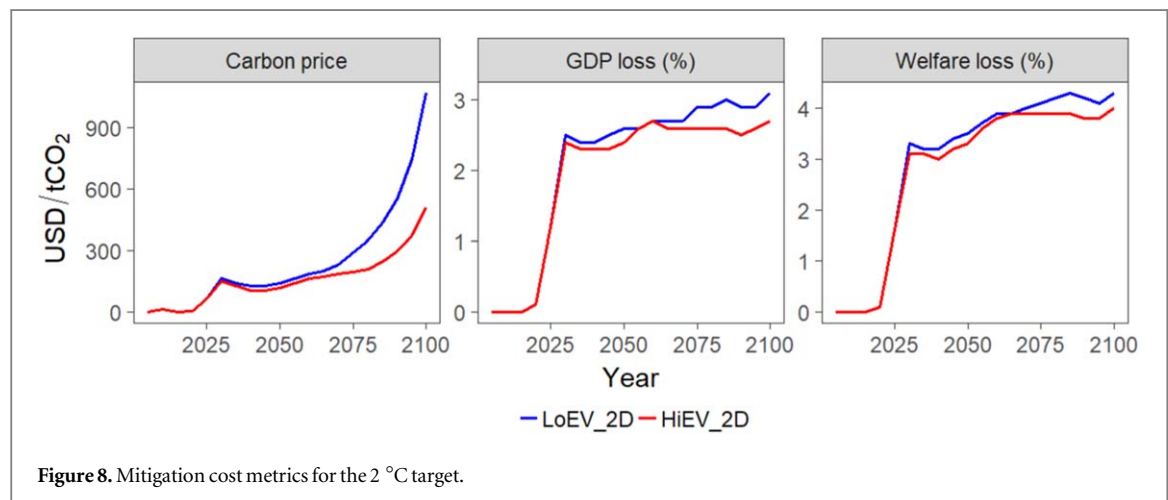
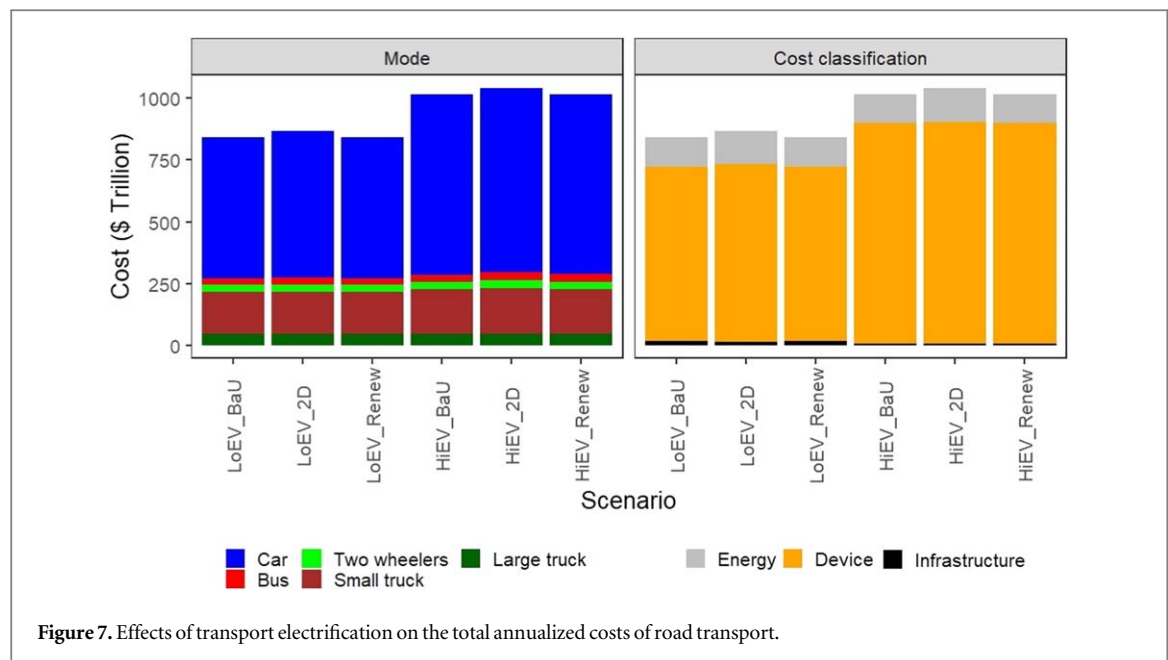
Figure 6. Impacts of transport electrification on the consumption of biomass.

