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Abstract

New Zealand is a small isolated island nation in the South Pacific with a population of 4.4 million people. As part of national branding to promote exports of bio-commodities especially from agriculture and horticulture and encourage tourism New Zealand is aiming to reduce greenhouse gas emissions to 50% of 1990 levels by 2050. New Zealand has an abundant supply of low cost renewable electricity generation that could be used for powering an electric vehicle fleet and reducing greenhouse gas emissions. This renewable resource using biomass and wind alone is as much as 11 times the 2009 annual electricity demand. In this study we investigate the potential impact of plug-in hybrids (PHEV) on greenhouse gas emissions (GHG) from the New Zealand vehicle fleet to 2050 using the partial equilibrium techno-economic model UniSyD. We find that the impact of consumer purchase perceptions of capital cost, fuel savings, and infrastructure availability have the effect of reducing the market share of PHEVs with a range of 64 km from 27% to 9% under a scenario where the oil and carbon prices stabilize in 2030 at US$120/bbl and US$60/t-CO_2eq. respectively. In addition we find the market share of PHEVs is strongly correlated with range. PHEVs with a range of 16 km achieve five times more market share than PHEVs with a range of 256 km however reductions in GHG are 10% and 8% respectively over a fleet with no PHEVs. By 2050 PHEVs could consume up to 5% of electricity from the national grid and reduce GHG emissions by over 20% if market share of the vehicle fleet reaches a predicted maximum of 27%. Fiscally neutral federal policies are shown to mitigate consumer barriers.

Keywords: Greenhouse gas emissions, renewable electricity, plug-in hybrids.

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New Zealand is a country of 4.4 million people situated in the South Pacific. It has two main islands and a geographical area about 70% of that of Japan. It is rich in both renewable and fossil energy resources.

In 2011 New Zealand publicly committed to reductions in 1990 greenhouse gas emissions of 50% by 2050 [2]. An important element in achieving this target lies in reducing emissions in the transport sector that accounted for 19% of gross GHG emissions in New Zealand in 2008 [3]. One of the significant technologies that will play a role in enabling New Zealand to meet its GHG emission reduction target is PHEVs. PHEVs have potential to achieve very low specific fuel consumption while improving the capacity and efficiency of the electricity grid. Data from a 2004 U.S. Department of Transportation study for one-day travel shows that 68% of vehicles in the U.S. were driven 64 km or less in one day with 42% driven 32 km or less. Given that the range of the recently released Chevrolet Volt is estimated at 56 km (USEPA) PHEVs have the potential to eliminate the use of fossil vehicle fuels for over 60% of domestic travel. The overall reduction in greenhouse gas emissions will depend on the primary energy used to generate the electricity that will be used to recharge the PHEV.

Data from the New Zealand Ministry of Economic Development (NZMED) (2010a) shows that in 2009 New Zealand produced 72.5% of its electricity from renewable energy. This Ministry also records (NZMED 2010b) that the government is aiming to increase the proportion of renewable to 90% by 2025. Using information from both Scion (2007) and Connell Wagner (2008) New Zealand's potential renewable electricity generation reserve using biomass and wind is as much as 11 times the 2009 annual electricity demand. This reserve factor is reduced to 5.3 (Table 1) if a wholesale electricity price limit of 8.4 USc/kWh is imposed and an upper bound estimate of 4.9 Mha of new afforestation area is assumed (Hall and Jack). The electricity generating potential of the principal primary energy sources are shown in Table 1.

In this study we explore the potential impact of PHEVs on future GHG emissions using the UniSyD partial equilibrium computer model of New Zealand's energy economy.

UniSyD Computer Model

UniSyD is a system dynamics model of New Zealand's energy economy. The model was initiated in 2002 in order to examine the impact of technological advances on New Zealand's energy economy out to 2050. Technologies of particular interest included co-generation of hydrogen and electricity, carbon sequestration, indigenous biofuel production, residential scale combined heat and power, vehicle prime movers using fuel cells and batteries and advanced internal combustion engines..

