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Copper-induced ripple effects by the expanding electric vehicle fleet: A crisis or an opportunity

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ABSTRACT

Copper is an essential element for electric vehicle (EV). Currently, little efforts have been directed toward understanding the EV-copper-resource-environment nexus. Autoregressive integrated moving average model combined with dynamic material flow analysis was developed for the nexus analysis in Fujian in China due to its vigorous EV promotion. Results showed that standardized passenger vehicle ownership would increase 3.34 times from 2018 to the peak year 2042, with about 12 times' and 139 times' increase of EV sales in baseline and aggressive scenarios respectively. Accordingly, EV-induced additional copper demand in Fujian would increase the same times as EV sales since 2018, leading to the expansion of copper processing that would incur increasing ripple effects, including 1) aggressive scenario's accumulative additional copper ore demand during 2013-2050 exceed 40 times Chinese reserve in 2016; 2) about 62% of on-road EV's CO_{2eq} reduction compared with Fuel vehicle would be offset by CO_2 emissions from baseline scenario's additional copper processing under Chinese power structure in 2018. Additionally, many other pollutants will also increasingly be emitted in response to the growing EV-induced additional materials' processing, which can further extend ripple effects from local to global environment, and finally threaten global sustainability. The ripple effects indicated the importance of pyramid tip product catalog pedigree to promote international cooperation in products' lifecycle management and extend cleaner production to cleaner consumption, efficient fleet cleaner production technologies, longer products' lifespan, circular design, and cleaner power supply.

1. Introduction

1.1. Electric vehicles and copper

An expected global copper demand is a factor 2.6 to 3.5 in 2045-2050 in comparison to 2010 – 2015 (Henckens et al., 2014; Elshkaki et al., 2016), and 3 to 21 times the current copper demand until 2100 (Schipper et al., 2018). However, global copper reserves are limited with only 7.9×10^8 tonnes in 2017, would be depleted within 40 years at the current mining rate (USGS, 2018). Even with high recovery and recycling rates, the cumulative copper demand would surpass the identified resources before 2100 (Schipper et al., 2018). Consequently, an supply gap is expanding in many countries, e.g. U.S. and China where the dependence on foreign copper imports raises concerns over likely copper supply's disruptions (Sen et al., 2019; Wang et al., 2019). Copper became one of bottleneck materials for the low-carbon energy transition (Valero et al., 2018), including the transition from fuel vehicles (FV) to electric vehicles (EV) which could be an important contributor of the gap, considering 1) in terms of manufacturing's material footprint, copper ores made up almost 20% of vehicle and 45% of battery (Sen et al., 2019); 2) decarbonization of energy and transportation systems linked to strong rise of copper demand (Schipper et al., 2018). Thus, estimating EV sales and related copper demand is necessary to close the gap. Except for copper (Naumanen et al., 2019), the expanding EV fleet is also leading to a rapid depletion of other scarce resources, e.g. natural graphite, lithium, nickel, cobalt, vanadium, cadmium, manganese, lead and rare-earth elements (Ballinger et al., 2019; Turcheniuk et al., 2018; Gies, 2015; Richa et al., 2014;

Abbreviations: ARIMA, Autoregressive Integrated Moving Average model; AS, Aggressive Scenario; BS, Baseline Scenario; EV, Electric Vehicles; FV, Fuel Vehicle; GHG, Greenhouse Gas; DMFA, Dynamic Material Flow Analysis; PVO, Passenger Vehicle Ownership; mmc1, Supporting Information 1; mmc2, Supporting Information 2; SPV, Standardized Passenger Vehicle; SPVO, Standardized Passenger Vehicle Ownership

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Vikström et al., 2013; Grosjean et al., 2012; Andersson and Råde, 2001).

1.2. EV's whole lifecycle environmental effects

As mentioned in some studies, on-road vehicles' environmental impacts may be mitigated by replacing FV with EV, by saving energy (Alirezaei et al., 2016), reducing carbon footprint and air pollutant emissions (Onat et al., 2015; Karaaslan et al., 2018). That is why many countries were determined to develop EV industry, including China where produced over 250 000 battery EVs in 2015, and the annual growth rate was 420% (CAAM, 2016). However, the mitigation may not be so obvious or even opposite if we consider the whole lifecycle environmental effects of EVs compared to FV, not just on-road phase, e.g. with 2015 electricity mix in Lithuania, EV generated 26% and 47% more greenhouse gas (GHG) emissions than FV fuelled with petrol and diesel, respectively (Petrauskienė et al., 2020). The over-focus on on-road EV's energy-saving and CO_2 reduction underestimates EV's whole lifecycle environmental impacts, in comparison to FV which caused a relatively low environmental impact during raw material extraction, product manufacture, and the disposal stage (Gradin et al., 2018). In addition, EV demand additional energy and material inputs in battery manufacturing and the construction of charging stations and associated power grid, which surely produced additional environmental impacts. The energy consumption and GHG emissions of a battery EV production range from 92.4 to 94.3 GJ and 15.0 to 15.2 t CO_{2eq}, which are about 50% higher than those of an FV (Qiao et al., 2017).

