Energy Strategy Reviews 45 (2023) 101056

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Beyond personal vehicles: How electrifying scooters will help achieve climate mitigation goals in Taiwan

Yuan-Hsi Chien [a], I-Yun Lisa Hsieh [a,b,*], Tsung-Heng Chang [a]

[a] Department of Civil Engineering, National Taiwan University, Taipei, 10617, Taiwan
[b] Department of Chemical Engineering, National Taiwan University, Taipei, 10617, Taiwan

ARTICLE INFO

Handling Editor: Mark Howells

Keywords:
Electric scooters
Lifecycle assessment
Total cost of ownership
Battery swapping
Net-zero emissions

ABSTRACT

Electrification is considered a key enabler for decarbonizing road transportation. Recently, increasing attention has been directed to the deployment of electric two-wheelers in cities across the globe. However, climate change mitigation potential across the diversity of today's available scooter models is still missing in the existing literature. With a focus on Taiwan—the world's highest density of scooters—we comprehensively examine the performances of 156 scooter models on the market to understand the potential cost and carbon trade-offs among two-wheeler purchase options. We find that such a trade-off does exist when choosing scooters with different powertrain technologies. Compared to gasoline scooters, low-carbon-emitting electric scooters are more costly to own but not necessarily more expensive to purchase—because battery-swapping techniques convert the capital cost of the battery itself into an operating expense. Surprisingly, all the Phase 7 emissions standard internal combustion engine scooters appear to meet the near-term climate goal for 2030 in Taiwan, providing a less-costly transition from liquid fuels to electrification. While all the e-scooters supplied with the current electric power meet the 2040 emissions reduction target, deep decarbonization of electricity generation is also required, along with a large-scale adoption (at least 90%) of electric scooters to achieve net-zero emissions by 2050.

1. Introduction

The 2015 Paris Agreement commits countries to limit the global average temperature rise to well below 2 °C, preferably to 1.5 °C, compared to pre-industrial levels. The transport sector accounts for around one-fourth of global CO2 emissions, and road transport is responsible for three-quarters of transport emissions [1]. Thus, to achieve the climate goals, the ground transportation sector across the globe is a must to be decarbonized. Electrification is considered an important pathway toward sustainability. When it comes to electric mobility, most attention has been placed on electric cars. However, great emission mitigation potentials could be realized through the wide-scale introduction of electric two-wheelers—especially in urban areas [2].

Motorized two-wheelers are especially the favored transport mode in South-East Asia countries, as they offer a nīumber of benefits—relatively affordable private vehicle ownership, quick and efficient personal transport, and space-saving vehicle option. However, although providing riders with a convenient means of traveling on congested city streets, gasoline-powered two-wheeled vehicles create significant emissions and cause severe environmental damage [3]. Electric two-wheelers tend to perform more energy-efficiently, thus becoming increasingly popular and being introduced in several cities worldwide [4]. Environmental consciousness, as well as financial incentives, are key motivating factors for electric vehicle (EV) adoption [5–8]. Lifecycle climate benefits and ownership costs of vehicle electrification have been broadly evaluated, as synthesized in the reviews and published articles [9–11]. Most of the existing life cycle assessment (LCA) studies focused on emission comparison across comparable passenger vehicles or two-wheelers with different powertrain technologies [12–18]. To capture the diversity of personal vehicle options on the market, Miotti et al. [19] assessed a comprehensive set of 125 car models available to consumers against climate change mitigation targets in the U.S. The study suggested that consumers are not required to pay more for vehicles with lower carbon emissions; subsidized EVs are not more costly than comparable ICEVs. The study also showed that EVs with nearly carbon-free electricity generation are needed to meet the 2050 climate policy targets.

Understanding the carbon footprints and ownership costs of vehicle choices from consumers' perspectives is essential for well-informed purchasing decisions and evidence-based policymaking. Nevertheless,

* Corresponding author. Department of Civil Engineering, National Taiwan University, Taipei, 10617, Taiwan.
E-mail address: iyhsieh@ntu.edu.tw (I.-Y.L. Hsieh).

https://doi.org/10.1016/j.esr.2023.101056
Received 15 September 2022; Received in revised form 12 November 2022; Accepted 6 January 2023
Available online 10 January 2023

comprehensive investigations on diverse two-wheelers models have not yet been conducted. Against this background, this study closely examines the cost and carbon intensities among all the available two-wheeler purchase options from consumers' perspectives to answer the following questions: What are the climate change mitigation potentials for different scooter technologies to facilitate the transition towards a net-zero emissions future? Are there any trade-offs between two-wheelers ownership costs and carbon emissions faced by today's consumers? With 610 two-wheeled vehicles per 1000 population, Taiwan has the highest motor scooter ownership rate globally [20]. Therefore, this study explores the Taiwanese two-wheelers market in order to cover a wide range of purchase options available to consumers. Note that motor scooters commonly seen on the roads in Taiwan are those with a step-through chassis and footrest platform. The most well-known brand of this motor scooter type is the Vespa, which was first introduced after the Second World War in Italy and has been exported worldwide since then [21].

Starting in 2016, the Taiwanese government has provided financial incentives to encourage people to replace their old, high-emitting gasoline scooters (internal combustion engine; ICE scooters) with cleaner ones—including battery electric scooters (e-scooters). Like global EV market adoption, fiscal subsidies are also a major driver of e-scooter adoption in Taiwan. The e-scooter sales market share reached a record 18.7% in 2019 but fell to below 10% in 2020 when the subsidies were cut [22]. Unlike the EV charging ecosystem, battery swapping has become mainstream (nearly 90%) for e-scooter recharging in Taiwan [22]. The Taiwanese company Gogoro has successfully popularized the idea by deploying a battery swap network. By the end of 2021, more than 2200 swap stations (i.e., GoStation) have been built nationwide—approaching the number of gas stations in Taiwan [23]. Before the emergence of Gogoro in 2016, lightweight e-scooters (with lower than 5 horsepower) used to be more common in Taiwan but are still available in the current market, taking about 13% of the sales market share [20]. On March 30, 2022, the Taiwanese government officially published "Taiwan's Pathway to Net-Zero Emissions in 2050″, setting out a clear timetable for the ICE ban, including electrifying all new sales of scooters by 2040 [24]. However, it remains questionable whether e-scooters can truly help achieve the emission goals and if they are economically attractive for large-scale adoption. Here, we address the concerns and contribute to the literature by evaluating the environmental and techno-economic aspects of various scooter models available for purchase today. Although Taiwan is selected as the study focus, we develop an interactive online tool (https://how-much-e-scooter.netlify.app/), allowing users to change input parameter values to enhance decision-making during the net-zero transition across the globe.

2. Methods

2.1. Scooter models selection

We examine the lifecycle carbon emissions and consumer ownership costs of a total of 156 scooters in Taiwan—including all the domestic internal combustion engine scooters powered by gasoline (ICE scooters) and battery electric scooters (e-scooters) that are available on the market in 2021. Emission standards for new ICE scooters in Taiwan are based on European regulations [25,26]: The Taiwan Phase 6 and Phase 7 emission limits are comparable but not identical to Euro 4 and Euro 5 limits—they are in fact more stringent in some respects. With the implementation dates of January 2017 and 2021, all the new ICE scooters produced in Taiwan should meet Phase 6 and Phase 7 standards, respectively [25]. We select 64 Phase 6 scooter models and another 45 models following the latest Phase 7 standards—all with engine capacity from 100 cc to 150 cc. Regarding e-scooters, there are two different charging versions on the market: battery swapping and battery charging. We consider all the e-scooter models (28 with swapping versions and 5 with charging versions) that have motors similar to ICE counterparts with 100 cc–150 cc and the other lightweight e-scooters (7 with swapping versions and 7 with charging versions) that are comparable to 50 cc ICE scooters.

