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TRANSPORT ELECTRIFICATION: A GLOBAL SIMULATION OF THE PENETRATION OF ELECTRIC VEHICLES

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ABSTRACT

Switching to electricity for road transport is considered as a promising solution to energy transition and CO_2 emission reduction. In this paper, an integrated assessment model, which contains an elaborate transport module for detailed behavioral and technological descriptions, is employed to investigate how the energy use and emission profiles would be altered by the electric vehicle (EV) adoption. A set of scenarios is created according to policy interventions for the promotion of electric mobility. The results show that the EV financial incentives will significantly boost the market shares and reduce effectively the CO_2 emissions produced by the light-duty vehicle, while carbon pricing only exerts a moderate influence. The regional heterogeneity of emission trajectories across various countries indicates that incentives for EV adoption require more attention in developing counties. Policy Instruments to promote electric mobility would entail considerable costs, which should be considered in the policymaking.

Keywords: transport electrification, electric vehicles, energy mix, emissions, integrated assessment model

NONMENCLATURE

Abbreviations

EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
ICE	Internal Combustion Engine
IAM	Integrated Assessment Model

1. INTRODUCTION

The transport sector is responsible for a quarter of global energy consumption. Due to the rapid motorization worldwide and overwhelming dependence on fossil fuels, the decarbonization of the transport sector has proved more challenging than other sectors [1]. The electrification of transport sector is essential for breaking transport dependency on oil and meeting the goal of decarbonization [2]. A number of countries around the world have set targets and timelines to phase out internal combustion engine (ICE) vehicles and introduced incentives to encourage drivers to shift to electric transport. Several strong financial incentives have been implemented to promote electric vehicles (EVs) into the market such as purchase subsidies, exemptions from tolls and registration fees, free ferry rides, and free municipal parking. Thus, it is necessary to investigate how the policy interventions would impact the market penetration of EVs and global energy use profiles.

Integrated assessment models (IAMs), which couple models of energy system technologies with economic and climate models, have been widely used to evaluate the technological and economic feasibility of achieving specific climate change mitigation goals [3]. IAMs are designed to involve socioeconomic factors as well as natural sciences components to achieve a better understanding of how human activities and social development affect the natural world, in particular, climate system. As a few of IAMs provide more elaborate representation of transport sector that incorporates mode choice and individual vehicle technologies, it becomes possible to employ the approach of IAMs to detect the interactive mechanism between transport sector and energy system.

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Although EVs have been considered as clean technology alternatives to conventional fossil fuel powered vehicles provided that electricity gets decarbonized in the long run, EVs still remain less cost-effective than gasoline vehicles. Policy interventions are needed to lower the up-front costs of EVs and facilitate the further penetration of electric mobility. On the other hand, carbon pricing is usually modeled in IAMs to weaken the economic competitiveness of transport technologies that rely on fossil fuels, which offers a generic policy tool to reduce the CO_2 emissions throughout all sectors. Therefore, the main purpose of this paper is aiming to create a better understanding of how the policy incentives might affect the EV penetration and energy transition, and what policies and strategies help achieve the goal of low-carbon future, by an IAM that incorporates elaborate transport representation.

2. METHODOLOGY

2.1 Model

The methodological framework of the IAM is employed to provide spatially flexible and temporally dynamic simulations of transport demand, energy use, and emissions, because it contains an elaborate transport module for detailed behavioral and technological descriptions such as vehicle device cost, fuel cost, vehicle speed, time, infrastructure, load factor, and preferences. The model considers different distances, modes, vehicle sizes and technologies for the global projection of passenger and freight transport demand in 17 regions around the world. The model structure and equations are described in detail in Zhang et al. (2018) [4]. In this paper, the model has been extended to incorporate more detailed descriptions on EV technological factors. Three main types of EVs are considered including hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV).

The historic transport demand and energy data for parameter estimation and calibration are collected from the database of the Asia-Pacific Integrated Model (AIM). Socioeconomic data are obtained by the shared socioeconomic pathways (SSP) database and a global computable general equilibrium (CGE) model [5]. The carbon price pathway is also calculated by the CGE model. Transport demand for different modes, sizes, and technologies, technology-specific energy intensity, and vehicle device cost are acquired from a bottom-up technological end-use model. The study phase of the integrated model is from 2005 to 2100 with one-year interval.

2.2 Scenario settings

A set of scenarios is created with regard to carbon pricing and financial incentives to represent the promotion of electric mobility. Here, a carbon price scenario, CP, is structured corresponding to a 2°C climate stabilization target, in which a carbon price is introduced to achieve 450 ppm CO_2 equivalent concertation (2.8 Wm^{-2}) by 2100. No carbon pricing would be imposed in the reference scenario, RF. For the scenario regarding financial incentives for EV promotion, FI, it is assumed that the capital costs of BEV would decrease by 80% during 2005 to 2100 due to a variety of measures for EV adoption, while they decease by 40% owing to the technological advancement, e.g., the decreasing battery cost, in the reference scenario.

