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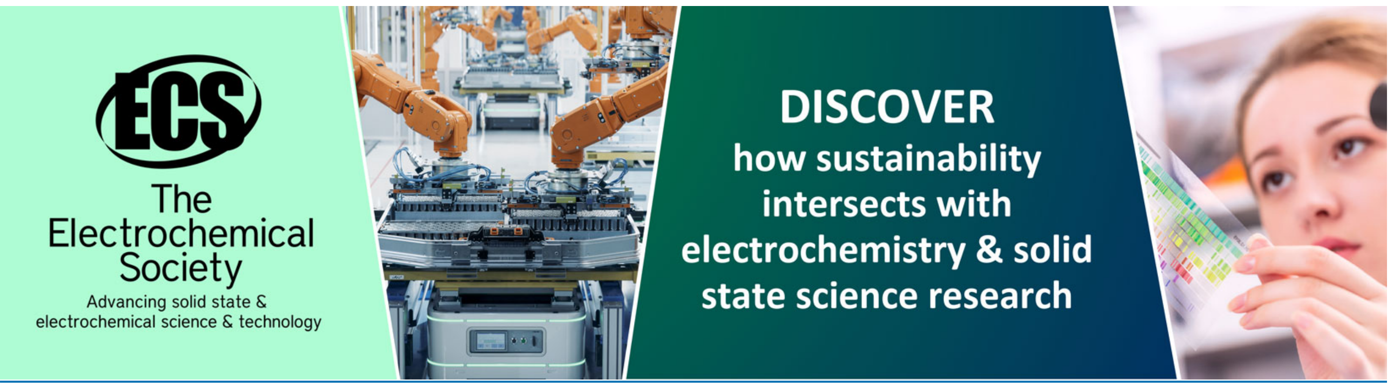

Evaluation of mitigation effects on air pollutants for electric scooters in Taiwan with the energy flow analysis and system dynamics approach

P Y Hsieh[1,4], L F W Chang[1], T Y Yu[2] and K C Wu[3]

[1]Graduate Institute of Environmental Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan (R.O.C.)
[2]Department of Risk Management and Insurance, Ming Chuan University, No. 250, Sec. 5, Zhong Shan N. Rd., Taipei 11103, Taiwan (R.O.C.)
[3]Institute of Applied Mechanics, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan (R.O.C.)

E-mail: d00541007@ntu.edu.tw

Abstract. This research establishes a localized dynamic system model to explore changes of air pollution emission in the transition of electric scooters (ES) considering energy transformation. The calculation of emission factors (EF) of criteria air pollutants and greenhouse gases for Heavy-duty Gasoline-powered Scooters (GSH) and Heavy-duty ES (ESH) is performed with energy flow analysis. Compared with the GSH, the EF of TSP, NOx, VOCs, and CO_2e for ESH reduce by, respectively, 14.8%, 97.4%, 100%, and 76.8% per kilometer travelled in 2016; although the SOx EF for ESH is 2.4 times higher than that for GSH, the increment is down to 22.2% in 2025. If the SOx emissions intensity of electricity reduce to 100 mg/kWh, the SOx EF for ESH will be lower than that for GSH. System dynamics and energy flow analysis can provide effective analysis about mitigation scenarios and these findings are helpful to local authorities for air quality management.

1. Introduction

Air pollution caused by the scooters' emissions is a serious concern in Taiwan with the world's highest density of scooters, reaching 378 per square kilometer. To improve the air quality, Environmental Protection Administration has established and actively promoted a program of "The development of Electric Scooter" since 1998. However, the market-share of electric scooters (ES) was not blooming and it held only around an 1% share of the motorcycle market in the past twenty years even the government offered a subsidy for purchasing ES.