the emissions in the energy-supply sector, because of the switch to renewable and less carbon intensive fuels (figure 5; see power generation composition and primary energy in supplementary figures S5 and S6). As shown in figure 4(b), deploying EVs alone could not effectively mitigate temperature increases, implying that an EV policy will not reduce CO₂ emissions from all sectors if the transport is not powered by decarbonized electricity generation (see emissions by sector in supplementary figure S7).

3.3. Biofuel

In the near future, biofuels such as ethanol and biogas are expected to be at the leading edge of transport decarbonization [32]. The widespread adoption of ambitious biofuel policies would apparently deliver a

rapid transition in the supply base of transport fuels. However, as shown in figure 2(a), it has already been confirmed that transport electrification exerts a negative impact on biomass consumption in the transport sector. More interestingly, similar results were apparent when all sectors were considered, as shown in figure 6. The deployment of EVs produced a lower consumption of biomass. Because biomass production may compete with other land uses or land covers, there is a major debate concerning whether the biomass feedstock production required by ambitious biofuel targets will threaten food security, exacerbate deforestation, destroy ecosystems, and aggravate rural poverty [33–35]. Our simulations of transport electrification proved that an EV policy could be a promising solution for easing the increasing demand on biomass,

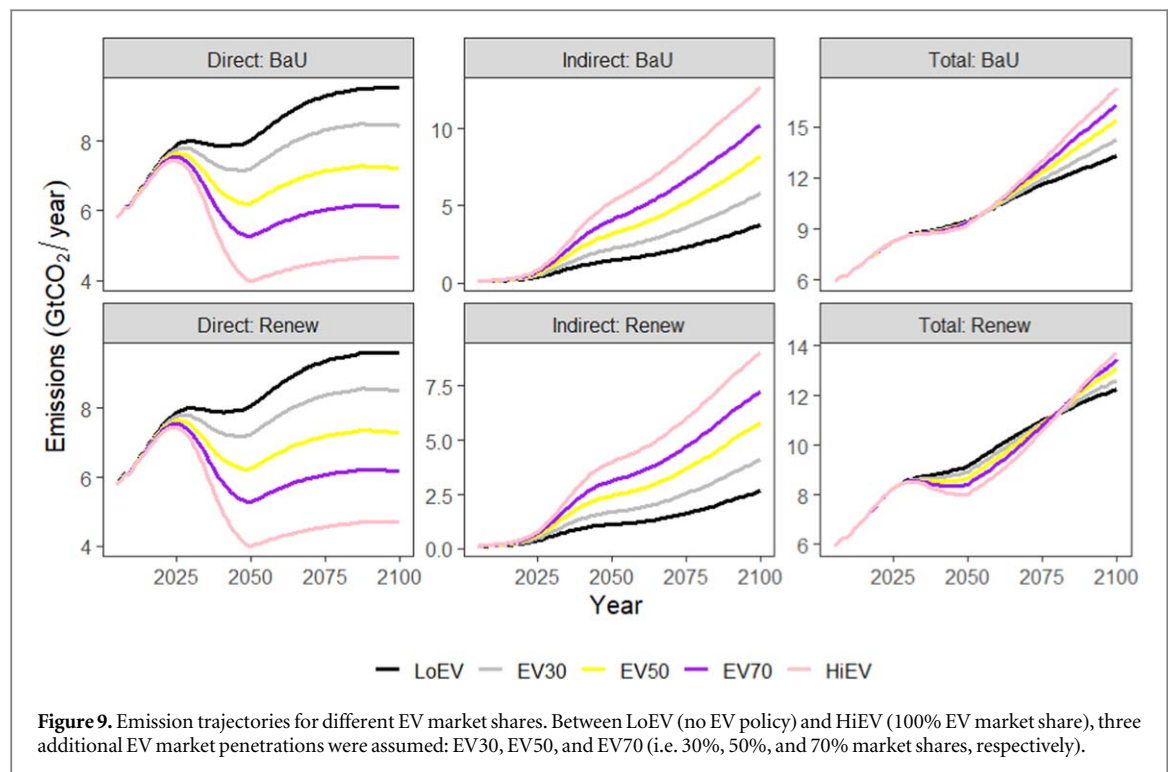


which would help mitigate the risk of increasing food insecurity due to ambitious biofuel goals.

