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Energy consumption, CO_2, and cost analysis of hybrid and battery electric motorcycle

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Abstract

The electrification of the two-wheel vehicle segment is an important strategy for decarbonising the transportation sector. This study aimed to assess the hybridisation of gasoline motorcycles with battery electric systems as an option for decarbonisation. A gasoline motorcycle that had been converted to a hybrid motorcycle was evaluated in several aspects: energy consumption, greenhouse gas (GHG) emission, and cost of energy. The vehicle was tested under the United Nations economic commission for europe (UNECE) Regulation No.40 and compared to a battery electric motorcycle. The test in internal combustion engine (ICE) mode consumed 233.31 Wh/km of specific energy, emitted 60.69 gCO_2/km and cost 1.65 US-cent/km on average. The test in hybrid mode consumed specific energy at 6 % higher and 4 % lower specific energy consumption than ICE, thus not improving the carbon dioxide (CO_2) emission and operating cost. In electric battery mode, energy consumption was saved by 83 %, with 35 % lower CO_2 and 74 % cost savings. The battery electric motorcycle runs more efficiently with 88 %

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lower energy consumption, 53.8 % lower CO_2 and saved cost by 82 %. If the hybrid controller is improved in future development, it could lower specific energy consumption by 41.7 %, reduce CO_2 by 11.2 % and save cost by 35.7 %.

Keywords: hybrid electric motorcycle; battery electric motorcycle; carbon dioxide emission; cost of energy.

I. Introduction

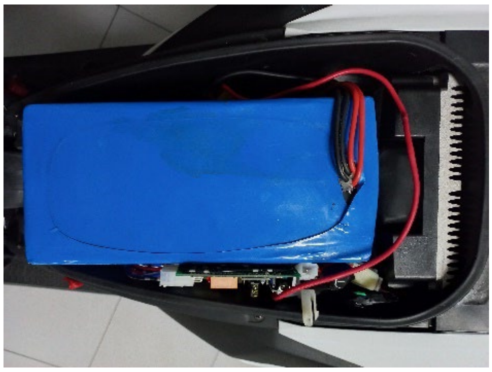
Climate change due to anthropogenic greenhouse gas (GHG) emissions has been a concerning global problem in recent decades. The contribution of GHG emissions by the transport sector in Indonesia as of 2022 was 24 % [1]. The decarbonisation strategy for the transport sector can be implemented by several options, i.e., utilising low-carbon fuel [2], carbon neutral fuel such as biofuel and electrification by hybrid and battery electric vehicle usage [3]. The applications are also supported by government policies in several countries, such as implementing strategies to encourage people to use low- and no-carbon vehicles, such as tax reduction [4], implementing low-emission zones [5], and subsidising purchases [6]. In addition, vehicle manufacturers compete to develop more innovative electric vehicles to attract customers. These could be related to the increasing global trend of electric vehicle sales number in the recent decade [7].

Motorcycles are a popular light-duty vehicle in Indonesia and other developing countries [8][9]. In 2022, its number constitutes ~84 % of the total vehicle in Indonesia [10]. Its contribution to the national GHG by the transport sector in 2022 was 36 % [11]. Therefore, increasing the electrification of this transport mode is expected to have a significant impact on the national GHG emissions.

The GHG emission by conventional and electric motorcycles has been evaluated in previous studies from different countries. Carranza *et al.* [12] reported a 90 % lower global warming potential by the usage of battery electric vehicles (BEV) than by internal combustion engine vehicles (ICEV) from the vehicles operated in Barcelona City, Spain. De Assis Brasil Weber *et al.* [13] compared BEV and internal combustion engine (ICE) motorcycles in Brazil and reported 68 % lower total CO_2 equivalent (CO_{2e}) emission by electric vehicles than ICE vehicles with E22 (22 % ethanol) gasoline. Despite higher total CO_2 equivalent emission in the electric generation, the higher energy conversion efficiency of BEV (47.1 %) resulted in lower operational CO_2 emission than ICE with E22, which performed with 16 % energy efficiency. Schneider *et al.* [14] reported 38.3 gCO_{2e}/km of total global warming potential by electric motorcycles compared to 61.2 gCO_{2e}/km by gasoline motorcycles. In a study of motorcycle taxi electrification in Kampala, Uganda, by Vanatta *et al.* [15], the electric motorcycle could reduce CO_2 emission by 36 % compared to the conventional one. On a lifecycle basis, a study by Chien *et al.* [16] reported that electrification could reduce carbon emissions by 63 % (from ICE), and the lightweight version could reduce more by 20 % due to 9 % more efficient operation. Montoya-Torres *et al.* [17] reported from their study in Ibague (Colombia) that CO_2 emission could be reduced by 17.96 % with the conversion of the car and motorcycle population by half to electric vehicles. In a different scenario, the same strategy with a fully renewable grid would improve the CO_2 emission by 2.11 % more. Further CO_2 reduction could be a result of eco-driving mode, as reported by Kusalaphirom *et al.* [18], which reduced CO_2 by 21 % from the aggressive style of driving. In a simulation by Rizki *et al.* [19], the implementation of car and motorcycle electrification in the Bali tourism area could reduce CO_2 by up to 1,945 tons, where 203 tons of reduction is a contribution from motorcycle electrification. Huu and Ngoc [20] estimated that the conversion of 10 % of the population of gasoline motorcycles to electric type could decrease CO_2 by 1,002,958 tons of CO_2 equivalent, and if all of the gasoline motorcycles is substituted by electric, the CO_2 is predicted to decrease by ~88 %. Ho *et al.* [21], in their study in Taiwan, estimated that if all ICEs are converted to electric motorcycles, ambient air could be improved with 23.54 % CO_2 reduction. Previous studies have shown that electric vehicles significantly reduce GHG emissions. Hence, it can be a main strategy to achieve the net zero emission target.

