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Modeling Future Energy Demand and CO_2 Emissions of Passenger Cars in Indonesia at the Provincial Level

Qodri Febrilian Erahman, Nadhilah Reyseliani, Widodo Wahyu Purwanto * and Mahmud Sudibandriyo

Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia
* Correspondence: widodo@che.ui.ac.id

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Abstract: The high energy demand and CO_2 emissions in the road transport sector in Indonesia are mainly caused by the use of passenger cars. This situation is predicted to continue due to the increase in car ownership. Scenarios are arranged to examine the potential reductions in energy demand and CO_2 emissions in comparison with the business as usual (BAU) condition between 2016 and 2050 by controlling car intensity (fuel economy) and activity (vehicle-km). The intensity is controlled through the introduction of new car technologies, while the activity is controlled through the enactment of fuel taxes. This study aims to analyze the energy demand and CO_2 emissions of passenger cars in Indonesia not only for a period in the past (2010–2015) but also based on projections through to 2050, by employing a provincially disaggregated bottom-up model. The provincially disaggregated model shows more accurate estimations for passenger car energy demands. The results suggest that energy demand and CO_2 emissions in 2050 will be 50 million liter gasoline equivalent (LGE) and 110 million tons of CO_2, respectively. The five provinces with the highest CO_2 emissions in 2050 are projected to be West Java, Banten, East Java, Central Java, and South Sulawesi. The projected analysis for 2050 shows that new car technology and fuel tax scenarios can reduce energy demand from the BAU condition by 7.72% and 3.18% and CO_2 emissions by 15.96% and 3.18%, respectively.

Keywords: energy demand; CO_2 emissions; Indonesia

1. Introduction

Since 2013, the transport sector has consumed more energy than any other sector in Indonesia. Approximately 40% of the energy demand (260.1 million BOE) in Indonesia is attributable to the transport sector [1], with road transport being the largest contributor. This situation is predicted to increase, due to the growth of car ownership.

Transportation plays an important role in modern society in terms of supporting the mobility of people; however, it also creates a major problem for the environment. CO_2 emissions in the road transport sector are mostly contributed by the use of passenger cars. This situation is worsened by the lack of improvements to the land transportation system. To ensure mobility under the present circumstances, most people choose to own a private car. The growth in car ownership is considered to be mainly responsible for rising energy demand. Passenger cars in Indonesia mostly consume gasoline, and high demand for gasoline has resulted in Indonesia's dependence on imported petroleum products [2]. Car ownership has a strong correlation with GDP per capita, as shown in many previous studies, including Dargay and Gately [3], Dargay and Gately [4], Dargay and Gately [5], Dargay, Gately and Sommer [6], Leaver, Samuelson and Leaver [7], and Wu, Zhao and Ou [8]. These studies suggest that the GDP per capita can affect the level of energy demand.

The issuing of Presidential Decrees 61/2011 and 71/2011 [9,10] mandated a mitigation plan for greenhouse gas emissions for each province. Based on these regulations, provincial governments were asked to prepare action plans to the reduction of CO_2 emissions. The action plans can be carried out by controlling the intensity and activity of passenger cars. The intensity is related to car technology, while car activity is related to car utilization. Certain policies for controlling the intensity and activity of passenger cars should be encouraged in order to decrease energy demand and CO_2 emissions [11,12]. Therefore, the historical energy demand from the use of passenger cars in each province should be known.

Previous studies have shown that transport energy demand can be projected through top-down models (e.g., Zhang et al. [13], Lu et al. [14], and Chai et al. [15]); however, to determine the impact of technological change, the energy demand projection for the road transport sector should be conducted using a bottom-up model [16]. Other studies have implemented a bottom-up model for projecting the transport energy demand (e.g., Eom and Schipper [17], Ma et al. [18], Baptista et al. [19], Ko et al. [20], and Deendarlianto et al. [21]). However, these studies have mostly been conducted at country level, whereas, because disparities exist among regions, this study was conducted at the provincial level. Moreover, the study contributes to estimating the passenger car energy demand by modeling the technological changes and the activities of the passenger car and to find out which is the best policy for lowering the energy demand and CO_2 emissions. This paper aims to model the future energy demand and CO_2 emissions of passenger cars in Indonesia by province in past (2010–2015) and future (2016–2050) periods.

The remainder of this paper is structured as follows. Section 2 proposes the methodology. Section 3 presents the results and discussion, and Section 4 provides the conclusions.

2. Methods

This section explains the methodology for assessing future energy demand and CO_2 emissions using a bottom-up model. Figure 1 explains the methodological structure of the current study.

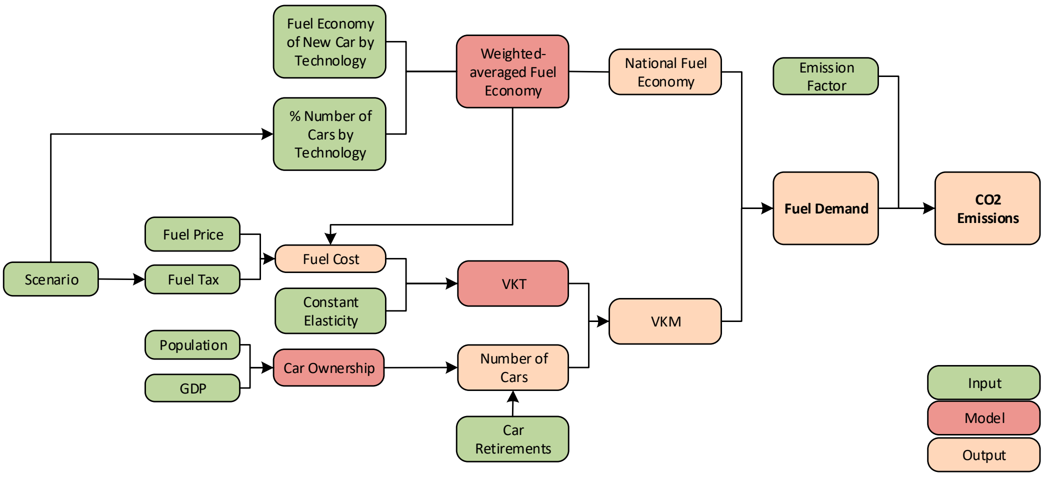


Figure 1. Schematic diagram of the methodology used.

As can be seen in Figure 1, the structures consist of the input, the model and the output. Input includes everything that is to be processed in the model, including data and scenarios. The model consists of car ownership, vehicle kilometers traveled (VKT), and weighted average fuel economy. These aspects of the model will generate the intermediate output of VKM and fuel economy, from which the fuel demand and CO_2 emissions are derived. This structure is applied for each province, and subsequently, the results are aggregated to obtain the national results.

2.1. *Provinces of Indonesia*

Administratively, Indonesia consists of 34 provinces, but the current study analyzed only 33 to adjust to the available data, and also because of the emergence of new provinces in Kalimantan. Each province has its own local government, governor, and legislative body. Spatially, Indonesia can be divided into five major regions: Sumatra, Java, Kalimantan, Sulawesi, and Nusa Tenggara-Maluku-Papua. Table 1 presents the related details.

Table 1. Five regions of Indonesia.

Region	Province	Region	Province
Sumatra	Aceh North Sumatra West Sumatra Riau	Kalimantan	West Kalimantan Central Kalimantan South Kalimantan East Kalimantan
	Jambi South Sumatra Bengkulu Lampung Bangka Belitung Islands Riau Islands	Sulawesi	North Sulawesi Central Sulawesi South Sulawesi Southeast Sulawesi Gorontalo West Sulawesi
Java	DKI Jakarta West Java Central Java D.I.Y East Java Banten Bali	Nusa Tenggara–Maluku–Papua	West Nusa Tenggara East Nusa Tenggara Maluku North Maluku West Papua Papua

Figure 2 shows the profile of Indonesia's territories according to their populations, which are highly concentrated in the west. The capital city of Indonesia known as the Special Capital Region of Jakarta (DKI Jakarta) is located in the Java region, contributing to the fact that this region is the most densely populated. These population trends are expected to continue if the government does not promote greater equity among the provinces.

Figure 2. Spatial population profiles among regions in Indonesia.

2.2. Input Data

Data such as provincial GDP, the number of passenger cars, the size of province area, and population are sourced from the Central Bureau of Statistics of Indonesia [22]. Energy demand for the transport sector, along with fuel price data, were collected from the Ministry of Energy and Mineral Resources of Indonesia [1]. Annual car sales data, which are categorized by engine displacement, were obtained from the Association of Indonesian Automotive Industries (Gaikindo) [23]. The Central Bureau of Statistics of Indonesia provides population projections until 2050 [24], and the projected provincial population takes into account the effect of urbanization. The provincial GDPs are based on commodity prices in the year 2000, and the projections are obtained using GDP growth until 2050 [25]. Finally, the data is inputted into the model.

2.3. Car Ownership

Car ownership exhibits a close relationship with GDP per capita [4]. This empirical relationship follows the Gompertz model, which has been developed in various studies [3–6]. It explains that, over the long term, the relationship between car ownership and GDP per capita corresponds to the following equation:

$$CO_i = CO_i^* \times e^{\alpha_i e^{\beta_i GDPP_i}} \tag{1}$$

where CO is the car ownership (vehicles/1000 people), CO^* is the saturated car ownership, $GDPP$ is GDP per capita, i is the province, and α and β are the constants that determine the shape of the curve. The constants α and β can be obtained according to the following equation [8].

$$ln\left(ln\frac{CO_i^*}{CO_i}\right) = ln(-\alpha_i) + \beta_i \cdot GDPP_i \tag{2}$$

In the equation, α and β are constants to determine the curve shape. The relationship between GDP per capita and long-term car ownership forms an S-shaped curve. This S-shape implies that at a relatively low level of GDP per capita, the growth rate of car ownership will rise slowly, then will grow dramatically at a certain GDP per capita level, and will finally slow down again at a high level of GDP per capita until reaching a steady state, which is known as car ownership saturation [5].