2.2. Life cycle assessment (LCA) of greenhouse gas (GHG) emissions

To better understand the environmental benefits of scooter electrification, LCA is used to compare the lifecycle emissions per distance driven among different scooter models. This study defines the system boundary in LCA to include two-wheeled vehicle manufacturing, upstream fuel, and feedstock production, and vehicle operation stages. Emissions from end-of-life procedures are excluded due to the lack of data and their expected negligible amount compared to emissions from vehicle production and operation [27]. We assume a nominal lifetime distance traveled of 102,400 km, with the national average kilometer ridden per year of 6400 km [28] and a lifespan of 16 years [29].

We derive the carbon emissions of scooter manufacturing from the published literature on cradle-to-gate emissions of lithium-ion batteries and scooter production [30,31], resulting in 2.2290 kgCO2eq/kg for e-scooters excluding battery, 2.4988 kgCO2eq/kg for ICE scooters (including ICE), and 10.3994 kgCO2eq/kg for battery production. Note that battery manufacturing is presented separately here because of its high carbon footprint relative to scooters themselves. Regarding the lifecycle emissions (i.e., well-to-wheel; WTW) of transportation fuels, we estimate the results based on the carbon footprint of the gasoline [32], the emission intensity of the electricity mixes [33,34], and fuel consumption rates for all the selected scooter models [35,36]. In Taiwan, the carbon emissions to produce a liter of gasoline is 0.65 kgCO2eq/L, to consume a liter of gasoline is 2.2631 kgCO2eq/L, and to generate a kilowatt-hour (kWh) of electricity (including fuel production and feedstock production stages; i.e., well-to-pump) is 0.552 kgCO_2eq/kWh in 2020 (Section 2.4 for details).[1]

2.3. Total cost of ownership (TCO) calculations

The total cost of ownership (TCO) denotes the costs incurred during the vehicle ownership period, including vehicle purchase costs, fuel costs, and non-fuel operating and maintenance costs. The TCO per kilometer calculation approach applied in this study is shown in the following formula,

$$TCO\ [NT\$ / km] = \frac{(IPC - RV_N \times PVF_N) + \sum_{i=1}^{N} FC_i \times PVF_i + \sum_1^N O\&M_i \times PVF_i}{N \times VKT} \tag{1}$$

where PVF_i is the present value factor at the end of year n with the equation of $1/(1+r)^i$, r is the discount rate (6%), and N is the scooter lifespan (16 years [29]). IPC is initial purchase costs incurred at time zero, which is made up of retail price and financial incentives (varying by county, as shown in Table S1). RV_N is the residual value after the ownership period N, which is estimated using the straight-line depreciation method with the assumed depreciation rate of 25% [37]. FC is the fuel costs incurred every year: (1)for ICE scooters, FC is determined by the fuel efficiency [36], gasoline prices (10-year average from 2012 to 2021 is NT$27.18/L [38]), and the annual kilometer ridden (VKT; 6400 km/yr [28]); (2) for e-scooters with monthly riding plans, FC depends on the swapping/charging subscription plan [39–41] (Table S2); (3) for e-scooters without riding plans, FC depends on fuel efficiency [35], electricity prices (the 10-year average is NT$2.73/kWh [42]), and

[1] The upstream WTP emissions of electricity generation is divided into the fuel production and the feedstock production periods. While the feedstock production emissions are obtained from the GREET-Taiwan model (0.022 kgCO_2eq/kWh) [34], the electricity production emissions (0.530 kgCO_2eq/kWh) are derived from the publicly available data (Section 2.4).

annual VKT. O&M is the non-fuel operating and maintenance costs per year, including compulsory insurance costs [43] (Table S3), maintenance costs [44,45](ICE scooters: based on Sanyang Motor official data; e-scooters: based on Gogoro official data; Table S4), and annual vehicle use taxes [46] (Table S3).

2.4. GHG emission intensity projections in the electricity system

The carbon emissions impact of electricity generation can be measured through GHG emission intensity, which is a key factor when evaluating the lifecycle climate benefits of vehicle electrification. In this study, we follow the European Commission definitions and compute the GHG emission intensity of electricity production as the ratio of carbon emissions from electricity generation and gross electricity generated [47]. The study scope includes all the electricity generated in Taiwan, not only limited to the electricity sold by Electricity Retailing Utility Enterprises[2] as defined in the power emission factor published by the Bureau of Energy [48].

By utilizing the data provided by Environmental Protection Administration (EPA) [49], Taiwan Power Company (i.e., Taipower[3]) [50], and Independent Power Producers (IPPs) [51], we estimate the GHG emission intensities of every fossil-fuel-fired power generator and the average carbon intensity of electricity generated in 2020. Furthermore, we project the future GHG emission intensity in Taiwan's electricity system throughout 2050 based on the power mix trajectory—derived from "Taiwan's Pathway to Net-Zero Emissions in 2050 (2050 Pathway to Net-Zero Emissions)" [52]. According to the government's roadmap for the power sector, the share of renewables in the electricity supply will significantly increase to at least 60%, with another 9–12% coming from hydrogen by 2050 to achieve net-zero emissions. The estimated future electricity mix and the associated GHG emission intensity of electricity during the fuel production and feedstock production periods are summarized in Table S5. It is noted that Taipower's development plans through 2027, such as the new installation schedule for natural gas generators and retirement dates of the existing coal-fired power generators, are considered when assessing the national average emission intensity of the thermal power plants [53].

2.5. Fuel efficiency targets to achieve net-zero emissions by 2050

In response to the rising global ambitions on climate change mitigation, Taiwan has established long-term GHG emissions reduction targets and committed to attaining net-zero emissions by 2050. The 2050 Pathway to Net-Zero Emissions sets the targets that direct GHG emissions from the road transportation sector should be reduced from 37.0 Mt in 2019 to 24.2 Mt in 2030, 13.7 Mt in 2040, and 3.2 Mt CO_2eq in 2050 [52]. By following the method applied by Miotti et al. [19], we estimate the fuel efficiency targets for on-road scooters in two steps: (1) allocate a fraction of the road transport emission targets to scooters; (2) divide these numbers by the total distance expected to be ridden by scooters. We note that the fuel efficiency target calculations face numerous uncertainties in allocating emission reductions across vehicle types (i.e., passenger cars, scooters, buses, and trucks) and scooter riding demand. While the policy decision will largely determine the former, the latter will be affected by various factors such as public transport systems and transportation innovations.