The implementation of electrification in two-wheel transportation also has the potential to be an attractive option from the perspective of lower operating costs [22]. In a study via data collection from ride-hailing applications using battery electric motorcycles, Suwignjo *et al.* [23] concluded that the driver saved income by 68 % compared to using the conventional one. Meanwhile, Niyonsaba *et al.* [24] suggested that changing the charging station from using the existing grid in Kigali (Rwanda) to a photovoltaic charging station could reduce the charging cost by 78 %. However, a study by Chien *et al.* [16] in Taiwan reported a higher total cost of ownership by electric scooters than by gasoline scooters. It suggested that a government subsidy be given in the future to encourage people to use this transport mode. These reports suggest that further comprehensive study is required,

(a)



(b)

Figure 1. (a) electric motor; (b) battery in the hybrid motorcycle.

including local policy, energy price, unit price, and battery replacement cost.

In addition, since the energy mix of each country is unique, a study in different countries with current situations might result in different impacts on GHG emissions. Thus, a comprehensive evaluation is required. A study by Demoral *et al.* [25] reported that despite the tailpipe GHG could be reduced by electrification, in a more comprehensive evaluation, it could result in a net increase of GHG emission from power generation. Therefore, decreasing the carbon intensity of the power system should be part of the general strategy. In a study by Charoen-amornkitt *et al.* [26], by implementing a 3kW photovoltaic charging system for battery electric motorcycles, the GHG emission could be reduced by around 2.6 to 3.0 Mt-CO_2 per year. In another study by Adiyasa *et al.* [27], with wind turbine and solar photovoltaic charging stations, the CO_2 emissions could be reduced by up to 2.5 tons/year. The reported studies showed that the conversion needs to be supported by a suitable decarbonisation strategy of the power generation sector or by providing integrated or independent renewable charging stations to achieve a net zero emission target [28].

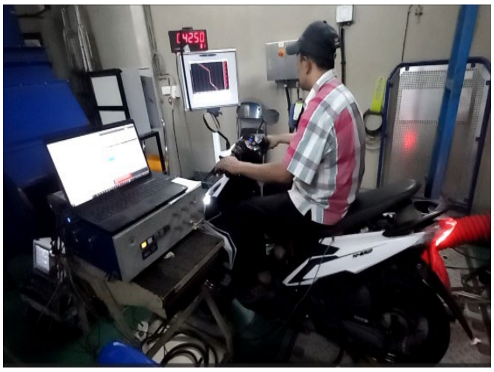
In Indonesia, the registration of battery electric motorcycles increased in 2023, although it was lower than the government's target [29]. Several reluctance to purchase this transport mode could be related to limited charging system availability in public spaces and long charging periods [30][31][32]. In addition, there are complaints regarding its lower performance in the uphill area and lower resale value than the conventional one [6][33]. Hybridisation of a conventional motorcycle by installing an electric motor could be an option to address this problem and become a method to encourage people to enter the ecosystem of electric vehicles. Choi and Yun [34] conducted simulations to hybridise gasoline motorcycles with battery electric motors by varying the battery equipped for the system and reported total cost savings over 15 years by 44 % and 26 % in Thailand and the Philippines, respectively. This suggests that a hybrid system is not only a potential solution for the technical problem but also could be attractive from an economic point of view rather than keeping the existing ICE system.

Prior to this study, a gasoline motorcycle was converted to a hybrid motorcycle. This aimed to provide flexibility in operation with the advantages of lower operating costs in battery mode for urban/flat areas and the ability to run at higher performance for hilly areas with the existing ICE mode. In this study, the performance of the hybrid motorcycle was assessed in several aspects: the energy consumption, GHG emission, and operational cost of battery by its operation in ICE, hybrid, and battery electric modes. These were compared to the results from electric motorcycles.

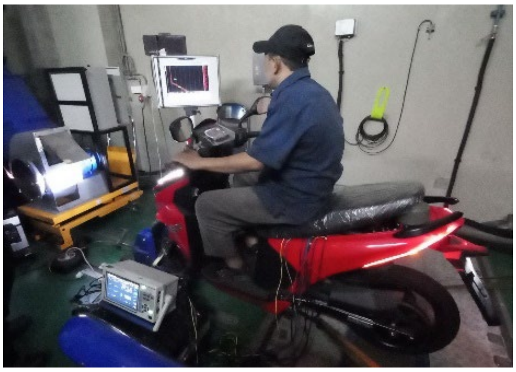
II. Material and Methods

A. Test vehicles and methodology

A Honda BeAT, which is a gasoline motorcycle manufactured by Astra Honda, was converted to a hybrid vehicle before the test. A brushless DC motor was installed on the wheel shaft, and a Lithium Ferro-phosphate battery was located in the baggage, as shown in Figure 1. Later, it is called a hybrid motorcycle in the next section. The conversion resulted in the curb weight of the vehicle becoming 122 kg. In hybrid mode operation, the change between internal combustion engine (ICE) mode and battery electric (BE) mode was controlled by a hybrid control module. In the early test, the vehicle was tested in BE mode at a constant speed of 30 km/h with simulated road load on the chassis dynamometer from full-to-empty battery power level, resulting in 39 km of travel distance. For comparison, a commercial electric motorcycle, Gesits G1, was used in this study. Specifications of the hybrid and electric motorcycles are described in Table 1. The test vehicles are shown in Figure 2.



(a)



(b)

Figure 2. Test vehicles: (a) Honda Beat hybrid; (b) Gesits G1.