The car ownership saturation is a condition in which GDP per capita continues to increase, while car ownership remains unchanged. Previous studies have suggested that there is a relationship between population density and the saturation level of car ownership [7]. For example, Leaver established a relationship between population density and car ownership saturation [7]. The higher the population density, the faster car ownership saturation occurs, and the current study uses this finding to determine the saturation level of car ownership for each province, as shown in the following equation:

$$CO^* = 606.5e^{(0.007 \times D)} \tag{3}$$

where D is population density. Since the analysis is conducted at the provincial level, the effects of urbanization have been included in the projected population data. Figure 3 summarizes the scheme of the car ownership projection model.

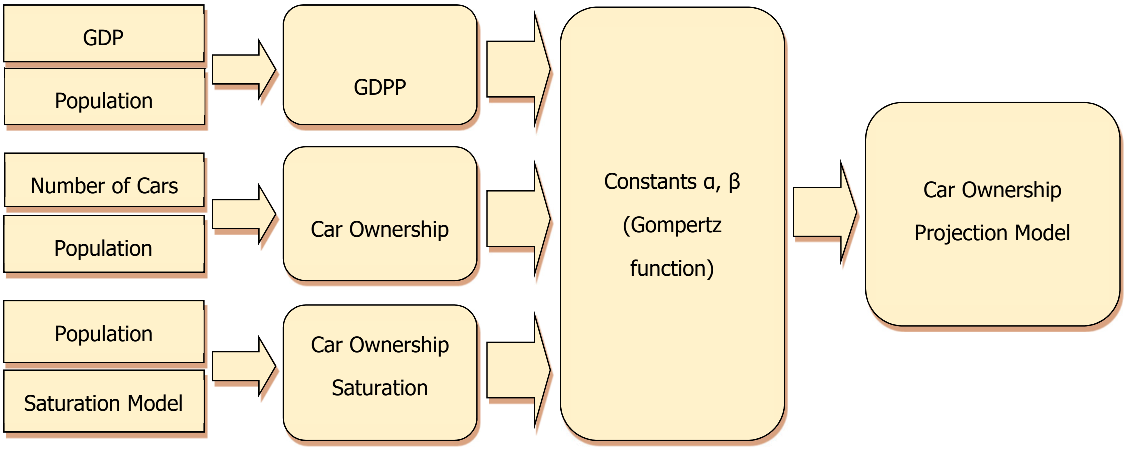


Figure 3. Scheme of the car ownership projection model.

2.4. Car Fuel Economy

Fuel economy is reported in units of L/100 km. National fuel economy is calculated from the weighted average of new and existing car shares and their respective fuel economies. The fuel economy of new cars is taken from a weighted average of annual car sales by fuel type, i.e., gasoline vs. diesel cars. Fuel economy is further characterized according to engine size: 800 < cc < 1200, 1200 < cc < 1500, 1500 < cc < 3000, and 3000 < cc for gasoline cars; and 1500 < cc < 3000 for diesel cars. Cars with an engine size of 800 < cc < 1200 are referred to as low-cost green cars (LCGC) [26].

In the projected scenario, due to the presence of new car technology (e.g., plug-in hybrid [PHEV] and electric vehicle [EV] technology), the fuel economy of a new car is weighted by the share of each type of car—gasoline, diesel, PHEV, and EV—according to the following equations.

$$FE_{NC} = \sum_{j} FE_j \times \%C_j. \tag{4}$$

$$FE = FE_{NC} \times \%C_{NC} + FE_{RC} \times \%C_{RC} \tag{5}$$

where *FE* is fuel economy, $\%C$ is the percentage of cars, and *j* is the type of car based on its technology (e.g., gasoline, diesel, PHEV, or EV). *NC* is new car and *RC* is the rest of the cars. Figure 4 describes the fuel economy aggregation scheme based on car technology.

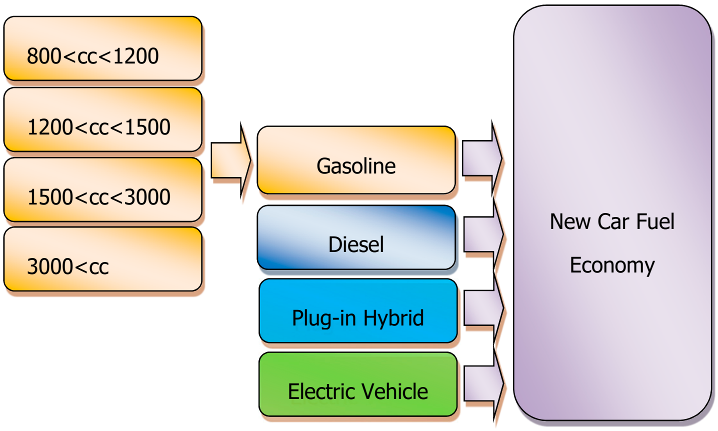


Figure 4. Fuel economy aggregation scheme based on car technology.

The historical fuel economy (2010–2015) for an engine size of 800 < cc < 1200, which is in the LCGC category, is 5.0 L/100 km [27]. Cars with engine sizes of 1200 < cc < 1500, 1500 < cc < 3000, and 3000 < cc have the highest market share and fuel economies of 8.20 L/100 km, 10.10 L/100 km, and 12.40 L/100 km, respectively [28–30]. Diesel cars, which have a fuel economy of 6.97 L/100 km [12], are considered to be 20% more efficient than gasoline cars. Car fuel economy for engine sizes 1200 < cc < 1500 and 1500 < cc < 3000 was contributed by sedan and MPV (Multi-Purpose Vehicle) types of vehicle, while for cars with engine size 3000 < cc, this was contributed by Sedan and SUV (Sport Utility Vehicle) types. The percentages of sedans, MPVs and SUVs are 6.1%, 93.2, and 0.6% of total cars, respectively.

The fuel economy for PHEV and EV cars was not applied in the historical situation, since their market share was zero until 2015. Figure 5 describes the aggregation scheme of the weighted average of fuel economy between new and other cars.

Fuel economy for new cars is considered starting in 2010; for the remainder of the cars, fuel economy before 2010 is assumed based on the IEA report [31].

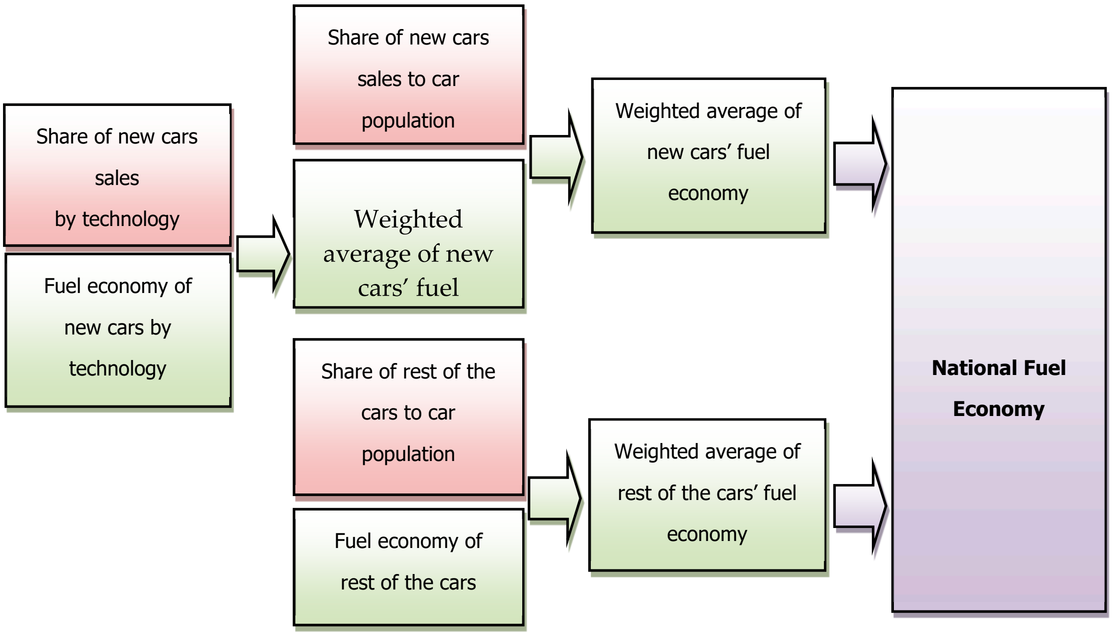


Figure 5. Aggregation of fuel economy between new and other cars.

2.5. Vehicle Kilometers Traveled

Vehicle kilometers traveled, VKT, is defined as the annual kilometers traveled for a single car. Previous studies show an inverse relationship between VKT and fuel price, meaning that car users will tend to reduce unnecessary travel when the fuel price increases. The extent to which VKT varies with changing fuel price can be modeled by the value of elasticities, according to the following equation [32].

$$VKT_i = VKT_i' \times \left(\frac{FC_i}{FC_i'}\right)^{\varepsilon} \tag{6}$$

where $VKT.$ represents the vehicle kilometers traveled in a given year, $VKT'.$ is the vehicle kilometers traveled in the previous year, $FC.$ is the fuel cost in a given year, FC' is the fuel cost in the previous year, and ε is the elasticity. VKT data per province can be obtained through calculations of fuel consumption, fuel economy, and number of vehicles in the historical year (2012–2015). Previous studies described that annual car travel is also influenced by car fuel economy [33]; therefore, the current study prefers to use fuel cost instead of fuel price in order to more effectively assess the impact of real situations on the behavior of private car users. Fuel cost is described as the retail fuel price multiplied by the national fuel economy. In the projection, the retail fuel price is obtained by the summation of crude oil price, refinery margin, and distribution fees to customers, and fuel taxes. Crude oil price is based on the US Energy Information Administration outlook [34], and the refinery margin follows the Asia refining margin outlook [35]. Meanwhile, the distribution cost is assumed to remain constant [36]. The sum of total cars traveling in a certain year is defined as car activity, VKM.

