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Vehicle Electrification in Chile: A Life Cycle Assessment and Techno-Economic Analysis Using Data Generated by Autonomie Vehicle Modeling Software

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Abstract

The environmental implications of converting vehicles powered by Internal Combustion Engines (ICE) to battery powered and hybrid battery/ICE powered are evaluated for the case of Chile, one of the worldwide leaders in the production of lithium (Li) required for manufacturing of Li-ion batteries. The economic and environmental metrics were evaluated by techno-economic analysis (TEA) and Life Cycle Assessment (LCA) tools - SuperPro Designer and Gabi®/GREET® models. The system boundary includes both the renewable and nonrenewable energy sources available in Chile and well-to-pump energy consumptions and GHG emissions due to Li mining and Li-ion battery manufacturing. All the major input data required for TEA and LCA were generated using Autonomie vehicle modeling software. This study compares economic and environmental indicators of three vehicle models for the case of Chile including compact, mid-size, and a light duty truck. Autonomie was utilized to predict the fuel economy for the hybrid electric vehicle (HEV) and electric vehicle (EV) for each of the three vehicle types. The baseline fuel economy without vehicle electrification for each case was 44, 29, and 19 mpg, respectively. The LCA and TEA results suggest that vehicle electrification for the case of Chile would improve the metrics of sustainability and economic impacts at the nationwide level. The electrification of compact, mid-size, and a light duty truck, reduce the nationwide GHG emissions by 27%, 47%, and 37%, respectively, for the HEV scenario. Use of renewable energies in vehicle electrification, including hydroelectric and photovoltaic energies, currently 39% of the generation mix, and gasoline usage reduction reduces GHG emissions of the country. The EV scenario; however, increases the GHG emissions of the subcompact vehicle by 22%, whereas this scenario reduces the emissions of the mid-size and the light-duty truck by 25% and 47%, respectively. Use of crude oil, natural gas, and coal in Chile, currently 61% of the generation mix, contributes to increase the life cycle emissions for the EV scenario. The results of this research demonstrate that vehicle electrification has a significant impact not only in the reduction of GHG emissions but also in the economy of the country. Overall, this research will help policymakers and scientific communities to develop strategies to promote and research HEV and EV.

Introduction

Lithium has become a key mineral as one of the essential components in the production of lithium-ion (Li-ion) batteries for electric and hybrid vehicles [1]. In the year 2013, Chile was leading the worldwide production of lithium-based on the United States Geological Survey (USGS) [2], which stated that Chile produced 37% of the worlds lithium, followed by Australia, who became the largest producer in the world by the year 2015. Mineral deposits of lithium are found in lithium-brine deposits particularly in Clayton Valley, Nevada and the giant Salar de Atacama, Chile [1]. In spite of the high costs associated with Li-ion chemistry batteries required by plug-in hybrid electric vehicles (PHEVs), they could be more cost-effective than other energy-storage systems due to their long life-time, higher charge-discharge efficiency, specific energy, and specific power [3]. Additionally, Chile is currently working on nationwide policies to incent EV adoption and renewable energy generations, expecting to reduce fossil fuel consumptions and GHG emissions [4].

Powertrain conversion of ICE based vehicles to HEV systems is already in progress not only in Latin American countries, but worldwide. Previous studies proposed not only to define an optimum hybrid powertrain configuration with respect to a specific drive cycle, but also to estimate the optimal fuel consumption based on such drive cycle and performance characteristics [5].

Vehicle Modeling

For an LCA/TEA analysis, a model of vehicle fuel economy (FE) and battery energy usage is required. In the literature, studies focusing on improved vehicle control strategies for FE

FIGURE 1 User interface examples of the Autonomie software [11].

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rely on highly accurate vehicle models [6]. In recent publications, it has been shown that highly accurate physics-based vehicle models developed in the Autonomie modeling software can be utilized [7].

Autonomie vehicle modeling software was developed by Argonne National Labs and has demonstrated high accuracy with today's top hybrid and plug-in hybrid electric vehicles in terms of engine operation, battery operation, and FE [8], [9]. It comes preloaded with a variety of vehicle types and architectures that can be modified by the user.

HEV do not externally charge and any net battery state of charge difference over a drive cycle is typically circumstantial. In practice, the FE is adjusted according to the HEV FE measurement standard [10].