3.4. Economic results

The economic costs and benefits of transport electrification over the long term were evaluated using a global transport model coupled with an economic model, with the coupling model describing the interactions between the transport sector and macroeconomy. Figure 7 shows the total annualized cost of road transport during 2005–2100. Cars and small trucks were the dominant modes, accounting for a major proportion of the cost, while device costs generated the highest capital cost compared with energy consumption and infrastructure. Stringent transport electrification goals require higher capital costs for the vehicle, mainly due to the more expensive components of EVs. Although the device cost of EVs is assumed to continue to decline over the coming decades, it is still likely to be higher than that of ICE vehicles.

Another measure of the economic effects of transport electrification is to detect how the cost of climate change mitigation would be modified with the stringent penetration of EVs, which can be indicated by carbon price, GDP loss rate, and welfare loss rate required to achieve an emission reduction consistent with the stabilization objective of the 2 °C scenario. Figure 8 shows that the carbon price for achieving the target of a 2 °C global temperature rise decreased from 1072 to 511 USD in 2100 due to the undertaking of an ambitious transport electrification policy. The GDP and welfare loss rate associated with pricing carbon can be thereby mitigated significantly because the goal of emission reduction can be achieved more easily by electrification of the road transport sector through EVs rather than by putting a heavy price on carbon emissions. Carbon-neutral road transport can instantly contribute to the reduction of transport-related emissions by accelerating the market diffusion of EVs, which helps to relieve the negative impacts of climate change mitigation efforts on the



macroeconomy. Therefore, economic development does not necessarily have to run counter to climate change policy goals when low-carbon transport technologies are taken into consideration.

3.5. Sensitivity analysis

Driven by transport electrification policies, the market share of EVs has been projected to increase significantly in the coming decades. However, there is still uncertainty related to the future prospects of complete EV penetration by 2050, because only a few governments have legislated to ban ICE vehicle sales. Thus, to understand more fully the relationships between policy settings and model outputs, it is necessary to test whether the model and its results are robust in the presence of uncertainty. One way to perform an uncertainty and sensitivity analysis is to simulate a range of transport electrification scenarios rather than by focusing on a 100% market share of EVs. Figure 9 displays the CO₂ emission trajectories, with consideration given to different EV market shares between the LoEV and HiEV scenarios. The trajectories of the direct emissions when assuming 30%, 50%, and 70% market shares of EV penetration were higher than those for HiEV and lower than those for LoEV, regardless of whether renewables penetrate further the energy mix or not. The indirect emissions exhibited contrasting features, but the greater the market share, the higher the indirect emissions. However, total emissions displayed the different dynamics between BaU and Renew. Without high preference for renewable energies, total emissions showed increasing trends in alignment with high market diffusion of EVs,

whereas opposite profiles can be found especially for the total emissions during 2030–2080 because the reduction in indirect emissions offsets the increases in direct emissions. The robustness of model coupling and stringent EV penetration was verified by a sensitivity analysis of the multiple market shares.

In addition, there were also uncertainties regarding the different socioeconomic assumptions of population and economic growth. Here, multiple socioeconomic pathways were assumed that were aligned with SSP1–3 to explore how socioeconomic factors influenced the emission profiles when considering stringent transport electrification. It was possible to determine whether there were futures where transport electrification was more or less beneficial, even in the absence of complete power sector decarbonization. Figure 10 shows the emission profiles for the three SSP scenarios. Transport electrification reduced direct emissions from the transport sector, but indirect emissions increased significantly in all three SSP scenarios. However, when considering the tradeoff between direct and indirect emissions, the total emissions displayed differences among the three SSPs. Interestingly, the stringent penetration of EVs reduced the total CO₂ emissions in SSP1, whereas in SSP2 and SSP3 there were increases in total emissions when the 100% market share of EVs was achieved. Even without a decarbonized power sector through carbon pricing or renewable energy policies, transport electrification aligned with SSP1 was able to meet the CO₂ emission reduction target.