2.6. Energy Demand and CO_2 Emissions

Energy demand is defined in units of liter gasoline equivalent (LGE). Cars that consume other fuels, such as diesel oil, should be converted into LGE using heating value comparisons between gasoline and diesel oil, where the heat value for diesel, biodiesel and gasoline is 35,327, 36,131 and 31,795 kJ/L, respectively. Energy demand can then be calculated according to the following equation:

$$E_i = VKM_i \times FE. \tag{7}$$

where E is the energy demand, and VKM represents vehicle kilometers, which represents the total number of cars traveling annually. Once the energy demand is determined, then CO_2 emissions can be calculated using the following equation:

$$G_i = E_i \times EF_k \tag{8}$$

where G represents the CO_2 emissions, EF is the emission factor, and k is the type of fuel (e.g., gasoline, diesel oil, and electricity). Equations (7) and (8) are consistent with the ASIF equation, which is widely used for calculating CO_2 emissions. Emission factors were obtained from the Ministry of Environment of Indonesia, which in turn based them on information from the Intergovernmental Panel on Climate Change (IPCC). Therefore, the emission factors for gasoline, diesel, biodiesel B100, and electricity were 69.3, 74.1, 62.9, and 224.4 kg CO_2/GJ, respectively [37,38]. Moreover, the electricity emission factor was based on the weighted-average data from all kinds of power plants in Indonesia [38].

2.7. Model Validation

The results of the analysis need to be validated to determine the accuracy of the model. This is accomplished by comparing the results with the fuel demand in 2010–2015 using the standard error of the estimate. The standard error of the estimate is a measure of the accuracy of predictions. It indicates how far data points are from the prediction line of the average. The following is the equation of the standard error of the estimate.

$$\sigma_{est} = \sqrt{\frac{\sum (E - E')^2}{N}}$$

where σ_{est} is the standard error of the estimate, E denotes the data points, E' is the predicted value, and N is the number of data points.

2.8. Scenarios

Scenarios for reducing CO_2 emissions from car utilization can be developed by managing the intensity and activity of cars. Controlling the intensity of cars can be achieved by encouraging the uptake of new technologies that allow for better fuel economy and emissions reduction. Therefore, the market share of new cars with better fuel technology should be increased in order to improve fuel economy. To purchase the most efficient cars in the market, consumers must first understand the efficiency features of the cars under consideration [39]. Therefore, fuel economy labeling should become a required policy to support the introduction of new car technologies that enable better fuel economy. Fuel economy labeling is carried out by obligating car manufacturers or dealers to provide information on the fuel economy of new cars. Car labeling policies are also useful as an important basis for other policies, such as fuel economy standards [12].

Car activity can be managed by regulating the fuel price, so that car users will limit unnecessary travel. The policy required to support this scenario is fuel taxes arrangement [12]. Fuel taxes are an appropriate policy for reducing car travel, because the higher the fuel prices are, the more people will reduce car travel, especially for unnecessary trips. Fuel taxes can provide significant incremental incentives to save fuel and can be integral to any policy package to promote sustainable transport, whereas fuel subsidies are considered to be counterproductive [12]. Fuel taxes also provide revenues to pay for infrastructure costs and to develop sustainable transport. Therefore, scenarios exploring these various policies are created in the current study and are divided into three parts: BAU, new car technology, and fuel tax regulation. These scenarios are intended for use in the projections from 2016 to 2050.

a. Business as Usual Scenario (BAU)

This scenario assumes that the available car technology is limited to gasoline and diesel cars; however, new car fuel economy is expected to improve. Projections for technological developments related to new car fuel economy follow recent developments in non-OECD countries for fuel economy improvement rates [31]. Fuel economy improvement can be applied for gasoline and diesel cars until 2050. The share of cars based on technology follows the historical pattern (2015), in which the shares of car sales for gasoline and diesel cars are 83% and 17%, respectively. For PHEV and EV, on the other hand, the sales remain at zero due to the lack of government initiatives encouraging sales. In the BAU scenario, the fuel tax percentage follows the current situation, which is 15% of the fuel price, and it is assumed that there will be no change in the following years.

b. Car Technology Scenario

The car technology scenario is related to the government's national energy plan for the market penetration of electric vehicles, as stated in Presidential Decree 22/2017 [40]. This scenario assumes that market penetration for PHEV and EV cars is growing significantly. The penetration for PHEV and EV cars follows the IEA's Blue Map scenario [41], wherein to reduce significant global emissions, it is necessary that the 2050 sales mix for PHEV and EV is equal to at least half of total annual car sales [41]. Therefore, the sales mix for PHEV and EV in 2050 is targeted at 50%, while the remaining 50% constitutes mixed sales of diesel and gasoline cars. Table 2 describes the percentage of car sales by type and scenario. The success of car technology scenarios for CO_2 emission reduction hinges on the significant decrease in the electricity emission factor. Based on the Blue Map scenario, the electricity emissions factor should be decreased to almost zero in 2050 [41]; therefore, the electricity emission factor for the car technology scenario is assumed to decrease gradually, reaching 27.8 kg CO_2/GJ in 2050. The target of reducing the emission factor of the electricity can be conducted by increasing the supply of electricity from renewable sources, i.e., geothermal, hydro, solar, wind and biomass.

Table 2. Comparison of percentages of new car sales by car technology and scenario.

Type of Car Technology	**BAU Scenario (%)**				**Car Technology Scenario (%)**			
	2020	**2030**	**2040**	**2050**	**2020**	**2030**	**2040**	**2050**
Regular Gasoline	83	83	83	83	78	68	48	33
Diesel	17	17	17	17	17	17	17	17
Plug-in Hybrid (PH)	0	0	0	0	5	10	25	35
Electric Vehicle (EV)	0	0	0	0	0	5	10	15

c. Fuel Tax Regulation Scenario

This scenario aims to study the effect of car activity on energy demand through the regulation of fuel tax. Changes in fuel cost could affect the VKT, which in turn could affect the VKM. The responses of car users to rising fuel costs are different in each province, and this is indicated through the elasticity. In 2015, the decrease in global crude oil prices caused a decline in fuel prices. The government took advantage of this situation by eliminating fuel subsidies, particularly for the transport sector. Since then, the government has imposed an economic price for gasoline. After the cessation of subsidies, tax policy became recognized as an effective instrument for controlling car travel. Currently, the two kinds of applied fuel tax are value added tax and motor vehicle fuel tax, with values of 10% and 5% of the retail price, respectively. Therefore, the total applied accumulated tax is 15% of the retail price.

A comparison with other countries in the ASEAN region shows that in 2012, the total tax related to fuel demand in these countries ranged from 4–36% [42]. Therefore, to make our scenario more plausible, the fuel tax was set at 30%. The fuel tax scenario assumes no changes in the share of new car sales, and the fuel economy of new cars follows the BAU scenario. Therefore, any changes in energy demand and CO_2 emissions are due solely to changes in car activity. Table 3 summarizes the comparison of assumptions among scenarios.

Table 3. Comparison of assumptions among scenarios.

Scenario		Annual Rate of Fuel Economy Improvement	Target Share of Car Sales to Total Car Sales in 2050	Fuel Tax Rate
Business as Usual (BAU)		Gasoline and Diesel Car 0.09%	No Change	15%
Car Technology	PH/EV	Gasoline, Diesel, PH/EV Car 0.09%; 0.09%; 1.40%	50% of PH/EV	15%
Fuel Taxes	Tax 30%	Gasoline and Diesel Car 0.09%	No Change	30%

3. Results and Discussion

3.1. Historical Results

3.1.1. GDP Per Capita

GDP data were collected from 2000 to 2015. The national GDP is an aggregation of all provincial GDPs. Each province contributes independently to the national GDP, and there are disparities among provinces. Based on provincial GDP data, it can be determined that 57% of the national GDP is from DKI Jakarta, East Java, West Java, and Central Java. However, the prosperity level is more suitably represented by GDP per capita. Table 4 describes the GDP per capita for each province.

Table 4. GDP per capita of provinces, 2000–2015 (Rp).

No.	Province	GDP Per Capita (Rp)				Annual Growth
		2000	2005	2010	2015	
1	Aceh	4,995,043	5,568,355	6,427,395	8,208,249	4.29%
2	North Sumatra	5,936,151	7,136,919	9,112,107	11,435,561	6.18%
3	West Sumatra	5,387,147	6,411,608	7,987,615	10,095,631	5.83%
4	Riau	14,034,330	15,108,162	17,531,364	18,746,113	2.24%
5	Jambi	3,964,314	4,583,988	5,622,244	7,397,381	5.77%
6	South Sumatra	5,988,369	6,917,533	8,535,492	10,555,139	5.08%
7	Bengkulu	3,105,780	3,801,072	4,842,777	6,010,136	6.23%
8	Lampung	3,448,223	4,097,222	5,028,805	6,344,406	5.60%
9	Bangka Belitung Islands	7,168,132	7,949,017	8,709,608	10,456,111	3.06%
10	Riau Islands	18,395,851	22,344,514	24,265,039	28,706,274	3.74%
11	DKI Jakarta	27,160,473	32,812,888	41,037,969	52,793,584	6.29%
12	West Java	5,484,062	6,165,875	7,454,209	9,245,740	4.57%
13	Central Java	3,672,917	4,497,646	5,763,579	7,399,348	6.76%
14	D.I.Y	4,317,566	5,140,272	6,068,938	7,463,150	4.86%
15	East Java	5,842,889	7,110,540	9,111,499	12,144,534	7.19%
16	Banten	6,535,249	7,187,098	8,284,732	9,923,154	3.46%
17	Bali	5,702,601	6,227,553	7,391,742	9,499,575	4.44%
18	West Nusa Tenggara	3,041,105	3,568,679	4,444,685	4,713,600	3.67%
19	East Nusa Tenggara	1,992,050	2,285,129	2,666,020	3,214,568	4.09%
20	West Kalimantan	4,803,628	5,533,075	6,875,073	8,405,443	5.00%
21	Central Kalimantan	5,944,899	6,898,169	8,467,974	10,404,069	5.00%
22	South Kalimantan	6,266,482	7,045,690	8,421,300	10,107,667	4.09%
23	East Kalimantan	12,325,552	14,314,410	18,747,036	32,503,297	10.91%
24	North Sulawesi	5,295,832	5,951,651	8,068,150	10,711,207	6.82%
25	Central Sulawesi	3,977,784	4,940,970	6,660,685	8,922,062	8.29%
26	South Sulawesi	3,506,238	4,526,019	6,352,030	8,623,764	9.73%
27	Southeast Sulawesi	3,170,649	3,960,096	5,194,289	6,794,659	7.62%
28	Gorontalo	1,764,308	2,162,664	2,792,392	3,668,652	7.20%
29	West Sulawesi	1,076,863	3,030,552	4,073,206	5,507,867	27.43%
30	Maluku	2,297,113	2,379,840	2,757,219	3,436,217	3.31%
31	North Maluku	2,394,251	2,453,784	2,909,660	3,526,332	3.15%
32	West Papua	1,238,184	8,227,709	12,232,275	19,351,973	97.53%
33	Papua	6,013,255	6,968,230	8,195,795	8,575,849	2.84%

3.1.2. Car Ownership

Table 5 shows car ownership levels in each province between 2000 and 2015. It shows that the province with the highest car ownership level is DKI Jakarta. Other provinces with substantial car ownership levels are Bali, Central Kalimantan, and Riau.