Life Cycle Assessment and Techno-Economic Analysis

The conversion of powertrains from ICE to HEV must take into consideration the local energy resources. It is claimed that converting ICE vehicles into PHEV reduces CO_2 emissions [12]; however, the well-to-pump emissions due to the electric power used to run the PHEV must be considered. Hence, the net benefit of reducing CO_2 emissions relies not only on the efficiency of the ICE, but also on the energy source used to generate the electricity consumed by PHEVs. Previous efforts evaluated the CO_2 emissions of a PHEV in Italy, including the engine and battery in the system boundaries [12]. The GHG emissions reported by the authors were 79 $gCO_{2\text{-eq}}.km^{-1}$for the New European Driving Cycle (NEDC), 102 $gCO_{2\text{-eq}}.km^{-1}$ for the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), 95 $gCO_{2\text{-eq}}.km^{-1}$ for the Artemis urban drive cycle and 74 $gCO_{2\text{-eq}}.km^{-1}$ for the Environmental Protection Agency (EPA) Federal Test Procedure (FTP75). These GHG emission differences are attributed to the different drive cycles used for the study, which were developed under different approaches and organizations. The substitution of ICE by HEV and EV requires a life cycle energy of 4.756 $MJ.km^{-1}$ to produce Li-ion batteries [13]. The life cycle GHG emissions associated with manufacturing of Li-ion batteries are reported to be 12 $gCO_{2\text{-eq}}.km^{-1}$ [13], 7-10 $gCO_{2\text{-eq}}.km^{-1}$ [14], and 7 $gCO_{2\text{-eq}}.km^{-1}$ for LFP (iron phosphate lithium-ion) and 10 $gCO_{2\text{-eq}}.km^{-1}$ for NCM (nickel cobalt manganese lithium-ion) [15].

The electricity produced in Chile mostly derived from fossil fuels, including 19.7% from natural gas, 33.3% from coal, and 8.4% from crude oil, followed by 37.1% from hydropower energy, 1% from wind power, and 0.4% from solar energy [16]. In Chile, 25% of the energy is consumed by the transportation system [17], contributing to 22% of the nationwide GHG emissions [4]. Vehicle hybridization is today becoming a common practice in Chile, mitigating tailpipe emissions; however, there is no research in the literature that assesses its environmental implications in terms of life cycle GHG emissions.

In addition to life cycle GHG emissions, the operating cost could play a pivotal role in the commercial success of the different vehicle configurations considered in this study. These vehicles require different quantities of gasoline, different sizes and configurations of batteries and different amounts of electricity for charging the batteries.. The evaluation of operating cost of conventional, hybrid and the electric vehicle is even more important for those countries like Chile where gasoline price of 1.22 $/L is more than the average gasoline price of U.S. of 0.61 $/L. Therefore, this study estimated operating costs of the different vehicle configurations considered in this study.

Methods

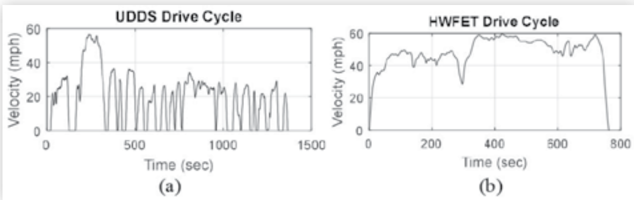
Goals and Scope

Life Cycle Assessment (LCA) is a framework for evaluating the energy use, emissions and impacts of direct, indirect, and supply chain processes [18]. Powertrain conversions provided by companies and small business in Latin America are not considering the optimization of the vehicles' powertrains from integrated engineering, environmental perspectives, and economics. To the best of the authors' knowledge, none of the previous LCA in the literature has evaluated the environmental and economic implications of vehicle electrification in Chile. Integration of vehicle modeling, LCA, and TEA of the conversion of vehicles' powertrains from ICE to HEV and EV systems, including Li-ion manufacturing, will be developed in this research by considering the case of Chile. The availability of local resources in Chile such as energy sources and lithium will be taken into consideration, utilizing Data Generated by Autonomie Vehicle Modeling Software.

Drive Cycle Development

Consideration was given to the type of drive cycles that are relevant to the Chilean driving environment. Chile Route 5 runs through most of the country and has a speed limit of 75 mph. Other highways have a speed limit of 62 mph. Additionally, there are numerous roads for city driving. Due

FIGURE 2 Velocity with respect to time of the city-focused UDDS drive cycle (a) and the highway focused HWFET drive cycle (b) developed by the U.S. EPA [19].



to these driving conditions, it was determined that using the U.S. EPA standard drive cycles are appropriate, which are shown in Figure 2. Using these drive cycles also has the advantage in that they have the significant presence in the literature and other researchers are familiar with them. The city-focused drive cycle is called the Urban Dynamometer Driving Schedule (UDDS) and the highway-focused drive cycles are called the Highway Fuel Economy Driving Schedule (HWFET).