The tests were performed by running the vehicle on a chassis dynamometer according to the speed prescribed in the UN ECE Regulation No. 40 test cycle [36] to simulate vehicle use in an urban area. The operating speed during the test consists of six repetitions of the urban cycle, as shown in Figure 3, with tolerances in each speed following the regulation. The test was performed by operating the hybrid motorcycle in three modes: ICE, BE, and hybrid. In hybrid mode, the unit was designed to run in BE mode at operating speed up to 30 km/h and in ICE mode at more than 30 km/h. However, the test in BE mode was run only up to 38 km/h as the maximum speed reachable by the electric motor, as illustrated in Figure 3 with the dotted line. In the test with Gesits G1 electric motorcycle in its "urban mode", the maximum speed was 50 km/h following the regulation.

Fuel consumption during the test was measured using AVL KMA Mobile with PLU measurement that is able to measure instantaneous liquid flowrate ranges from 0.16 l/h to 300 l/h. The flowmeter was installed between the outlet of the fuel pump and the fuel injector inlet, as shown in Figure 4. In the electric mode test, the electric power was measured with the Hioki CT6843A current clamp and Hioki Grabber Clip L9243 voltage probe. The voltage probe was installed on the positive and negative outlets of the motorcycle's battery. For measuring power during charging, the current clamp and probe were installed before the charger. Those were connected to a Hioki PW-3390 power analyser to process, analyse the signal and log the data.

B. CO_2 emission and cost analysis

CO_2 emission from gasoline operation was calculated from the measured fuel consumption. Meanwhile, CO_2 emission from the operation in battery or hybrid mode was calculated from the consumed electric energy during the charging process. The calculation included emission factors of electric energy as described in ref. [12][13][14]. CO_2 emission from the consumption of 90 RON gasoline is 2.368 kgCO_2e/litre. This is a calculated result from 72,783.5 kgCO_2/TJ of local emission factor which is the interpolated value of respective local emission factor of 88 and 92 RON:

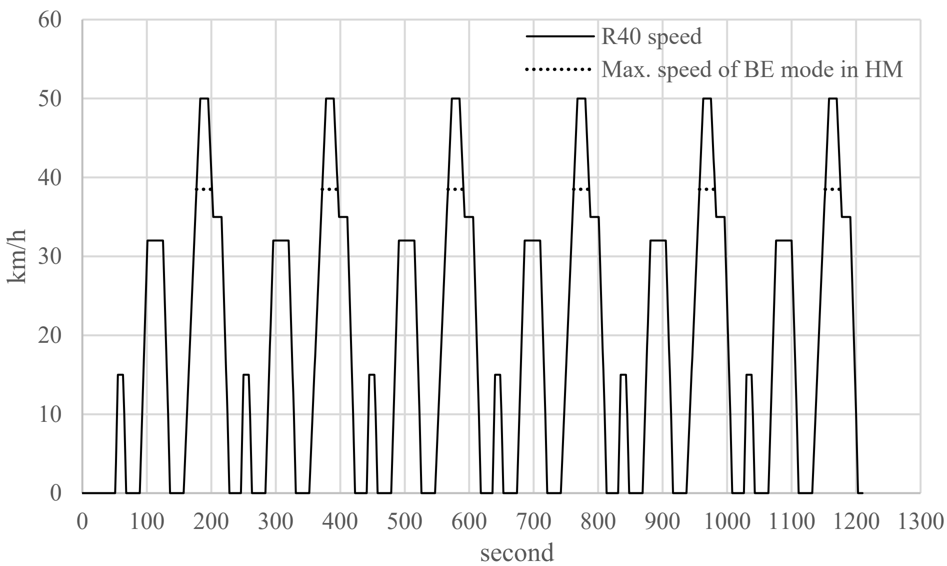


Figure 3. Vehicle speed during the test according to UN ECE Regulation No. 40 [36]

Table 1.
Specifications of the test vehicles.

Parameter	Hybrid	Gesits G1 [35]
Motor power (kW) in ICE/BEV	ICE: 6.38/ BEV: 1.5	2 (Peak= 5)
Max. horsepower (hp)	ICE: 8.56	6.7
Max. torque (Nm)	ICE: 9.01	30
Max. speed (km/jam)	38.6	70
Battery type	Li-FePO4	Li-NCM
Battery voltage (V)	61	72
Battery capacity (Ah)	15.5	20
Range (km) with full charged battery	39 (tested at 30 km/h)	50
Curb weight (kg)	122	94.5

72,967 $kgCO_2/TJ$ and 72,600 $kgCO_2/TJ$, as defined by Ministry of Energy and Mineral Resources of Indonesia in ref. [37][38]. The lower heating value of gasoline is 43.97 MJ/kg and the density is 0.74 kg/litre. The emission factor of 0.87 $kgCO_2/kWh$ was used to estimate the prospective impact of GHG emissions, representing power generations in Java, Madura and Bali (Jamali) interconnected grid of Indonesia [39].

Cost analysis was calculated based on fuel and energy consumption and price. A calculation with 90 RON was chosen, considering this fuel is used by the majority of the users in this segment. The price of 90 RON gasoline produced by Pertamina was IDR10,000 or US cents 64 per litre. The electricity price was IDR 1444.70/kWh, a price of 1300 and 2200 VA electric network, which is in the majority installed in the low-to-medium segment that likely purchases the test vehicles. The operating cost was calculated using a conversion rate of USD1 = IDR15,500 when this study was carried out.

Figure 4. Modification of the fuel delivery system of motorcycles to accommodate the flow measurement.