Due to the lack of future trend studies in Taiwan, we make the following assumptions and calculations. Firstly, we assume the scooter share of the total road transport emissions remains at the 2020 level—which was found to be 21.6% [54]. Secondly, we assume the annual scooter riding demand per scooter stays constant. The scooter use intensity (i.e., two-wheeled vehicle kilometer traveled; VKT) is estimated from the regular exhaust inspection records of scooters provided by the EPA [28], which is 6400 km per year on average in 2020. Lastly, Taiwan's scooter market dynamics (such as scooter ownership demand) are explored. According to the government household survey [55], passenger car ownership follows an S-shaped curve as income increases, but the scooter ownership rate shows an inverted U-shaped pattern in Taiwan. This observation is consistent with the recent study pointing out that two-wheeler ownership will increase in the beginning stage as income increases but will start decreasing once a threshold income is exceeded—which is called the "Motorcycle Kuznets Curve" [56,57]. Based on Tsai et al. [54], the scooter stock in Taiwan will peak at 13.96 million in 2024 and then decrease to 13.83 million in 2030, 13.25 million in 2040, and 12.11 million in 2050. By dividing the GHG emission targets for scooters by the expected total number of scooters and the annual two-wheeled VKT, we obtain the required fuel consumption rates for meeting 2030, 2040, and 2050 targets.

3. Results

3.1. GHG emissions and ownership costs of 156 scooters on the market

Fig. 1 shows the cost-carbon space of the scooters available on the market today in Taiwan (see Table S6 for all the data points). We find that the lifecycle carbon footprints and ownership costs differ a lot from one to another, both within and across scooter technology types. Overall, advanced powertrain technologies (e-scooters) produce lower carbon emissions but cost more than their gasoline counterparts. For example, the most popular e-scooter, Gogoro VIVA MIX, emits 62% less than the average ICE scooter; however, riders need to pay 38% more for ownership without subsidies and 22% more with subsidies.

Today's consumers face a trade-off between costs and carbon emissions when selecting a scooter model with different powertrain technologies. This trade-off is also encountered (but not so obvious) when consumers choose between the Phase 6 and Phase 7 gas scooters. On the other hand, with the same powertrain technology, scooters with lower emissions are generally less expensive to own. As one example, Yamaha Jog, one of the best-selling scooters in Taiwan, is not only the least emitting but also the most affordable ICE scooter. Note that the carbon footprints of personal vehicles – BEV (Tesla Model 3) and ICEV (Toyota Corolla Altis) – are also evaluated and displayed in the figure, highlighting that electric two-wheelers offer a much more sustainable means of personal vehicle transport.

When only considering the scooter purchase prices (Fig. 1(b)), we find that most e-scooters do not have higher upfront costs than ICE scooters. This observation contrasts the previous study regarding personal vehicles, which showed that the comparison would shift in favor of ICEVs [19]. The main reason causing this difference is primarily because battery swapping techniques convert the capital cost of the most expensive component – battery – to an operating expense. Separating the battery from an e-scooter brings it on par with an ICE counterpart or even lower in some cases. Consumers who are not sensitive to the initial cost when buying a scooter may find e-scooters are cost-competitive to own.

Currently, the governments provide purchase subsidies for both e-scooters and ICE scooters with the Phase 7 emission standard.[4] The purchase subsidy amount varies by powertrain technology, e-scooter class, and county, as displayed in Table S1. While the Phase 7 ICE scooter buyers can receive NT$3000 to $9000 in subsidies, e-scooter purchase subsidies vary greatly—ranging from NT$10,000 in Hualian to

[2] Electricity Retailing Utility Enterprise is defined as a public utility that purchases electricity to resell it to the users.

[3] Taipower is the leading state-owned electric power company in Taiwan, providing about 68% of the national electricity needs [59].

[4] Whether ICEs should be financially supported for "the coexistence and co-prosperity of gasoline- & battery-powered scooters" remains a debate over the past few years in Taiwan [60,61].

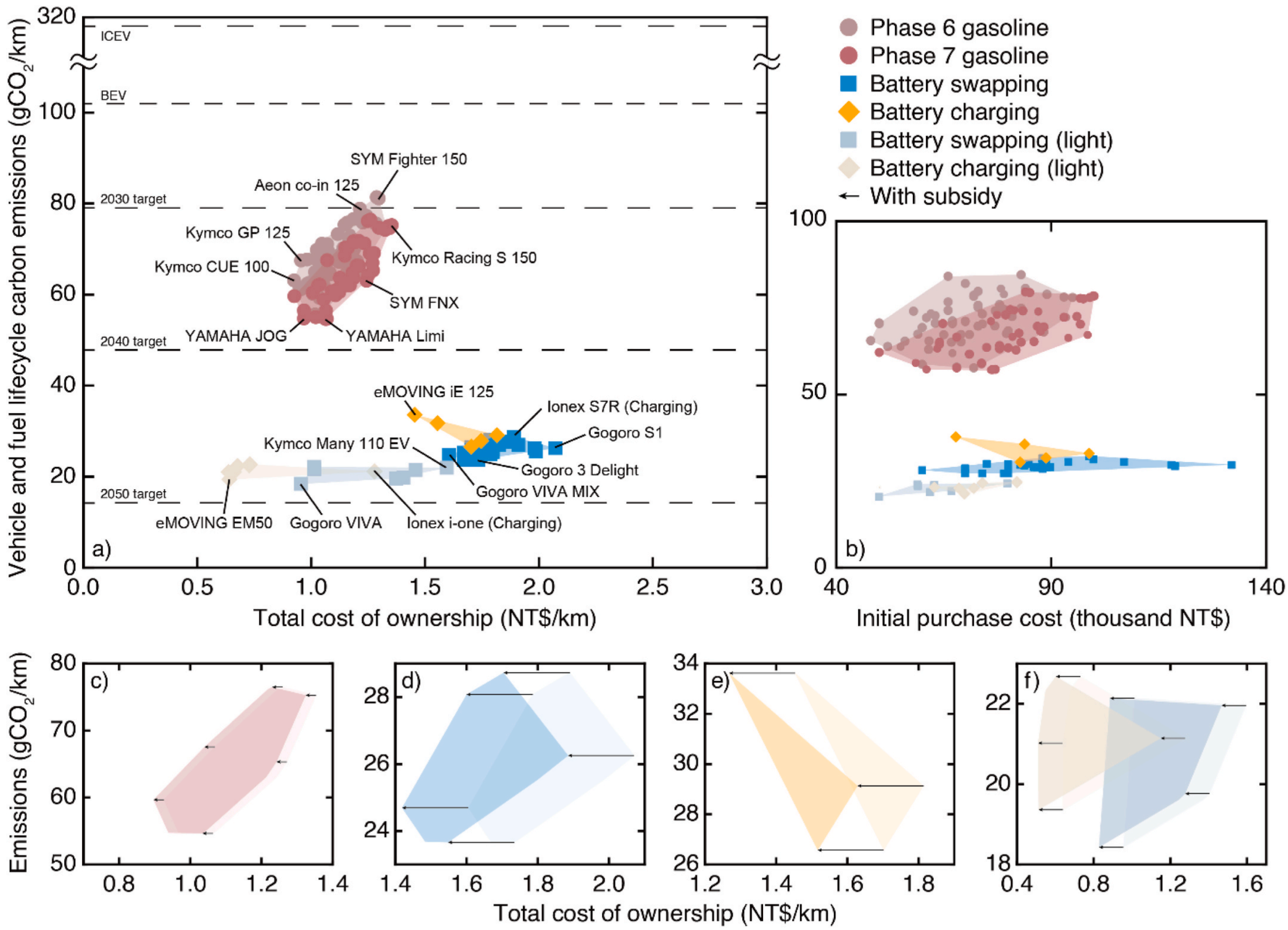

Fig. 1. (a) Costs and carbon emissions comparison of 156 new scooter models offered in the Taiwan market in 2021, assuming a 16-year lifetime, 6400 km ridden annually, a 6% discount rate, and without subsidies. Carbon emissions of personal vehicles are also examined and indicated for comparison (ICEV: Toyota Corolla Altis; BEV: Tesla Model 3); (b) Same as panel (a), but the x-axis refers to the initial purchase costs only without subsidy. (c–f) TCO with and without subsidy: (c) ICE scooters with the Phase 7 standard; (d)–(e): e-scooters with battery swapping and charging versions; (f) lightweight e-scooters with battery swapping and charging versions. Estimated GHG emissions and ownership costs for each of the 156 analyzed scooter models can be found in Table S6.