The market share of scooters in Taiwan has changed dramatically in the past three years with the first Heavy-duty ES (ESH) launched in 2015 (table 1) [1]. The market-share of ES has finally exceeded 4% in 2017, and exceeded 7% in 2018 to the end of April. Focus on the market for ES, the relative market-share of Light-duty ES (ESL) fell from 100% in 2014 to 18% in 2017, and its market share was only 8% from January to April 2018. On the other hand, the market-share of ESH rose rapidly from 0% in 2014 to 82% in 2017, and exceeded 91% from January to the end of April 2018. However, the market share of the gasoline-powered scooter (GS) has dropped from 99% in 2014 to 96% in 2017, while it was only 93% from January to the end of April in 2018. In the GS market, the average market-share of Heavy-duty GS (GSH) accounted for 97%, and the one of Light-duty GS (GSL) accounted only for 0.5%.

Table 1. Market share of Scooter in Taiwan (*the data of 2018 includes Jan. to Apr.).

	2012	2013	2014	2015	2016	2017	2018*	Avg.
ES	**1.35**	**1.07**	**0.76**	**1.56**	**2.45**	**4.41**	**7.05**	**2.66**
ESH (%)	0.00	0.00	0.00	0.55	1.53	3.61	6.45	1.73
ESL (%)	1.35	1.07	0.76	1.01	0.92	0.80	0.59	0.93
GS	**98.65**	**98.93**	**99.24**	**98.44**	**97.55**	**95.59**	**92.95**	**97.34**
GSH (%)	97.15	96.39	96.17	94.77	94.74	92.96	90.73	94.7
GSL (%)	0.50	0.50	0.51	0.51	0.52	0.68	0.23	0.49
Others (%)	1.00	2.04	2.55	3.16	2.29	1.95	1.99	2.14

This study mainly discusses that the changes in the number of heavy-duty scooters with time, including GSH and ESH, and assesses the reduction of air pollution by substituting a GSH for an ESH for two reasons. First, the average market share of GSH plus ESH is around 96.05% from 2015 to 2017. The market share of ESH is higher than 92.95%, and that of ESH is higher than 6.45% from January to the end of April in 2018. Second, ESH in Taiwan has become a more attractive. ESH is also the battery-swapping electric scooter for now, which improve the disadvantage that wait to charge. Besides, a company of ESH launched portable battery chargers as an alternative option for customers to increase the ES's competitiveness [2].

This study consists of three main parts to gain a more comprehensive assessment of the change of air pollution emission. Firstly, a new system dynamic (SD) model of the transition to ES with time and the assessment of localized air pollutant emission of GSH and ESH is built up to understand the reduction potential for the transitions of ESH and energy. Secondly, calculations of emission factors (EF) of criteria air pollutants (NOx, VOCs, TSP and SOx, hereinafter CAPs) and greenhouse gases (CO_2, CH_4, and N_2O, hereinafter GHGs) for GSH and ESH are performed by energy flow analysis, which the boundary combines associate stationary, mobile and area pollution source. Thirdly, three scenarios of power structure and different speeds of ESH transitions were set to identify the key parameters for achieving the reductions of GHSs and air pollution now and in the future.

2. New system dynamic model of the number of electric scooter transition with time

System dynamic (SD) is a useful tool to help address complex issues involving delays, feedbacks and nonlinearities, and to explore complex long-term policies [3]. In the transportation research, there are many papers apply SD to study system issues in transportation, such as [4] and [5]. To explore the growing trend of ES and their influence on the reduction assessment of air pollution under various scenarios between 2016 and 2035, this paper builds up a new SD model of ESH transition and an assessment of CAPs and GSGs emission. There are three functions of the model. First, the model could show the flexible interconnections between the transition to ES and the reduction of energy consumption and environmental impacts. Second, the model could explore the key parameters for the development of ESH. Third, the model could assess the possibility that the benefits of carbon and CAPs reduction in the future.

The main variables influencing the market-share of scooter include the taxes imposed on GSH, the subsidy for purchasing ESH, the convenience of energy supplements for ESH, etc. Figure 1 shows a version of ESH and GSH stocks to simulate the dynamic behavior of complex ES transition and CAPs reduction in this study.