III. Results and Discussion

A. Performance test results

Specific energy consumption during the test by electric motorcycle (EM) and hybrid motorcycle (HM) in the internal combustion engine (ICE), hybrid (Hyb.) and battery electric (BE) modes are depicted in Figure 5, respectively. The hybrid unit in ICE mode consumed 233.7 and 233 Wh/km, while its operation in hybrid mode consumed 247.4 and 223.3 Wh/km. Lower specific energy consumption resulted in the battery electric mode of a hybrid motorcycle that consumed 38.4 and 39.0 Wh/km with a trade-off in maximum operating speed of ~38 km/h. Lower energy was consumed in the test of electric motorcycles that consumed specific energy of 27.5 and 26.9 Wh/km. From two tests in each mode, the variation in energy consumption by hybrid mode was 9.7 %, higher than the ICE and BE modes, which were 0.3 % and 1.7 %. During the test, the change between ICE and BE modes

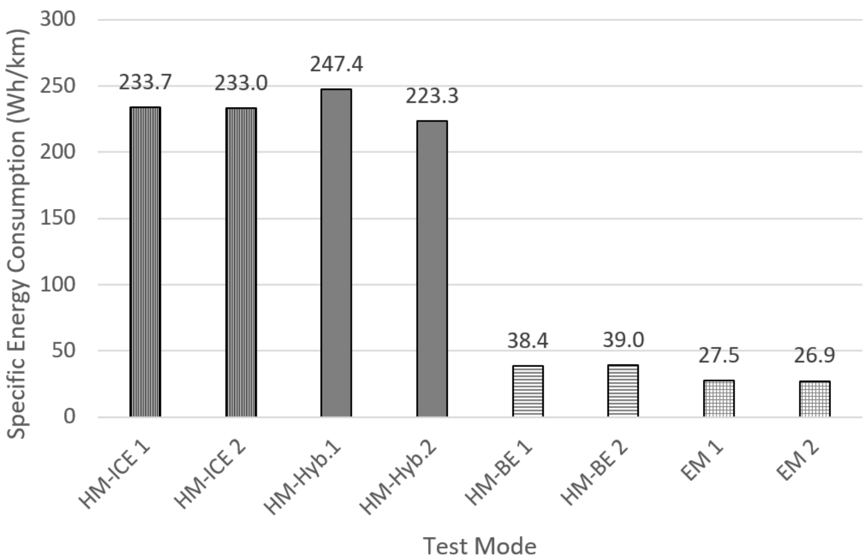


Figure 5. Specific energy consumption of hybrid and electric motorcycle in the tested mode (HM: hybrid motorcycle, ICE: internal combustion engine, Hyb.: hybrid mode, BE: battery electric, EM: electric motorcycle).

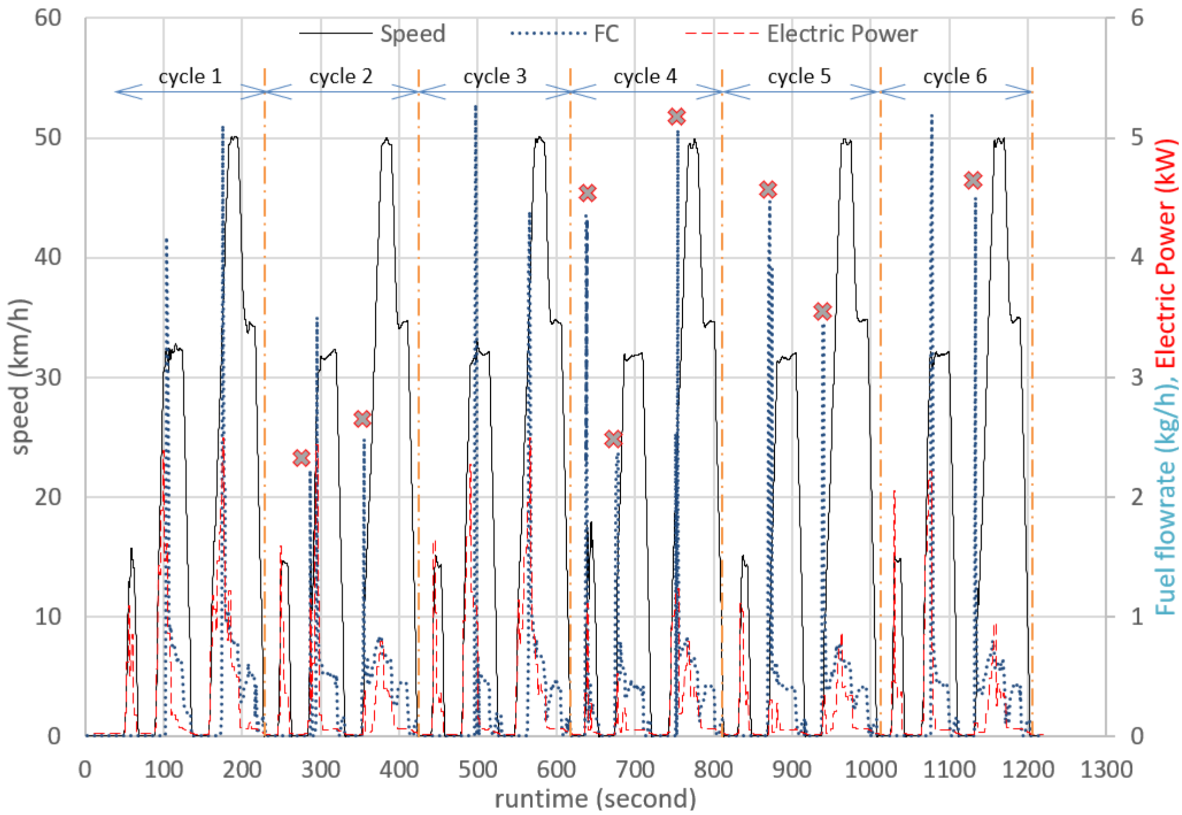


Figure 6. Regarding speed, fuel consumption, and electric power during the hybrid motorcycle (HM-Hyb. test) test, the wrong mode changes are indicated with a cross.

did not consistently follow the designated transition speed. For example, from idle to 30 km/h, where BE mode should have picked up, sometimes the engine was started, and the vehicle ran in ICE mode until it stopped. In the other cycle, the mode changing to the ICE mode was at the wrong speed, not smoothly and back to the previous mode. Further analysis will be presented in the next section. Despite higher energy consumption in hybrid mode, the test in electric mode (HM - BE) saved energy by ~83 % compared to its ICE mode. However, the maximum speed in the electric mode was only 38 km/h, not 50 km/h as targeted in the R40 cycle. Meanwhile, electric motorcycles in urban mode consume 27.5 and 26.9 Wh/km of electricity.