UniSyD is a bottom-up model with a high degree of technological specificity. UniSyD version 5.0.7 contains 50 sectors that are listed in Table 2. The model uses system dynamics software which was chosen for the ability to represent connections between variables by a network diagram. This visualisation capability was considered important as a number of programmers were expected to contribute to the model code and this capability would improve induction times for new programmers.

UniSyD5.0.7 models in 13 different regions of New Zealand. Primary energy sources modeled are coal, natural gas, wind, solar, geothermal and hydro. Resource prices are dynamic as they are determined from supply curves for each resource in each region. An example of the supply curve for electricity from geothermal in the Waikato region is shown in Figure 1.

The minimization of costs in the 13 regions takes place in four separate markets. The first market is the electricity market that contains detailed performance characteristics for each existing electricity generation facility in New Zealand as well as details for additional technologies likely to be viable to 2050. The optimal generating mix is determined by matching the exogenously set regional electricity demand to the least cost of generation required to meet the demand in that region. Demand in both the electricity and hydrogen markets is forecast on the growth trend on the previous three years and is predicted three years into the future to provide sufficient time for construction of new generating plant. The cost of generation in each region is then compared with the cost of importing electricity from outside the region to determine the optimum generation mix.

The second market is the hydrogen market. Small scale options for generation in this market include both electrolysis and small scale steam methane reforming located on the forecourts of refilling stations. Large scale options include steam methane reforming, coal gasification, and co-generation of hydrogen and electricity. The large scale options also have a further option of sequestration.

The third market is the lignocellulose market. Lignocellulose is sourced from wood. The optimal use of the resource is determined by the maximum unit energy price that can be obtained when the resource is used for either bioethanol or biogasification for either hydrogen or electricity production.

The final market is the vehicle market. Existing internal combustion engine vehicles (ICEV) compete with new technologies for market share. The market share is based upon a weighting of technology cost and consumer preference. Consumer preference is modeled by a logit choice formula (Train, 2008; Santini and Vyas, 2005). Two options of logit are used. These are firstly a standard logit and secondly a conditional logit (Leaver and Leaver, 2011). The difference in the two logit models lies principally in the specification of consumer preference. The standard logit collates consumer preferences into a single variable whereas the conditional logit provides for more explicit assessment of the impact of factors such as driving range, payback period for increased capital costs from fuel savings, and refuelling infrastructure.

The standard logit model is defined in Eq. (1) as:

$$S_i = \frac{\exp(\beta_i p_i - \gamma_i)}{\sum_j \exp(\beta_j p_j - \gamma_j)} \quad (1)$$

where S_i is the sales share of vehicle *i*, *p* is the annual vehicle cost including capital and operating expenses, β is the price elasticity and γ represents the intrinsic preference parameter that captures consumer preference for considerations such as availability of refueling infrastructure.

The ***conditional*** logit model is adapted from Train 2008 and is defined in Eq. (2) as:

$$S_i = \frac{\exp(\beta_{FC} U_{FCi} + \beta_{PP} U_{PPi} + \beta_{DR} U_{DRi} + \beta_{CMDD} U_{CMDDi} + \beta_{PLDD} U_{PLDDi} + \beta_{CV} U_{CVi})}{\sum_j \exp(\beta_{FC} U_{FCj} + \beta_{PP} U_{PPj} + \beta_{DR} U_{DRj} + \beta_{CMDD} U_{CMDDj} + \beta_{PLDD} U_{PLDDj} + \beta_{CV} U_{CVj})} \quad (2)$$

where the utility variables are dependent on fuel cost (FC), purchase price (PP), driving range (DR), convenient medium distance destinations (CMDD), possible long distance destinations (PLDD) and reluctance to drive conventional vehicles (CV).