Vehicle Model Development

To develop high fidelity models, the Autonomie modeling software was used to model three types of vehicles commonly used in Chile:

1. Sub-compact car
    a. Defined as having 85-89 ft^3 interior volume
    b. 62 kW max engine power, 1.74 m width, 1.52 m height, 1150 kg weight, 0.33 Coefficient of Drag
2. Mid-size car
    a. Defined as having 85-89 ft^3 interior volume
    b. 115 kW max power, 1.85 m width, 1.47 m height, 1550 kg weight, 0.31 Coefficient of Drag
3. Class 2B Truck
    a. Defined as having 6,001-10,000 lbs weight limit
    b. 210 kW max power, 2.03 m width, 1.94 m height, 2950 kg weight, 0.37 Coefficient of Drag

In each case, the built-in parallel pre-transmission hybrid model from Autonomie was used as the base vehicle. A subcompact version was created by matching size, weight, the coefficient of drag, and engine size to a Chevy Aveo. The midsize version was created by matching vehicle specification to a Honda Accord, and a class 2B truck version was created by matching the specs to a Ford F-150.

FIGURE 3 Examples of a Chevy Aveo which the sub-compact car model is based on (a), a Honda Accord which the mid-size car model is based on (b) and a Ford F-150 which the class 2B truck model is based on (c).

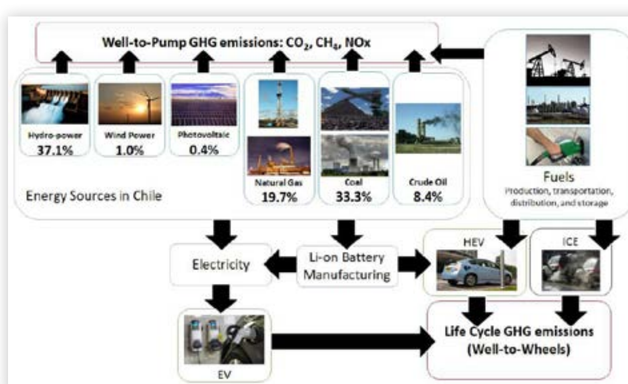
Next, a conventional ICE, a hybrid electric configuration, and an electric configuration (battery only) were created for the sub-compact, mid-size, and class 2B vehicles. These were created by using the engine and battery "scaling" feature in Autonomie. For the conventional configuration, the battery capacity was scaled to 0 Amp hours. For the hybrid electric configuration, the battery capacity was scaled to 6.5 Amp hours for the sub-compact car, and 10 Amp hours for the mid-size car and class 2B truck. For the electric configuration, the engine was scaled to a max power of 0 kW and the battery capacity was scaled to 90 Amp hours for the sub-compact car, mid-size car, and class 2B truck.

System Boundary, Functional Unit, and Impacts Assessment

The boundary of the system is illustrated in Figure 4. The system considers the indirect life cycle emissions due to fuels production, transportation, distribution, and storage for the baseline ICE and the HEV/EV cases by applying the well-to-pump method. For the HEV and EV cases, the system includes the emissions due to electrical usage assuming the energy sources of Chile for the year 2013: 37.1% hydropower, 1.0% wind power, 0.4% photovoltaic, 19.7% natural gas, 33.3% coal, and 8.4% crude oil. These energy sources are also considered in the manufacturing of Li-ion batteries. The baseline ICE and the HEV systems take into consideration the tailpipe emissions due to combustion obtained from Autonomie. The functional unit of this study is the distance traveled, in miles, by the three vehicles type and for the ICE, HEV, and EV cases.

Life cycle GHG emissions ($CO_{2\text{-eq}}$) is defined by the Intergovernmental Panel on Climate Change (IPCC) as the direct and indirect amount of energy consumed by the system multiplied by the emission factor based on the type of energy technology [20]. The GHG emissions estimated in this study considered the associated well-to-wheel emissions due to Li-ion batteries manufacturing, gasoline and electricity usage by the three vehicles type for the ICE, HEV, and EV cases. The Life Cycle Assessment (LCA) tools used in this study are Gabi® and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET)® Model from Argonne.