Higher energy consumption by HM - Hyb. 1 than HM-Hyb. 2 could be attributed to the inconsistency of inter-mode changing between ICE and BEV mode, which is executed by the hybrid control unit. The instantaneous energy consumption during the test was analysed from the measured fuel consumption and electric power during the HM - Hyb. 2 test, as presented in Figure 6. The spiking fuel flow rate in the blue dot line indicates the starting of the engine as the controller changes the vehicle to ICE mode. The hybrid control system was designed to accelerate firstly in BEV mode. Starting from 30 km/h, the controller changes to operate in ICE mode. Hence, the engine started, accelerated the wheel up to 50 km/h, kept running until stopped and went back to BEV mode in the idle condition. However, the controller showed inconsistencies during the operation. The first acceleration in cycle four should be run fully in BEV mode. From the second acceleration curve up to 33 km/h in each cycle, the hybrid motorcycle indicated too early changes in many cycles, at lower than 30 km/h. The second acceleration curve in cycles number 2, 4, and 5 indicates such inconsistency. In addition, this also happened in the third acceleration curve in cycles number 2, 4, 5, and 6. These indicate that the hybrid control system needs improvement. Furthermore, the mode changes to ICE, which starts the engine at a relatively lower temperature and directly accelerates the wheel to achieve the target speed, resulting in an excessive spike that deteriorates fuel consumption. This suggests that significant improvement in the starting mechanism is required to lower fuel consumption during hybrid operation.

The specific CO_2 emission resulting from the test vehicles in each mode is shown in Figure 7. Operating a hybrid motorcycle in ICE mode (HM - G) resulted in 60.91 and 60.47 gCO_2/km. In hybrid mode, it produced 76.55 and 69.10 gCO_2/km. If the emissions by hybrid are compared to the ICE mode, it results in 12 to 27 % higher CO_2. Higher CO_2 emissions by hybrid mode than ICE mode could be attributed to the inconsistency of the control system in running the vehicle at the designated operating speed for each mode. Therefore, the objective of the hybrid operation was not achieved.

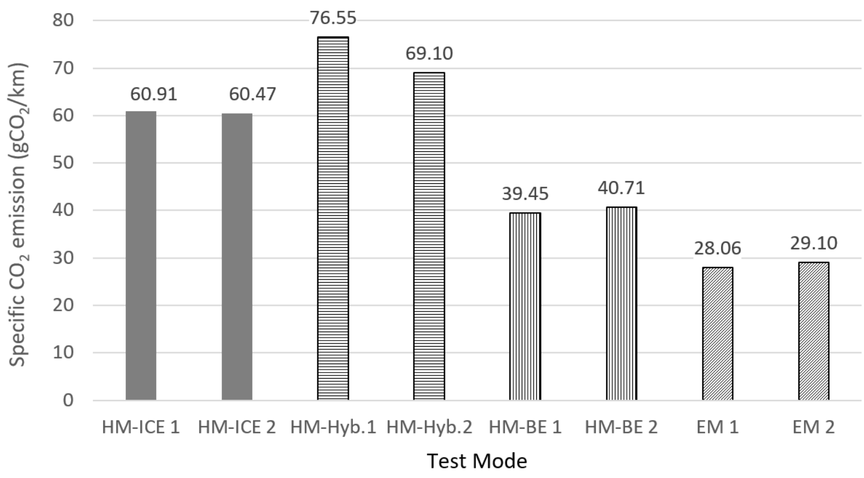


Figure 7. Specific CO_2 emission by each mode of hybrid motorcycle (HM) and electric motorcycle (EM).

Meanwhile, in BE mode, the operation resulted in a reduction in CO_2 emission to 39.45 and 40.71 gCO_2/km. These equal to 33 % to 35 % reduction from the average of ICE mode. A more significant reduction in CO_2 emission could be achieved by operating electric motorcycles that produced 28.06 to 29.10 gCO_2/km or a CO_2 reduction of 53.8 %. These were achieved while keeping comparable performance relative to ICE mode in a hybrid unit with the ability to reach 50 km/h of maximum speed during the test. Higher CO_2 emission by BE mode in a hybrid motorcycle than in Gesits electric motorcycle could be related to heavier vehicles and the hybrid mechanism that kept the engine and CVT transmission connected to the wheel. The results in BE mode operation suggest that the modification could contribute to the reduction of CO_2 emission by 35 %.

Energy costs for operating motorcycles in each mode during the tests are shown in Figure 8. The operation of a hybrid motorcycle in ICE mode costs 1.66 and 1.65 US-cent/km. The inconsistent control of a hybrid system that did not reduce fuel consumption significantly resulted in a 9 % higher and the same operating cost of energy at 1.79 and 1.65 US-cent/km. Considerable cost reduction was achieved by operating in an electric mode that spent 0.42 and 0.44 US-cent/km or saved the cost by 74 % relative to ICE mode. Further benefits could be realised by electric motorcycle usage, which costs 0.30 and 0.31 US cents/km, or 82 % savings from hybrid units with ICE mode. These results suggest that despite being less cost-efficient than an electric motor, using a battery electric mode in a hybrid could be an attractive option while keeping its performance in the existing ICE mode.

