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A Well-to-Wheel Analysis of Greenhouse Gas Emissions from Passenger Vehicles in Thailand: Strategies for Enhancing Sustainable Transportation

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ABSTRACT

This paper aims to analyze greenhouse gas (GHG) emissions from passenger vehicles with a particular focus on comparing EVs and internal combustion engine vehicles (ICEVs) using various ratios of ethanol and gasoline blends in Thailand. For this purpose, four passenger vehicle models of both EVs and ICEVs are selected based on their power output and popularity in Thailand, and their GHG emissions are analyzed by employing a well-to-wheel (WTW) analysis. The results indicate that EVs achieve over a 60% reduction in GHG emissions compared to ICEVs running on gasoline**.** Interestingly, blending ethanol with gasoline has resulted in more than a 50% decrease in GHG emissions compared to using pure gasoline. Despite the considerable benefits of EVs, the transition from ICEVs to EVs could potentially impact the biofuel and agricultural sectors, directly influencing the Thai economy and society due to its agricultural-based economy. To achieve a balanced transitional pathway from ICEVs to EVs, this paper suggests adopting several strategies, for example, continuing to blend biofuels with petroleum products until the full adoption of EVs, shifting biofuels from transportation to electricity generation, and advancing technology to develop new biofuel products. These strategies could provide valuable insights for future research on GHG emissions mitigation and offer a basis for evaluating the effectiveness of decarbonization policies in Thailand.

1. INTRODUCTION

Climate change currently represents a worldwide emergency that goes beyond national boundaries. The impacts of climate change have been progressively intensifying across the natural, economic, and social systems vital for human livelihood. Climate change could endanger health, food security, housing, safety, and employment opportunities. Given rising concerns about the impacts of climate change, Thailand has been steadily strengthening its regulations and implementing more stringent measures aimed at reducing carbon dioxide and pollutant emissions. The Thai government aims to mitigate the effects of climate change by targeting a 30-40% reduction in GHG emissions by 2030. Additionally, the government agreed to attain carbon-neutral status by 2050 and reach Net Zero Emissions (NZE) by 2065 [1]. In the case of Thailand, the country where consumption of energy relies heavily on fossil fuels and domestic energy resources are scarce, environmental consequences and energy import dependency are matters of concern. In 2023, energy imports accounted for about 79% of total commercial primary energy consumption in the country [2]. Of the total commercial primary energy import in 2023, crude oil accounted for 61%, followed by natural gas (23%) and coal (14%) [3]. In addition, more than 75% of petroleum products consumption has been mainly contributed by the transport sector. Given heavy reliance on imported fossil fuels, the Thai government has targeted the transport sector to reduce fossil fuel imports as well as mitigate GHG emissions attributed to fossil fuel consumptions. In order to achieve its objectives, the government has prioritized the development of EVs as a key policy. Since 2015, the government has officially implemented policies aimed at advancing EVs development [4]. In view of environmental considerations, EVs are widely regarded as the future of transportation. This is due to their capabilities of efficient conversion of electrical energy into mechanical energy, resulting in significant reductions in tailpipe emissions comparing to ICEVs [5]. Therefore, EVs has become an attractive option to replace the traditional ICEVs. While EVs are acknowledged as environmentally friendly, whether or not EVs will indeed offer a green and sustainable alternative will depend on the fuel mix for producing electricity. A number of studies have been conducted on the life cycle assessment of EVs in comparison with ICEVs for various countries [5-17]. However, in the case of Thailand, the literature provides a few studies undertaken to examine these issues. For example, Gabriel et al. [18] conducted an analysis of the life-cycle environmental impacts of buses in Bangkok. Charoen-amornkitt et al. [19] investigated energy consumption and carbon emissions of different designs of battery swapping stations for electric motorcycles in Thailand. A study by Suttakul et al. [20] assessed the energy consumption and carbon emissions of EVs based on real-world driving tests conducted on different roads in Chiangmai. And, Achariyaviriya et al. [21] provided an analysis of potential carbon emission reductions resulting from the transition to EVs in Thailand. Despite some research works investigating the life cycle environmental impacts of EVs in Thailand, a comparative study on GHG emissions from EVs and ICEVs using various ratios of biofuels and petroleum products blends in Thailand is still limited. In fact, biofuels have been one of the key strategies to lower GHG gas emissions and imports of crude oil over the last two decades [22]. The promotion of EVs could pose several challenges for various sectors, including the electricity, transport, and especially biofuel sectors [4, 23, 24]. This paper, therefore, provides a comparative analysis of GHG emissions from EVs and ICEVs with various ratios of biofuels and petroleum products blends. This analysis would contribute to establishing a balanced transitional pathway from ICEVs to EVs.

2. POLICY AND DEVELOPMENT OF EVS AND BIOFUELS IN THAILAND

Given limited domestic fossil fuels and being an agricultural-based country, the Thai government has prioritized bioenergy as a key strategy for decreasing reliance on fossil fuels and addressing climate change caused by pollution over the past two decades. Since the 2000s, various plans and initiatives have been introduced to encourage the adoption of biofuels in the transportation sector [22]. Since these plans and initiatives were introduced, domestic production of biofuels has increased steadily, from 76 KTOE in 2006 to 2,112 KTOE in 2023 [25]. In the 2000s, biofuels emerged as an alternative to substitute petroleum products in Thailand. For example, gasoline consumption in the country has continuously declined, from 4,422 KTOE in 2006 to 125 KTOE in 2023. However, the consumption of gasohol (a blend of gasoline and ethanol) in 2023 has increased significantly by more than 10 times compared to its consumption in 2006 [25]. The significant increase in biofuels production has also posed numerous challenges, such as threats to food security, water resource shortages, and issues related to land allocation for biofuel cultivation [22, 26]. In Thailand, the impact of a significant rise in biofuel production became evident in 2011. For instance, Thailand's ambitious biodiesel targets resulted in a severe scarcity of palm oil for cooking in 2011, which caused retail prices to spike [24].