FIGURE 4 Boundaries and inputs of system for the LCA and TEA.



TEA

As discussed earlier, TEA in this study considered operating costs of the different vehicle configurations in the case of Chile. The operating cost of ICE includes cost of gasoline. The operating cost of HEV includes cost of gasoline, manufacturing cost of batteries normalized by service life in miles, and cost of electricity. The operating cost of EV includes manufacturing cost of batteries normalized by service life in miles, and cost of electricity. The Autonomie models were used to determine the gasoline consumption for the conventional vehicle, the required number and capacities of batteries and gasoline for hybrid electric vehicle, and the required number and capacities of batteries for the electric vehicle. These data were used to determine operating cost of the different vehicle configurations were considered in this study. The average gasoline price of Chile of 1.22 $\$.L^{-1}$ was used to determine operating cost of conventional and hybrid electric vehicles. The production cost of the battery and its service life were assumed to be 800 $\$.kwh^{-1}$ and 100,000 miles, respectively [21]. The average cost of electricity for the case of Chile is 0.158 $\$.kwh^{-1}$ [22].

Results

The results of this research are divided into three components. First, the authors show Autonomie vehicle model results for three vehicle models including compact, mid-size, and a light duty truck. The vehicle model outputs include among others the FE and the electrical energy from Li-ion batteries for the baseline ICE, and the HEV and EV scenarios. Second, the authors present the life cycle GHG emissions implications at the system level, considering indirect impacts due to local energy sources in Chile, gasoline and Li-ion battery manufacturing, and the tailpipe emissions for the ICE, HEV, and EV. Lastly, the authors present the economic impacts for the case of Chile in a tradeoff between gasoline savings, and battery manufacturing and electrical consumption.

Vehicle Model Results

For each of the three vehicle configurations and three architectures for each configuration (9 total models), the UDDS and HWFET drive cycles were simulated in Autonomie and the resulting FE and battery electrical energy consumption was recorded and is shown in Tables 1, 2, and 3. The conventional configuration uses no electrical energy due to the absence of an energy storage battery. The hybrid electric configuration uses an insignificant amount of electrical energy as is expected during normal operation. Normal operation of a hybrid electric vehicle is to operate in a "charge-sustaining" mode that preserves a 50% battery state of charge. When applying the HEV FE measurement standard [10] for the HEV tested, it was found that there was not enough battery state of charge difference over the drive cycles to change the FE. FE improvements are realized through the increased powertrain efficiency from electric hybridization. The electric configuration is said to achieve an infinite amount of FE since no fuel is used. However, this configuration uses a significant amount of electric energy.

TABLE 1 The fuel economy and battery electrical energy consumption for the conventional, hybrid electric, and electric configurations of the sub-compact vehicle.

Sub-compact Car	UDDS Drive Cycle	HWFET Drive Cycle
Conventional Configuration	FE = 44.0 mpg Elec. Energy = 0 kWh	FE = 53.3 mpg Elec. Energy = 0 kWh
Hybrid Electric Configuration	FE = 65.0 mpg Elec. Energy = 0 kWh	FE = 58.3 mpg Elec. Energy = 0 kWh
Electric Configuration	FE = ∞ mpg Elec. Energy = 3.05 kWh	FE = ∞ mpg Elec. Energy = 3.80 kWh

TABLE 2 The fuel economy and battery electrical energy consumption for the conventional, hybrid electric, and electric configurations of the mid-size vehicle.

Mid-size Car	UDDS Drive Cycle	HWFET Drive Cycle
Conventional Configuration	FE = 28.7 mpg Elec. Energy = 0 kWh	FE = 42.31 mpg Elec. Energy = 0 kWh
Hybrid Electric Configuration	FE = 57.7 mpg Elec. Energy = 0 kWh	FE = 47.29 mpg Elec. Energy = 0 kWh
Electric Configuration	FE = ∞ mpg Elec. Energy = 2.82 kWh	FE = ∞ mpg Elec. Energy = 3.71 kWh

TABLE 3 The fuel economy and battery electrical energy consumption for the conventional, hybrid electric, and electric configurations of the sub-compact vehicle.