The model lets the tax incentive which is from the GSH and the tax would become the subsidy which is a part of incentive to buy ESH in substitution for GSH. Another incentive to buy ES is the ratio of the amount of electricity supplement stations to the gas stations, and this research assumes the ratio would increase with the growth of ESH. The *policy factor* in the model that would influence the market penetration of ESH. The market-shares of ESH and GSH are set 4% and 93% in 2017; those are 97% and 0% in 2035.

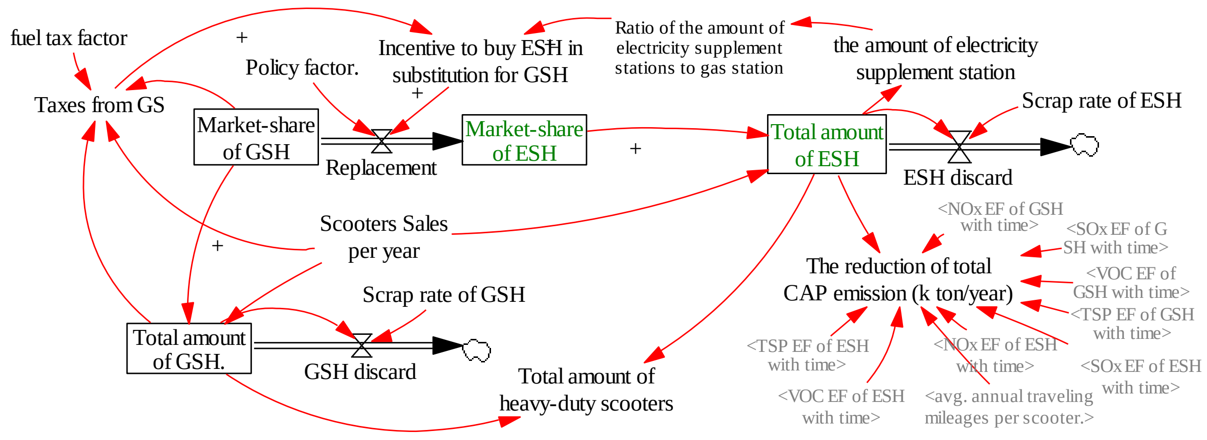

Figure 1. Simplified causal loop and stock-and-flow diagrams for GS and ESH stock.

The main variables influencing the emission of scooter include EF_k, the number of scooters and kilometers traveled. The formula for calculating the air pollution emissions of GSH and ESH of the air pollutant emission is $E_{i,k} = EF_{i,k} \times KT \times N_i$. The $E_{i,k}$ indicates the emission (ton/year) in the i-th type of energy flow path for the k-th pollutant, $EF_{i,k}$ indicates the respective emission factors for the k-th pollutant, KT indicates the average kilometers travelled per year per scooter, and N_i indicates the respective number of scooters. The next section shows more details of the calculation of $EF_{i,k}$.

3. The $\mathrm{EF_k}$ of CAPs and GHGs for GSH and ESH in Taiwan with energy flow analysis

3.1. The comparisons of EF_k between GSH and ESH

Most papers agree that the efficiency of an electric vehicle is higher than a gasoline vehicle and the emission of GHGs is less considering well-to-wheel, for example [6], [7] and [8], but the reduction of CAPs would be affected by the power structure of each country.

The $EF_{i,k}$ which this study built up combine all EFs of components and the energy efficiency in the energy flow path. The components in the energy flow path of GSH mainly include shipping, refinery, gas station and final burn in the engine of a vehicle. The components in the energy flow path of ESH mainly include power sector, transmission and distribution of electricity, charging station and final stage of ESH. To sum up, the formula of $EF_{i,k}$, which combines all emissions in each energy path stage, is

$$EF_{i,k} = \sum_{j=1}^{n-1} \left(EF_{i,j,k} \div \prod_{t=j}^{n} \eta_{i,t}\right) + EF_{i,n,k} \tag{1}$$

where $EF_{i,j,k}$ indicates the respective emission factors for the k-th pollutant in the j-th stage of the i-th path (mg/km), i indicates the type of energy flow path for GSH or ESH, j indicates the different stages or components in each path, n indicates the number of components in the energy flow path, k indicates the different air pollutant emission factors in each component, $\eta_{i,t}$ indicates the efficiency of the t-th stage in the i-th path.