In recognition of the concerns regarding the issues of biofuels impacts on food, water, and land use systems, as previously discussed, the Thai government is pursuing new policies and measures for achieving its objectives to reduce reliance on fossil fuel energy and alleviate climate change issues. Transitioning to electric transportation is anticipated to be one of the effective policies for meeting the goals. To support the successful implementation of its EV adoption promotion policy, the Thai government initiated the development of an electrical infrastructure plan, referred to as the EV roadmap, in 2016. According to this roadmap, the government aims to achieve 1.2 million EVs by 2036 [4]. Furthermore, the Thai government has intensified efforts to promote EV deployment by forming the National Electric Vehicle Policy Committee in 2020 [4]. Following the formation of the committee, the government launched the 30@30 policy, targeting zero-emission vehicles (ZEVs) to account for 30% of the country's total domestic vehicle production by 2030. This target represents approximately 725,000 electric cars and light trucks, in addition to 675,000 electric two-wheelers [27]. This is consistent with the government's commitment to attain carbon-neutral status by 2050 and achieve NZE by 2065. This commitment stems from the attendance of the government in the 26th Conference of the Parties (COP26) under the United Nations Framework Convention on Climate Change (UNFCCC) in 2021 [1]. Furthermore, Thailand has committed to enhance its Nationally Determined Contributions (NDC), setting a more ambitious goal to cut GHG emissions by 30-40% by 2030, up from its earlier target of 20-25%.

To promote the adoption of electric vehicles (EVs), the Thai government has introduced a range of incentives aimed at encouraging the use of EVs, such as passenger vehicles, electric light trucks, and electric two-wheelers. In order to position the nation as a major hub for EV production in Asia, the cabinet initially approved a tax incentive package for EVs in February 2022 [28]. The package comprised initiatives to boost supply, incentives to stimulate demand, and supportive policies, all scheduled for implementation between 2022 and 2025 [29, 30]. The package was split into two stages: the initial stage covering 2022 to 2023 and the second stage extending from 2024 to 2025. During the first stage, the measures focused on fast-tracking EV deployment by providing exceptions on import tariffs and excise taxes, as well as concessions to stimulate demand and encourage investments in the sector [29]. This applies to both the import of Completely Built Up (CBU) vehicles and two-wheelers and the domestic assembly of Completely Knocked Down (CKD) cars in Thailand. In the second stage (2024-2025), the measures focused on promoting the deployment of locally produced EVs by gradually eliminating import tariff exceptions for CBU cars [30]. This initiative seeks to make CBU vehicles more expensive relative to locally manufactured ones, encouraging producers to shift EV production to Thailand to sufficiently supply growing demand.

3. METHODOLOGY

In this study, a well-to-wheel (WTW) analysis is employed to examine the GHG emissions of EVs in comparison to ICEVs with various ratios of biofuels and petroleum product blends. A WTW analysis is an application of Life Cycle Assessment (LCA) designed to assess the total energy requirements and environmental impacts associated with vehicle operation [5]. A number of research studies have extensively employed a WTW analysis to assess energy consumption and emissions of various vehicle types across different countries [5-10, 12-14, 16-18, 31-40]. This WTW analysis typically encompasses two primary processes, including well-to-tank (WTT) and tank-to-wheel (TTW) processes. A well-to-tank (WTT) evaluates the energy consumption and environmental impacts associated with the production, extraction, and transportation of the fuels used to power vehicles [5]. It accounts for all the energy and emissions generated from the primary source (e.g., oil wells, renewable energy generation) to the point where the fuel is dispensed into the vehicle's fuel tank. And a tank-to-wheel (TTW) considers the energy consumed and emissions that occur during the actual operation of the vehicle. By combining both WTT and TTW analysis, a WTW analysis provides a comprehensive view of the energy consumption and GHG emissions associated with a vehicle throughout its entire lifecycle, from the initial energy source to its on-road operation [10, 16]. The well-to-wheel concept is presented in Figure 1.

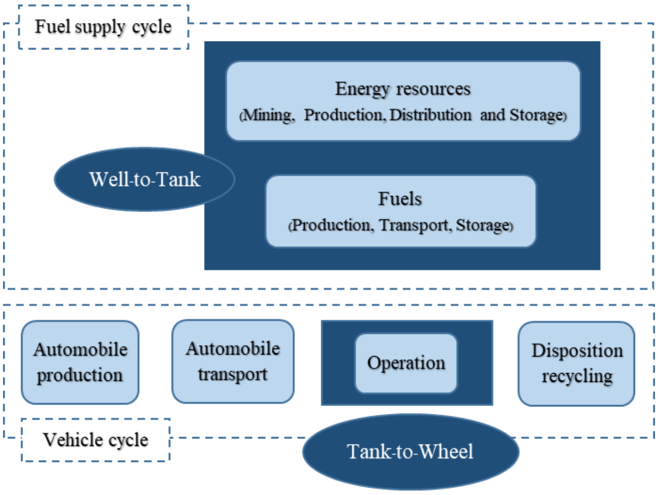

Figure 1. Concept of well-to-wheel analysis [37, 41]