3. RESULTS

3.1 Market shares

Figure 1 shows the long-term impacts of carbon pricing and financial incentives for electric mobility promotion on global market shares of light-duty vehicle in three scenarios. In the reference scenario, HEV, PHEV, and BEV make up 11%, 8%, and 17% of the global market in 2100, while the market share of ICE will decrease to 64%, due to the technological improvement of electric mobility. Such transition would be accelerated by the carbon pricing and EV financial incentives. In particular, BEV share is growing faster in FI scenario than CP scenario. Financial incentives for purchasing an electric car result in a rapid increase of BEV share to 74% in 2100, whereas carbon pricing bolsters the BEV share to 33% in 2100.

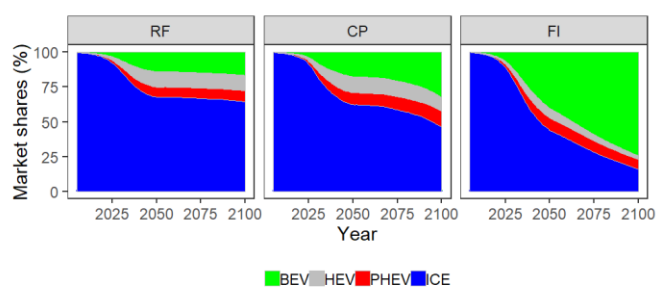

Fig 1 Global maket shares of light-duty vehicle

3.2 Energy mix

As shown in Fig 2, changes in energy mix are characterized as a shift from oil to electricity and biomass. In the reference scenario without carbon pricing or EV incentives, energy consumption required by light-duty vehicle increases from 36 EJ to 83 EJ during 2005 to 2100, with oil continuing to power the car as a dominant contributor, though electricity and biomass are playing increasing roles. The imposition of a carbon price can significantly reduce the oil consumption and stimulate the usage of electricity and biomass. More electricity will be consumed when the targets for the implementation of electric road transport are promoted in the EI scenario. Energy transition can be achieved with stringent policy interventions such as carbon pricing and EV financial incentives, otherwise oil still accounts for considerable proportions in the coming decades.

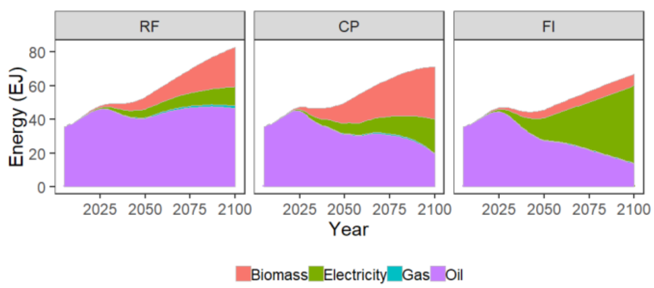

Fig 2 Global energy consumption by light-duty vehicle

3.3 Emissions

The CO_2 emission trajectories from light-duty vehicle in 17 regions during 2005 to 2100 is displayed in Fig 3. The financial incentives for EV adoption are more effective to reduce the CO_2 emissions than carbon pricing, which is consistent with the higher market share of BEV in FI scenario. Because the goal of zero emissions cannot be achieved without extensive electrification of light-duty vehicle, carbon pricing will contribute less to emission reduction compared with direct EV incentives. Fig 3 also presents the regional heterogeneity of emission trajectories. Without carbon pricing or incentives for EV adoption, the emission trajectories in developed countries such as the United States, Japan, and the European Union present tendencies of decrease, while increasing trends can be found in developing countries like Brazil, China, and India. This heterogeneity across developed and developing countries exists probably because car ownerships in developed countries have reached saturation levels already, whereas developing countries are witnessing an explosive increase of car usage in the 21st century. The implementation of policy instruments is a greater concern in developing countries, since it can reverse the increasing trends of CO_2 emissions.

4. DISCUSSION AND CONCLUSION

The IAM that accommodates a transport module offers a methodology appropriate for and capable of capturing the interactions among the dynamics of transport electrification, energy system, and emissions. Compared with the individual energy model, such integrated approach can provide elaborate behavioral and technological descriptions on the EV adoption. Mode preference, technological selection, travel time, load factor, and device cost can be incorporated into the projection of energy consumption to structure scenarios for transport energy policy assessment. By using this integrated model, the transport planners and energy policymakers can come together to evaluate the