Class 2B Truck	UDDS Drive Cycle	HWFET Drive Cycle
Conventional Configuration	FE = 18.3 mpg Elec. Energy = 0 kWh	FE = 23.5 mpg Elec. Energy = 0 kWh
Hybrid Electric Configuration	FE = 30.2 mpg Elec. Energy = 0 kWh	FE = 25.6 mpg Elec. Energy = 0 kWh
Electric Configuration	FE = ∞ mpg Elec. Energy = 3.20 kWh	FE = ∞ mpg Elec. Energy = 4.73 kWh

The subcompact car provided the highest FE numbers of all three architectures potentially due to the lightweight and the improved engine efficiency from using a smaller engine. Conversely, the mid-size car yielded the lowest battery energy cost for the electric configuration potentially due to the lower drag inherent in the mid-size architecture and increased energy efficiency from the elimination of its larger engine. Lastly, the truck experienced the lowest FE and highest electrical energy consumption due to the significant increase in vehicle weight compared to the sub-compact and mid-size architectures.

Life Cycle GHG Emissions of Vehicle Electrification in Chile

The life cycle GHG emissions presented in this section include the direct and indirect energy requirements for the baseline ICE and for the HEV and EV cases. The tailpipe emissions were obtained from Autonomie. The emissions from well-to-pump to produce gasoline is 1,850 $gCO_{2\text{-}eq}.gallon^{-1}$ [23]. The fuel economies obtained from Autonomie vehicle modeling were utilized to compute the well-to-pump emissions for each case due to gasoline consumption. By considering the local energy sources in Chile for the year 2013, the well-to-pump emissions to produce electricity is 0.49 $gCO_{2\text{-eq}}.Wh^{-1}$ [24]. The energy requirements presented in the previous section are utilized to compute the well-to-pump electrical emissions for each vehicle and electrification case. These energy requirements were also utilized to compute the Li-ion battery mass for each case, assuming densities from 80 $Wh.kg^{-1}$ [21] and a battery lifetime of 100,000 miles. Well-to-pump emissions for the HEV and EV considered the battery mass of each vehicle type and the Energy requirements for Li-ion battery manufacturing (Figure 5). In the production of Li-ion batteries, lithium manganese oxide, aluminum, graphite, PDVF, and battery management system are the most significant resources in the life cycle energy [25], impacting in the overall life cycle emissions.

The GHG emissions obtained from the LCA model are presented in Figure 6. The results reveal that GHG emissions are reduced by 27%, 47%, and 37% in the electrification of the subcompact, midsize and light-duty truck for the HEV case, respectively. For the EV case; however, GHG emissions are increased by 22% for the subcompact vehicle, whereas the midsize and light-duty truck emissions are reduced by 25%, and 47%. This suggests that vehicle electrification for the EV cases only provides environmental benefits for light-duty trucks with respect to the HEV case.

The drivers towards the GHG emissions of EV are the well-to-pump emissions due to electricity sources in Chile, where 61% accounts for fossil fuels, overcoming the emissions displaced by gasoline combustion and manufacturing in the subcompact and midsize vehicles. For the HEV case, 78% of the emissions are due to direct combustion, followed by 16% from petroleum refinery to produce gasoline and 4% of well-to-pump emissions from electricity use. Li-ion battery manufacturing is the less significant component in the life cycle emissions for the HEV case, 2%. However, Li-ion battery manufacturing contributes to 32% for the EV case, whereas the remaining 66% is due to electricity consumption. The results illustrate the tradeoff between well-to-pump emissions due to electricity consumption, and life cycle emissions due to fuel consumption for the case of Chile. The LCA results suggest that there is an optimum point that exists for vehicle electrification that must be evaluated on a case by case basis to minimize the life cycle GHG emissions.

FIGURE 5 Energy requirements for Li-ion batteries manufacturing. Each process is divided by the local energy sources in Chile: solar, wind, hydropower, coal, natural gas, and petroleum crude. Adapted from [25].