The well-to-wheel process of ICEVs involves five key steps: (1) crude oil extraction, (2) fuel production (refining), (3) fuel transportation/distribution, (4) refueling, and (5) power deliver to the wheel [6]. The well-to-wheel process of ICEVs is primarily divided into two major phases. The initial phase includes the energy source extraction, fuel production, fuel transportation, and refueling the vehicle (well-to-tank). And, the subsequent phase entails using the stored fuel to drive the vehicle (tank-to-wheel) [16]. Therefore, the estimation of greenhouse gases emissions of ICEVs can be calculated by employing Eq. (1).

$$GHG_{WTW-ICEVs} = (GHG_{WTT} + GHG_{TTW}) \times FE \qquad (1)$$

where,

$GHG_{WTW\text{-}ICEVs}$	is the GHG emissions from the entire well-to-wheel cycle for ICEVs (unit: gCO_{2eq}/km).
GHG_{WTT}	is the GHG emissions from the well-to-tank cycle (unit: gCO_{2eq}/litre).
GHG_{TTW}	is the GHG emissions from tank-to-wheel cycle (unit: gCO_{2eq}/litre).
FE	is the fuel efficiency of ICEVs (unit: litres/km).

Alternatively, the well-to-wheel process of BEVs encompasses five stages: (1) energy resources extraction, (2) electricity production, (3) electricity transmission and distribution, (4) vehicle charging, and (5) powering the wheels [6]. BEVs, therefore, follow a different well-to-wheel process characterized by two main components. First, it involves extracting the energy source, processing it, and transporting it to the power plant, known as "well-to-power plant". Then, it entails transmitting the required electricity to the vehicle and using this power to drive the vehicle, referred to as "power plant-to-wheel" [16]. By combining the emissions estimated from the two stages, the total GHG emissions associated with operating an electric vehicle can be obtained. This combined value can be calculated by using Eq. (2).

$$GHG_{WTW-EVs} = \left\{ \sum_{e} P_e \left(GHG_{e,WTPP} + GHG_{e,PPTW} \right) \right\} \times VE \qquad (2)$$

where,

$GHG_{WTW\text{-}EVs}$	is the GHG emissions from the entire well-to-wheel cycle for EVs (unit: gCO_{2eq}/km).
P_e	is the share of each energy resource in the power production mix.
$GHG_{e,\,WTPP}$	is the GHG emissions from each electricity source in the well-to-power plant cycle (unit: gCO_{2eq}/kWh).
$GHG_{e,\,PPTW}$	is the GHG emissions from each electricity source in the power plant-to-wheel cycle (unit: gCO_{2eq}/kWh).
VE	is the vehicle efficacy of electric vehicles (unit: kWh/km).

4. RESEARCH SCOPE AND FRAMEWORK

The research scope, in this paper, focuses on analyzing the life cycle of fuels to propel the vehicle, with an emphasis on gasoline passenger vehicles in Thailand. This emphasis is motivated by the fact that the majority of EVs in Thailand fall under the passenger car classification, representing the largest segment in terms of overall numbers. From 2018 to 2023, passenger cars accounted for over 60% of the total vehicle population in Thailand [42]. In order to analyze and compare the GHG emissions of BEVs and ICEVs from a well-to-wheel viewpoint, four car models of BEVs and ICEVs are selected from various vehicle categories based on their driving power output and popularity in Thailand. These models are chosen due to their dominance in Thailand's vehicle market, representing the largest share of the total vehicle population. For example, the selected ICEV models represented over 70% of all gasoline-powered passenger ICEVs in the country in 2023 [42]. For BEVs, the selected models also accounted for a substantially large share, exceeding 75% of all passenger BEVs in the country in 2023 [42]. Table 1 presents the specifications of four selected vehicle models of BEVs and ICEVs available in Thailand. It is worth noting that the specifications and fuel economy of vehicle models analyzed in this study are predominantly obtained from the government's database, which contains detailed information on vehicle characteristics and performance testing. Given growing concerns about environmental pollution, the Thai government introduced a fuel economy policy in 2015, shifting the basis of the excise tax from engine size to CO_2 emissions [43]. In response to the government's fuel economy policy, the Ministry of Industry (MOI) has established regulations requiring automobile manufacturers and importers to display Eco stickers, which indicate the fuel consumption rate and CO_2 emissions of vehicles. Additionally, the MOI collaborated with the Ministry of Finance (MOF) to develop a cloud-based application for Eco Stickers that allows other relevant government agencies to access a shared database for inspection and CO_2 tax calculations [43]. In Thailand, the Eco Sticker is a label affixed to new vehicles to provide consumers with essential information on fuel efficiency, emissions, and safety standards to support informed purchasing choices [44]. The Eco Sticker allows local consumers to access standardized vehicle information in order to compare specifications across different models before making a decision. This protects consumers from exaggerative advertisement and ensures fairness in their purchasing process. The Eco Sticker provides comprehensive information including fuel consumption, CO_2 emissions, emission standards, safety features, vehicle specifications, factory-installed equipment, manufacturer or importer information, retail price, and excise tax rate. This information is based on testing and data provided by manufacturers, ensuring accuracy and reliability. Therefore, fuel economy data for the selected ICEV and EV models were obtained from the Eco Sticker issued by the Office of Industrial Economics (OIE) [44]. It is also important to note that the fuel economy data provided on the Eco Sticker for all vehicle models is based on combined driving conditions, which include both urban and highway driving scenarios.