Table 5. Car ownership in provinces, 2000–2015 (Vehicles/1000 People).

No.	Province	2000	2005	2010	2015
1	Aceh	6	15	21	31
2	North Sumatra	14	18	25	36
3	West Sumatra	6	8	24	43
4	Riau	10	40	80	100
5	Jambi	9	17	30	51
6	South Sumatra	8	21	51	87
7	Bengkulu	7	10	19	27
8	Lampung	6	9	10	20
9	Bangka Belitung Islands	5	8	17	41
10	Riau Islands	10	28	73	93
11	DKI Jakarta	148	196	242	345
12	West Java	9	11	13	21
13	Central Java	6	6	13	25
14	D.I.Y	21	32	72	99
15	East Java	12	20	27	37
16	Banten	2	3	8	12
17	Bali	34	97	134	170
18	West Nusa Tenggara	3	7	23	31
19	East Nusa Tenggara	2	8	29	36
20	West Kalimantan	6	20	65	78
21	Central Kalimantan	3	26	83	101
22	South Kalimantan	11	24	43	58
23	East Kalimantan	15	30	56	71
24	North Sulawesi	11	16	32	65
25	Central Sulawesi	9	35	54	68
26	South Sulawesi	8	15	22	32
27	Southeast Sulawesi	1	4	9	17
28	Gorontalo	0	5	63	85
29	West Sulawesi	35	54	72	99
30	Maluku	16	20	21	27
31	North Maluku	1	1	1	3
32	West Papua	18	29	68	92
33	Papua	5	8	20	28

According to the Gompertz model, in long-term projections, car ownership will form an S-curve. The differences in the S-curve shape in each province will depend on the value of α, β, and the saturation level for car ownership. The values of α and β are strongly influenced by the historical relationship between car ownership and provincial GDP per capita, while the saturation level for car ownership will be different in each province due to differences in population density.

Table 6 shows the results of the car ownership analysis, which pertain to the car ownership model and are based on the historical situation, particularly from 2000 to 2015. The R^2 value shows the accuracy of α and β in the linearized Gompertz model (Equation (2)).

Table 6. Results of car ownership analysis by province using the Gompertz model.

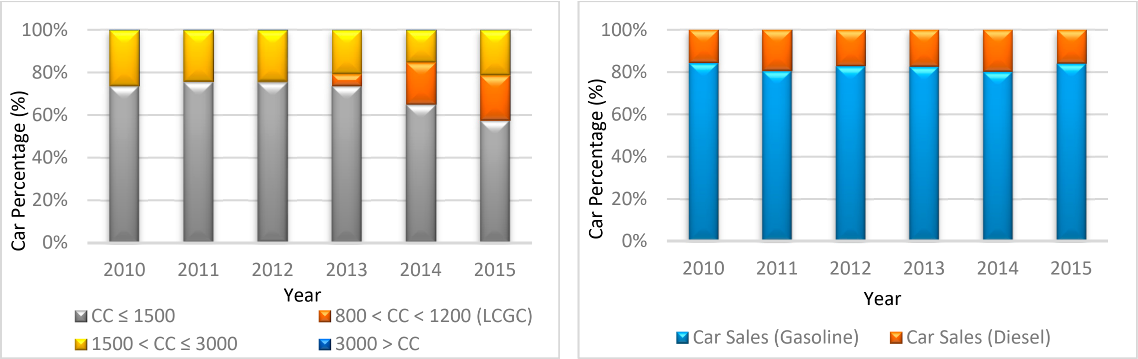
No	Province	Pop. Density (Pop/Ha)	α	β	CO* (Vehicles/1000 People)	R^2
1	Aceh	0.76	−8.2	−0.00000013	603.31	0.877
2	North Sumatra	1.77	−5.0	−0.00000005	599.06	0.997
3	West Sumatra	1.11	−10.0	−0.00000013	601.82	0.943
4	Riau	0.62	−36.7	−0.00000017	603.91	0.915
5	Jambi	0.58	−7.5	−0.00000016	604.06	0.919
6	South Sumatra	0.85	−12.3	−0.00000018	602.93	0.937
7	Bengkulu	0.85	−6.8	−0.00000013	602.92	0.951
8	Lampung	2.14	−6.7	−0.00000011	597.53	0.977
9	Bangka Belitung Islands	0.70	−21.4	−0.00000020	603.59	0.930
10	Riau Islands	1.43	−24.9	−0.00000010	600.57	0.791
11	DKI Jakarta	21.28	−3.5	−0.00000004	523.08	0.973
12	West Java	11.12	−5.7	−0.00000006	561.47	0.974
13	Central Java	9.91	−7.9	−0.00000013	565.96	0.957
14	D.I.Y	10.63	−9.1	−0.00000023	563.25	0.917
15	East Java	7.63	−5.0	−0.00000005	575.06	0.884
16	Banten	10.38	−11.8	−0.00000012	564.55	0.905
17	Bali	6.55	−6.9	−0.00000020	579.55	0.697
18	West Nusa Tenggara	2.18	−18.0	−0.00000040	597.36	0.899
19	East Nusa Tenggara	0.94	−18.3	−0.00000063	602.56	0.804
20	West Kalimantan	0.30	−14.5	−0.00000025	605.25	0.813
21	Central Kalimantan	0.14	−19.1	−0.00000025	605.91	0.799
22	South Kalimantan	0.93	−9.1	−0.00000014	602.62	0.870
23	East Kalimantan	0.17	−4.5	−0.00000003	605.81	0.651
24	North Sulawesi	1.52	−6.8	−0.00000011	600.12	0.969
25	Central Sulawesi	0.41	−5.9	−0.00000012	604.77	0.721
26	South Sulawesi	1.77	−5.2	−0.00000007	599.07	0.867
27	Southeast Sulawesi	0.56	−9.5	−0.00000015	604.14	0.955
28	Gorontalo	0.79	−30.9	−0.00000084	603.17	0.826
29	West Sulawesi	0.64	−3.3	−0.00000011	603.80	0.951
30	Maluku	0.23	−4.2	−0.00000009	605.53	0.850
31	North Maluku	0.30	−10.4	−0.00000018	605.22	0.928
32	West Papua	0.07	−4.0	−0.00000004	606.21	0.825
33	Papua	0.08	−17.0	−0.00000020	606.14	0.949

The α value indicates that the Gompertz curve shifts either to the left or to the right along the x-axis. The lower the value of α, the more the Gompertz curve shifts to the right along the x-axis, and thus, the more distant it gets from a saturated condition. The β value indicates the growth rate of car ownership for certain year ranges. The smaller the β is, the higher is the car ownership growth.

Car ownership saturation shows an asymptotic value, where car ownership is in the steady state. As depicted in Table 6, DKI Jakarta has the lowest car ownership saturation level, due to having the highest population density. Therefore, DKI Jakarta will be the first province that will experience saturation.

3.1.3. National Car Fuel Economy

Figure 6 shows the market shares of gasoline cars sold by engine size during 2010–2015. It shows a decline in the share of cars with engine sizes of cc < 1500 and 1500 < cc < 3000 and an increase in the share of cars with an engine size of 800 < cc < 1200 (LCGC). During 2013–2015, the increase in LCGC accounted for a decrease in the sales of cars with larger engine sizes. Figure 6 also shows the shares for gasoline vs. diesel cars during 2010–2015. The higher level of current diesel car sales is because several car manufacturers have started to offer diesel technology in their vehicles. In contrast, PHEV and EV are still not commercially available in the Indonesian automobile market, and therefore their shares remain at zero.



(**a**) (**b**)

Figure 6. Shares of car sales by (**a**) engine size (gasoline cars) and (**b**) engine type.

Based on market share data, the national car fuel economy showed a decline, as shown in Figure 7. The accumulated car fuel economy describes the average fuel economy for all cars in Indonesia, while the car sales fuel economy describes the fuel economy only for cars that were sold in a given year. Fuel economy for sold cars improved after 2012, which was mainly due to the increasing number of LCGC cars. The fuel economy discrepancy between sold cars and accumulated cars is in the range of 1–1.56 L/100 km, where this discrepancy is estimated to be larger throughout the years.

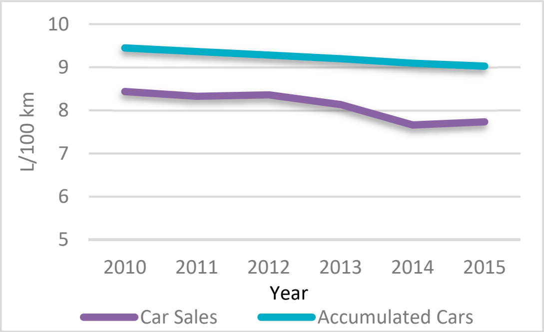


Figure 7. Fuel economy of sold cars and accumulated cars.

3.1.4. Vehicle Kilometers Traveled

Vehicle kilometers traveled, VKT, exhibits disparities between provinces, as seen in Table 7, which indicates the changes in the historical VKT during 2012–2015. VKT changes as fuel cost changes, and the magnitude of thoses changes depends on elasticity.

VKT declines in provinces due to increases in fuel cost. The fuel economy improvement, as shown in Figure 7, is unable to offset the increase in fuel price. Therefore, the total fuel cost is still increasing. Elasticities in the provinces range from −0.067 to −1.051. Elasticity greater than 1 indicates an elastic change in VKT when there is a slight change in fuel cost. An elasticity value less than 1, on the other hand, indicates a small change in VKT with a change in the fuel cost. The East Kalimantan province shows perfect elasticity; therefore, the changes in the fuel cost will be proportional to the VKT changes. Moreover, the highest VKT is observed in Banten. This may be due to Banten's adjacency to the central capital region of DKI Jakarta. Consequently, Banten has many residents who are commuters; these people live in Banten but work in DKI Jakarta.