$42,000 in Kinmen county. By selecting the direct subsidy in the capital city of Taiwan (Taipei) as an example,[5] we evaluate the impacts of the purchase incentive program on the cost-competitiveness of advanced powertrain technologies; the results are shown in Fig. 1(c)–(f). The government is closing the cost gaps through subsidies and differences in taxes collected, making the subsidized Phase 7 ICE scooters achieve TCO parity with the Phase 6 ones. However, the subsidized e-scooters are still much more costly than their ICE counterparts by 21%–78%.

3.2. Breakdown of GHG emissions and ownership costs comparisons

Fig. 2 shows the average GHG emissions and ownership costs of 156 scooters available on the market today, broken down by different contributors. Within the same powertrain technology, the Phase 7 emissions per km are, on average, 5% lower than the Phase 6 ICE scooters; however, these carbon reduction benefits are uncertain—depending on the various model-specific fuel consumption rates. Besides, e-scooters with charging mode produce 15% more emissions per km than those with swappable batteries due to the lower fuel efficiency. Across the different powertrain technologies, scooter electrification would significantly reduce carbon emissions by 63%. Increased emissions from battery and electricity production phases are offset by decreased emissions during the vehicle operation phase (owing to enhanced powertrain efficiency). Moreover, lightweight e-scooters would further reduce emissions by 20% compared to normal electric ones by consuming 9% less electricity per km.

Despite their environmental advantages, e-scooters cost much more than their ICE counterparts—even considering the government subsidies (Fig. 2(b)). When adopting an e-scooter (no matter with charging or swapping versions), customers are not buying the most expensive part – the battery ownership, making the upfront purchase costs of e-scooters competitive with ICE ones even in the absence of incentives. Nevertheless, customers have to pay a monthly fee for riding, ranging from NT $ 299 to 899—depending on the subscription plans and scooter models (Table S2); these riding plans cause e-scooters to be more costly to operate and own. The current financial incentives for e-scooters purchased in Taiwan amount to 19,000 NT$ reductions in lifetime 16-year (i.e., 102,400 km) TCO, equivalent to 0.19 NT$ reductions per kilometer traveled. However, government subsidies are not sufficient to make e-scooters more economically attractive nowadays, and making subsidy policy does not meet the societal goals (for more details regarding

[5] The purchase subsidies from the central and local government in Taipei are as follows: Phase 7 ICE scooter NT3,000; e-scooters NT19,000 for normal and NT13,000 for lightweight.

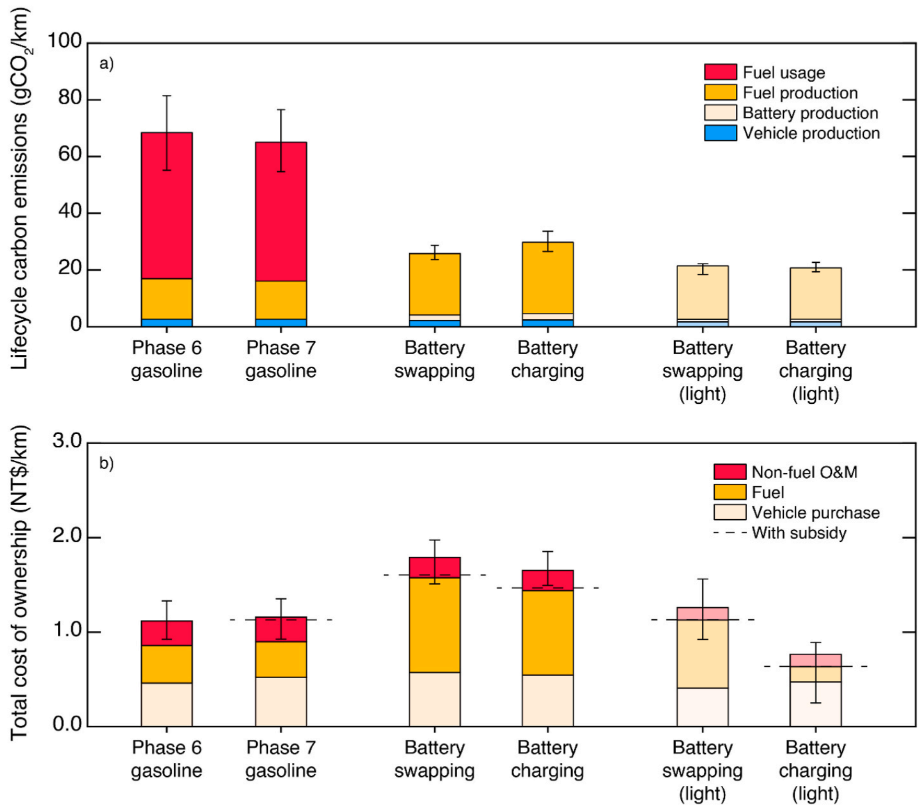

Fig. 2. Averages by scooter class and powertrain technology of (a) lifecycle GHG emissions and (b) total ownership costs for the data displayed in Fig. 1. Error bars are from model differences in the purchase price, fuel economy, and battery size.

energy policy failure, see Ref. [58]).

3.3. Scooter use intensity impacts on trade-offs between carbon and costs

Within the same powertrain technology, the cost-carbon comparison of different emission standards or charging versions for the comparable scooter models could provide further insights. We find that ICE scooters with stricter emission limits always cost more for the same scooter model. However, the existence of a cost-carbon trade-off in selecting an e-scooter model with swapping or charging mode depends on the customers' riding intensity (i.e., VKT). Under lower scooter use intensity conditions, such as the citizens in Taipei county, e-scooters with charging mode cost less than their swapping counterparts. In regions with relatively high scooter use intensity, like Kaohsiung county, swappable e-scooters are found to be cheaper overall than the charging version. A breakeven analysis is conducted to determine at what annual distance-ridden level battery charging version would become more cost-attractive. Take the Ionex S6 for an example (see inset Fig. 3). Both