From Table 1, driving power output refers to the maximum power a vehicle's engine can generate to drive it forward, typically measured in units such as horsepower or kilowatts**.** This power output directly influences the vehicle's acceleration, maximum speed, and its capability to overcome resistance. However, real-world maximum power is influenced by several factors such as driving style, traffic conditions, and environmental influences. The driving power output is employed in this study to establish a comparison level ranges between BEVs and ICEVs. In addition to maximum power, other specifications are also provided in Table 1, such as maximum torque, vehicle weight and battery capacity.

For emission calculations, this study employs Microsoft Excel, a widely used and versatile tool for data analysis. Furthermore, in this paper, the GHG emissions of BEVs for each model are estimated and compared with those of ICEVs using various ratios of ethanol and gasoline blends. Therefore, fuels employed in this research include gasoline, ethanol, and electricity. In order to estimate GHG emissions, this study requires emission factors from various processes, including gasoline production, ethanol production, primary energy production and electricity generation. The emission factors for gasoline production including crude oil extraction, transportation (both overseas and domestic), and petroleum refining [41, 45, 46]. For ethanol in the case of Thailand, production primarily relies on sugarcane and cassava as the main raw materials. And, the process for producing ethanol covers crop cultivation, fertilization, ethanol conversion and transportation. The emission factors for each process and crop, however, vary depending on the types of fuel used in the production. For sugarcane, emissions arise from the use of fuels and fertilizers, including diesel (for cultivation and transportation), fertilizers (such as nitrogen, phosphorus, and potassium), and coal (for ethanol conversion). Nguyen et al. [47] provide comprehensive data on energy consumption for sugar cane-based ethanol production. For cassava, emissions result from fuel and fertilizer use, including diesel for cultivation and transportation, fertilizers, as well as electricity and bunker oil for ethanol conversion. The data on energy use for cassava-based production is thoroughly provided by Nguyen et al. [48]. In addition to energy consumption data, the emission factors for each fuel type used in the ethanol production process are sourced from the Thailand Greenhouse Gas Management Organization (TGO) [49]. For electricity generation process, the emission factors (kg/kWh) for each energy source are thoroughly obtained from the Thailand National Science and Technology Development Agency (NSTDA) [50]. And the information on electricity generation by source are available from and the Department of Alternative Energy Development and Efficiency (DEDE) [25].

Table 1. Specifications of four selected vehicle models of BEVs and ICEVs employed in this paper **[44]**

Driving Power Output (HP)	**Models of BEVs**	**Models of ICEVs**
90-100	*BEV1*[1] - 95 HP electric motor - 150 N.m of maximum torque - 38.5 kWh of battery capacity - 1,151 kg of vehicle weight	*ICEV1*[2] - 92 HP engine - 109 N.m of maximum torque - 1,057 kg of vehicle weight
160-170	*BEV2*[1] - 170 HP electric motor - 250 N.m of maximum torque - 49 kWh of battery capacity - 1,650 kg of vehicle weight	*ICEV2*[2] - 165 HP engine - 213 N.m of maximum torque - 1,361 kg of vehicle weight
190-200	*BEV3*[1] - 201 HP electric motor - 310 N.m of maximum torque - 50.25 kWh of battery capacity - 1,680 kg of vehicle weight	*ICEV3*[2] - 190 HP engine - 243 N.m of maximum torque - 1,571 kg of vehicle weight
290-300	*BEV4*[1] - 295 HP electric motor - 420 N.m of maximum torque - 60 kWh of battery capacity - 1,909 kg of vehicle weight	*ICEV4*[2] - 300 HP engine - 370 N.m of maximum torque - 1,460 kg of vehicle weight

Note: 1. More information on the technical specifications of the BEV1, BEV2, BEV3 and BEV4 is available in previous studies [51-54], respectively. 2. Further details on the technical specifications of the ICEV1, ICEV2, ICEV3 and ICEV4 can be found in previous studies [55-58], respectively.

The framework for estimating GHG emissions from WTW process of BEVs and ICEVs is presented in Figure 2. The WTW process is divided into two processes consisting of WTT and TTW processes. In the case of ICEVs, the fuels used comprise gasoline and ethanol. Consequently, in order to calculate GHG emissions from WTT process of gasoline, the energy consumed throughout the entire process—including crude oil extraction, transportation (both overseas and domestic), and petroleum refining—is considered. Regarding ethanol, this paper employs sugar cane and cassava as raw materials for producing ethanol. This is due to the fact that sugarcane and cassava have been the primary feedstock for ethanol production in Thailand since the initiation of the biofuel promotion policy [59]. In 2022, sugarcane and cassava accounted for about 70% and 30%, respectively, of the feedstock used for ethanol production in Thailand [60]. In order to estimate GHG emissions of WTT process of ethanol, this research considers the entire processes involved, including crop cultivation, crop fertilization, ethanol conversion and transportation. For BEVs, the fuel source used is only electricity. In the context of Thailand, electricity supply comes from both domestic production and imports from neighboring countries. And, the country's electricity generation uses various energy resources including natural gas, coal and lignite, diesel, solar, biomass, hydropower and wind. Some energy resources used for power production, such as natural gas, coal, and crude oil, need to be imported due to limited domestic energy resources. The calculation of GHG emissions from WTT process of generating electricity in this research, therefore, considers the processes of energy resource production as well as power generation. It should be noted that, in this paper, the process of energy resource production specifically covers conventional energy including natural gas, coal, lignite, and diesel. And, electricity imported from neighboring countries are excluded from the estimation of GHG emissions of WTT process of electricity. This exclusion is due to the fact that electricity imported from neighboring countries is mainly from hydroelectric source. For the power generation process, GHG emissions are calculated, in this study, based on the electricity generation mix in the year 2023. It should be noted that the analysis does not account for potential changes in the energy mix over time.