Table 7. Vehicle Kilometers Traveled in Provinces, 2012–2015 (km/car/year).

No.	Province	2012	2013	2014	2015	Elasticity
1	Aceh	8902	7867	7113	6647	−0.646
2	North Sumatra	11,962	11,319	10,822	10,499	−0.288
3	West Sumatra	15,432	13,916	12,791	12,085	−0.541
4	Riau	9623	9142	8768	8525	−0.268
5	Jambi	5827	5182	4710	4416	−0.613
6	South Sumatra	6799	6110	5600	5281	−0.559
7	Bengkulu	10,242	9574	9062	8733	−0.352
8	Lampung	16,858	15,591	14,629	14,014	−0.409
9	Bangka Belitung Islands	17,743	15,363	13,660	12,621	−0.753
10	Riau Islands	10,563	9909	9406	9082	−0.334
11	DKI Jakarta	4762	4334	4013	3811	−0.492
12	West Java	33,674	31,320	29,523	28,371	−0.379
13	Central Java	10,753	10,106	9608	9286	−0.324
14	D.I.Y	5231	4638	4204	3935	−0.629
15	East Java	10,641	10,024	9547	9239	−0.313
16	Banten	48,432	44,062	40,793	38,728	−0.494
17	Bali	6612	5917	5404	5084	−0.581
18	West Nusa Tenggara	8213	7953	7748	7612	−0.168
19	East Nusa Tenggara	6994	6594	6285	6085	−0.308
20	West Kalimantan	7740	7131	6671	6378	−0.428
21	Central Kalimantan	7889	7311	6872	6590	−0.398
22	South Kalimantan	10,001	9326	8810	8478	−0.365
23	East Kalimantan	10,525	8608	7307	6543	−1.051
24	North Sulawesi	10,696	9600	8791	8284	−0.565
25	Central Sulawesi	5368	4874	4506	4273	−0.504
26	South Sulawesi	18,582	18,108	17,730	17,479	−0.135
27	Southeast Sulawesi	8336	7906	7573	7356	−0.276
28	Gorontalo	9325	8642	8122	7789	−0.398
29	West Sulawesi	3945	3895	3854	3828	−0.067
30	Maluku	11,336	10,035	9085	8497	−0.638
31	North Maluku	38,195	35,925	34,174	33,042	−0.320
32	West Papua	8690	8299	7994	7794	−0.241
33	Papua	17,289	15,564	14,286	13,484	−0.550

3.1.5. Energy Demand and CO_2 Emissions

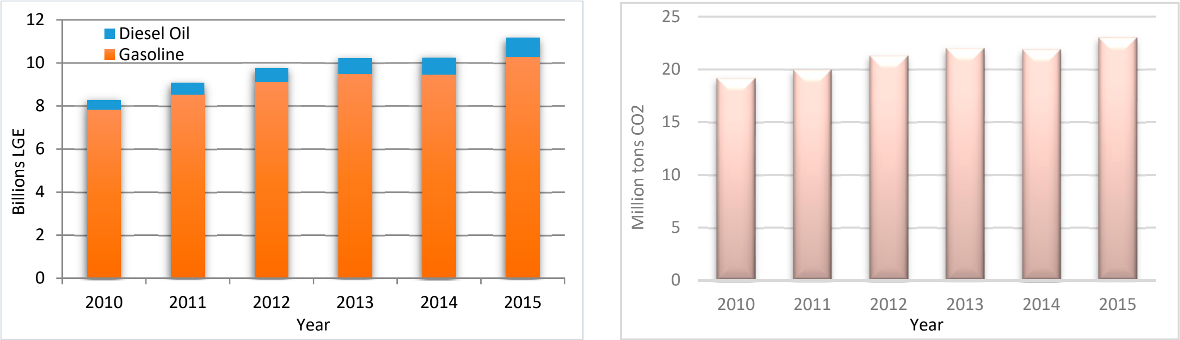
The energy demand for provinces tends to increase from 2010 to 2015, as depicted in Table 8. The five provinces with the highest energy demand, i.e., West Java, East Java, DKI Jakarta, Central Java, and Riau, are quite similar to the top five provinces in GDP rating. This shows that more than 50% of car energy demand arises from the Java region.

National energy demand is an aggregation of energy demand for all provinces. As depicted in Figure 8, national energy demand increased by 29% from 2010–2015, while GDP increased by 34% for the same period. In other words, energy demand and GDP increased almost proportionally during this time. Although energy demand showed a gradual steady increase, stagnation occurred during 2013–2015. This was caused by the increase in gasoline prices due to government regulation, with the result being that most people reduced unnecessary travel.

The CO_2 emissions profile is quite similar to that of energy demand and shows a gradual increase from 2010 to 2015. About 95% of the total emissions were from gasoline cars, and the remainder were from diesel cars. The emissions from diesel cars resulted from the consumption of a fuel mix of diesel oil and biodiesel that was mandated by the Ministry of Energy and Mineral Resources Regulations 32/2008 and 25/2013 [43,44]. Biodiesel mix usage increased from 1% in 2010 to 10% in 2015. The mandatory biodiesel mix regulation played a role in CO_2 emissions reductions in 2010 and 2015, which were 0.02% and 0.11%, respectively.

Table 8. Car energy demand among provinces, 2010–2015 (LGE).

No	Province	2010	2011	2012	2013	2014	2015
1	Aceh	80,272,962	83,459,252	96,186,659	97,151,788	88,041,546	92,007,033
2	North Sumatera	368,195,076	398,778,700	428,807,615	433,495,984	434,806,571	471,777,332
3	West Sumatera	171,715,475	191,061,362	212,860,361	210,369,069	231,204,316	244,306,713
4	Riau	401,637,066	424,232,500	459,651,842	456,782,973	449,075,161	488,310,136
5	Jambi	51,014,129	57,683,445	65,676,461	71,232,337	65,564,801	68,754,473
6	South Sumatera	243,740,412	285,420,963	309,373,517	349,723,175	318,295,916	335,691,155
7	Bengkulu	30,708,475	32,460,514	37,205,988	39,572,877	37,694,000	40,625,685
8	Lampung	124,065,421	167,065,519	189,579,767	197,602,219	196,189,768	210,202,499
9	Bangka Belitung Islands	35,605,535	37,772,088	62,464,307	62,710,826	62,720,635	64,810,117
10	Kepulauan Riau	122,207,893	129,159,132	139,937,588	141,387,616	138,772,831	149,853,524
11	DKI Jakarta	1,041,349,357	1,128,301,346	1,212,311,139	1,199,831,839	1,153,330,676	1,207,272,570
12	West Java	1,733,899,566	2,105,777,600	2,302,590,272	2,435,271,958	2,371,599,183	2,548,918,144
13	Central Java	427,186,435	563,028,914	626,886,265	658,273,258	666,448,449	720,390,417
14	D.I.Y	121,431,212	128,677,346	139,728,931	133,105,959	124,060,828	129,877,218
15	East Jawa	1,011,926,496	1,069,281,965	1,145,698,694	1,128,630,903	1,102,302,720	1,193,007,164
16	Banten	386,896,273	421,268,116	454,630,752	497,883,116	461,856,866	490,402,758
17	Bali	323,614,972	342,779,339	354,166,716	328,268,247	308,332,155	324,423,028
18	West Nusa Tenggara	81,830,739	86,357,530	90,167,797	92,074,655	93,458,079	102,697,056
19	East Nusa Tenggara	90,600,494	95,731,381	95,951,047	92,317,948	92,448,663	100,106,854
20	West Kalimantan	208,164,352	220,190,058	223,421,205	208,194,952	201,069,751	214,994,820
21	Central Kalimantan	136,805,275	144,669,366	148,016,116	143,807,128	139,959,792	150,126,893
22	South Kalimantan	146,094,739	154,448,564	168,224,184	165,499,922	163,589,675	176,070,648
23	East Kalimantan	194,524,071	206,911,074	222,905,541	193,585,308	169,301,566	169,552,498
24	North Sulawesi	73,766,474	78,123,605	84,540,991	118,237,705	111,633,930	117,658,795
25	Central Sulawesi	71,377,751	75,552,719	77,884,330	72,505,069	70,734,641	75,027,803
26	South Sulawesi	312,293,952	353,372,892	370,622,887	393,444,364	386,676,987	426,360,187
27	Southeast Sulawesi	15,219,392	18,787,111	21,832,002	25,485,292	25,825,223	28,056,494
28	Gorontalo	58,001,180	61,335,857	65,203,277	61,777,834	63,334,762	67,934,623
29	West Sulawesi	31,033,577	35,094,179	36,785,788	39,566,758	39,304,488	43,651,669
30	Maluku	35,038,104	37,132,142	38,651,965	35,763,610	32,921,279	34,434,362
31	North Maluku	4,312,530	4,543,853	6,847,329	8,468,084	9,045,675	9,782,882
32	West Papua	42,763,281	45,158,205	46,431,041	46,741,345	51,636,318	56,308,624
33	Papua	93,191,714	98,682,995	101,732,042	96,536,439	101,630,751	107,288,022
	Indonesia	8,270,484,380	9,282,299,634	10,036,974,419	10,235,300,557	9,962,867,999	10,660,682,198



(**a**) (**b**)

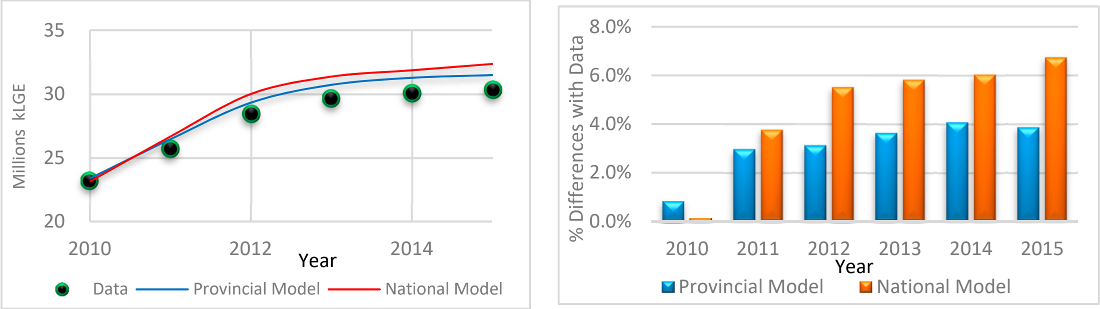
Figure 8. Historical (**a**) energy demand and (**b**) CO_2 emissions, 2010–2015.