3.2. System boundary for the GHGs and traditional air pollutants emission assessment

In this paper, the boundary, that combines associate stationary, mobile and area pollution source, of $EF_{i,k}$ assessment concludes the direct and indirect emission of CAPs and GHGs. The stationary pollution sources include power plants and refineries. The mobile pollution sources include the end pipes of ESH and GSH. The area pollution sources include gas stations and petroleum shipping.

In Taiwan, more than 81% of gasoline comes from China Petroleum Corporation (CPC) and more than 75% of electricity comes from Tai-power company in 2016. In this way, this research analyzes the emission per liter of gasoline production in the refinery of CPC, and the emission per electricity of Tai-power company. The main data sources in the study are from Taiwan Emission Data System (TEDS) 9.0 [9], Tai-Power report [10], CSR of CPC [11], AP-42 [12], IPCC Assessment Report [13], and literatures [14]. The main settings of input parameters in the SD model are below: the intensity of $EF_{i,k}$ for electricity production is according to Tai-power system in 2016 [10], and the intensity of $EF_{i,k}$ for gasoline production is according to the data of CPC in 2016 [11]; the habit of riders to use scooters in Taiwan is keeping, and annual sale of scooters will maintain 852,747 which is the average sale of scooters from 2015 to 2107; the average speed of scooter is 40km/hr. (η of GSH is 40.86 km/L and η of ESH is 23.60 km/kWh with the headlights turn on.)

3.3. Scenarios design

Since the EF of ESH is directly related to the structure of the power sector, this study designs the following three scenarios according to the different source of electricity to figure out the potential of air pollutant reduction for ES transition.

- Scenario 1 (s1): Assuming the electricity is from Tai-power system structure in 2016.
- Scenario 2 (s2): Assuming the 20% electricity is from green energy, 30% electricity is from coal-fired power plants and 50% electricity is from natural gas-fired power plants in 2025.
- Scenario 3 (s3): Assuming the EF_k of coal-fired power plants, LNG-fired power plants and oil-fired power plant keep the same as those in 2016, the structure of power sector changes with the energy transition planned by the government, and the speed of ESH transition changes with Policy factor.

4. Results and discussion

4.1. The assessment of EF_k for ESH and GSH

Under the current energy and power structure in Taiwan (s1), the emission of total CAPs and CO_2e are reduced by 94.3% and 76.8% to substitute a GSH for an ESH. Compared with the GSH, the ESH will reduce the emissions of TSP, NOx, and VOC by 14.8%, 97.4%, and 100% per kilometer travelled; the emission of SOx would increase by 136.2%.

However, in s2, the EF of SOx for ESH increase by only 22.2% of the one for GSH, and the EF of CO_2e for ESH is only 18.8% that for GSH. The reduction of EFs of TSP, NOx, and VOC for ESH is 15%, 98%, and 100%. Table 2 and figure 2 show the value and the structure of the EF_k in each energy flow stage for GSH and ESH in s1 and s2. The gray bottom means the main emission source in energy flow. For GSH, the EFs (mg/km) of TSP, NOx, SOx, VOCs, CO_2e in s1 are almost equal to those in s2. For ESH, the main structure of CAPs distribution is different from GSH, and EFs (mg/km) in s2 of TSP, NOx, SOx, VOC, CO_2e are smaller than those in s2; SOx EF in s2 is only 47.9% that in s1.

