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To cite this article: Zhenhua Chen *et al* 2021 *Environ. Res. Lett.* **16** 045011

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

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in the U.S

OPEN ACCESS

RECEIVED

1 November 2020

REVISED

29 January 2021

ACCEPTED FOR PUBLICATION

3 February 2021

PUBLISHED

1 April 2021

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Zhenhua Chen¹ , Andre L Carrel^{1,2} , Christina Gore³ and Wei Shi⁴ ¹ City and Regional Planning Section, The Ohio State University, Columbus, OH, United States of America² Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Columbus, OH United States of America³ Department of Agricultural, Environmental, and Development Economics, The Ohio State University, Columbus, OH, United States of America⁴ Global Data Insight & Analytics, Ford Motor Company and the Ohio State University, Dearborn, MI, United States of AmericaE-mail: chen.7172@osu.edu**Keywords:** environmental impact, economic impact, electric vehicle, consumer choice, computable general equilibrium modelSupplementary material for this article is available [online](#)**Abstract**

Battery electric vehicles (BEVs) have received increasing attention in recent years as BEV technical capabilities have rapidly developed. While many studies have attempted to investigate the societal impacts of BEV adoption, there is still a limited understanding of the extent to which widespread adoption of BEVs may affect both environmental and economic variables simultaneously. This study intends to address this research gap by conducting a comprehensive impact assessment of BEV adoption. Using demand estimates derived from a discrete choice experiment, the impact of various scenarios is evaluated using a computable general equilibrium model. Three drivers of BEV total cost of ownership are considered, namely, subsidy levels, cash incentives by manufacturers, and fuel costs. Furthermore, in light of current trends, improvements in BEV battery manufacturing productivity are considered. This research shows that changes in fuel price and incentives by manufacturers have relatively low impacts on GDP growth, but that the effect of subsidies on GDP and on BEV adoption is considerable, due to a stimulus effect on both household expenditures and on vehicle-manufacturing-related sectors. Productivity shocks moderately impact GDP but only affect BEV adoption in competitive markets. Conversely, the environmental impact is more nuanced. Although BEV adoption leads to decreases in tailpipe emissions, increased manufacturing activity as a result of productivity increases or subsidies can lead to growth in non-tailpipe emissions that cancels out some or all of the tailpipe emissions savings. This demonstrates that in order to achieve desired emissions reductions, policies to promote BEV adoption with subsidies should be accompanied by green manufacturing and green power generation initiatives.

1. Introduction

Transportation has overtaken power generation as the largest single source of greenhouse gas emissions in the United States. A key to reducing the carbon footprint of this sector is the widespread adoption of battery electric vehicles (BEVs), which, unlike hybrid-electric vehicles (HEVs) or plug-in HEVs (PHEVs), do not have an onboard combustion engine. Despite the increasing maturity of BEV technology, the share of BEVs in the US private fleet remains very low. One reason for this may be the fact that, on average, BEVs continue to be more expensive to purchase

than conventional or hybrid vehicles of comparable size and type, although this is partially offset by the lower operating costs of BEVs (Breetz and Salon 2018). Since 2007, in an effort to boost BEV adoption, US federal and state governments have created tax incentives and fee rebate mechanisms in order to reduce the purchase price that end consumers pay for a BEV.

There are currently several developments that could increase BEV adoption in the near future. First, there is a push by US policymakers to renew federal subsidies for BEVs since the previous federal tax credit, which offered purchasers of a new BEV up to

\$7500, is being phased out. The Clean Cars for America proposal would invest \$454 billion into electrifying the US automobile fleet. Subsidies would start at \$3000 per new vehicle purchase and could reach \$5000–\$8000 according to some estimates. Second, an increasing number of automotive manufacturers is launching new BEV models with purchase prices that are comparable to upper-class conventional vehicles. As the number of BEVs on the market grows, manufacturers may offer cash incentives to potential buyers (Bjerkkan *et al* 2016). Third, there are continued productivity improvements in battery manufacturing, with corresponding reductions in the cost of BEV batteries (Hensley *et al* 2012). Reductions of BEV purchase prices as a result of these factors would directly affect adoption rates, but they are overlaid with another relatively unpredictable factor, namely, the development of fuel prices. A lower fuel price may negatively affect BEV adoption by eroding the operating cost advantage of BEVs when compared to conventional vehicles (Sierzchula *et al* 2014, Bjerkkan *et al* 2016) and thereby counteract some of the effects of purchase price reductions. A higher fuel price, on the other hand, would have a compounding effect.

While these factors all affect BEV adoption, the changes that each factor causes in capital flows would ripple through various industry sectors and supply chains in different ways, with different effects on the overall economy. Moreover, the different impacts apply to emissions patterns as well, which arguably are the ultimate goal of BEV adoption policies. Reductions in tailpipe emissions are only one effect of BEV adoption, as one must also consider the emissions caused by the manufacturing, maintenance, and operation of BEVs as well as the conventional and hybrid vehicles they replace.

With this background in mind, the objective of our paper is to assess the broad economic impacts of various BEV adoption scenarios, taking into account the economic effects on household expenditure patterns as well as the automotive industry and associated sectors as a whole. Furthermore, we assess the impacts on greenhouse gas emissions, including direct emissions by combustion engines, power generation for charging BEVs, and non-tailpipe emissions generated by automotive manufacturing. We aim to compare the four impact drivers outlined above (subsidies, purchase price adjustments, fuel costs, and battery manufacturing productivity improvements) in order to gain an understanding of the relative magnitudes of the potential effects, both on their own and compared to each other. This can inform policymaking and pave the way for assessing the effects of combined economic and technological trends in future research. To achieve this objective, we present a combination of a computable general equilibrium (CGE) model of 70 economic sectors that captures economy-wide effects with a discrete choice model of consumers' vehicle purchasing behavior. The discrete

choice model was estimated using a unique, stated preference data set on BEV adoption that was collected in three US regions in 2019.