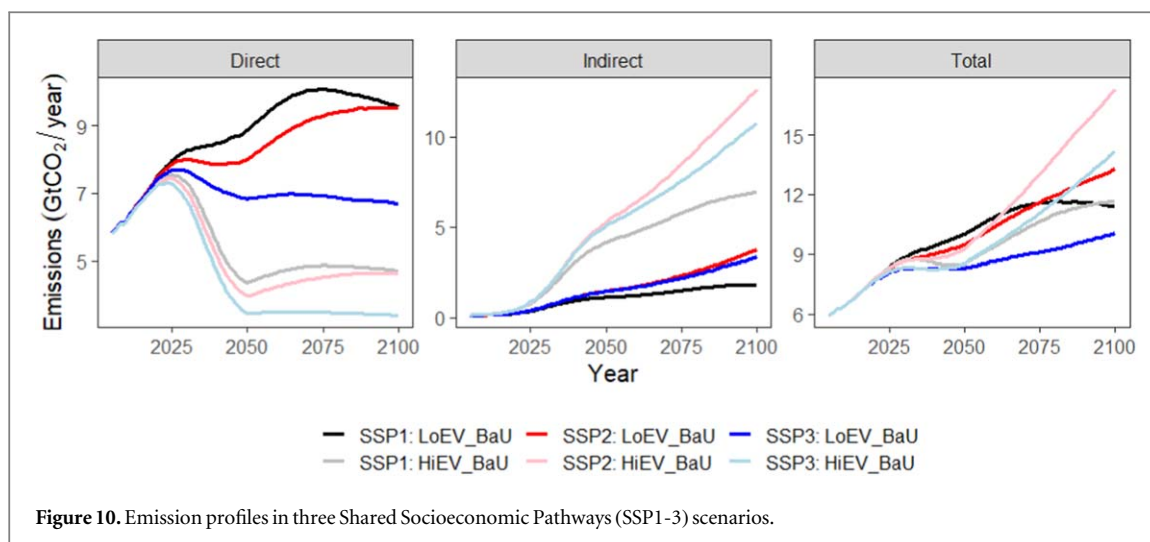


Figure 10. Emission profiles in three Shared Socioeconomic Pathways (SSP1-3) scenarios.