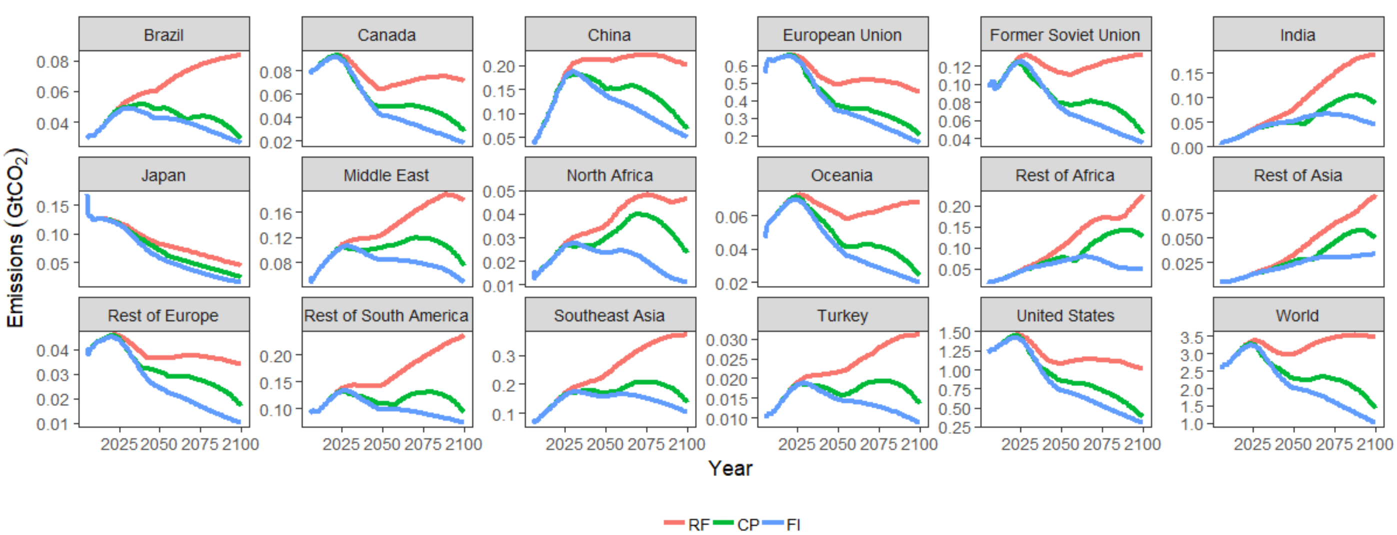

Fig 3 Regional CO_2 emission trojectories

common-sense measures available to support a transition towards low-carbon future.

Scenario simulations reveal that the direct EV incentives are more effective than carbon pricing to stimulate the deployment of EVs and encourage an energy transition away from fossil fuels, as the purchase and operation costs can be reduced due to the subsidies, toll exemption, and other incentives. However, carbon pricing might have a more significant influence on the energy consumption and emissions from the whole transport sector including passenger and freight. As shown in Fig 4, although the emissions produced by light-duty vehicle would decline sharply owing to the EV incentives, total emissions from transport sector present higher trajectories than those in carbon pricing scenario, because putting a price on carbon will decarbonize not only the light-duty vehicle but also other passenger and freight transport such as bus, two-wheeler, truck, rail, shipping, and aviation.

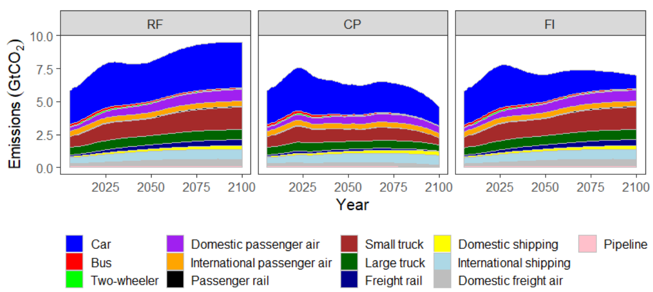

Fig 4 Global emissions by mode

While this study focuses on the impacts on the energy use and emissions, detecting the economic effects is one advantage of the IAM. The imposition of carbon pricing for achieving climate change mitigation targets is bound to bring economic costs such as GDP loss, while the national and local governments need to pay for finical incentives to consumers who purchase EVs to encourage the adoption of electric mobility. Fig 5 shows the GDP loss generated by carbon pricing and the cost of EV incentives. The GDP loss in carbon pricing scenario is greater than the economic cost in FI scenario, implying the cost-effectiveness of the direct financial incentives for the deployment of EVs. However, it should be noted that, in spite of the higher economic costs, carbon pricing works by shifting the responsibility of paying for the damages of climate change from the public to not only the car consumers and drivers but all the GHG emission producers. Electrifying the whole transport sector including air, rail, water, and road transportation might require much more cost for the financial incentives.

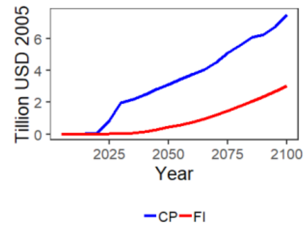

Fig 5 Economic costs

There remain considerable limitations to be addressed in the future. The scenario of financial incentives, in which subsidies, exemptions of tolls and parking charge, and other policy instruments are not modelled independently but are introduced globally into the model as decreases of capital costs, might not be realistic, but intends to show how to represent the EV adoption and detect its impacts on energy use. Moreover, heterogeneous consumer preferences on EVs are not taken into consideration due to the data availability and the aggregated nature of the IAM. The relationships between the heterogeneous preferences and the penetration of EV deserve more attention.

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