In terms of TTW process, the calculation of GHG emissions applies only to ICEVs. And, fuel used for propelling ICEVs include gasoline and various blends of ethanol and gasoline, such as E10 (10% ethanol and 90% gasoline), E20 (20% ethanol and 80% gasoline), and E85 (85% ethanol and 15% gasoline). These ratio blends are selected in this study because they are petroleum products sold in Thailand.

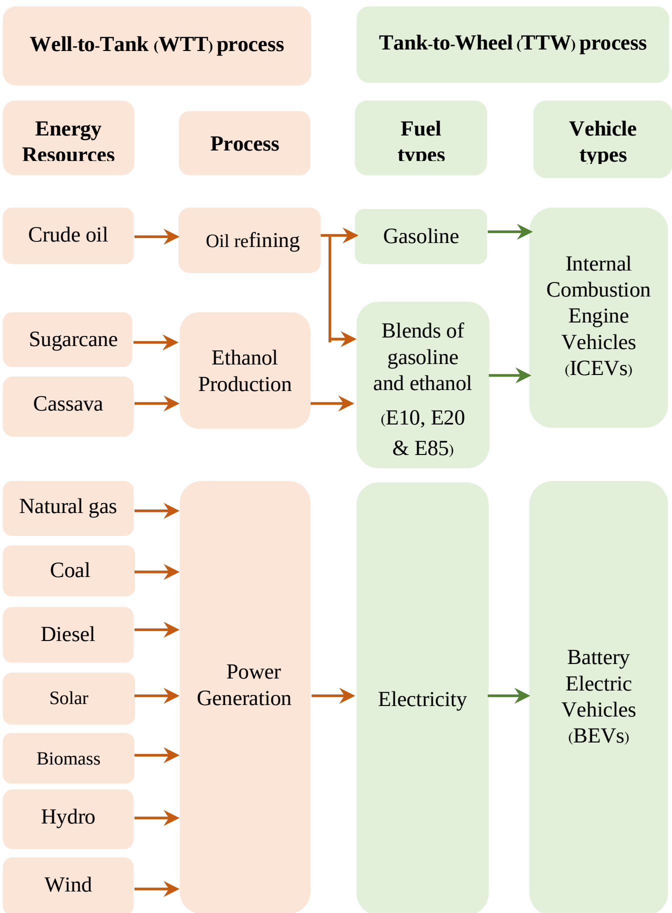

Figure 2. The framework of WTW process in this study

5. DATA CONSIDERATION

This study requires extensive data to conduct a comparative analysis of GHG emissions from EVs and ICEVs with various ratios of ethanol and gasoline blends. In the context of WTW analysis, GHG emissions are calculated from both two processes – WTT and TTW processes. In view of WTT process, the data required for estimating GHG emissions includes energy consumed and emissions generated during the entire production process of each fuel such as gasoline, ethanol and electricity. For gasoline production, the information on energy consumption and GHG emission factors for the process of crude oil extraction, transportation, and petroleum refining was taken from the Intergovernmental Panel on Climate Change (IPCC) and previous research works [41, 45-46, 50, 61]. It should be noted that the gasoline used in the calculations for this research is gasoline with an octane rating of 91. In terms of calculating GHG emissions from ethanol production process, this paper takes into account the whole life cycle of ethanol production including cultivation, fertilizer, ethanol conversion and transportation. And, as discussed earlier, raw materials for producing ethanol in Thailand are sugar cane and cassava. Therefore, the information on energy use and emissions factors for calculating GHG emissions from sugar cane-based and cassava-based ethanol production process in the case of Thailand was thoroughly presented in relevant research studies and the TGO [47-49]. In regard to the electricity generation process, this study requires the data on energy consumption and emissions factors from both the production of energy resources and the generation of electricity. This data can be collected from various sources including the TGO, IPCC and DEDE [2, 25, 54-58].

6. EMPIRICAL RESULTS AND DISCUSSIONS

This section presents the empirical results of the GHG emissions of the selected vehicle models obtained from the application of methodologies described in Section 3 and Section 4. The well-to-wheel GHG emissions for the selected vehicle models are illustrated in Figures 3-6. It should be noted that this study provides a comparative well-to-wheel emissions analysis based on standardized and validated vehicle specifications and fuel characteristics. The dataset is obtained from governmental databases, where emissions values are derived from standardized test conditions. While this approach ensures reliability and consistency, incorporating advanced statistical analyses in future research could enhance the understanding of emissions dynamics.