The rest of the paper is organized as follows. Section 2 provides a literature review with a focus on BEV adoption and the economic impact assessment of BEV adoption using CGE methods. Section 3 introduces the modeling framework, scenarios and data. Section 4 presents the simulation results, and section 5 discusses the implications, and section 6 concludes.

2. Literature review

Given the rapid development of BEV technology, many studies have attempted to understand what factors affect the adoption of BEVs. Two research methods were primarily adopted. The first one is an econometric analysis of revealed and stated preference data. Rezvani *et al* (2015) found that the adoption of BEVs is affected by several factors, such as purchase cost, hands-on experience with BEV technology, emotions related to driving a BEV, and environmental concerns. Coffman *et al* (2016) categorized the factors driving BEV adoption as internal or external, referring to the characteristics of the BEV itself and to factors that are beyond the direct control of BEV car manufacturers. Specifically, battery costs, purchase price, driving range, and charging time were considered internal factors, whereas fuel prices, policy incentives, consumer characteristics, availability of charging stations, travel distances, public visibility, and vehicle diversity were considered external factors. Macro-effects of unemployment and fuel prices were also found to drive the adoption of hybrid vehicles in the US (Jenn *et al* 2013), a finding that may also apply to BEVs, and Mersky *et al* (2016) found that the growth of BEV sales was closely linked to regional income levels. Hess *et al* (2012) used a cross-nested logit model to understand the combined decision on vehicle type and fuel type, and they found that incentives were necessary to promote consumer interest in BEVs. Similarly, Breetz and Salon (2018) concluded that state and federal subsidies were necessary for BEVs to be cost-competitive in 14 US cities. Langbroek *et al* (2016) evaluated the effect of policy incentives on BEV adoption and showed that policy incentives have a positive influence on adoption.

Several pioneering works have also adopted CGE models to evaluate the environmental impacts of electric vehicle adoption. For instance, Karplus *et al* (2020) evaluated the conditions under which the PHEV could most contribute to reductions in greenhouse gas emissions in the US and Japan. Both the vehicle cost and climate policy were evaluated using CGE analysis. Their results showed that the potential of PHEV adoption on emissions reduction depends on the carbon intensity of electric power generation. Schmelzer *et al* (2018) evaluated the social costs and

benefits of electric vehicles in Austria. One highlight of their analysis is that the CGE assessment is integrated with a discrete choice model to estimate the demand for overall vehicle purchases through the change of a price index for aggregated vehicle purchases. However, one major limitation of this study is that the stimulus effects of subsidy on both BEV adoption and vehicle manufacturing production were not considered. Similarly, Hirte and Tscharaktschiew (2013) examined optimal subsidy levels for BEV adoption in Germany. While the evaluation was conducted through shocks of the power tax in a spatial CGE model, the direct effects of the subsidy on vehicle manufacturing sectors were not modeled explicitly. Miyata *et al* (2017) provided a different assessment of the economic impact of subsidies on BEV adoption in a Japanese city. Based on hypothetical simulation scenarios, their study showed that an increased subsidy of BEV-related sectors is likely to promote economic growth and reduce greenhouse gas emissions.

The aforementioned studies to evaluate the economic impact of BEV adoption have two major shortcomings. First, many lacked behavioral realism regarding consumer responses, either because of data or model limitations. Therefore, they performed the impact assessments based on hypothetical scenarios that were not grounded in behavioral data or using simplified, reduced-form models. Although some studies exist that incorporate behavioral data, evidence from the US context remains sparse. Second, they generally focused on specific aspects of consumer costs, but did not consider multiple drivers of the total cost of ownership (TCO) of BEVs concurrently. This limited their ability to compare the impacts of different drivers of the TCO that ultimately affect BEV adoption. This paper extends the previous literature in several ways. First, our assessment was conducted by integrating a discrete choice survey and a CGE model, thus ensuring that the results are behaviorally realistic. Second, we present a framework for the environmental and economic impact of BEV adoption. It recognizes the various factors that affect TCO, and ultimately, BEV adoption, but also considers changes in non-tailpipe emissions as well as tailpipe emissions for a holistic assessment. Based on this framework, we present an evaluation of key direct impact drivers across several scenarios, including demand-side effects due to price reductions, fuel cost changes, and subsidy policies, and supply-side effects, such as improvements in battery manufacturing productivity. This allows us to compare and contrast different mechanisms driving BEV adoption. The framework and results have the potential to facilitate decision-making on future BEV investment and policies to achieve better economic and environmental outcomes.

3. Methods and materials

3.1. Modeling framework

To fill these research gaps, we developed a comprehensive modeling framework capturing the various key drivers affecting BEV adoption (see figure 1) based on the literature review. In general, BEV adoption is likely to be influenced by four main factors: the prevalence of BEV charging infrastructure, TCO, vehicle characteristics, and the preferences and attitudes of consumers (Coffman *et al* 2016, Liao *et al* 2017, Singh *et al* 2020). TCO is driven by five factors, including purchase costs, energy costs, depreciation costs, insurance, maintenance and repair costs. The purchase cost, in turn, is driven by the availability of subsidies (e.g. tax rebates), price incentives from manufacturers, the productivity of battery manufacturing, and the productivity of the manufacturing of other vehicle components. Preferences and attitudes are influenced, among other things, by consumers' degree of awareness of environmental issues.