Vehicle technologies consist of ICEVs, HEVs, PHEVs, hydrogen fuel cell vehicles (HFCV), biofuelled vehicles (BICEV), and battery electric vehicles (BEV).

The primary control panel for the model provides for the setting of scenario starting parameters. The modeler can choose one of three technology learning curves for new vehicle technologies. These represent the range of cost reductions extracted from the literature. The year in which the technology is available to consumers is also set along with the current and predicted prices of oil, natural gas and carbon dioxide equivalent. Finally any restrictions on the use of coal as a primary energy source can be specified.

Methodology

The potential market share of PHEVs is examined under a PHEV-scenario where:

i. PHEVs and EVs are available from 2015; FCVs from 2020; and sales of conventional vehicles are not constrained.

ii. Oil and carbon prices stabilize in 2030 at US$120/bbl and US$60/t-CO_2eq. respectively.

iii. No liquid natural gas (LNG) facilities are constructed in New Zealand, thereby preventing the importation of LNG. As of 2011 there are no publicly announced plans to construct an LNG terminal. However, as New Zealand is an isolated island nation this may change depending on the extent of future domestic natural gas discoveries and the international price of natural gas.

iv. Carbon dioxide sequestration costs are capacity based starting at US$1.6 per tonne CO_2 equivalent (/t $CO_{2\text{-eq}}$)) and reaching a maximum of US$16 /t $CO_{2\text{-eq}}$.

Results

The profile of New Zealand's electricity generation and vehicle fleet for a 64 km range PHEV fleet is shown in Figure 3.

In Figure 3a the dominant base load generation is hydro. Natural gas generation is phased out in 2028 and is replaced by lower cost coal fired generation and an increasing proportion of wind generation. The percentage of renewable electricity generation increases from an estimated 68% in 2010 to 95% in 2050. By 2050 the generation profile is 17% geothermal, 34% hydro, 41% wind and 8% other. In Figure 3b the wholesale electricity price varies from US3.8c (NZ6.3c) in 2018 to US9.1c (NZ15.2c) in 2030. Figures 3c and 3d show the profile of the vehicle fleet in which only HEVs and PHEVs compete with ICEVs. In 2050 the light vehicle fleet (<3.5t) consists of 47% HEVs, 44% ICEVs, and 9% PHEVs. The heavy vehicle fleet consists of 44% HEVs, 46% ICEVs, and 1% PHEVs. In Figure 3e the use of transport energy in 2050 is 34% HEVs, 60% ICEVs with 3% fossil fuel PHEV and 3% electric PHEV. In Figure 3f vehicle emissions represent 77% of the total emissions from the road transport and electricity generation sectors.

The impact of PHEV electric range on market share is shown in Figure 4.

In Figure 4 the market share of PHEVs increases to 2030 as the costs of fossil based fuel for ICEVs rises with increasing carbon tax and oil price. After 2030 market share increases very slowly. By 2050 PHEVs with a 256 km range would have a market share of 2.2% whereas PHEVs with a range of 64 km have 9.2% market share.

The impact of consumer choice is shown in Figure 5. The standard logit used in this study assumes that PHEVs have readily available infrastructure for recharging and servicing and have the same level of reliability as ICEVs. Market share of PHEVs with a range of 64 km reaches 27% under this scenario. The conditional logit assumes infrastructure develops as market share increases, that consumers weight capital costs higher than fuel costs and that consumers have a small preference for driving new technology vehicles providing they are reliable. Market share reaches only 9% under this scenario.

Figure 6 shows the fraction of total electricity consumption due to PHEVs. The increase in consumption is a maximum of 5.1% for the standard logit application to a 64 km PHEV. This reduces to 2.5 % for the conditional logit application.

Figure 7 shows reductions in GHG emissions under the conditional logit over a fleet with no PHEVs. Greenhouse gas reductions range from 8% for a PHEV fleet of range 256 km to 10% for a fleet with a range of 16 km. By 2050 PHEVs could reduce GHG emissions by 23% if market share of the vehicle fleet reaches a predicted maximum of 27% under the standard logit.