Table 2. The EFs (mg/km) and data in each stage of GSH and ESH in s1 and s2 (avg. v=40 km/hr)

		TSP	NOx	SOx	VOC	Total CAPs	CO_2e
s1	**EF_k of GSH** (port to gas station + tail pipe)	**80.39** (0.39+80.0)	**251.44** (5.24+246.20)	**2.716** (2.416+0.3)	**1,105.74** (29.24+1076.50)	**1,440.29** (37.28+1403.0)	**65,668** (7,879+57,789)
	EF_k of ESH (port to charging station + tail pipe)	**68.52** (0.52+68.0)	**6.56** (6.56+0.0)	**6.414** (6.414+0.0)	**0.26** (0.26+0.0)	**81.75** (13.75+68.00)	**15,262** (1,5262+0.0)
s2	**EF_k of GSH** (port to gas station + tail pipe)	**80.39** (0.39+80.0)	**251.34** (5.14+246.20)	**2.509** (2.209+0.3)	**1,105.74** (29.24+1076.50)	**1,439.98** (36.98+1403.0)	**65,486** (7,697+57,789)
	EF_k of ESH (port to charging station + tail pipe)	**68.31** (0.31+68.0)	**5.02** (5.02+0.0)	**3.065** (3.065+0.0)	**0.03** (0.03+0.0)	**76.43** (8.43+68.00)	**12,319** (1,2319+0.0)

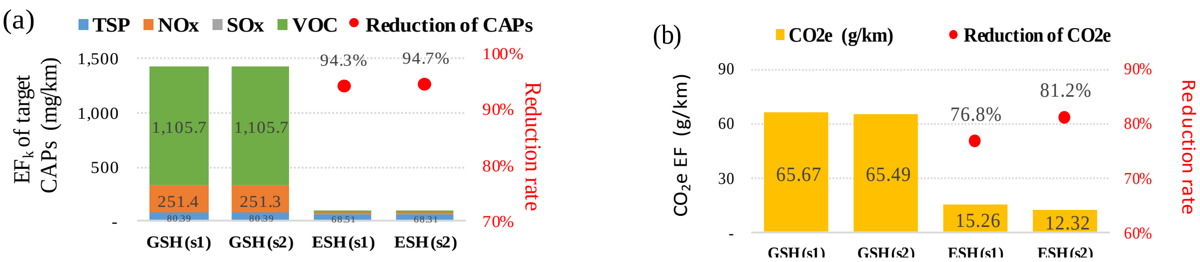

Figure 2. Comparison of EF_k for GSH and ESH (in s1 and s2).

4.2. The changes of the number of scooters, CAPs, GHGs with time

Figure 3(a) shows the potential reduction of target pollutants in s3 to substitute a GSH for an ESH with the energy transition and ESH transition from 2017 to 2025. In s3, this study sets the dynamic transition rate of ESH as the parameter *Policy factor* varies between 5 and 10. The trend of potential reduction for total CAPs are getting better. The increment potential for SOx is 145% in 2017 and is down to only 22% in 2025. The trend of potential reduction for CO_2e is from 77% to 81%.