However, efforts for reducing CO_2 emissions can be more easily understood through examination of the intensity of CO_2 emissions per car activity. In 2010, the CO_2 emissions intensity per car activity was 207 g CO_2/km, while in 2015 it decreased to 198 g CO_2/km. This indicates a gradual decline of 0.94% per year.

With respect to emissions intensity per car activity, a comparison between countries listed on the International Council on Clean Transportation (ICCT) report in 2010 showed the following: in Asian countries such as Japan, India, China, and South Korea, it was in the range of 130–180 g CO_2/km; for countries in the Americas, such as the United States, Canada, and Mexico, it was in the range of 180–220 g CO_2/km; and for the European Union, it was 135 g CO_2/km [45]. Based on these comparisons, the CO_2 emissions intensity per car activity in Indonesia can be said to be high. Therefore, more efforts should be undertaken to significantly reduce CO_2.

3.1.6. Model Validation

Validation compares other data with the results for the provincial and national models. Looking at the standard error of results for 2010–2015, the provincial model has a standard error of estimates 0.0326, while the national model's was 0.0516. This finding demonstrates that the accuracy of the provincial model is higher than the national model. Figure 9 illustrates the comparison of energy consumption between the model results and the data from Ministry of Energy and Mineral Resources of Indonesia [1].



(**a**) (**b**)

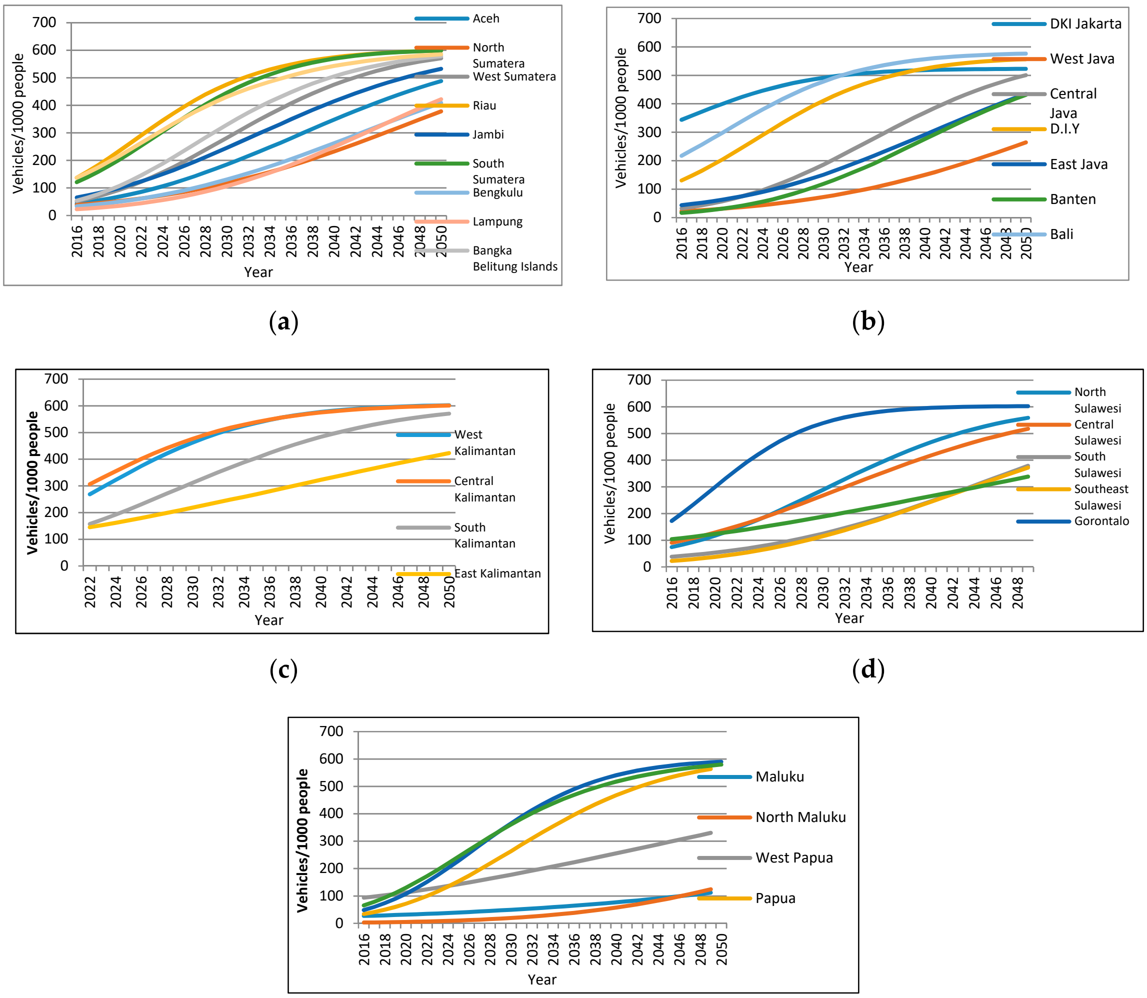
Figure 9. Comparison of energy consumption between data with model results. (**a**) Energy consumption; (**b**) Percentage.

3.2. Projection Results

3.2.1. Projection of Car Ownership

Figure 10 shows car ownership projections for provinces grouped by region. These projections show disparities among provinces. In 2015, the difference of car ownership among provinces was in the range of 3–344 vehicles/1000 people, with the average car ownership across provinces being 64 vehicles/1000 people. In 2050, the discrepancy is expected to widen, with an estimated range of 117–603 vehicles/1000 people and average car ownership across provinces at 479 vehicles/1000 people. In 2050, the smallest discrepancy is expected to appear for the Kalimantan and Sumatra regions, and the largest for the Nusa Tenggara, Maluku, and Papua regions. The provinces of Maluku and North Maluku, which are mostly situated on an archipelago, show relatively low rates of car ownership. The first province to experience car ownership saturation is DKI Jakarta, with most provinces approaching the saturated condition and a few more that are just starting to approach saturation.

Figure 11 shows a comparison of the top five provinces by number of cars. In 2015, the number of cars in Jakarta was the highest, but in 2050, Jakarta is not expected to be in the top five, because car ownership in Jakarta has already reached saturation, with the population at its maximum level. In 2050 it is also expected that approximately 50% of cars will continue to be concentrated in the Java region.



(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 10. Projection of car ownership in (**a**) Sumatra (**b**) Java (**c**) Kalimantan (**d**) Sulawesi (**e**) Nusa Tenggara, Maluku, Papua.

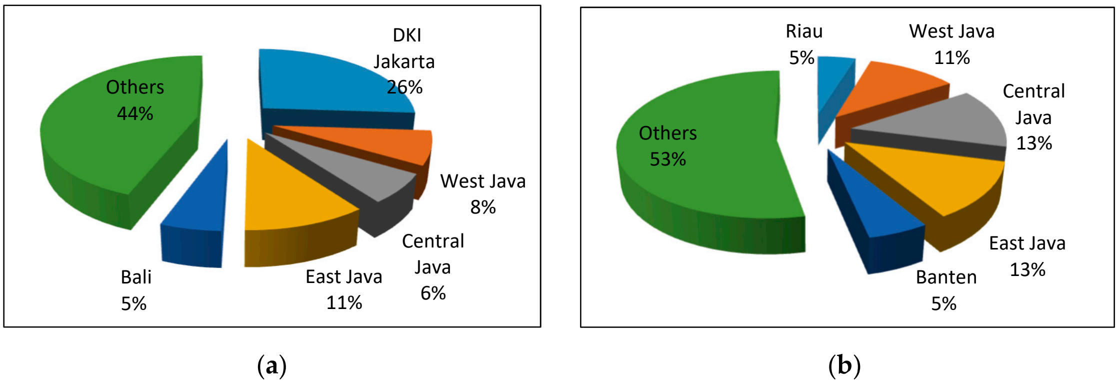


Figure 11. Comparison of the Top 5 provinces by number of cars (**a**) in 2015 (**b**) in 2050.

3.2.2. Impact of Policy Scenario

The BAU scenario is used as a reference for the other scenarios in terms of energy demand and CO_2 emissions reduction. The differences between the BAU scenario and other scenarios are in the intensity and activity of cars; therefore, fuel economy and VKT will also differ among scenarios. Fuel economy in the BAU scenario shows an improvement, as depicted in Figure 12.

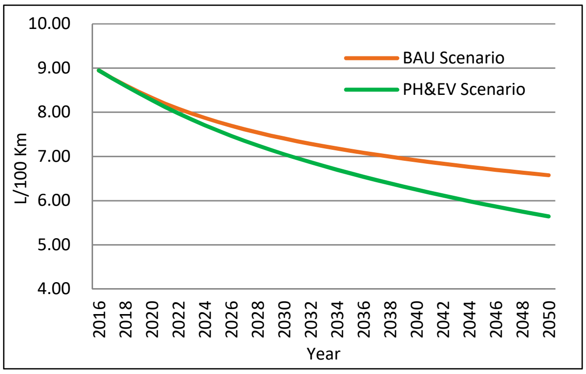


Figure 12. Projected National Fuel Economy, 2016–2050.