B. Results of the simulated improvement of hybrid control

The higher variation in energy consumption by the hybrid operation described in the previous section suggests that the control system needs to be improved. In this section, the potential of fuel consumption reduction by increasing electric mode in the hybrid operation via simulation is described. The measured fuel and electric power consumption in hybrid test no. 2 and the electric power in the battery mode test no. 2 were used in the simulation. The simulated fuel

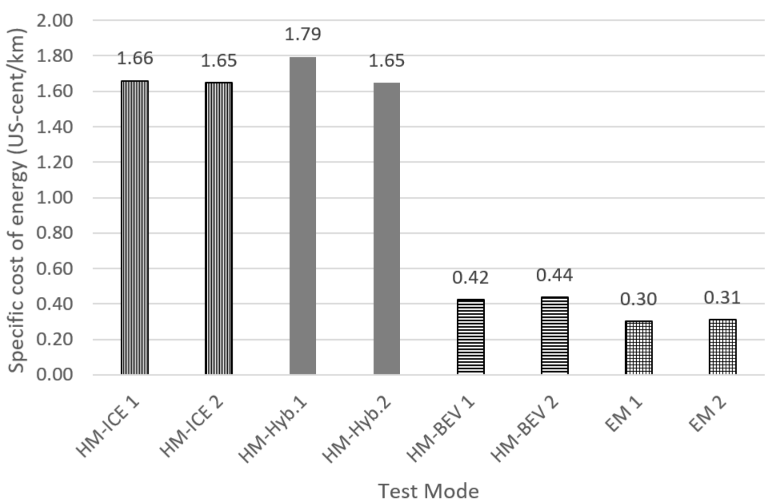


Figure 8. Cost of energy by each operating mode of Hybrid Motorcycle (HM) and Electric Motorcycle (EM).

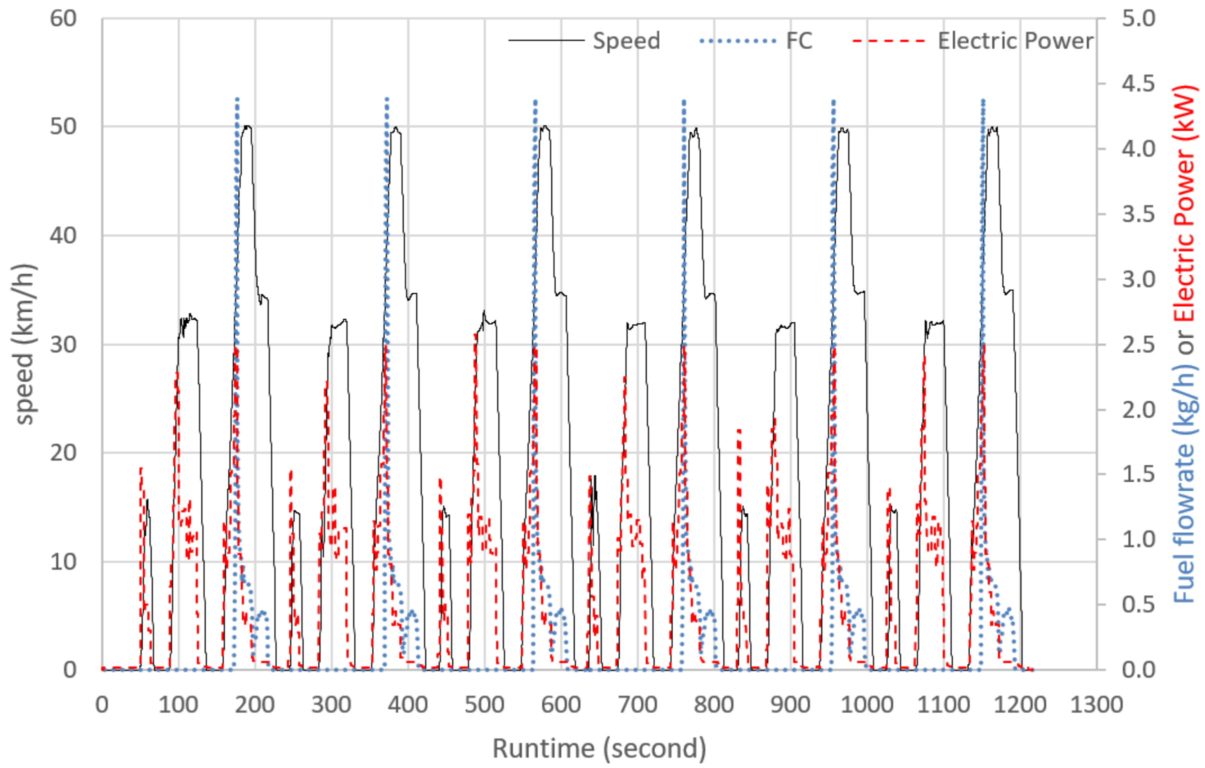


Figure 9. Curves of speed, fuel consumption and electric power produced from the simulated performance of hybrid operation after improvement of the control module.

mass flow rate and electric power curves are shown in Figure 9. These were produced using the electric power during the first and second acceleration hump of each cycle from BE mode, while the electric power and fuel consumption in the third hump was taken from the third cycle of hybrid test no. 2.