6.1 WTW GHG emissions from BEVs and ICEVs with driving power output of 90–100 HP

It is observed from Figure 3 that the well-to-wheel GHG emissions from the BEV1 are notably lower than those from the ICEV1, measuring approximately 59 gCO_2eq per kilometer. In view of ICEVs using various ratios of ethanol and gasoline blends, it is evident that GHG emissions from the ICEV1 using 100% gasoline are the highest, about 120 gCO_2eq/km. Subsequently, the ICEV1 using E10 and E20 exhibits emissions of approximately 112 gCO_2eq/km and 105 gCO_2eq/km respectively. This indicates that higher shares of ethanol in gasoline contribute to a decrease in GHG emissions. In addition, it is worth mentioning that GHG emissions from the WTT process of ICEVs using 100**%** gasoline are lowest as compared to the ICEVs using E10 and E20, and substantially lower than BEVs, which exhibit the highest emissions from the WTT process. This could be attributed to the various fossil fuels consumption levels across different fuel production processes. For example, fossil fuel consumption for producing 1 MJ of gasoline, cassava-based ethanol, sugar cane based-ethanol and electricity, in Thailand, was 0.17, 0.57, 0.73 and 1.95 MJ, respectively [25, 41, 47-48]. It is further noticed from Figure 3 that GHG emissions from TTW process has significantly contributed to total GHG emissions for ICEVs using gasoline, E10 and E20. GHG emissions from TTW process for ICEV1 using gasoline, E10 and E20 were 104 gCO_2eq/km, 94 gCO_2eq/km and 83 gCO_2eq/km, respectively.

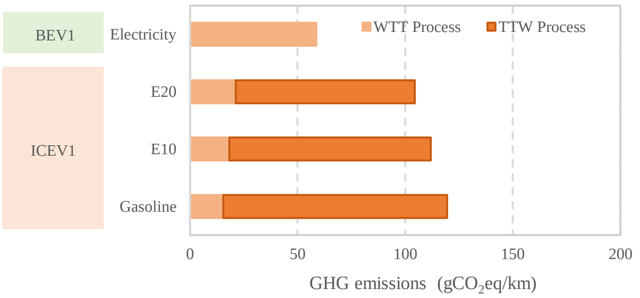

Figure 3. GHG emissions from vehicle models with driving power output of 90-100 HP

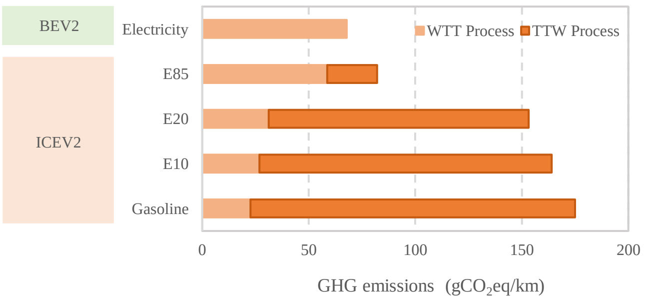

Figure 4. GHG emissions from vehicle models with driving power output of 160-170 HP

6.2 WTW GHG emissions from BEVs and ICEVs with driving power output of 160–170 HP

From Figure 4, the WTW GHG emissions from the BEV2 are approximately 68 gCO_2eq/km – slight increase as compared to the BEV1. This could suggest that a greater increase in the driving power output of EVs results in a minimal rise in their GHG emissions. However, WTW GHG emissions from ICEV2 using gasoline, E10, E20 and E85 are about 175, 164, 153 and 82 gCO_2eq/km, respectively. The substantial reduction in WTW GHG emissions from ICEV2 using E85 compared to E20, E10, and gasoline could be due to the high ethanol share in the fuel. It is further observed from Figure 4 that a higher proportion of ethanol results in a noticeable increase in GHG emissions from the WTT process. For example, GHG emissions from the WTT process of the ICEV2 using E85 are the highest and even exceed those of the BEV2. In view of GHG emissions from the TTW process, it is revealed from Figure 4 that an increase in the proportion of ethanol in gasoline significantly reduces GHG emissions from the TTW process of ICEVs. This is a result of a significant difference in GHG emissions between the combustion of gasoline and ethanol. GHG emissions from 100% gasoline and 100% ethanol are 2.43 $kgCO_2eq$/litre and 0.01 $kgCO_2eq$/litre respectively [50]. Based on the forgoing discussions, a blend of gasoline with ethanol are an effective way for reducing GHG emissions. Especially, in the case of ethanol proportion increases, such an increase could lead to a significant drop in GHG emissions. For instance, ICEV2 using E85 contributed to a reduction of over 50% in WTW GHG emissions compared to those using gasoline.

6.3 WTW GHG emissions from BEVs and ICEVs with driving power output of 190–200 HP

The results from Figure 5 indicate that the WTW GHG emissions from BEVs and ICEVs with a driving power output of 190-200 HP follow a similar trend to those with a driving power output of 160-170 HP. The WTW GHG emissions from the BEV3 are approximately 72 gCO_2eq/km, which is moderately higher than those of the BEV1 and BEV2. In the case of ICEVs, WTW GHG emissions from the ICEV3 are marginally lower than from those of the ICEV2. WTW emissions from the ICEV3 using gasoline, E10, E20 and E85 are about 169, 159, 148 and 79 gCO_2eq/km, respectively. This is primarily due to better fuel economy of the ICEV3 in comparison to the ICEV2. The fuel economy of the ICEV3 and ICEV2 are 16.4 and 15.9 km/litre [44].