Our assessment focuses on examining the effect of the four factors highlighted in yellow due to the following considerations. First, subsidies offered by the government are policy-relevant and represent a mechanism for exerting direct control over the purchase price and thus BEV adoption. Hence, the understanding of the effect will provide important implications to develop a sound policy for BEV adoption. Incentives offered by manufacturers to consumers are another mechanism affecting purchase prices. Such incentives may become more common as competition between BEV manufacturers intensifies, so it is important to understand their implications. Second, we assess the impact of energy costs, which tend to fluctuate but are a major driver of the TCO and are expected to be central to a consumer's decision regarding fuel type. Lastly, we consider a technological trend that uniquely affects BEVs, and that has a major impact on BEV purchase prices, namely, the productivity of battery manufacturing. Given that our assessment focuses on the short-run impact of BEV adoption, we omit depreciation and maintenance and repair costs, which depend on the duration of vehicle ownership and are very uncertain at the time of purchase, as well as insurance costs. The influence of these factors on BEV adoption is assumed to be negligible (Van Velzen *et al* 2019)⁵. Lastly, advances in vehicle component manufacturing productivity are expected to be lower than in battery manufacturing (Lutsey and Nicholas 2019) and are hence also omitted.

⁵ Van Velzen *et al* (2019) propose a future framework to estimate the total cost of ownership for BEVs, and none of those are perceived as important factors affecting BEV TCO development in both their self-collected interview data and literature analysis.

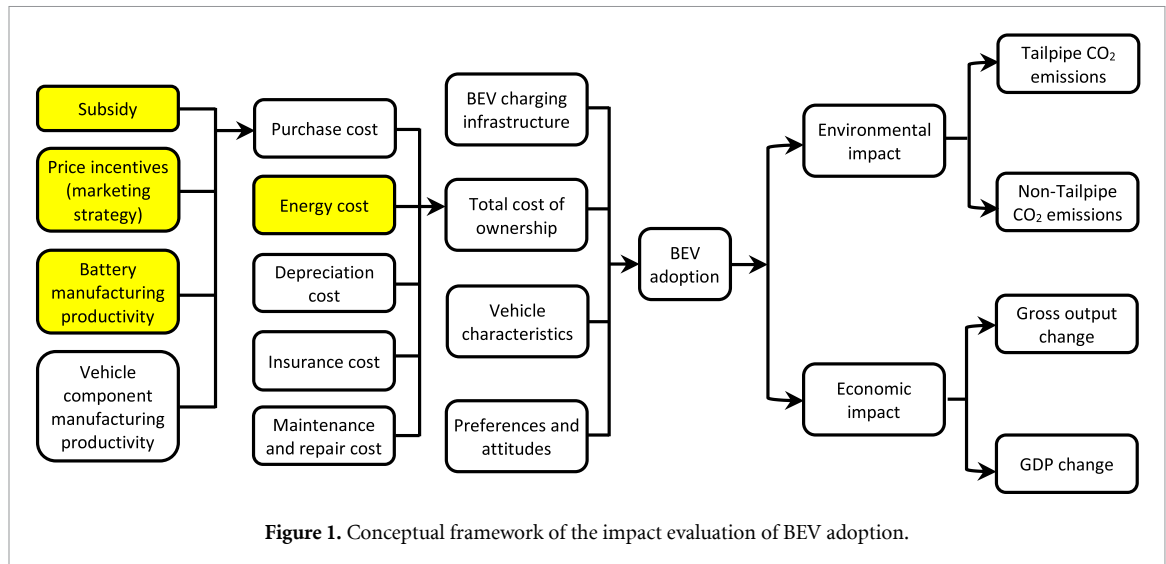


Figure 1. Conceptual framework of the impact evaluation of BEV adoption.

To evaluate the impact of the highlighted factors, we conduct a CGE analysis. CGE models are generally considered a state-of-the-art approach to macroeconomic impact assessment. The model reflects multi-market interactions in the form of behavioral responses of individual producers and consumers to changes in prices, technology, taxes, and other external shocks, subject to constraints on capital, labor, and natural resources (Dixon and Rimmer 2002). A CGE model characterizes the economy as a set of interconnected supply chains. It represents a significant advance over its predecessor, input–output (I–O) analysis, by maintaining the I–O model’s strengths (Chen and Rose 2018) while overcoming several limitations (Rose 1995). CGE models have been used extensively to assess environmental and economic impacts of transportation infrastructure investment (e.g. Truong and Hensher 2012, Chen and Haynes 2014, Chen *et al* 2016), and even BEV adoption (e.g. Karplus *et al* 2010, Schmelzer *et al* 2018).

We performed our assessment using an upgraded version of the US Computable General Equilibrium (USCGE) model⁶. It consists of 70 producing sectors, along with nine household income groups, three government actors (two federal and one state and local), and external agents (i.e. foreign producers). The model is static, as it does not trace the time-path of impacts, such as economic cycles associated with employment and investment changes.