The simulation was used to predict potential fuel savings and the increase of electric motor employment during the hybrid mode operation. The ratio of the fuel and electricity to the total energy consumption consumed during the vehicle used in hybrid mode produced from the simulation compared to the ones from tests is depicted in Figure 10. Data from ICE mode is presented in the average value of both tests. The improvement of hybrid control could reduce fuel consumption, hence increasing the ratio of electric energy by 19.1 % to the total energy consumption from the previous 8.2 % and 6.31 %. Therefore, energy consumption could be reduced from 247.4 and 223.3 to 135.9 Wh/km, which equals a 39 % to 45 % reduction from the hybrid test results. Compared to the average of ICE tests, the improvement could reduce the specific energy consumption by 41.7 %. Furthermore, the improvement could reduce CO_2 emission by 55.1 gCO_2/km, as shown in Figure 10(c), improved by ~20 % from HM-Hyb. 2. Compared to the average of ICE mode, CO_2 could be improved by 11.2 %. In addition, a reduction in fuel consumption could reduce the operating cost from 1.79 and 1.65 US-cent/km to 1.07 US-cent/km or an improvement of 40.5 %, as shown in Figure 10(d). Compared to the average ICE mode, it potentially could save the cost by 35.7 %. Generally, the simulation results showed that the improvement in the hybrid control module could result in a positive impact of hybridisation to decarbonise the transport sector.

C. Discussions

Two-wheel vehicle electrification with a battery electric motor is considered a practical option that offers economic benefits by lowering the cost of energy compared to an ICE motorcycle [22][23][24]. This has drawn the attention of the public in Indonesia, as shown by its increasing population, which has received strong support from the government by giving a purchasing subsidy [29]. However, the limited availability of charging stations in public spaces could be a reason to avoid shifting to this transport mode [30][31][32]. On the other hand, the hybridisation of ICE motorcycles as an option that provides flexibility to run the existing ICE mode for performance purposes has not yet been explored extensively. In the previous study, Choi and Yun [34] simulated the economic benefit of hybrid motorcycles with fuel and electric price data from Thailand and the Philippines in an energy balance software. Despite it was not yet completed with experimental data from a converted motorcycle, the study reported that the investment cost of hybridisation in Thailand could be back in 1.2 years and around two years in the Philippines from the fuel

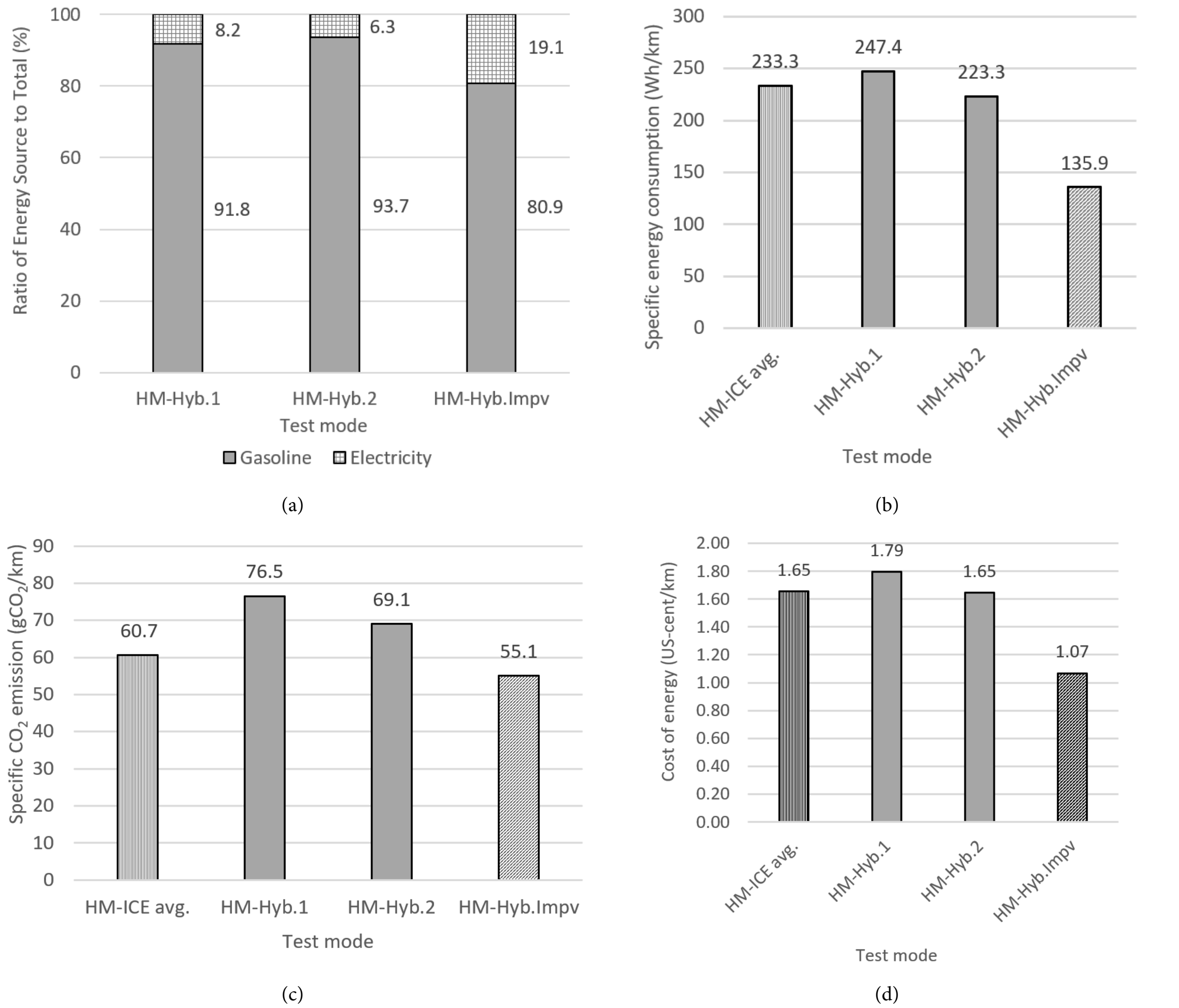


Figure 10. (a) The ratio of energy source to total energy consumption; (b) Specific energy consumption; (c) CO2 emission; (d) Operating cost by simulated improvement of hybrid control module (HM - Hyb. Impv) compared to hybrid test results (HM - Hyb. Test) and an average of ICE mode (HM - ICE avg.).

cost saving. The projections for 15 years of usage showed that a cost reduction of 44 % in Thailand and 26 % in the Philippines could be realised by hybridisation. As the study did not cover the technical aspect, further study is required to explore the potential and challenges of hybridisation in real applications.