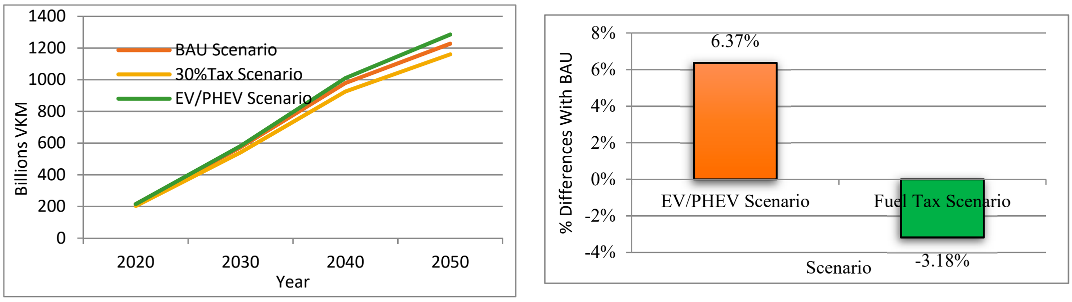
Fuel economy improvement in the projected BAU scenario occurs because car manufacturers are expected to improve their fuel economy regardless of the enactment of specific policies. However, this improvement in fuel economy is not as significant as in the car technology scenario. The car technology scenario leads to significant improvement in fuel economy. According to a previous study [46], fuel economy improvements can occur even if technological developments for increasing vehicle efficiency are only directed at improving fuel economy, and the performance of the vehicle remains constant. This study has analyzed possibilities in fuel economy improvement through modifications such as decreasing the weight and size of the car, in the absence of technological developments that increase the acceleration and horsepower performance [46]. These kinds of modifications are used in the assumptions of car fuel economy improvements for the car technology scenario.

The VKTs decrease slightly in the BAU scenario due to fuel price increases. Changes in fuel prices are more likely to occur as crude oil price increases, according to the crude oil price projections reported by the US Energy Information Administration [34]. Table 9 shows the *VKM* at BAU conditions for each province.

Table 9. *VKM* projection results for provinces, BAU scenario, 2016–2050 (million *VKM*).

No	Province	2016	2020	2030	2040	2050
1	Aceh	1332	1701	4128	6749	8285
2	North Sumatera	5125	6406	13,544	23,550	33,210
3	West Sumatera	2964	4406	11,910	17,758	19,007
4	Riau	6887	10,596	20,416	22,872	21,605
5	Jambi	900	1138	2534	3770	4279
6	South Sumatera	4717	6533	13,263	15,422	14,630
7	Bengkulu	499	667	1603	2829	3833
8	Lampung	2353	3192	8688	17,472	25,492
9	Bangka Belitung Islands	861	1320	3537	4797	4901
10	Riau Islands	2291	3211	6062	7035	6842
11	DKI Jakarta	12,181	12,428	15,171	14,914	13,635
12	West Java	27,079	33,387	72,478	131,456	198,790
13	Central Java	9183	14,281	42,067	73,286	87,673
14	D.I.Y	1726	2199	4119	4763	4560
15	East Java	14,251	18,439	41,458	70,599	92,029
16	Banten	7127	10,982	36,683	73,275	99,262
17	Bali	4190	4825	7407	7905	7391
18	West Nusa Tenggara	1632	3249	9989	13,504	13,306
19	East Nusa Tenggara	1875	3242	8277	10,790	10,870
20	West Kalimantan	3592	5197	10,415	11,926	11,252
21	Central Kalimantan	2523	3408	6035	6717	6347
22	South Kalimantan	2418	3428	7869	10,995	11,600
23	East Kalimantan	2561	2366	3658	4721	5423
24	North Sulawesi	1358	1772	3999	5737	6167
25	Central Sulawesi	1023	1240	2415	3366	3756
26	South Sulawesi	5192	6934	15,327	26,892	37,333
27	Southeast Sulawesi	384	574	1600	2960	4066
28	Gorontalo	1398	2089	3604	3708	3402
29	West Sulawesi	470	554	844	1095	1270
30	Maluku	357	352	525	721	950
31	North Maluku	108	163	546	1351	2604
32	West Papua	590	668	1034	1358	1591
33	Papua	1332	2258	7260	11,323	12,256
	Indonesia	130,478	173,204	388,465	615,618	777,617

The *VKM* projections in the BAU scenario show disparities among the provinces. In 2050, the five provinces with the highest *VKM* will be West Java, East Java, DKI Jakarta, Central Java, and Riau. National *VKM* is an aggregation of the *VKM* of all provinces. The comparison of national *VKM* among the different scenarios is shown in Figure 13.



(**a**) (**b**)

Figure 13. Comparison of VKM among the scenarios: (**a**) 2016–2050, and (**b**) 2050.

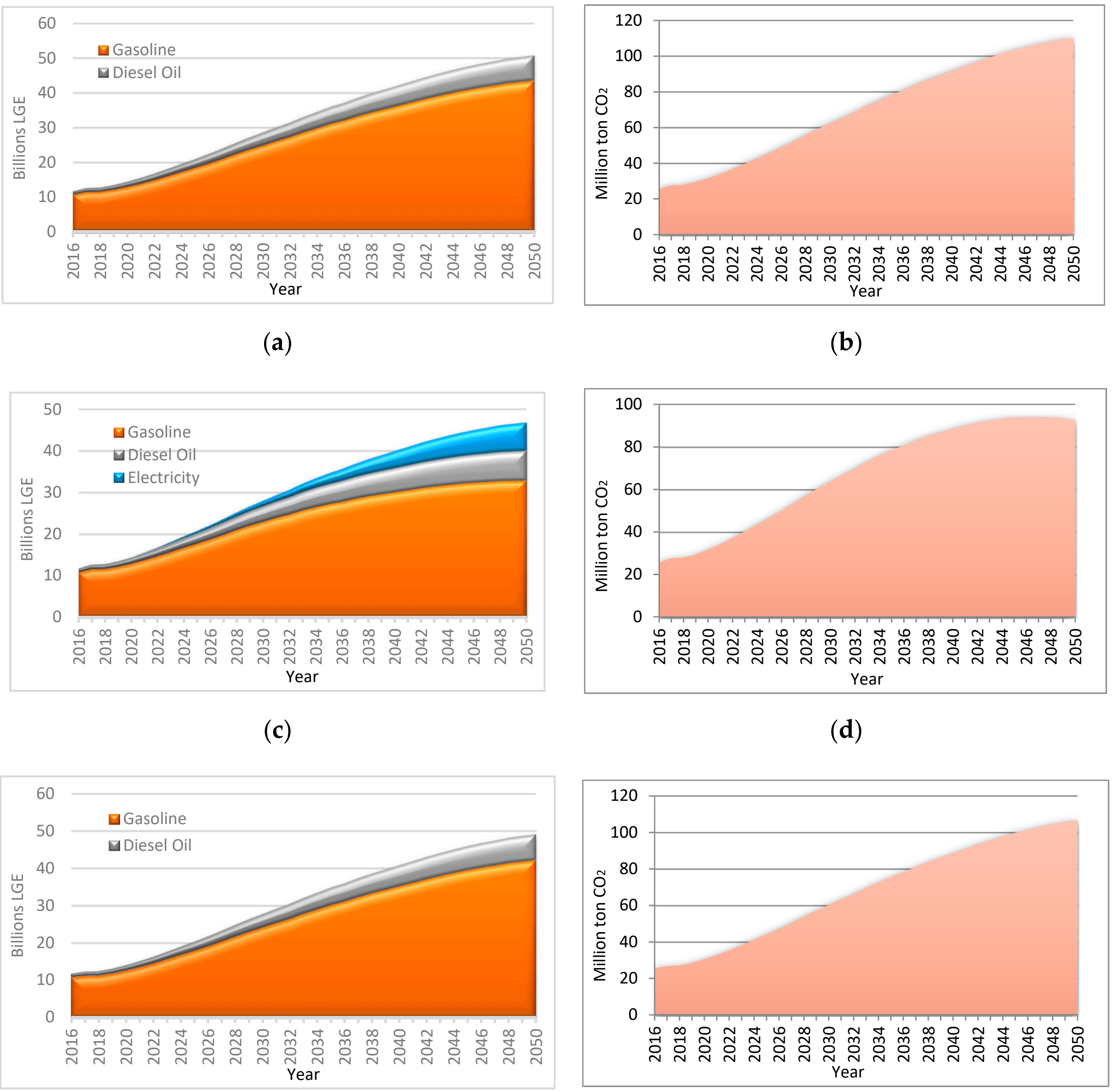
Based on Figure 13a, the fuel tax scenario has the lowest value for VKM. The fuel tax scenario reduces VKM by 3.18%, while the VKM in the car technology scenario tends to be higher than in the BAU scenario, because the significant fuel economy improvement causes the fuel cost to decrease. Consequently, this may precipitate an increase in VKM. This effect is commonly referred to as a rebound effect, such that fuel economy improvement does not reduce energy demand but instead increases it.

The energy demand projections for all provinces are shown in Table 10. The top five provinces in terms of energy demand increase are North Maluku, Southeast Sulawesi, Banten, Papua, and Lampung. These increases are caused by the growth rate of car ownership, which is influenced by a combination of α and β and also by the high VKT in preceding years. The highest energy demand is predicted to occur in 2030, because a take-off phase in levels of car ownership is expected in many provinces in that year.

Table 10. Energy demand projections for provinces, BAU scenario, 2016–2050 (LGE).