International trade is represented through an Armington substitution function between imports and domestic production and constant

elasticity of transformation function between exports and domestic sales. Household consumption is represented by a linear expenditure system of aggregate commodities. The input and import substitution elasticity parameters were sourced and checked against extant literature. The production activities are structured in the form of a constant elasticity of substitution (CES), in which factor inputs, such as capital and labor, are substitutable, subject to the input share parameter and the CES. The production function is hierarchical, representing sequential decision-making relating to the choice of input combinations in each tier or ‘nest.’ Figure 2 illustrates the nesting structure of the production activities in the model. The structure was revised from Rose *et al* (2009) and Chen and Rose (2018), with a disaggregated structure to reflect substitution among various intermediate sectors, including a specific structure of 16 vehicle-manufacturing-related sectors.

The CGE model simulates macroeconomic impacts in terms of changes in gross output and GDP as a response to a shock. To measure the various effects of BEV adoption, exogenous variables in the USCGE model must be identified appropriately for each direct impact driver. Given the impact of purchase prices and fuel costs on BEV adoption, the economic impact of adoption is modeled through corresponding changes in household expenditures. Several scenarios in which government subsidies for BEV adoption are provided are modeled through a negative shock of the ad valorem tax on vehicle manufacturing and service-related sectors. A higher level of subsidy corresponds to a larger tax reduction on vehicle manufacturing-related sectors⁷. The impact of battery manufacturing productivity improvements

⁶ The model was originally developed by Oladosu and Rose for environmental policy analysis (Rose and Oladosu 2002) and for consequence analysis of natural disasters and terrorism events (Rose *et al* 2009). The model was previously used to analyze the impact of cyber-attacks on automobile industries (Rose and Chen 2020).

⁷ The effect of subsidies is essentially treated as a positive incentive in the form of financial aid or support extended to BEV related economic sector. Hence, the effect can be measured through a negative shock of the indirect business tax (in other words, a reduction of

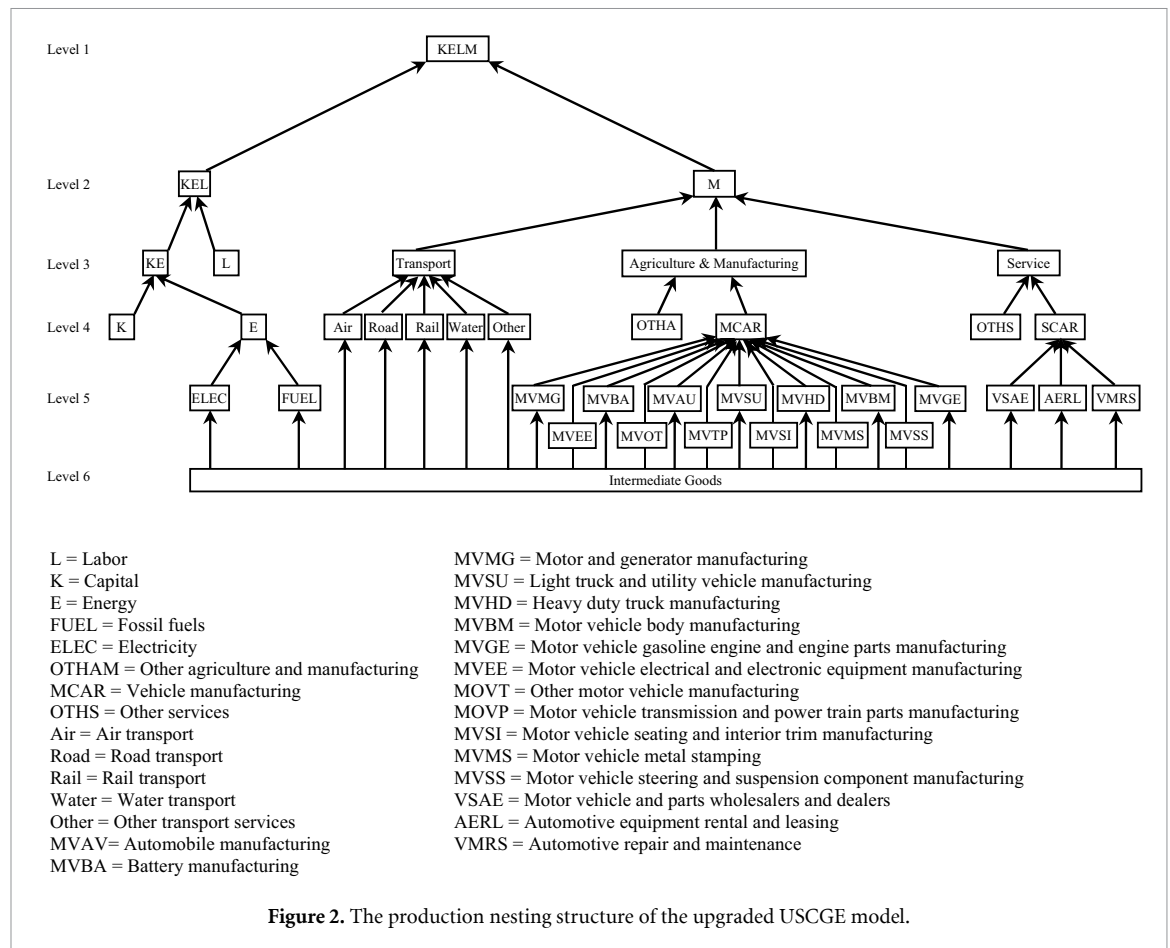


Figure 2. The production nesting structure of the upgraded USCGE model.

was implemented by shocking the factor productivity parameter at Level 5 (the vehicle-manufacturing level) for the battery manufacturing sector.