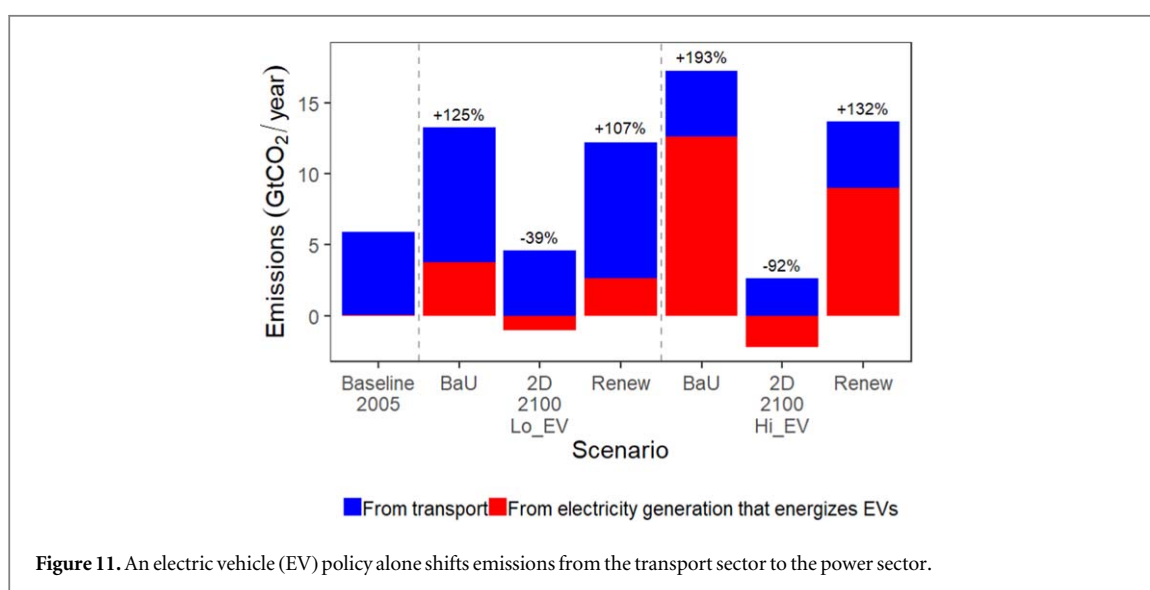
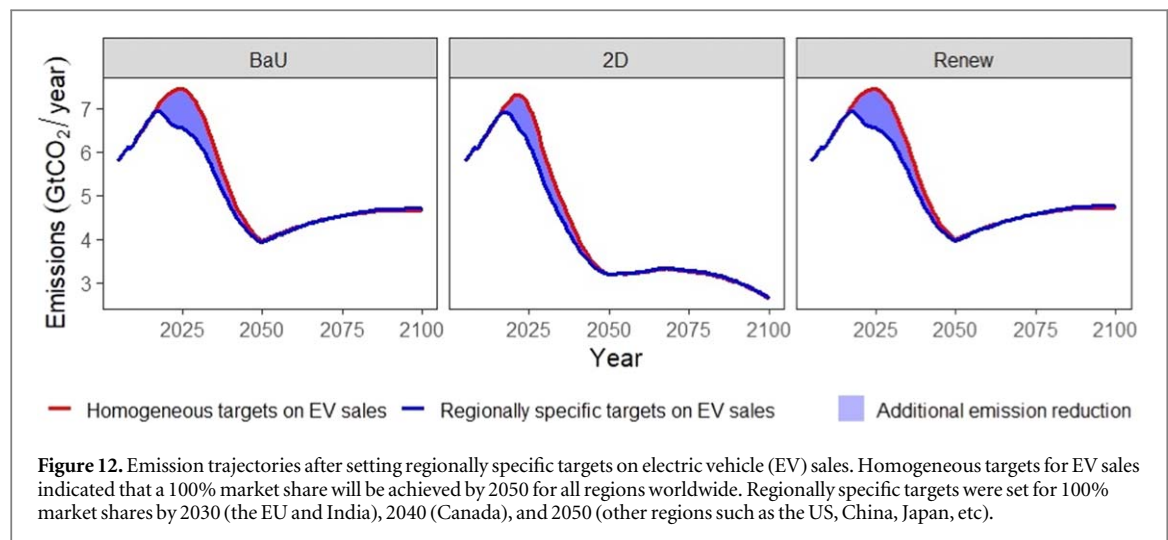


Figure 11. An electric vehicle (EV) policy alone shifts emissions from the transport sector to the power sector.

4. Discussion and conclusion

Many governments have encouraged the adoption of EVs as an important step toward a clean energy future because of their contribution toward reducing direct emissions from transport. However, our research confirmed that an EV policy without decarbonizing power generation fails to contribute to emission reduction, although direct emissions from transport can be reduced significantly because an EV policy would shift emissions from the transport sector to the power sector (figure 11). Despite the rapid technological progress made with EV technologies, an analysis of combined transport electrification and energy policies revealed an uncomfortable truth—transport electrification alone does not successfully reduce emissions and mitigate climate change. Instead, to meet stringent climate targets, the linkages between the transport sector and energy sector deserve attention. Renewable energy as a means to decarbonize power generation needs to play a key role when electrifying the transport sector.

Although homogenous targets of 100% market share were established for the stringent EV scenarios in 17 regions, governments have actually set different timelines for the phase-out of ICE vehicles (see supplementary table S4). According to these different national transport electrification goals, heterogeneous market shares for EV scenarios were designed to reflect policy variation and estimate the emission trajectories considering regional heterogeneity in policy timelines and goals. Figure 12 shows the emission trajectories with the setting of regionally specific ICE bans. It was assumed that more ambitious targets for EV penetration would be established in the EU, Canada, and India, in view of their national strategies for transport electrification, while default values for deploying EVs were set for other countries and regions such as the US, China, and Japan. Regardless of whether carbon pricing and renewable energy policies were deployed, additional emission reductions could be realized globally due to the different regional EV diffusion policies. Because transport emissions in the EU, Canada, and India account for approximately a



quarter of global transport emissions, earlier timelines for ICE bans in these three regions would accelerate the global emission reduction. The regional emission trajectories considering these policy variations are provided in supplementary figure S8.