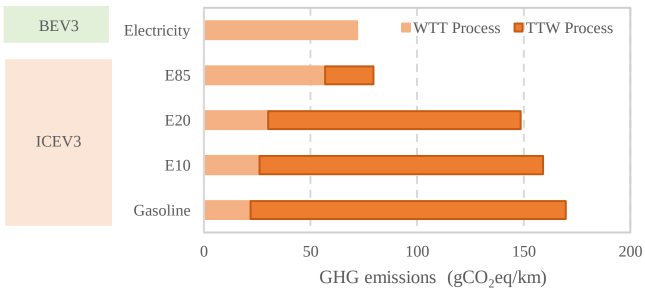

Figure 5. GHG emissions from vehicle models with driving power output of 190-200 HP

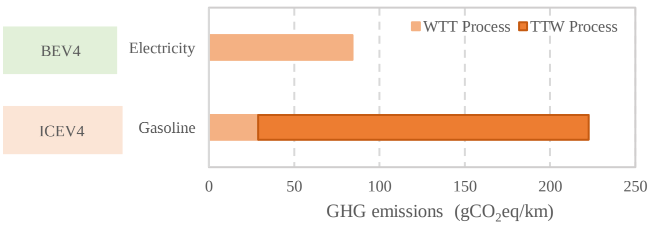

Figure 6. GHG emissions from vehicle models with driving power output of 290-300 HP

6.4 WTW GHG emissions from BEVs and ICEVs with driving power output of 290–300 HP

According to Figure 6, the WTW GHG emissions from the BEV4 are about 84 gCO_2eq/km – marginally higher than those of the BEV1, BEV2, and BEV3. On the other hand, the WTW GHG emissions from the ICEV4 reach their highest compared to other ICEVs with lower driving power output. The WTW GHG emissions from the ICEV4 are about 222 gCO_2eq/km. It is interesting to note that ICEVs with higher driving power output lead to a significantly higher rate of WTW GHG emissions while BEVs with higher driving power output result in moderate increase in WTW GHG emissions. For example, ICEVs using gasoline exhibit an 85% increase in WTW GHG emissions, ranging from 120 gCO_2eq/km for ICEV with a driving power output of 90 HP, to 222 gCO_2eq/km for ICEV with a driving power output of 300 HP. On the contrary, WTW GHG emissions from BEVs with 90-300 HP driving power output experience an increase of 42%, ranging from 59 gCO_2eq/km for BEV with driving power output of 90 HP, to 84 gCO_2eq/km for BEV with driving power output of 300 HP.

7. POLICY IMPLICATIONS

With an aim to provide strategies to establish a balanced transitional pathway from ICEVs to EVs, this paper conducts a comparative analysis of the well-to-wheel GHG emissions from EVs and ICEVs using different ratio of ethanol and gasoline blends in the case of Thailand. A summary of key findings is as follows.

- EVs significantly reduce WTW GHG emissions compared to ICEVs. The WTW GHG emissions from EVs are three to five times lower than those from ICEVs with gasoline. For example, WTW GHG emissions from the BEV4 are about 67 gCO_2eq/km – more than three-fold decrease in comparison with the ICEV4. In addition, GHG emission from EVs could be further reduced if electricity generation incorporates more renewable energy sources. In the case of Thailand, fuel mix for power production in 2023 was predominantly natural gas, accounting for about 57% of the fuel consumption; renewable energy for 29%; coal and lignite for 14%; and other sources (i.e. fuel oil, diesel, and residual gas) – for only 0.5% [25].
- In terms of driving range, EVs with longer ranges would contribute to a greater reduction in GHG emissions compared to ICEVs. For instance, the WTW GHG emissions from the BEV1 and ICEV1 are 50 gCO_2eq/km and 120 gCO_2eq/km. Therefore, over a distance of 100,000 km, the BEV1 would generate just 5,000 $kgCO_2eq$, whereas the ICEV1, using gasoline, would produce a much higher WTW GHG emissions of 12,000 $kgCO_2eq$.
- Regarding driving power output, ICEVs with higher power outputs would significantly increase GHG emission rates. In contrast, EVs with higher power outputs result in only a minor increase in GHG emissions compared to those with lower power outputs. The ICEV4 emits 222 gCO_2eq/km WTW GHG emissions, while the ICEV1 emits 120 gCO_2eq/km. Interestingly, the BEV1 generates approximately 50 gCO_2eq/km, whereas the BEV4 produces just 67 gCO_2eq/km WTW GHG emissions. This could be viewed in the context of customer preference, where those who prefer high-power vehicles may find EVs to be much more attractive than ICEVs due to their much lower emissions. However, customers who prefer high-power vehicles often opt for sports cars for their exceptional power and driving dynamics. To attract these customers, EVs needs to transform into sport cars by enhancing its performance, handling, and visual appeal. With this transformation, EV manufacturers could become more competitive in the traditional ICEV sports car market and potentially achieve greater profitability.
- Blending ethanol with gasoline has also contributed to reducing WTW GHG emissions in ICEVs. It is evident from the earlier discussions that increased shares of ethanol in gasoline leads to a significant reduction in WTW GHG emissions. For instance, WTW GHG emissions from the ICEV3 are reduced by 6% with E10, 12% with E20, and 53% with E85 compared to using gasoline. Additionally, in view of comparison between EVs and ICEVs with ethanol blending, the WTW GHG emissions from the ICEV3 using E10, E20, and E85 are approximately 2.7 times, 2.5 times, and 1.3 times, respectively, higher than those of the BEV3. This suggests that higher shares of ethanol in gasoline could be an effective strategy to mitigate GHG emissions from ICEVs during the transition from ICEVs to EVs.