3.2. Scenarios

Following the motivation for this research, we defined 12 scenarios for the analysis, including one base scenario. At the time of the study, all common BEV models were sedans, so the analysis focused exclusively on the sedan market. Overall vehicle sales, as well as the markets for all other vehicle types (e.g. SUVs, pickup trucks) were assumed to remain constant. Considering the data used for this analysis, the baseline year was defined as 2018, with the scenarios covering hypothetical changes over a 6 year period from the beginning of 2019 to the end of 2024. The base scenario (S0) assumes that in 2024 the average price for a new BEV is \$40 000 and the average US fuel price remains at the 2018 level, namely, \$2.71 gallon⁻¹ (US Energy Information Administration 2020). The base price of BEVs was obtained as the average price of a Tesla Model 3 in 2018, which accounted for about 59% of total BEV sales in 2018 (US Department of Energy 2020a). The average purchase prices of conventional and hybrid vehicles were

\$22 500 and \$27 500, respectively, and were not varied across scenarios. The technical capabilities and attributes of the vehicles remained fixed throughout the analysis unless otherwise stated. We investigated two fuel price scenarios (S1 and S2), namely, a 20% drop in fuel costs to \$2.17 gallon⁻¹ and a 20% increase to \$3.25 gallon⁻¹. Future gas price fluctuations are likely due to several factors, for instance, pressure due to decreasing demand for gasoline as consumers switch to BEVs, but also cutbacks in oil supply by oil-producing countries in order to prop up gasoline prices.

Two scenarios (S3 and S4) in which BEV purchase prices drop by \$1000 and \$3000 due to pricing incentives by manufacturers but without a subsidy were investigated. It is assumed that manufacturers' lost revenue due to these incentives is not reimbursed by the government. Two scenarios (S5 and S6) in which government subsidies of \$3000 and \$8000 are offered, thereby lowering the purchase price. We assumed that the \$3000 and \$8000 represented the aggregate subsidy from all government sources, but due to the data limitations, the cost of administering a subsidy program was not considered. Furthermore, four scenarios (S7–S10) were defined in which the productivity of battery manufacturing increases. Based on Lutsey and Nicholas (2019), who suggested that BEV battery costs decrease by about 7% annually, we developed a lower-bound productivity increase scenario (S7)

tax rate), which is a standard approach to measure subsidy in CGE modeling (see, e.g. Miyata et al 2018).

Table 1. Direct impact drivers of various simulation scenarios.

ID	Scenario	BEV sedans 2024 ^a	BEV price	Household expenditure change ^b	Subsidy shock ^c	Fuel price (\$ gallon ⁻¹)	Battery manufacturing productivity ^d
S0	Base case	23.57%	\$ 40 000	0.97%		\$2.71	
S1	Lower-bound fuel cost	20.22%	\$ 40 000	0.90%		\$2.17	
S2	Upper-bound fuel cost	27.09%	\$ 40 000	1.05%		\$3.25	
S3	Price reduction of \$1000	25.21%	\$ 39 000	0.97%		\$2.71	
S4	Price reduction of \$3000	28.60%	\$ 37 000	0.96%		\$2.71	
S5	Subsidy of \$3000	25.16%	\$ 37 000	0.96%	−2.83%	\$2.71	
S6	Subsidy of \$8000	37.76%	\$ 32 000	0.83%	−9.84%	\$2.71	
S7	LB productivity shock ^e	23.57%	\$ 40 000	0.97%		\$2.71	7%
S8	UB productivity shock ^e	23.57%	\$ 40 000	0.97%		\$2.71	14%
S9	LB productivity and price shocks ^e	29.95%	\$ 36 196	0.94%		\$2.71	7%
S10	UB productivity and price shocks ^e	35.12%	\$ 33 380	0.81%		\$2.71	14%
S11	LB simultaneous case ^e	35.44%	\$ 33 196	0.87%	−2.83%	\$2.17	7%
S12	UB simultaneous case ^e	50.09%	\$ 25 380	0.96%	−9.84%	\$3.25	14%

Notes

^a Percentage of new sedan sales that are assumed to be BEVs in 2024.

^b The annual change in household expenditures on new vehicle purchases was calculated based on the estimated annual sales of BEVs, hybrid, and conventional vehicles from the discrete choice model and the assumed vehicle prices. This takes into account all new vehicle sales. The annual change is relative to the corresponding expenditures in 2018.

^c The subsidy shock captures the effects of BEV subsidies through a negative shock of sales taxes on the corresponding vehicle-related sectors. The percent change was calculated using estimated demand for BEVs times the subsidy amount per vehicle, then divided it by the total sales tax on the related sectors.

^d Adjustment of productivity parameter of the vehicle battery sector 'MVBA' by the corresponding amount.

^e LB = lower bound; UB = upper bound.

of 7% annually and an upper-bound scenario (S8)⁸. Hence, BEV adoption rates would not be affected, but there would nonetheless be economic effects. In the other two scenarios (S9 and S10), we assumed that the market for BEVs was perfectly competitive and that all savings were passed on to consumers in the form of purchase price reductions, thus affecting BEV adoption rates. Lastly, two 'simultaneous' scenarios (S11 and S12) were defined where the effects of fuel prices, subsidies, and productivity shocks in perfectly competitive market conditions were combined. The lower-bound simultaneous case (S11) includes the lower-bound fuel cost, subsidy shock, and productivity shock, and the upper-bound simultaneous case (S12) includes the respective upper-bound cases.