Discussion

The principal barrier to the adoption of PHEVs is the short time frame that consumers demand for payback of additional capital cost through fuel savings. Most consumers demand payback for fuel savings in less than five years (Hidrue et al., 2011) and many fleet owners turn their vehicles over in less than four years (Sovacool & Hirsh, 2008). The cost difference between PHEV's is a function of the electric range of the vehicle. Increasing the electric range increases the vehicle capital cost. The potential energy savings of PHEV's over conventional vehicles does not increase linearly with electric range as a result of the skewed distribution of distance traveled per commuter trip. Adoption of PHEV's will initially favor short electric range vehicles with lower additional capital costs which also achieve favorable fuel savings. The difference in market share in PHEV's with a range of 16 km to that with a range of 128 km is approximately 5%. Improving the market share or growing the electric range of PHEV's will be the result of improving energy savings potential either through further reduction in battery costs or higher increases in fossil fuel prices.

Any fiscally neutral policy designed to promote the adoption of PHEVs is best targeted at subsidizing the capital cost of PHEVs. Consumers value each increment in capital cost at twice that of fuel savings (Train, 2008). The capital cost subsidy could be recovered with either an additional fossil fuel tax or by a sales tax based on the size of any internal combustion engine.

This study shows that PHEV fleets with ranges of less than 64 km will maximize market share in a total fleet also consisting of ICEVs and HEVs at about 10% and limit additional electricity consumption to about 2%. These estimates assume vehicle choice is subject to the conditional logit. Greenhouse gas reductions are less dispersed for vehicles of all ranges with reductions ranging from 8% to 10% as a result of reducing fuel economy of PHEVs with higher range due to additional battery weight and from the skewed distribution of distance traveled per commuter trip.

Conclusions

We find that the impact of consumer purchase perceptions of capital cost, fuel savings, and infrastructure availability have the effect of reducing the market share of PHEVs with a range of 64 km from 27% to 9% under a scenario where the oil and carbon prices stabilize in 2030 at US$120/bbl and US$60/t-CO_2eq respectively. In addition the market share of PHEVs is strongly correlated with range. PHEVs with a range of 16 km achieve five times more market share than PHEVs with a range of 256 km however reductions in GHG are 10% and 8% respectively over a fleet with no PHEVs. By 2050 PHEVs could consume up to 5% of electricity from the national grid and reduce GHG emissions by over 20% if market share of the vehicle fleet reaches a predicted maximum of 27%. Fiscally neutral federal policies aimed at subsidizing the capital cost of PHEVs will have a significant impact on consumer adoption of PHEVs.

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Table 1. Primary resource electricity generation potential.

Primary Resource	Reserves: Electricity equivalent (MWh/capita)	Reserves: 2009 Demand multiplier	Resource type
Coal (Barry et al)*	39.8	3.91	Fossil
Gas**	3.6	0.35	Fossil
Wind	29.3	2.87	Renewables
Biomass	20.2	1.98	Renewables
Geothermal	3.1	0.31	Renewables
Hydro	1.4	0.14	Renewables
Total	**94.1**	**9.21**	
2009 Demand	10.2	1	

* Assumes 100 years 40% conversion factor.
** Assumes 100 years 50% conversion factor.