No	Province	2016	2020	2030	2040	2050
1	Aceh	119,148,323	141,523,449	303,607,934	461,464,806	540,244,217
2	North Sumatera	458,543,142	533,014,420	996,144,764	1,610,238,179	2,165,457,146
3	West Sumatera	265,192,718	366,591,863	875,942,962	1,214,204,525	1,239,355,128
4	Riau	616,226,815	881,589,123	1,501,512,434	1,563,904,525	1,408,724,650
5	Jambi	80,552,871	94,647,348	186,339,112	257,809,352	279,043,157
6	South Sumatera	422,063,720	543,568,995	975,487,176	1,054,481,349	953,949,811
7	Bengkulu	44,636,584	55,464,461	117,917,482	193,412,673	249,924,630
8	Lampung	210,516,097	265,594,157	638,973,126	1,194,670,091	1,662,176,551
9	Bangka Belitung Islands	77,063,962	109,808,609	260,164,030	328,000,084	319,551,372
10	Kepulauan Riau	204,942,989	267,180,562	445,877,246	481,031,935	446,116,423
11	DKI Jakarta	1,089,849,014	1,034,018,568	1,115,802,771	1,019,749,331	889,080,510
12	West Java	2,422,887,664	2,777,829,389	5,330,535,379	8,988,375,156	12,962,040,540
13	Central Java	821,685,057	1,188,229,370	3,093,896,625	5,010,986,595	5,716,720,151
14	D.I.Y	154,409,331	182,962,705	302,952,178	325,705,446	297,304,363
15	East Jawa	1,275,065,275	1,534,166,702	3,049,075,086	4,827,280,936	6,000,723,531
16	Banten	637,695,462	913,691,429	2,697,915,219	5,010,194,194	6,472,332,110
17	Bali	374,879,124	401,436,895	544,728,515	540,503,534	481,907,250
18	West Nusa Tenggara	146,061,501	270,335,225	734,625,142	923,360,040	867,604,144
19	East Nusa Tenggara	167,767,743	269,777,612	608,735,560	737,792,520	708,745,604
20	West Kalimantan	321,358,616	432,411,794	766,017,330	815,450,870	733,708,303
21	Central Kalimantan	225,759,254	283,570,145	443,844,722	459,285,481	413,845,972
22	South Kalimantan	216,361,886	285,199,263	578,752,860	751,783,980	756,379,095
23	East Kalimantan	229,105,517	196,859,130	269,020,170	322,828,260	353,611,885
24	North Sulawesi	121,545,236	147,408,264	294,134,362	392,257,298	402,148,817
25	Central Sulawesi	91,562,634	103,195,605	177,637,834	230,150,517	244,921,880
26	South Sulawesi	464,591,258	576,928,440	1,127,220,035	1,838,777,953	2,434,305,858
27	Southeast Sulawesi	34,396,473	47,753,362	117,644,424	202,392,077	265,101,108
28	Gorontalo	125,043,868	173,800,532	265,064,967	253,555,081	221,825,482
29	West Sulawesi	42,066,227	46,053,319	62,040,380	74,887,606	82,830,661
30	Maluku	31,965,517	29,320,690	38,589,159	49,286,590	61,960,934
31	North Maluku	9,620,306	13,548,369	40,155,478	92,387,460	169,790,491
32	West Papua	52,763,586	55,606,413	76,011,800	92,843,257	103,709,345
33	Papua	119,173,052	187,851,251	533,985,506	774,195,128	799,173,697
	Indonesia	11.674.500.823	14,410,937,457	28,570,351,767	42,093,246,828	50,704,314,820

In DKI Jakarta, the energy demand tends to be stable, even decreasing in 2050. This decrease is due to the fuel economy of cars, which continues to decline from year to year, while car ownership remains stable because of the steady population. According to the projections from the Central Bureau of Statistics of Indonesia, in 2050 DKI Jakarta's population is predicted to increase by only 14%, while the average population growth throughout all provinces will be approach 41%. This means the number of cars in DKI Jakarta cannot increase significantly. As a result, decreases in fuel economy would be able to offset the increase in VKM, while for the other provinces, the reverse situation applies. Figure 14 shows the comparison between scenarios for energy demand.



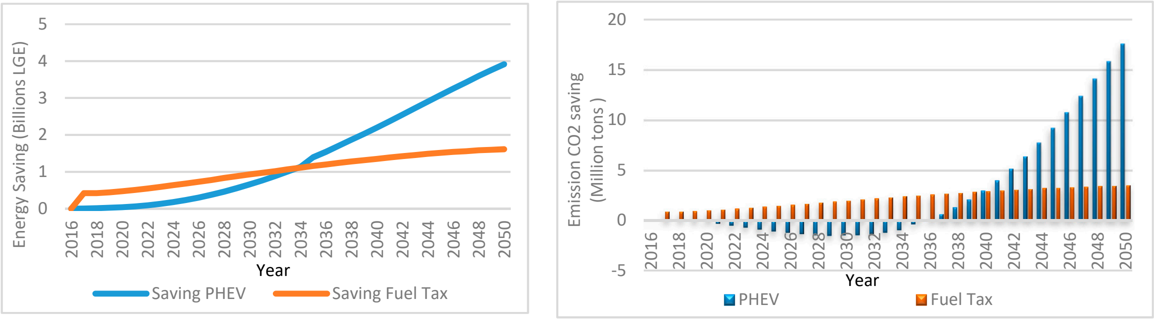
(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 14. Results of energy demand and CO_2 emissions among scenarios. (**a**) Energy Demand (BAU Scenario); (**b**) CO_2 Emissions (BAU Scenario); (**c**) Energy Demand (Car Tech. Scenario); (**d**) CO_2 Emissions (Car Tech. Scenario); (**e**) Energy Demand (Fuel Tax Scenario); (**f**) CO_2 Emissions (Fuel Tax Scenario).

The BAU scenario projections show that in 2050, the energy demand and CO_2 emissions will reach 50 million LGE and 110 million tons, respectively. This situation is about 4.3 times higher than in 2015. Moreover, the energy demand in the car technology and fuel tax scenarios will reach 46 and 49 million LGE, while the CO_2 emissions will reach 93 and 107 million tons, respectively. Figure 15 shows the comparison of CO_2 emission reduction in 2050 among all scenarios. The highest performance in terms of CO_2 emissions reduction occurs in the car technology scenario. The car technology scenario shows greater reduction due to the sales mix of PHEV and EV reaching 50% in 2050, with the accumulated number of PHEV and EV cars reaching 17.6 million, or 18% of the total car population. Moreover, the large number of CO_2 emission reductions in the car technology scenario occurred due to significant decarbonization of the electricity generation and share technology vehichle.



(**a**) (**b**)

Figure 15. Comparison between scenarios for energy demands and CO_2 emission savings (**a**) Energy demand savings; (**b**) CO_2 emission savings.

To realize this market penetration of PH/EV, several problems need to be overcome: limited battery car capacity, the cost of batteries, charging infrastructure, economies of scale, and the total cost of operating the PH/EV against liquid fuel car operation. The government needs to devise better strategies, including a roadmap outlining battery charging infrastructure, fiscal policies to reduce the total cost of PH/EV, in order to create a more competitive market for the PH/EV cars. Further strategy to be implemented is green incentives to increase the willingness to pay of the electric vehicle, therefore the electricity vehicle's ownership will be increased.

The fuel tax scenario reduces CO_2 emissions through VKM reduction. Since 2015, the government has eliminated subsidies, demonstrating that a fuel tax can be an effective means to control car travel. A tax of 30% could reduce CO_2 emissions by 3.18%. However, the tax regulation should take into account the people's purchasing power. Therefore, the government should increase the people's purchasing power and consider fuel price based on fuel quality. Figure 16 shows the expected CO_2 emissions disparities among provinces in 2050.

Figure 16. CO_2 emissions disparities among provinces, BAU scenario, 2050 (million ton CO_2).

The disparity of CO_2 emissions among provinces is quite striking, especially the disparity between western and eastern Indonesia. Special attention should be given to western Indonesia, then, particularly the Java region. The five provinces expected to contribute the most to CO_2 emissions by 2050 are West Java, East Java, Central Java, Banten, and South Sulawesi. The CO_2 emissions in DKI Jakarta are not expected to change much, while adjacent provinces are likely to experience high CO_2 emissions.

In 2050, the values for CO_2 emissions intensity per car activity for the BAU and car technology scenarios are 145 and 114 g CO_2/km, respectively, while the values for the fuel tax scenario are similar to those for the BAU scenario. The car technology scenario shows a significant improvement, with 15.96% lower emissions than in the BAU scenario. However, such emission reductions require a significant reduction in electricity emission factors to be near zero kg CO_2/GJ by 2050 which can be done through increasing the supply of electricity from renewable energy sources.

4. Conclusions

This study analyzes energy demand and CO_2 emissions in Indonesia in a historical situation (2010–2015) and during a projected period (2016–2050) resulting from the use of passenger cars. The results show disparities among provinces, which are mainly due to differences in GDP, population, area, and the number of cars. The historical situation shows that in 2015, the energy demand and CO_2 emissions from passenger cars amounted to 10 million LGE and 23 million tons of CO_2, respectively. In 2050, these values are expected to reach 50 million LGE and 110 million ton of CO_2, respectively, which is 4.3 times higher than that in 2015.

The five provinces with the highest CO_2 emissions in the historical situation, particularly in 2015, are West Java, East Java, DKI Jakarta, Central Java, and Banten. In 2050, the top five are predicted to be West Java, Banten, East Java, Central Java, and South Sulawesi. Therefore, special attention needs to be accorded to these provinces.

Compared to the BAU condition, the car technology and fuel tax scenarios could reduce energy demand by 7.72% and 3.18% and CO_2 emissions by 15.96% and 3.18%, respectively. The car technology scenario requires certain policies in order to achieve the reduction in CO_2 emissions, such as car economy labeling and fuel economy standards. Economy labeling is an obligation for car manufacturers and dealers to provide information on car fuel economy, while fuel economy standards are enacted by limiting car fuel economy based on the vehicle's class and intended purposes. In addition, this scenario requires a significant reduction in electricity emission factors to be 27.8 kg CO_2/GJ by 2050.

The projected fuel tax scenario could reduce CO_2 emissions by 3.18% in 2050. This scenario could be realized by imposing higher taxes in order to limit car activity. The higher the tax, the lower the CO_2 emissions; however, the imposition of fuel tax should also consider the ability of people to buy fuel, which is in line with GDP per capita.

The model for energy demand and CO_2 emissions of passenger cars at the provincial level can improve the accuracy of the analysis when aggregated to the country level, which is proven by model validation.

The current study's results could be used by provincial governments as an overview of energy and CO_2 emissions contributions by passenger cars. Furthermore, some scenarios have been given to illustrate possibilities for CO_2 emissions reduction. Special attention should be given to provinces which are the largest contributors to the current problem and also to those expected to experience significant increases in CO_2 emissions in the future.

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Nomenclature

BOE	Barrel oil equivalent
ASIF	Activity Structure Intensity Fuel
LCGC	Low Cost Green Car
CO	car ownership
*CO**	saturated car ownership
GDPP	GDP per capita
D	population density
FE	fuel economy
FC	fuel cost
VKT	vehicle kilometer traveled
VKM	vehicle kilometers
ϵ	elasticity
EF	emission factor
E	energy demand
G	CO_2 emission

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