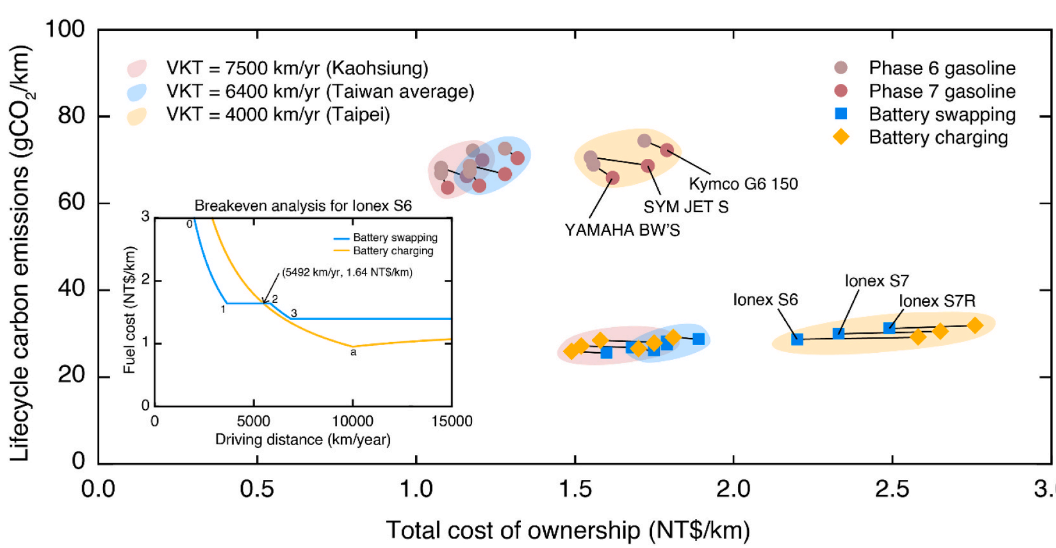

Fig. 3. Cost-carbon space for the counterpart scooters with different emission standards (phase 6 versus phase 7 gasoline) and charging versions (swapping versus charging) under 4,000, 6400, and 7500 km ridden annually. The inset shows the breakeven analysis results for fuel costs with various VKT between battery charging and swapping versions, using Ionex S6 as an example.

swapping and charging versions are offered in the market with different subscription plans: For swapping mode, the monthly subscription plans start at 499 NT$ for monthly VKT below 304 km (point 0 to 1) and increase to 799 NT$ when monthly VKT is greater than 488 km and less than 573 km (point 2 to 3). For charging mode, the monthly flat fee is 699 NT$ with a maximum annual VKT of 10,000 (point a). After exceeding the kilometers packaged in a plan, customers need to pay an additional charging fee per kilometer ridden. We find that the battery-swapping version would cost less than the charging one when the annual VKT is below 5500. Fig. 3 also points out that no matter which propulsion system a scooter is equipped with, the greater intensity a scooter is used, the cheaper per-km TCO would be.

3.4. Scooter models for achieving net-zero emissions targets in taiwan

We find that, surprisingly, all the Phase 7 ICE scooter models meet the 2030 emissions reduction targets, but none of them meets the medium- and long-term climate goals (Fig. 1(a)). To enable climate goals for 2040, electrifying nearly half of the on-road operating scooters (i.e., 47%) is needed under the current electricity mix. 100% e-scooter stock share in 2040 implies that consumers should start switching from ICE scooters to electric ones around 2025, given the average scooter ownership lifespan of 16 years. However, with the current electricity carbon intensity, none of the currently available e-scooter models meet the long-term 2050 target. According to the power sector roadmap, renewable energy will account for 60% of Taiwan's power supply in 2050, decreasing the grid emission intensity by 77% from 2020 to 2050. Fig. 4(a) illustrates the expected lifecycle GHG emissions reductions achieved by improving grid carbon intensity throughout 2050. The results indicate that deep decarbonization of the electric power system and scooter electrification are simultaneously needed to achieve the 2050 net-zero emissions target. Under the expected power mix trajectories, the emissions targets require the on-road fleet consisting of at least 62% and 89.7% e-scooters, with the rest of 38% and 10.3% Phase 7 ICE scooters in 2040 and 2050, respectively (Fig. 4(b)).

3.5. Sensitivities of ownership costs and GHG emissions to parameters

A number of factors contribute to the ownership cost and lifecycle GHG emissions, making the cost-carbon space of scooters vary under different conditions. We explore the uncertainties in four parameters: discount rate, scooter ownership years, e-scooter purchase subsidies, and carbon intensity of electricity. Fig. 5 illustrates the cost and carbon ratios of e-scooters to ICE scooters with respect to these parameters. The 2020 average ownership costs and GHG emissions of 156 scooters displayed in Fig. 1 are used to calculate the base of the tornado diagram (Fig. 5); the baseline TCO and carbon ratios are 1.56 and 0.42, respectively. Note that the impacts of the uncertainty in annual distance ridden are already examined in Section 3.3 and thus not included here.

The discount rate reflects the relative importance of the upfront costs compared to annual potential savings/expenses on fuel and maintenance. Our sensitivity analysis results show that the discount rate only has a minor impact on the cost ratio. Increasing the discount rate from 2% to 10% (baseline is assumed to be 6%) increases the e-scooter/ICE scooter TCO ratio from 1.55 to 1.57. This result is mainly driven by the fact that instead of future savings, there are even more expenses on fuel (electricity) for swappable e-scooters that technically convert the upfront costs of the battery to future operating costs. According to the results for sensitivity to ownership lifespan, the TCO ratio is still not sensitive to this variable (though more than the discount rate). Longer ownership years would amplify the fuel cost differential between e-scooters and ICE scooters, causing the TCO ratio to increase from 1.52 to 1.60 when the lifespan lengthens from 12 years to 20 years. Purchase subsidies have been a key factor in promoting e-scooter deployment. However, the cost-carbon space mapped out in Fig. 1(a) assumes no subsidies because the governments are expected to phase out the incentive programs as the e-scooter market matures. In Fig. 5(a), we include the purchase incentives of NT$42,000 (i.e., the highest subsidy amount in Taiwan) to examine the sensitivity, which decreases the TCO ratio to 1.32—illustrating the strong influence of government subsidy on e-scooter ownership costs.

The decarbonization level of the electric power sector varies by country, making the climate benefits of scooter electrification differ across the globe. To evaluate whether e-scooters provide carbon advantages over ICE scooters across the globe, we explore the sensitivity of the emissions to grid carbon intensity. Fig. 5(b) suggests that the makeup of the power mix determines the carbon footprint mitigation potential of electrifying scooters. Decreasing the carbon intensity of electricity generation from 0.625 $kgCO_2/kWh$ to 0.012 $kgCO_2/kWh$ would lower the ratio of the emissions for e-scooters relative to ICE scooters by 82% (from 0.65 to 0.03). Note that South East Asian countries with many scooters are indicated in the figure, showing that even in Indonesia, where electricity is mainly generated from fossil fuels (~88%), scooter electrification still delivers great environmental benefits.