Table 1 shows an overview of the scenarios. For each scenario, the percentages of new vehicles purchased per year that are conventional vehicles,

hybrid vehicles, and BEVs were estimated using a discrete choice model (see section 2.3). Since the respective choice experiment focused on participants who were planning to buy a new vehicle in the 5 years spanning 2019–2024, we assumed that the engine type distribution estimated by the discrete choice model represented market shares of new sedans at the end of the analysis period, in 2024. Thus, under the base scenario (S0), we estimated that in 2024, 23.57% of new sedans would be BEVs. Market shares from 2019 to 2023 were linearly interpolated and used to calculate household expenditures per year on new sedans, given the average vehicle prices assumed in each scenario. Hence, annual household expenditure changes were used as input to the CGE model.

3.3. Data

The analysis was conducted using three data sources. First, the economic data used for the CGE analysis is a social accounting matrix of the US national economy in 2018, which was obtained from IMPLAN and consisted of 70 economic sectors. Second, the data for the

⁸The markup of price over production cost savings depends on the market power of the firm(s) in the industry (Clarke and Davies 1982, Hall 2018). For simplicity, we assume a monopolist obtains all the cost savings as profit opportunity.

estimation of the discrete choice model were collected between May and December 2019 during an online survey of 1657 individuals, including 711 respondents from the Los Angeles metropolitan area, 527 from the Atlanta metropolitan area, and 417 from the three major metropolitan areas in Ohio (Columbus, Cincinnati, Cleveland). All respondents had indicated that they planned to buy a new (not used) car within the next 5 years. Respondents were presented with eight hypothetical choice situations where they were asked to imagine that they were buying a new vehicle and that they had narrowed down their choices to three vehicles with different engine types (conventional, hybrid, and BEV) but otherwise identical specifications. The attributes that were shown for each vehicle included the purchase price, annual fuel-equivalent costs, and annual CO₂ emissions. These attributes of each vehicle type were varied across the eight choice situations, following an orthogonal design. Other vehicle attributes were not explicitly mentioned to respondents and were assumed to be the same across choice situations. Data validity was ensured through the inclusion of a 'status quo' alternative, a 'cheap talk' (Varela *et al* 2014), and attention checks. More details on the design of the choice experiment are provided in appendix 1 (available online at stacks.iop.org/ERL/16/045011/mmedia). The survey data were not specifically collected for the purposes of this analysis, and thus do not capture all elements shown in figure 1. For instance, maintenance and repair costs, depreciation, and charging infrastructure were not included. We estimated a mixed multinomial logit model of vehicle engine type choice with random coefficients, as explained further in appendix 2. The market shares for the scenarios were then generated by simulation, using the estimated coefficient values and the characteristics of the decision-makers in the data set. Third, the CO₂ emissions per year for each scenario were calculated using emission factors from the US Environmental Protection Agency (EPA)'s annual Inventory of US Greenhouse Gas Emissions and Sinks (US EPA, 2020) in the case of non-tailpipe emissions and the Alternative Fuels Data Center in the case of tailpipe emissions (US Department of Energy 2020b).

4. Results

The results of the CGE analysis are summarized in table 2⁹. In the base case, BEV adoption is

likely to increase the gross output and GDP of the national economy by \$0.464 billion and \$0.377 billion, respectively, and both non-tailpipe and tailpipe CO₂ emissions would decrease. Scenarios S1 and S2 show that while BEV adoption is moderately sensitive to fuel cost, the corresponding changes in annual GDP are. The BEV price reductions by \$1000 and \$3000 in scenarios S3 and S4 are likely to generate an increase in GDP of \$0.377 billion and \$0.372 billion, respectively. The price reduction of \$1000 does not reduce CO₂ emissions as much as a 20% increase in fuel costs, and the corresponding change in household expenditures is so small that the effect on GDP is not detectible. In the case of the \$3000 price drop, the substitution of BEVs for conventional vehicles in combination with the lower purchase prices results in slightly reduced aggregate household expenditures and thus, in a negative effect on the economy in the short run. BEV subsidies were found to have a significant positive effect on the economy. The difference between the lower-bound and upper-bound subsidy in national GDP growth is estimated to be \$7.744 billion, or 0.036% of total GDP. Again, BEVs are substituted for conventional vehicles, but subsidies compensate for the decreased household expenditures. Scenario S7 through S10 present the results of productivity shocks in battery manufacturing in monopolistic and perfectly competitive markets. The results show that if savings are not passed on to consumers, a marginally higher GDP growth is achieved compared to the competitive market situation, but in the latter case, the CO₂ reduction effect is higher. The 'simultaneous' scenarios (S11 and S12) show overall positive effects on the economy, with the upper-bound case generating GDP growth equivalent to 0.06% of total GDP.