Our findings should not be interpreted to downplay the contribution of transport electrification to climate change mitigation or to deemphasize the role of EVs as a potential solution toward a low-carbon transition. Rather, we highlight the interaction required between transport electrification and the power sector to formulate more harmonized and inclusive policies. Combining transport electrification with energy policies, such as carbon pricing, could facilitate emission reductions from transport and a simultaneous transition to a low-carbon future. Interestingly, transport electrification can also be considered a potential policy tool to alleviate the negative impacts of biofuel development on food security due to ambitious climate change mitigation targets. Moreover, it was found that the emission reduction effect of stringent EV goals was not dependent on the decarbonized power sector or accompanying energy policies in SSP1, which depicts features of a sustainable future, with low fossil-fuel dependence and an increasing share of renewables. SSP1 is characterized as ‘Taking the Green Road’, with low population projections but high productivity, leading to lower CO₂ emissions and fewer challenges to climate change mitigation. Because the world is oriented toward lower resource use and energy intensity in SSP1, a widespread transition to a zero-carbon road transport sector might not have side effects. Because the effectiveness of transport electrification policy is determined by socioeconomic pathways, transport planners, energy experts, policymakers, economists, and stakeholders need to work together to develop a joint strategy for transport electrification to reduce CO₂ emissions quickly and effectively.

Mitigation cost measures represent the economical attractiveness of transport electrification as a mitigation opportunity, because it reduces the loss rates of

economic growth due to imposition of a carbon tax for achieving climate change mitigation targets. The impact on the dynamics of the macroeconomy of transport electrification needs to be considered when evaluating the feasibility and cost-effectiveness of EV policies. Climate action does not have to decrease economic growth and it is not certain that economic sacrifice will be required. It is possible to propose a win-win strategy of low-carbon transition and economic development. On the other hand, from the viewpoint of consumers, an electrified transport sector requires additional vehicle purchase costs for EVs compared to a conventional ICE driven vehicle, mainly because of the cost of the battery. Although battery costs are projected to decrease due to improvements in the materials used as well as the potential for large-scale manufacturing [22], economic policy incentives such as subsidies for EVs need to be considered to reduce the additional costs of EVs directly and stimulate consumers to purchase them. In this study, scenario settings for stringent EV penetration were represented only by ICE vehicle bans, and did not involve other specific EV policies, such as purchasing subsidies, exemptions from tolls, and registration fees. Further studies are needed to determine how financial incentives for EV use would modify the market share of EVs in the coming decades.

Although this study was aimed at determining the role of transport electrification using a global transport model coupled with economic and climate models, there are limitations to the study that should be noted. The temporal dynamics associated with EV charging were not taken into consideration and, therefore, the current model framework did not conduct an analysis of the hourly balance between EV charging loads and electricity generation. In future studies, a detailed hourly profile of EV charging should be explicitly represented. In addition, the emissions produced from the EV manufacturing process were not included in the global transport model, and will need to be incorporated when estimating the

life-cycle emissions of EVs, because a considerable proportion of a vehicle's carbon footprint is generated at the factory, before the vehicle travels on the road. Because EV studies are cutting edge and present interdisciplinary challenges, this study constitutes only the first step toward understanding the important potential tradeoffs between efforts to electrify the transport sector and decarbonize the power sector. Further research is required to improve the interdisciplinary methodological framework, extend the scope of EV studies to the field of climate change, and assess how global and national transport electrification policies should develop in the coming decades. In particular, transport electrification studies could easily be extended to include energy security, disruptive technological innovations (e.g. autonomous cars, car-sharing, artificial intelligence, etc), and local air quality and health risks associated with air pollution to enable climate target-oriented transport planning and policymaking.

Acknowledgments

The author acknowledges support from the Japan Society for the Promotion of Science (JSPS) KAKENHI Grant No. 19K20507, and the Environment Research and Technology Development Fund (2-1908) of the Environmental Restoration and Conservation Agency of Japan.

Data availability statement

Any data that support the findings of this study are included within the article. Scenario data for all the scenarios are available within the supplementary material.

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