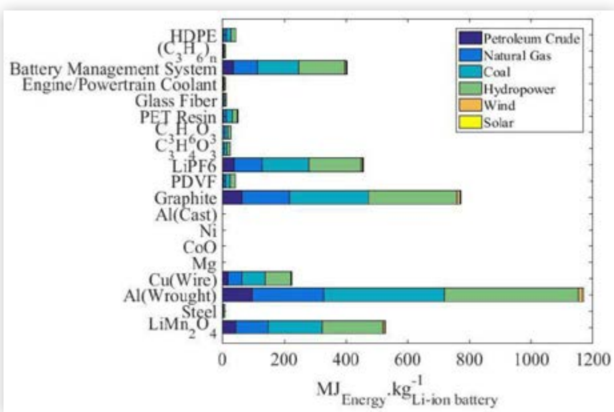
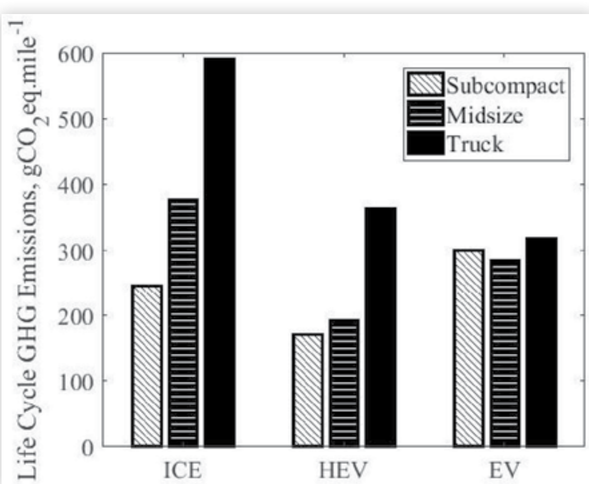


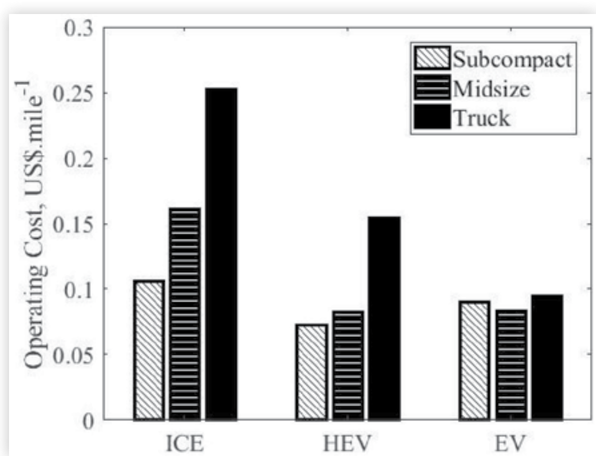
FIGURE 6 Life cycle GHG emissions for the three vehicle types: subcompact, midsize, and truck. The results are presented for each case: baseline ICE, and the HEV and EV.



Techno-Economics of Vehicle Electrification in Chile

Figure 7 depicts the required operating cost of the different vehicle configurations. Generally, hybrid and electric vehicles are cheaper than conventional vehicles. This is mainly due to the lower fuel economy of the conventional vehicles. While the operating cost of the electric truck was about 40% less than the hybrid truck, about 19% more operating cost was found for the mid-size vehicle. On the other hand, the similar level of operating cost was found for the mid-size vehicle. These differences are due to the differences in the fuel economy and the structural configurations of vehicles.

FIGURE 7 Operating cost for the three vehicle types: subcompact, midsize, and truck. The results are presented for each case: baseline ICE, and the HEV and EV.



Summary/Conclusions

Electrification of the subcompact, midsize and light-duty truck improved their fuel economy and reduced their life cycle GHG emissions and operating cost for the HEV case. When converting powertrains from ICE vehicles to EV; however, life cycle GHG emissions were increased for the subcompact vehicle due to well-to-pump emissions contributed by fossil fuels of the existing energy system in Chile. The operating cost of EV was reduced when compared to the conventional vehicles. Further assessments considering the new photovoltaic plant at Vallenar in the Atacama region in Chile, the largest in the Americas, will impact the environmental metrics evaluated in this study. The GHG emissions from the hybridized vehicles are reduced not only due to about 40% of electricity derived from hydropower, and other renewable energy sources, such as wind, and photovoltaic, but also because the increased fuel economies for the three vehicles researched here. Yet, model fidelity should be improved for the vehicles models by obtaining more specific vehicle model data and developing drive cycles for Chile. Nevertheless, this research has demonstrated that clean energy sources in Chile make the adoption of HEV not only economically feasible due to the increase of fuel economies, but also environmentally viable due to significant reductions in life cycle GHG emissions.

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Definitions/Abbreviations

EPA - Environmental Protection Agency

FE - Fuel Economy

GHG - Greenhouse Gas

HWFET - Highway Fuel Economy Driving Schedule

LCA - Life Cycle Assessment

TEA - Techno-economic Analysis

U.S. - United States

UDDS - Urban Dynamometer Driving Schedule

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