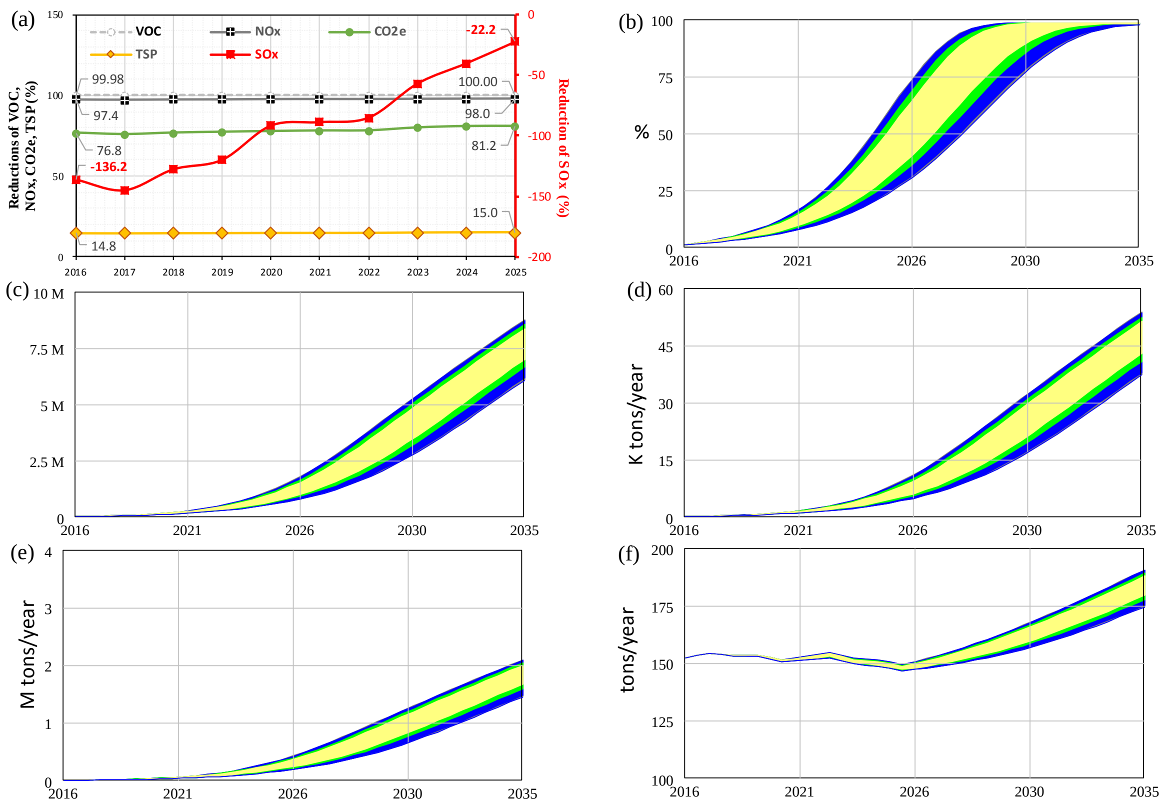

Figure 3. Sensitivity analysis on policy factor and the output variables on the SD model (in s3). (a) The reduction potential of target pollutants, (b) The yearly market-share of ESH, (c) The number of ESH (unit), (d) The reduction of total CAPs emission to substitute a GSH for an ESH, (e) The reduction of CO_2e and (f) The total emission of SOx from GSH and ESH.

The annual sale of ESH will be higher than that of GSH within 2022 and 2028 according to the trend of market share for ESH (figure 3(b)). With a different market share of ESH, the number of ESH would reach 6 to 9 million in 2035 (figure 3(c)); the reduction of total CAPs and CO_2e emission to substitute a GSH for an ESH would reach 37 to 54 kilotons and 1.5 to 2.1 million tons in 2035 (figures 3(d) and 3(e)). Figure 3(f) presents the increasing trend of SOx emission (174 to 191 tons/year in

2035) from all GSH and ESH. The blue line represents the base case, while the colored bands are the confidence bands where the data of results can be found with probabilities equal to 50%, 75%, 95%, and 100%.

4.3. Discussion and suggestion

The emission of total CAPs and CO_2e are reduced by 94.3% and 76.8% to substitute a GSH for an ESH in 2016; however, the SOx emission of ESH is 2.4 times higher than that of GSH according to the results. The findings will be helpful to provide decision makers with information for analysis. For example, the SOx emission of ESH would be less than that of GSH if the government applies clean coal technology or enhances the efficiency in the energy path of ESH to reduce emissions intensity of SOx from current 236 mg/kWh to 100 mg/kWh and it would be better before 2022.

System dynamics and energy flow analysis can provide dynamic analysis of air pollution reduction scenarios. The locally-based EFs in this study are helpful in making decision in optimal dispatch for air emission reduction. The parameters and the model could be further applied to assess portfolios against multi-criterion objectives such as electric bus and vehicles.

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