Table 2. Sectors of UniSyD5.0.7

Bio Plant Siting	Future Electricity Plant Construction
BioDiesel Generation	Future Fossil Generation Costs
BioDiesel Plant Siting	Future Hydrogen Plant Construction
BioEth Generation	Geo Generation
Biomass and Waste Gas Generation	H_2ICE Vehicle Market
Biomass Gasification Large Scale H_2 Plant	HEV Vehicle Market
BioH_2 Plant Economics	Hydro Generation
BioVehicle Market	Hydrogen Generation
Carbon Emissions	Hydrogen Plant Siting
Centralized Natural Gas Reforming	Lignocellulosic BioEth Production
Coal Cogen H_2 and Electricity Plant	Logit Factors
Cogen Plant Economics	MicroCommercial CHP using Piped H_2
Coal Gasification Large Scale H_2	MicroResidential CHP using Piped Natural Gas
Coal H2 Plant Economics	Natural Gas Resources
Coal Generation	New H_2 BioEth & BioDiesel Fuel Demand
Coal Resources	Petrol Vehicle Market
Cogen Generators	PHEV Vehicle Market Part 1 Petrol
Constants	PHEV Vehicle Market Part 2 Electric
Distributed Commercial and Residential Solar PV	Small Steam Reforming
Electricity Demand	Socio-Political Indicators
Electricity Generation and Pricing	Standard Logit Values
Electrolysis	Vehicle Capital and Fuel Cash Flows
Fossil Plant Siting	Vehicle Cost Comparison
Future BioDiesel Plant Construction	Vehicle Fleet Percentage
Future BioEthPlant Construction	Vehicle Fuel Mandate Ramp
	Wind Generation

Figure 1. Supply curve for electricity from geothermal in the Waikato region.

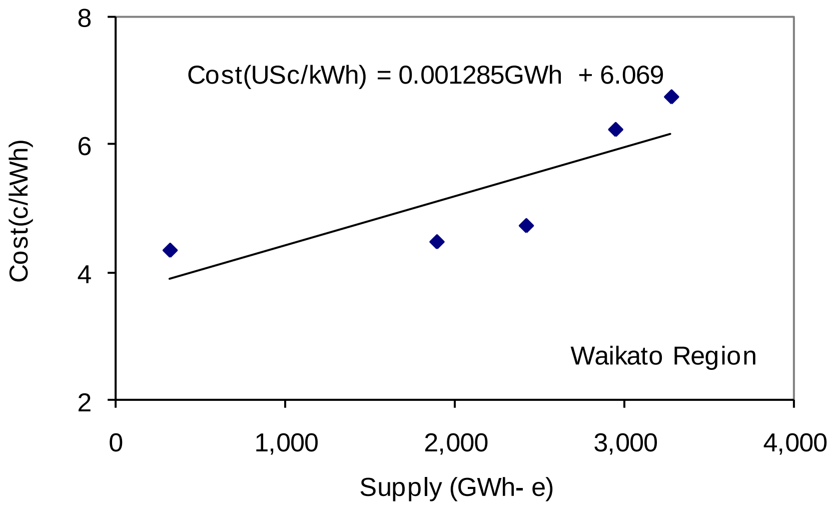

Figure 2. UniSyD control panel for primary variables.

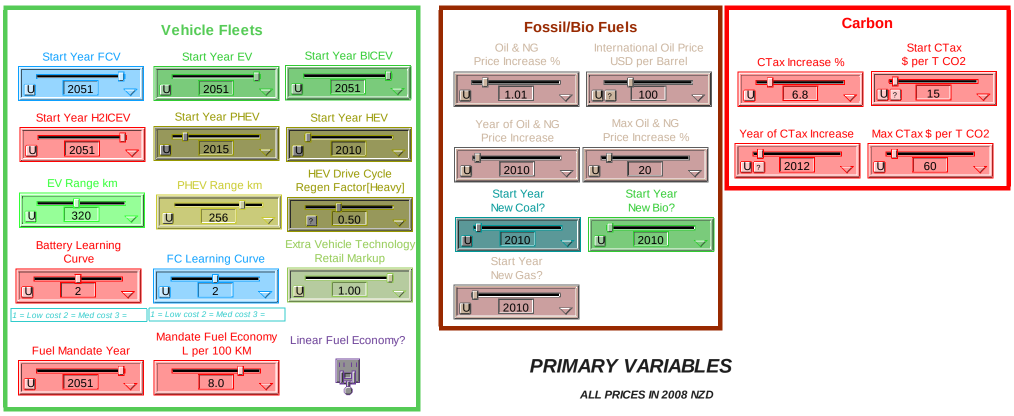

Figure 3. Profile of the electricity generation and vehicle fleet sectors.