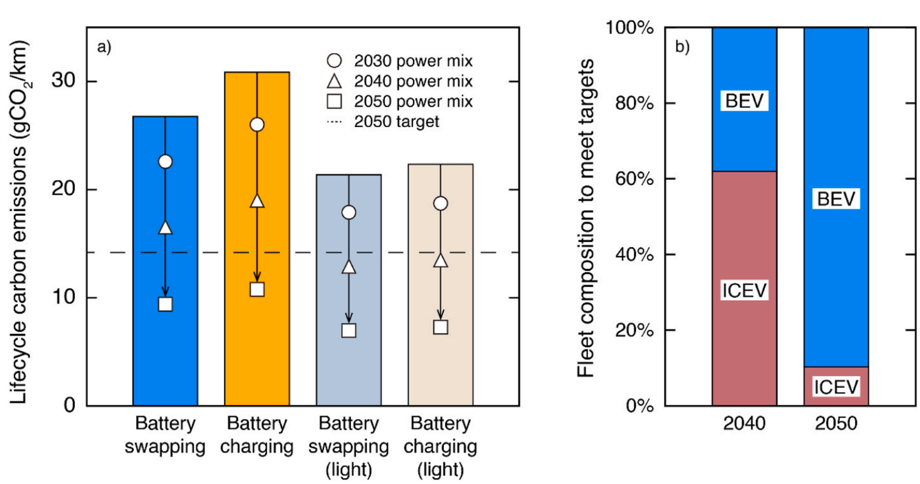

Fig. 4. (a) Average lifecycle GHG emissions projections of e-scooters as a function of improving carbon intensity of the electricity generation under Taiwan's power sector transformation roadmap for the net-zero emissions target by 2050. (b) Fleet composition with minimum shares of battery powertrain technology to meet the 2040 and 2050 net-zero emissions targets, based on the average fuel efficiency of the available models shown in Fig. 1.

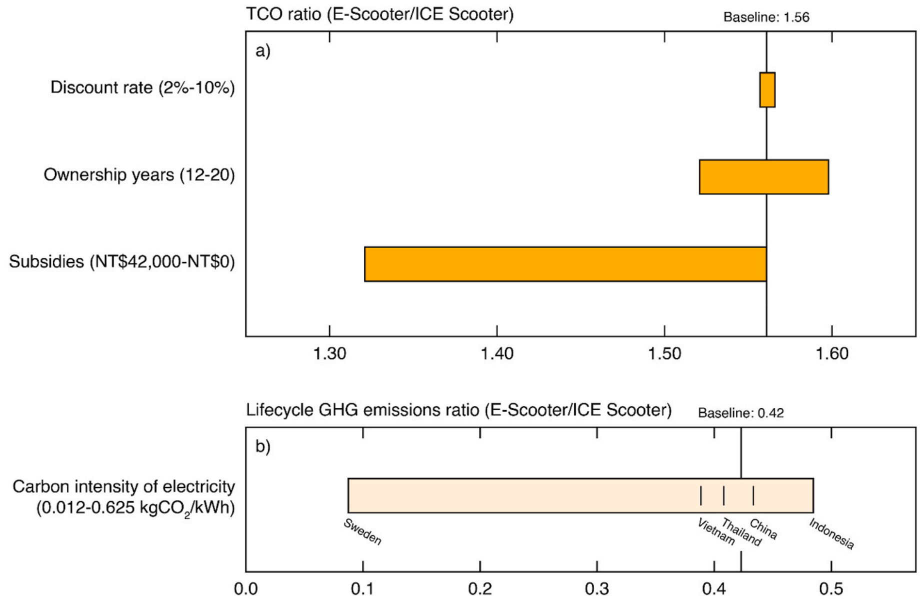

Fig. 5. Sensitivity analysis for the ratios of e-scooters relative to ICE scooters: (a) total cost of ownership (TCO); (b) lifecycle carbon emissions.

4. Discussion

This paper examines the cost and carbon performances of a comprehensive set of 156 scooter models on the market today. With the world's highest density of scooter ownership, Taiwan is selected as a study interest to cover a broad spectrum of scooter models. Two-wheelers have been a favored and dominant mode of personal transport in many countries, especially in South-East Asia, mainly because of their comparatively lower private vehicle ownership costs. Despite its popularity, two-wheeled vehicles have not yet been thoroughly studied across the diversity of today's available models against climate change mitigation targets in the existing literature. This study, therefore, fills the current scientific gap in understanding the potential trade-offs among two-wheeler purchase options from consumers' perspectives.

We find that consumers do not face a trade-off between costs and emissions when selecting a scooter model within the same powertrain technology: The less-emitting scooters generally correspond to lower ownership costs. However, such cost and carbon trade-off does exist when choosing scooter models with different powertrain technologies. Consumers have to pay up to 124% more (110% more costly with subsidies) for e-scooters having 56% lower emissions than their ICE counterparts. When only considering the purchase prices, the cost differences between electric and ICE scooters become even more significant because swappable batteries technically convert the initial capital cost of the battery – the most expensive component – to an operating cost. These findings suggest that the existing government subsidies are not sufficient to fill the cost gaps and thus fail to encourage wider e-scooter adoption—which might be further exacerbated amid the rising inflation. Financial incentives play a significant role in encouraging consumers to switch to low-emission scooters. However, with the government beginning to cut the e-scooter purchase subsidies, we expect that the e-scooter uptake will slow down in the foreseeable future, causing a problem for Taiwan in achieving its net-zero emissions future.

Surprisingly, it appears that all the available Phase 7 ICE scooters meet the near-term 2030 climate target—implying that ICE scooters with higher fuel efficiency are a promising form of two-wheeled transportation to facilitate a less-costly transition from liquid fuels to electrification. Our analysis results provide good evidence and reasons why the government is simultaneously subsidizing the Phase 7 ICE purchases besides electric ones. Nevertheless, none of the Phase 7 ICE scooters meet the target for the mid-term future goal—exceeding 36% on average. In contrast, all of the available e-scooter models, even with the current electricity supply mix, can meet the 2040 climate goal. The long-term net-zero emissions, however, do require the deep decarbonization of the power grid. Under the government's power sector transformation roadmap, the GHG emission intensity will continue to decline with the increase in renewables and a decrease in coal-fired electricity. To enable a net-zero emissions future, the share of e-scooters would need at least 90% in the operating scooter fleet by 2050, with more than 60% renewable power supply. The study highlights that the climate impacts of e-scooter deployment depend on the decarbonization progress of the electric grid. Consequently, policies to encourage scooter electrification should go hand-in-hand with support for low-carbon electricity generation.

Credit author statement

Yuan-Hsi Chien: Formal analysis, Investigation, Writing - Original Draft, Visualization. I-Yun Lisa Hsieh: Conceptualization, Methodology, Supervision, Writing - Review & Editing. Tsung-Heng Chang: Formal analysis, Investigation, Writing - Original Draft.

Declaration of 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.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the National Science and Technology Council, Taiwan (MOST 109-2222-E-002 -006 -MY2, NSTC 111-2222-E-002-019).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2023.101056.

References

[1] IEA, Transport Sector CO2 Emissions by Mode in the Sustainable Development Scenario, 2000-2030 – Charts – Data & Statistics - IEA. https://www.iea.org/data-and-statistics/charts/transport-sector-co2-emissions-by-mode-in-the-sustainable-development-scenario-2000-2030, 2022 (accessed 21 July 2022).

[2] M. Weiss, P. Dekker, A. Moro, H. Scholz, M.K. Patel, On the electrification of road transportation – a review of the environmental, economic, and social performance of electric two-wheelers, Transport. Res. Transport Environ. 41 (2015) 348–366, https://doi.org/10.1016/j.trd.2015.09.007.