The inference drawn from the forgoing discussions is that BEVs clearly emits much lower GHG emissions than ICEVs. Despite the distinct benefits of BEVs, the transition from ICEVs to BEVs may take time for widespread adoption. In the case of Thailand, the number of total registered vehicles reached 44 million units in 2023 [42]. Of the total registered vehicles, ICEVs using gasoline had the largest share (68%), followed by ICEVs using diesel (29%), ICEVs using LPG (Liquefied Petroleum Gas) and CNG (Compressed Natural Gas) (2%), HEVs (0.7%), BEVs (0.3%), and PHEVs (0.1%) [42]. Given a high number of ICEVs, the transition to 100% electric vehicles is unlikely to be possible in a short time period. In addition, the impacts on the biofuel and agricultural sectors when replacing ICEVs with BEVs should also be seriously considered. This is because blending biofuels with petroleum products has provided several benefits for the Thai economy and society in the last two decades. In fact, a blend of biofuels and petroleum products has been a key energy policy of the Thai government since 2000s [59]. As a result of the implemented biofuel promotion policy, various stakeholders in the supply chain, including biofuel refineries, crop factories, and farmers, have been incentivized to increase biofuel production. Being an agricultural-based economy, approximately 30% of Thailand's population is involved in farming [62]. Therefore, replacing ICEVs with EVs would undoubtedly have economic and social impacts on biofuel and agricultural sectors. A study by Dranka and Ferreira has shown that the combined use of EVs and biofuels could enhance the potential to achieve carbon reduction goals [63]. In order to establish a balanced transitional pathway from ICEVs to EVs, this paper suggests adopting the following strategies and developments.

- A blend of biofuels and petroleum products could be implemented as ongoing strategy to reduce GHG emissions from ICEVs during the transition period to 100% EVs. However, incorporating higher proportions of biofuels into petroleum products would help alleviate more GHG emissions. This strategy could continuously maintain the demand for biofuels and energy crops for transition period. As a result, the impacts on the biofuel and agricultural sectors would be mitigated. It is further recommended that the implementation of the government's policy to establish a significant price gap between 100% petroleum products and biofuel-petroleum blends could bolster this strategy to achieve greater reduction in GHG emissions.
- Adopting the use of biofuels for electricity generation

instead of transportation could help maintain a continuous demand for biofuels as well as reduce GHG emissions from the electricity generation sector. The popular liquid biofuels for producing electricity, for example, biodiesel, ethanol and pyrolysis bio-oil [64]. In addition to liquid biofuels, gaseous biofuels such as biogas and syngas have also been widely used for power generation [65]. Despite their attractiveness, biofuels are not widely favored for electricity production due to their high production and maintenance costs [66]. This creates a price disparity between conventional fuels and biofuels, which hampers the development and promotion of biofuels for electricity generation. Advancing biofuel production technology would be an effective way to increase productivity and make biofuel production more cost-effective.

- A research and development of new biofuel products would also support the continuing utilization of biofuels and energy crops, and hence sustaining their demand. Technological advancements could lead to the adoption of new biofuel products. For example, Sustainable Aviation Fuels (SAF), a biofuel used in aircraft propulsion, has properties similar to conventional jet fuel but offers a lower carbon footprint [67]. Increasing SAF production could support the economic viability of the biofuel industry, create supplementary economic benefits, and boost extra income for farmers. Furthermore, another biofuel product, torrefied pellets, could serve as a viable alternative to fossil fuels for power generation. Torrefied pellets are a form of solid biofuel produced from biomass that has undergone a thermal treatment process called torrefaction [68]. This process dries the biomass, removes volatile organic compounds, and partially decomposes the hemicellulose, resulting in a product with higher energy density, better grindability, hydrophobic properties, uniformity, and reduced biological degradation [69]. Torrefied pellets could be used as a renewable alternative to coal in power generation due to their ability to be co-fired with coal in existing power plants with minimal adjustments, thus makes them an attractive option for mitigating carbon emissions.

8. CONCLUSION

With a view to providing a balanced transition from ICEVs to EVs, this paper conducts an analysis of GHG emissions from passenger vehicles, focusing on a comparison between EVs and ICEVs using different ethanol-to-gasoline blend ratios in Thailand. A well-to-wheel analysis is employed to examine the GHG emissions of four selected EVs models compared to ICEVs with different ethanol and gasoline blends. The selection of four passenger vehicle models is based on their driving power output and popularity among available models in Thailand. The findings revealed that EVs emit significantly lower GHG emissions than ICEVs. For example, EVs could achieve a substantial reduction of over 60% in well-to-wheel GHG emissions compared to ICEVs running on pure gasoline. Especially, high-power EVs are much more attractive than high-power ICEVs due to their substantially lower emissions. The results further revealed that blending ethanol with gasoline has also contributed in a decrease of more than 50% in well-to-wheel GHG emissions compared to using pure gasoline. While EVs are environmentally friendly, the transition from ICEVs to EVs could potentially affect the biofuel and agricultural sectors, thus directly impacting Thailand's economy and society due to its agricultural-based nature. To establish a balanced transition from ICEVs to EVs, this paper proposes several strategies and developments. These include the continuation of using a blend of biofuels with petroleum products until EVs are fully adopted, the shift of utilizing biofuels in transportation to electricity generation, and the technological advancement for developing new biofuel products. These strategies could offer beneficial implications for future research on GHG emissions reduction in the transportation sector and provide a foundation for assessing the effectiveness of decarbonization policies in Thailand.

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