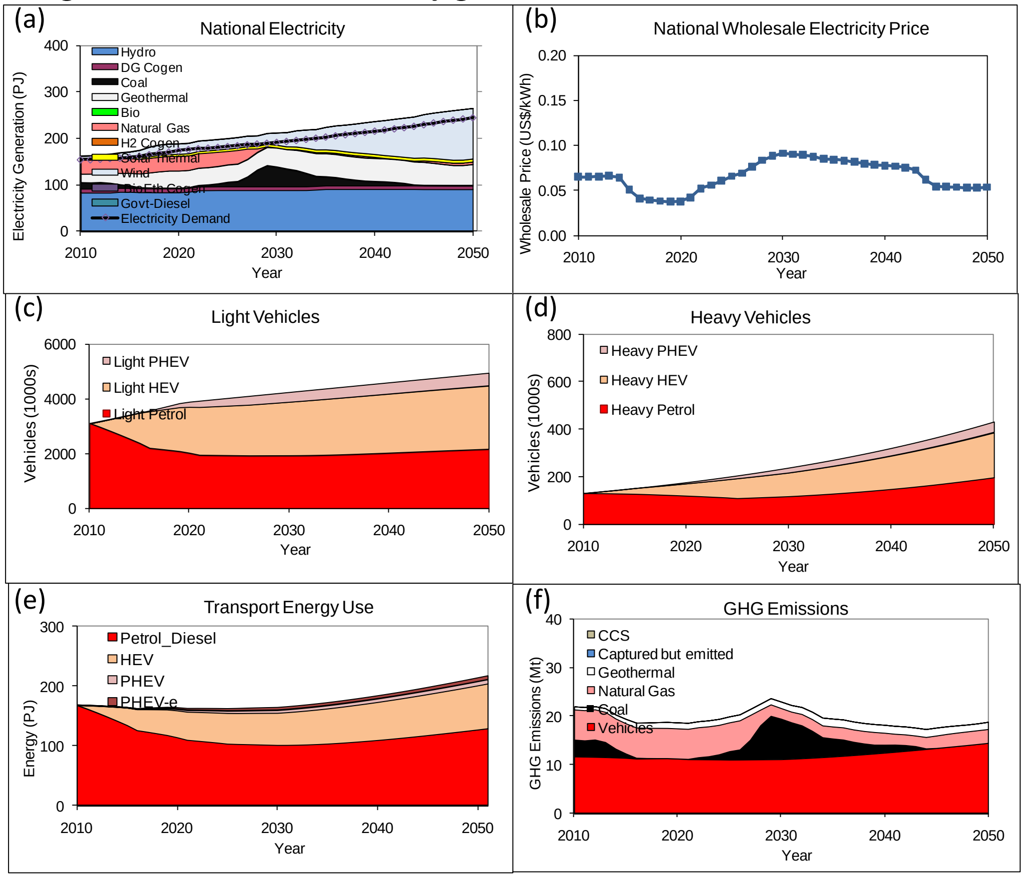

Figure 4. Impact of range on PHEV market share.