Test results of the hybrid motorcycle in this study indicate that conversion of an ICE to a hybrid motorcycle, which was run in battery electric mode, increased energy conversion efficiency, reduced CO_2 emission, and saved the cost of energy. The vehicle test in the early stage of this study with simulated road load at 30 km/h on chassis dynamometer from full to empty battery level resulted in a maximum operating range of 39 km. This operating range under battery electric mode suggests that it is suitable for daily commuting range in greater Jakarta, Indonesia, where the average home-to-work travel distance of the people in the surrounding cities ranges from 12 to 30 km [40]. In addition, it showed considerable competitiveness compared to the battery electric motorcycle from the perspective of GHG reduction and energy cost saving. The simulated improvement showed that it could run with higher energy efficiency, reduced CO_2 emission, and lower cost of energy with modification in the control system. Several methods need to be considered in the improvement, including installing a smart control system with artificial intelligence that recognises the operating conditions, increasing response time to shorten the transient condition during the transition from ICE to electric mode, and optimising the starting mechanism to provide soft start in the middle of hybrid mode. A future study of annual cost saving, the breakeven point of the investment, and potential cost saving over a certain period of usage of this motorcycle is recommended.

Hybrid motorcycles could be part of the solution for the low availability of public charging stations, as mentioned in some references [30][31][32]. In addition, it could answer the public's reluctance to enter the electric vehicle ecosystem by providing flexibility with existing ICE performance and technical features [6][33]. In general, this study showed that hybridisation of an ICE motorcycle could be recommended as a part of a strategy to decarbonise the transport sector. Further GHG reduction by a hybridisation strategy could be achieved by decreasing the carbon intensity of the power system by a higher share of renewable energy in the electrical power system or by building independent photovoltaic and wind turbine charging stations, as suggested in [26][27].

IV. Conclusion

This study aimed to evaluate the performance of hybrid motorcycles and to assess whether the implementation of hybridisation for motorcycles as a popular light-duty vehicle could contribute to the net-zero emission strategy in Indonesia and become a cost-efficient option for the user. A gasoline motorcycle, which is converted to a hybrid motorcycle (HM), was tested on a chassis dynamometer and compared to a battery electric motorcycle, following the UNECE R40 test cycle to represent the urban driving cycle. Several conclusions are made from the test results. On average, the operation of HM in ICE mode consumed 233.3 Wh/km, resulting in 60.7 gCO_2/km and cost 1.65 US-cent/km. In two tests of hybrid mode, it consumed specific energy at 6 % higher and 4 % lower than the average of ICE mode, with a 9.7 % variation between the two tests. The inconsistent mode selection by the hybrid control system caused an insignificant reduction in fuel consumption in the hybrid mode. Consequently, the CO_2 emission deteriorated by 14 % to 26 % and the cost of energy was higher by 9 % or similar to the operation in ICE mode. In battery electric mode, HM consumed less energy by ~83 %; hence, CO_2 could be reduced by 37 % and saved the cost by 74 % relative to the ICE mode on average. Higher impact for decarbonisation resulted from electric motorcycles that reduced CO_2 emission to 29.1 gCO_2/km or 53.8 % lower CO_2 and cost saving by 82 %, thanks to 88 % more energy efficient operation than the hybrid unit in ICE mode. A simulation work using fuel and electric power data set from the tests was conducted to analyse the potential fuel saving and CO_2 reduction by HM in hybrid mode from future improvement of the hybrid control system. The predicted reduction in specific energy consumption by hybrid mode with the future improvement of the controller was 41.7 %, which resulted in a CO_2 reduction of 11.2 % and a saving of the operating cost by 35.7 % relative to ICE mode.

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Declarations

Author contribution

T. Yuwono: Writing - Original Draft, Writing - Review & Editing, Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Supervision. **K.F.A. Sukra**: Investigation, Data curation, Formal analysis. **R.T. Soewono**: Resources, Supervision. **D. Indriatmono**: Resources, Formal analysis. **N.M. Fuad**: Resources, Investigation, Formal analysis. **M. Ma'ruf**: Formal analysis. **R.D. Samanhudi**: Formal analysis. **A. Kurniawan**: Project Administration. **R.C. Nugroho**: Supervision. **A. Wahidin**: Formal analysis. **V. Hayoto**: Resources. **M.T. Suryantoro**: Supervision. **Mokhtar**: Resources. **M.N. Hidayat**: Resources. **B. Wahono**: Resources, Software, Methodology. **M. Pratama**: Resources, Software, Methodology. **A. Nur**: Resources, Software, Methodology. **A. Dimyani**: Resources, Software, Methodology. Suherman: Resources. **M.K.A. Wardana**: Resources. **A. Praptijanto**: Resources. **Y. Putrasari**: Funding Acquisition, Resources, Supervision. **B. Prawara**: Resources, Supervision. **H. Budianto**: Resources.

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Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Additional information

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