With the exception of the upper-bound subsidy scenarios, the impacts of the different scenarios on non-tailpipe emissions were generally small. In those cases, the CO₂ tailpipe emissions savings were significantly greater than the changes in non-tailpipe CO₂ emissions, and even though the latter were both positive and negative, the combined effect was consistently negative. Decreases in non-tailpipe CO₂ emissions were due to the effects of household expenditure changes and a shift of economic activity to less polluting industrial sectors. However, subsidies and productivity improvements tend to result in an increase in non-tailpipe CO₂ emission, which could be due to growing production capacities both upstream and downstream of vehicle manufacturing sectors. Thus, the stimulus effects of these shocks essentially outweigh the dampening effects caused by changes in household expenditures. In scenarios S6 and S12, however, the significant subsidy effect achieved through a reduction of indirect taxes on the vehicle-manufacturing sectors, combined with productivity increases, boosts economic activity and results in increased non-tailpipe CO₂ emissions that

⁹The sensitivity of the various shocks of the CGE model with respect to the change of the economic impact outcome was summarized in appendix 3. In addition, we also tested the sensitivity of the two fundamental parameters: elasticities of substitution for factor input, and the Armington elasticity. The impact result shows a consistent linear relationship with respect to the changes of various CGE input variables and key elasticity parameters.

Table 2. Results of the CGE simulation analysis. All values are annual.

ID	Scenario	Gross output change (\$ billion)	GDP change (\$ billion)	Non-tailpipe CO ₂ emissions (million metric tons)		Tailpipe CO ₂ emissions (million metric tons)	Gross output percent change	GDP percent change	Non-tailpipe CO ₂ % change ^a	Tailpipe CO ₂ % change ^a
				Non-tailpipe CO ₂ emissions (million metric tons)	Tailpipe CO ₂ emissions (million metric tons)					
S0	Base case	0.464	0.377	-0.035	-1.589	0.001	0.002	-0.0005	-0.0239	
S1	Lower-bound (LB) fuel cost	0.453	0.368	-0.034	-1.552	0.001	0.002	-0.0005	-0.0232	
S2	Upper-bound (UB) fuel cost	0.470	0.383	-0.036	-1.640	0.001	0.002	-0.0005	-0.0246	
S3	Price reduction of \$1000	0.464	0.377	-0.035	-1.623	0.001	0.002	-0.0005	-0.0243	
S4	Price reduction of \$3000	0.457	0.372	-0.035	-1.674	0.001	0.002	-0.0005	-0.0251	
S5	Subsidy of \$3000	5.007	3.487	0.624	-1.674	0.014	0.017	0.00935	-0.0251	
S6	Subsidy of \$8000	16.308	11.231	2.262	-1.813	0.046	0.054	0.03389	-0.0272	
S7	LB productivity shock	1.085	0.969	0.130	-1.589	0.003	0.005	0.00195	-0.0239	
S8	UB productivity shock	1.709	1.564	0.296	-1.589	0.005	0.008	0.00444	-0.0239	
S9	LB productivity and price shocks	1.073	0.960	0.131	-1.694	0.003	0.005	0.00197	-0.0254	
S10	UB productivity and price shocks	1.636	1.503	0.303	-1.773	0.005	0.007	0.00454	-0.0266	
S11	LB simultaneous case	5.585	4.043	0.794	-1.778	0.016	0.020	0.01189	-0.0266	
S12	UB simultaneous case	17.548	12.413	2.593	-2.019	0.050	0.060	0.03884	-0.0302	

Note

^a Changes in CO₂ emissions are relative to total US CO₂ emissions in 2018.

are not fully offset by the savings in tailpipe CO₂ emissions.

5. Discussion

Our results provide a valuable comparison of the economic and environmental effects of different scenarios for BEV adoption and battery manufacturing productivity. The effects on GDP and CO₂ were found to vary considerably and highlight the importance of performing holistic assessments of the impacts of BEV adoption that consider the specific mechanisms driving adoption rates. Under the base case, BEV adoption would grow without further interventions thanks to changing consumer preferences and BEVs becoming available at the \$40 000 price point. Subsidies and price reductions would further increase BEV adoption relative to the base case, with the only exception being the scenario in which fuel prices drop with no changes in BEV purchase prices to balance out that effect.

Changes in fuel price and incentives provided by manufacturers with no public subsidies have relatively low impacts on GDP growth in percentage terms of overall GDP. Subsidies and productivity shocks, on the other hand, have larger impacts on GDP growth. In fact, the results show that subsidies represent the most effective way of boosting BEV adoption as well as GDP. A subsidy of \$8000 could generate an annual GDP value change of \$11.231 billion, which exceeds the \$9.815 billion that we estimate the direct cost of the subsidies to be. To a lesser extent, this effect is also present with a \$3000 subsidy, leading us to conclude that both subsidy scenarios have positive net effects on economic growth. Such a result is not surprising, as the subsidy on BEV was modeled as a negative shock of the ad valorem tax, which promotes economic growth through a positive shock of the vehicle-manufacturing-related sectors. A productivity shock in a monopolistic market would lead to marginally higher GDP growth than if the price reductions were passed on to consumers (i.e. the perfectly competitive market), but in the latter case, the BEV adoption rate would be boosted. Such a result reveals the fact that any incentive strategies involving a price reduction would lead to the substitution of BEVs for (internal combustion engines) ICEs, which is likely to generate a mild negative consequence to the economy due to the drop of the aggregate household expenditure on new vehicle purchases. This also reflects the fact that in the short-run, a higher level of BEV adoption may be unavoidably associated with a dampening effect on the macroeconomy due to its negative influence on the ICE manufacturing-related economic activities.