[3] S.M. Platt, I.E. Haddad, S.M. Pieber, R.-J. Huang, A.A. Zardini, M. Clairotte, R. Suarez-Bertoa, P. Barmet, L. Pfaffenberger, R. Wolf, J.G. Slowik, S.J. Fuller, M. Kalberer, R. Chirico, J. Dommen, C. Astorga, R. Zimmermann, N. Marchand, S. Hellebust, B. Temime-Roussel, U. Baltensperger, A.S.H. Prévôt, Two-stroke scooters are a dominant source of air pollution in many cities, Nat. Commun. 5 (2014) 3749, https://doi.org/10.1038/ncomms4749.

[4] M. Kjærup, M.B. Skov, N. van Berkel, E-Scooter, Sustainability – a clash of needs, perspectives, and experiences, in: Human-Computer Interaction – INTERACT 2021: 18th IFIP TC 13 International Conference, Springer-Verlag, Bari, Italy, 2021, pp. 365–383, https://doi.org/10.1007/978-3-030-85613-7_26.

[5] M. Verma, A. Verma, M. Khan, Factors influencing the adoption of electric vehicles in Bengaluru, Transportation in Developing Economies 6 (2020) 17, https://doi.org/10.1007/s40890-020-0100-x.

[6] W. Sierzchula, S. Bakker, K. Maat, B. van Wee, The influence of financial incentives and other socio-economic factors on electric vehicle adoption, Energy Pol. 68 (2014) 183–194.

[7] J.H.M. Langbroek, J.P. Franklin, Y.O. Susilo, The effect of policy incentives on electric vehicle adoption, Energy Pol. 94 (2016) 94–103.

[8] insightxplorer, Willingness to buy an EV because of environmental issues,. https://www.ixresearch.com/news/news_05_25_21, 2021 (accessed June 22 2022).

[9] A. Nordelöf, M. Messagie, A.-M. Tillman, M. Ljunggren Söderman, J. Van Mierlo, Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int. J. Life Cycle Assess. 19 (2014) 1866–1890, https://doi.org/10.1007/s11367-014-0788-0.

[10] B. Marmiroli, M. Messagie, G. Dotelli, J. Van Mierlo, Electricity generation in LCA of electric vehicles: a review, Appl. Sci. 8 (2018) 1384, https://doi.org/10.3390/app8081384.

[11] P. Letmathe, M. Suares, A consumer-oriented total cost of ownership model for different vehicle types in Germany, Transport. Res. Transport Environ. 57 (2017) 314–335, https://doi.org/10.1016/j.trd.2017.09.007.

[12] M. Wang, A. Elgowainy, P.T. Benavides, A. Burnham, H. Cai, Q. Dai, T.R. Hawkins, J.C. Kelly, H. Kwon, D.-Y. Lee, U. Lee, Z. Lu, L. Ou, Summary of Expansions and Updates in GREET® 2018, Argonne National Lab. (ANL), Argonne, IL (United States), 2018, https://doi.org/10.2172/1483843.

[13] N.C. Onat, M. Kucukvar, O. Tatari, Conventional, hybrid, plug-in hybrid or electric vehicles? State-based comparative carbon and energy footprint analysis in the United States, Appl. Energy 150 (2015) 36–49.

[14] W. Shen, W. Han, T. Wallington, S. Winkler, China Electricity Generation Greenhouse Gas Emission Intensity in 2030: Implications for Electric Vehicles, vol. 53, Environmental Science & Technology, 2019, https://doi.org/10.1021/acs.est.8b05264.

[15] B. Cox, C. Bauer, A. Mendoza Beltran, D.P. van Vuuren, C.L. Mutel, Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios, Appl. Energy 269 (2020), 115021, https://doi.org/10.1016/j.apenergy.2020.115021.

[16] B.M. Sopha, S. Setiowati, S. Ma'mun, Environmental Assessment of Motorcycle Using a Life-Cycle Perspective, https://www.semanticscholar.org/paper/Environmental-Assessment-of-Motorcycle-using-a-Sopha-Setiowati/53d30e4dd49587c83634330a6053e199105fe239, 2017 (accessed June 22 2022).

[17] G. Carranza, M. Do Nascimiento, J. Fanals, J. Febrer, C. Valderrama, Life cycle assessment and economic analysis of the electric motorcycle in the city of Barcelona and the impact on air pollution, Sci. Total Environ. 821 (2022), 153419, https://doi.org/10.1016/j.scitotenv.2022.153419.

[18] M. Kazmaier, T.T. Taefi, T. Hettesheimer, Techno-economical and ecological potential of electric scooters: a life cycle analysis, Eur. J. Transport Infrastruct. Res. 20 (2020) 233–251, https://doi.org/10.18757/ejtir.2020.20.4.4912.

[19] M. Miotti, G.J. Supran, E.J. Kim, J.E. Trancik, Personal vehicles evaluated against climate change mitigation targets, Environ. Sci. Technol. 50 (2016) 10795–10804, https://doi.org/10.1021/acs.est.6b00177.

[20] R.O.C. Moi, Department of Household Registration, Number of Registration of Scooters (機動車輛登記數), https://stat.motc.gov.tw/mocdb/stmain.jsp?sys=100&funid=b3301, 2022 (accessed June 21 2022).

[21] Piaggio, The history of Vespa, From its Origins in 1946 to the Myth, Vespa. https://www.vespa.com/au_EN/timeline/ (accessed 10 November 2022).

[22] Bureau of Industry, M. of E. A., R.O.C., Website of Electric Vehicle Industries, https://www.lev.org.tw/index, 2021 (accessed June 22 2022).

[23] Gogoro Network, Gogoro Find Us. https://www.gogoro.com/tw/findus/, 2022. (Accessed 21 June 2022).

[24] National Development Council, Taiwan's Pathway to Net-Zero Emissions in 2050, National Development Council, https://www.ndc.gov.tw/en/Content_List.aspx?n=B927D0EDB57A7A3A&upn=A2B386E427ED5689, 2021, (accessed June 22 2022).

[25] tw 7car, What Is Phase 7 Emission Standard? (七期環保是什麼?) https://www.7car.tw/articles/read/62930, 2019 (accessed 21 July 2022).

[26] Bennetts.co.uk, What Does Euro 5 Mean for Motorcycling?,https://www.bennetts.co.uk/bikesocial/news-and-views/features/bikes/euro-5-emissions-what-they-mean-to-motorcycles, 2019 (accessed 21 July 2022) .

[27] K. Klemola, LIFE-CYCLE IMPACTS OF TESLA MODEL S AND VOLKSWAGEN PASSAT, 2016, p. 57.

[28] Environmental Protection Administration, The Regular Exhaust Inspection Records, the Regular Exhaust Inspection Records,https://motor.epa.gov.tw/Report/Report_List.aspx, 2021 (accessed 11 July 2022).

[29] Ministry of Transportation and Communications, Monthly Statistics of Transportation and Communications, https://www.motc.gov.tw/ch/home.jsp?id=578&parentpath=0%2C6&mcustomize=statistics301.jsp, 2021 (accessed June 21 2022).

[30] Q. Dai, J.C. Kelly, L. Gaines, M. Wang, Life cycle analysis of lithium-ion batteries for automotive applications, Batteries 5 (2019) 48, https://doi.org/10.3390/batteries5020048.

[31] F.-S. Pan, Y.-M. Lee, Life Cycle Inventory Analysis of Electric Scooters and Gasoline-Fueled Scooters, 2002. https://ndltd.ncl.edu.tw/cgi-bin/gs32/gsweb.cgi?o=dnclcdr&s=id=%22090NTPU1399011%22.&searchmode=basic.