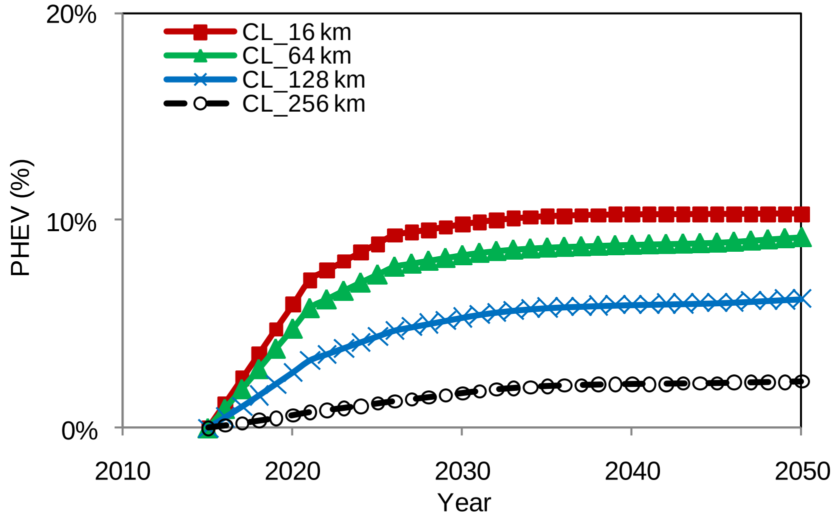

Figure 5. Impact of logit choice on PHEV market share.

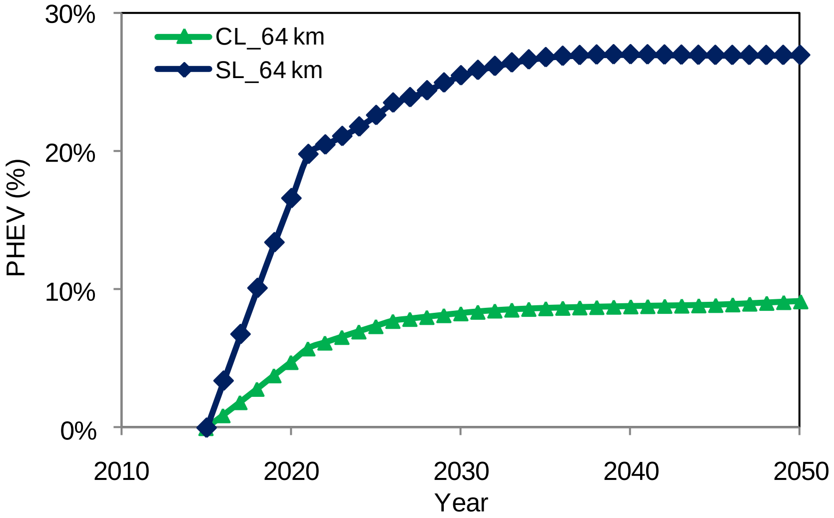

Figure 6. PHEV impact on electricity consumption.

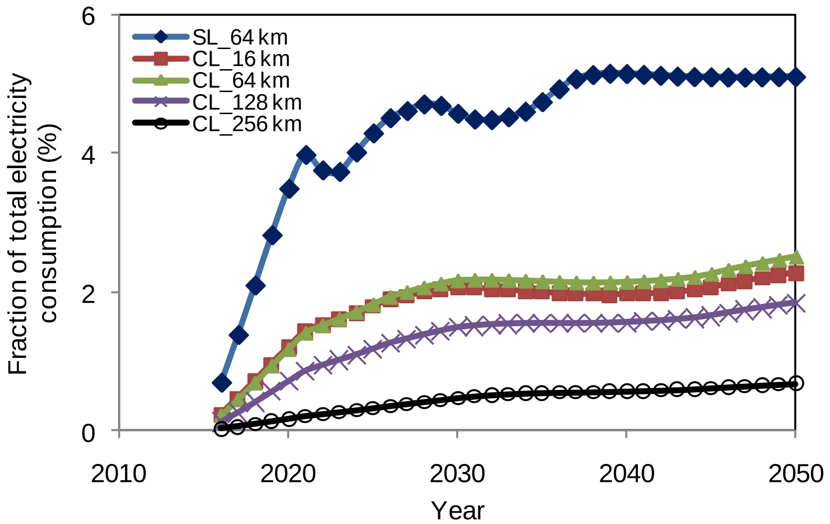

Figure 7. Impact of PHEVs on GHG reductions.