The environmental effects paint a more complex picture: In the case of productivity shocks and subsidies, the increased availability of capital in the automotive manufacturing sector would lead

to growth in manufacturing activity. This, in turn, would increase non-tailpipe CO₂ emissions. The net sum of non-tailpipe and tailpipe CO₂ emissions is lower than the base case in only three scenarios, S2–S4. In all other scenarios, overall emissions would decrease less than in the base case. Nonetheless, all scenarios except those with subsidies of \$8000 still lead to a reduction in CO₂ emissions relative to the starting point, generally around 0.02%–0.03% of total US emissions. On the other hand, due to manufacturing growth, the \$8000 subsidies lead to growth in non-tailpipe CO₂ emissions that exceed the savings from reduced tailpipe CO₂ emissions. This leads to net increases of around 0.007%–0.008% of total US emissions. Thus, while high subsidies have a large positive effect on economic growth and BEV adoption, it is imperative that they be accompanied by other policies to promote greener manufacturing practices and greener power generation in order to avoid growth in emissions. In this context, greener power generation would reduce the emissions caused by charging BEVs. Our results further show that productivity shocks in a competitive market, where savings are passed on to consumers, have a clear advantage over the scenarios in monopolistic markets in terms of emissions outcome. We assume that in reality, the outcome of a productivity shock would lie somewhere between these two bounds.

The simultaneous cases recognize that realistically, several developments are likely to occur. The upper-bound case can be thought of as a ‘best-case’ scenario in which high subsidies coincide with large gains in manufacturing productivity and a rising gas price. Taken together, these trends would yield an additional \$1.2 billion in GDP growth. The lower-bound simultaneous scenario, in which fuel prices move in such a way as to counteract more modest BEV subsidies and productivity improvements, shows that even fuel price drops cannot cancel out the economic benefits of the BEV subsidy and productivity improvement.

6. Conclusion and limitations

In conclusion, we find that subsidies for BEV adoption have very desirable effects both in terms of boosting economic growth and BEV adoption. Our results also demonstrate the importance of considering emissions holistically, as changes in non-tailpipe emissions can undo some of the benefits of BEV adoption from reduced tailpipe emissions. Therefore, in order to reap the full environmental benefits of BEV adoption, it is important to consider strategies for reducing non-tailpipe CO₂ emissions from vehicle manufacturing and emissions from power generation.

We find that subsidies have significantly more leverage on GDP and BEV adoption than changes

in fuel price, and by maintaining capital flows into the manufacturing sector, potential GDP losses due to non-subsidized price drops are avoided and the industry's transition to greener products is supported. A combination of subsidies with rising productivity and fuel price trends can further amplify the positive effect of the subsidies. Our research findings are consistent with Miyata *et al* (2018), who also found a positive effect of BEV subsidies on GDP and CO₂ emissions in Japan. Conversely, our findings differ from Hirte and Tscharaktschiew (2013), who concluded that subsidies had an opposite effect on the economy in Germany. These seemingly contradictory results may be attributable to the way in which subsidies were incorporated in the CGE analysis, where Hirte and Tscharaktschiew used a negative shock of the power tax instead of the BEV-related manufacturing sectors. We hope that the evaluation framework introduced in this study will help clarify this situation as it adds evidence to the finding that subsidies have positive effects. This study has several limitations. First, our assessment focuses on the sedan market only and assumes that sales of other vehicle types are unaffected. While this decision was due to limitations in data availability, it would be possible to adapt the general model structure to non-sedans and thus to the full new vehicle market. Second, the model results are based on the assumptions that the three vehicle types presented in the choice experiment were equivalent unless otherwise mentioned and that their characteristics remain fixed throughout the 6 year analysis period. This is a simplification, as the current BEV fleet differs from other vehicle types in terms of technical capabilities, including important aspects such as range, but considerable advances in BEV technology and the diversity of BEV models on the market are expected in the coming years. Third, the assumption that the total vehicle market would remain constant is also a simplification. Relaxing this assumption would have introduced additional uncertainty regarding substitution effects between sedans and non-sedans, and data on non-sedan fuel type choice behavior were not available. These limitations should be addressed in future research with appropriate data and projections on market developments. Fourth, the assessment only focuses on a static and short-run impact assessment. Future evaluations may expand the scope by considering other types of BEVs and also incorporating long-run effects, such as improvements of vehicle energy efficiency and evolutions in economic structure. The results in this study must be interpreted from the perspective of pre-COVID-19 market conditions, and future research could build on it to incorporate post-COVID-19 conditions. Lastly, the availability of charging infrastructure, which is an important driver of BEV adoption (Greene *et al* 2020), is not represented in the modeling framework. However, the data that would have been necessary to do so were not available to

us, so incorporating this additional variable is left to future research.

Future work could also expand the focus to comparing environmental impacts in greater detail, following approaches such as those used by Xie *et al* (2012), who integrated a travel demand model, and Gao and Winfield (2012), who used life cycle assessment with consideration of the energy efficiency of various BEV types. In addition, a valuable avenue for future research is the incorporation of additional consumer behavior responses that could affect BEV adoption, such as the rebound effect (Berkhout *et al* 2000) or other changes in travel patterns as the vehicle fleet becomes more fuel-efficient. Similarly, a CGE framework such as the one introduced in this study could be expanded to capture the effects of manufacturer-related policies like the Corporate Average Fuel Economy (CAFE) standards or zero-emissions vehicle mandates (Sykes and Axsen 2017).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgements

The authors wish to acknowledge the generous support by Ford Motor Company, via the Ford University Alliance Program, as well as supplemental funding by the Ohio State University Sustainability Institute and the Ohio State University Decision Sciences Collaborative that made this research possible. In addition, we also appreciate the valuable feedback received from the two anonymous reviewers. Views presented in this study do not represent any organizations and authors are responsible for any errors or mistakes.

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