[32] R.O.C. EPA, Executive Yuan, Carbon Footprint Information Website (產品碳足跡資訊網), https://cfp-calculate.tw/eng/WebPage/LoginPage.aspx, 2020 (accessed June 22, 2022).

[33] Bureau of Energy, M. of E. A., R.O.C., Carbon Intensity in 2020 (109年度電力排碳係數), Bureau of Energy, M. of E. A., R.O.C. World wide information website. (2021). https://www.moeaboe.gov.tw/ECW/populace/news/Board.aspx?kind=3&menu_id=57&news_id=20933 (accessed June 22, 2022).

[34] C.-Y. Liang, Environmental Protection Administration, CIER, Life-Cycle Analysis for Taiwan Vehicles, 2016.

[35] Bureau of Energy, M. of E. A., R.O.C., Energy Efficiency of Electric Vehicles (電動車輛能源效率標示),https://auto.itri.org.tw/energy_efficiency_mark_ecar.aspx, 2022 (accessed June 22, 2022).

[36] Bureau of Energy, M. of E. A., R.O.C., Energy Efficiency of ICE Scooters(各車型耗能證明核發月資料), https://www.moeaboe.gov.tw/ECW/populace/content/wfrmStatistics.aspx?type=6&menu_id=1304&sub_menu_id=5758, 2022 (accessed June 21 2022).

[37] M. of F. Taxation Agency, Service Life of Fixed Assets, https://law.dot.gov.tw/law-ch/home.jsp?id=12&parentpath=0,2&mcustomize=law_view.jsp&lawname=201803090218&article=0&article2=0&istype=L, 2018 (accessed June 23, 2022).

[38] C.P.C. Co, Taiwan, History Price of Gasoline and Diesel,https://www.cpc.com.tw/historyprice.aspx?n=2890, 2020 (accessed 21 July 2022).

[39] Gogoro Network, Riding Plans for Gogoro Network (電池服務資費方案-Gogoro), https://promotion.gogoro.com/tw/subscription/, 2022 (accessed June 23, 2022).

[40] Ionex, Riding Plans for Ionex (電池服務資費方案-Ionex), https://ionex.com.tw, 2022 (accessed June 23 2022).

[41] eMOVING, Riding Plans for eMOVING (電池租賃資費方案-eMOVING), https://www.e-moving.com.tw/iE125Renew, 2021 (accessed June 23, 2022).

[42] Taiwan Power Company, Historical Price of Electricity, 2021. https://www.taipower.com.tw/upload/43/43_04/%E6%AD%B7%E5%B9%B4%E7%B5%B1%E8%A8%88/%E6%AD%B7%E5%B9%B4%E5%B9%B3%E5%9D%87%E9%9B%BB%E5%83%B9-110.pdf.

[43] Fubon Insurance Co, Compulsory Insurance Insure Online (機車強制險線上投保-富邦), Ltd., https://www.fubon.com/insurance/b2c/content/main/new.html, 2021 (accessed June 23 2022).

[44] Sang Yang Motor, Maintenance Cost by SYM, 2021. https://tw.sym-global.com/storage/system/servicearea/maintenance/2021-maintenance-all.pdf.

[45] Gogoro Network, GogoroCare, https://www.gogoro.com/tw/gogorocare/, 2022 (accessed 23 June 2022).

[46] Directorate General of Highways, M. of T. and C., R.O.C., Fuel tax table (燃料費率) (2022). https://www.thb.gov.tw/page?node=b58eb9aa-3160-429b-af08-645d5ae19f4c (accessed 23 June 2022).

[47] E.U. EEA, Greenhouse Gas Emission Intensity of Electricity Generation in Europe 2021, 2022. https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1.

[48] R.O.C. Cdri, What is carbon intensity of electricity? (什麼是電力排碳係數?), https://escs.cdri.org.tw/?page_id=69, 2020 (accessed 19 July 2022).

[49] Environmental Protection Administration, Greenhouse Gas Emissions Information Platform for Businesses, 2020. https://ghgregistry.epa.gov.tw/ghg_rwd/Main/Examine/Examine_2.

[50] Taiwan Power Company, Annual Report of Taipower, 2020. https://www.taipower.com.tw/tc/page.aspx?mid=43&cid=30&cchk=203b0d86-6759-42c4-8c05-4080862a6cf9#b02 (accessed 11 July 2022).

[51] M. of E.A. Bureau of Energy, IPP Fire Power Station, 2020. https://www.moeaboe.gov.tw/ECW/populace/content/Content.aspx?menu_id=999 (accessed 11 July 2022).

[52] National Development Council, Taiwan's Pathway to Net-Zero Emissions in 2050, Taiwan's Pathway to Net-Zero Emissions in 2050, 2022,. https://www.ndc.gov.tw/Content_List.aspx?n=FD76ECBAE77D9811.

[53] Taiwan Power Company, Long-term Power Development Planning, 2021. https://www.taipower.com.tw/tc/page.aspx?mid=212&cid=122&cchk=260a432c-fc0e-47e0-a90e-2bc0cc52cb61 (accessed 11 July 2022).

[54] C.-Y. Tsai, T.-H. Chang, I.-Y.L. Hsieh, Evaluating vehicle fleet electrification against net-zero targets in scooter-dominated road transport, Transportation Research Part D: Transport and Environment114 (2023) 103542. https://doi.org/10.1016/j.trd.2022.103542.

[55] Directorate General of Budget, Accounting and Statistics, the Survey of Family Income and Expenditure, 2020. https://win.dgbas.gov.tw/fies/a11.asp?year=109.

[56] M.Y. Chu, T.H. Law, H. Hamid, S.H. Law, J.C. Lee, Examining the effects of urbanization and purchasing power on the relationship between motorcycle ownership and economic development: a panel data, International Journal of Transportation Science and Technology 11 (2022) 72–82, https://doi.org/10.1016/j.ijtst.2020.12.004.
[57] S. Nishitateno, P.J. Burke, The motorcycle Kuznets curve, J. Transport Geogr. 36 (2014) 116–123, https://doi.org/10.1016/j.jtrangeo.2014.03.008.
[58] M.M. Sokołowski, R.J. Heffron, Defining and conceptualising energy policy failure: the when, where, why, and how, Energy Pol. 161 (2022), 112745, https://doi.org/10.1016/j.enpol.2021.112745.
[59] Taipower, Co., Historical Amount of Power Ganerated, 2017. https://www.taipower.com.tw/tc/page.aspx?mid=212&cid=120&cchk=f3a1b1e0-03e5-45fa-b72e-b28c5cb94f37(accessed 19 July 2022).
[60] Y.-Y. Wang, Y.-H. Wu, H.-Y. Liang, Tendency and Policy of Scooters Form Taiwan in 2020 (「油電平權？」：2020全臺電動機車銷售趨勢與政策), 2021, https://rsprc.ntu.edu.tw/zh-tw/m01-3/en-trans/open-energy/1552-37-0225-open.html (accessed 15 July 2022).
[61] T.-L. Hsu, What Is the Next Step of E-Scooter Policy? (電動機車政策的下一步？), 2021. https://e-info.org.tw/node/231318 (accessed 15 July 2022).