1.3. EV's copper-induced environmental effects

Higher environmental impacts of EV during manufacturing was caused mainly by aluminium and copper which were used more in EV while other vehicle material including steel, iron, and plastic were used more in FV (Hawkins et al., 2013). Copper is a metal with high energy and material intensities, critical for mitigating global environment changes (Elshkaki et al., 2016; Northey et al., 2013; Kuipers et al., 2018). Copper's water footprint averages 70.4 kL/t Cu (Northey et al., 2013), can be one of the main reasons why the EV water use is 70 times higher than the FV (Onat et al., 2018). Thus, additional copper demand caused by the transition from FV to EV undoubtedly demanded more energy and resources and discharged more wastes, indicating that scenario analysis of replacing FV with EV and assessment on its ripple effects are essential to ensure both environmental sustainability and sound development of the transportation industry.

1.4. Fujian case

There has been a substantial boom in China for automobiles, with the civil vehicle ownership increasing from 10.4 million in 1995 to 209.07 million in 2017 (NBSC, 2018; NBSC, 1999). Their environmental impacts have correspondently grown greater. While, the potential growth of EV share in the fleet will aggravate the impacts, as the accumulative EV production had been more than 2.8 million vehicles till 2018 in which 70.4% is passenger EV and 78.5% is battery EV (DECCU, 2019). Here, passenger vehicle fleet with expanding EV share in Fujian was taken as an example for exploring EV-induced resource and environmental effects, as it is the first province enforcing EV deployment in China (FJPPG, 2017) and the main production base of the world's largest manufacturer of EV batteries (CATL) (http://www.powerlife.com.cn/15562.html). Based on its historical data of production and consumption of vehicles since 1970, future passenger vehicle ownership (PVO) was predicted by using an integrated model of dynamic material flow analysis (DMFA) combined with autoregressive integrated moving average model (ARIMA) for analyzing EV sale trends and their copper demand and its ripple effects.

2. Case background

China accounted for 9.44% of global copper production and less than 3.42% of global copper reserves in 2017 (USGS, 2018), and 19% of global copper stocks in 2012 (Glöser et al., 2013). Its copper consumption dependence on the international market continued to enhance with growing copper demand due to the scarcity of its domestic copper resources (MLR, 2010; Zhang et al., 2015). Copper supply gap in China has enlarged greatly in the last two decades (Zhang et al., 2012), the imports of copper ore and its concentrate, unwrought copper and its alloys, and copper materials were all more than the exports in 2017, the former two had increased by more than 18 times since 1997 (Table S1). In summary, future copper supply for China will be unstable associated with rapidly rising net import reliance and more serious shortage with ongoing electrification of its transportation fleets.

The most serious copper shortage in China could occur in Fujian where PVO is rapidly increasing and EV deployment has been vigorously spurring (ETC, FD, STD, and DRC in FJ, 2014; FJPPG, 2014; 2017; 2018; Huang, 2017). The EV promotion can increase copper supply gap caused by the PVO expansion. Moreover, the gap can further expand because the majority of EV copper is used in battery and the world's largest battery maker - CATL is headquartered in Fujian, with 10.4 GWh installed capacity of power batteries in 2017 (http://www.sohu.com/a/242071919_430808 and http://m.elecfans.com/article/631034.html) and 24 GWh annual power battery production capacity being under construction in 2018 (http://www.evpartner.com/news/38/detail-32845.html). Thus, this article focuses on estimating future EV-induced additional copper demand in Fujian, so that we can find out if replacing FV with EV will be helpful for reducing environmental pollution and resources demand.

3. Methodology

3.1. Research framework

The growing environmental impacts from the boom of PVO calls for the analysis of the necessity of adopting emerging transportation system, i.e. discussing the advantages and disadvantages of replacing FV with EV from the perspective of environmental sustainability. Here, EV refers to passenger EV in which battery EV accounts for dominant share in all EVs in this case. The overall environmental effects from an emerging transportation system depend on not only the CO_{2eq} reduction from on-road vehicles, but also ripple effects of the whole lifecycle of vehicles and their supporting system on the environment. Before the discussion of the effects, it is necessary to project the trend and structure of the emerging transportation system, i.e. the future expansion of PVO and its EV share. ARIMA integrated with DMFA was applied for the projection, considering that PVO will change with many interacting factors, including per capita disposable income, local vehicle production, and other factors, according to Pearson correlation analysis (Table 1). The scenarios of EV share expansion in PVO, i.e. EV sale scenarios, can be designed on the local decisive factor of EV growth,

Table 1
Pearson correlation coefficient between SPVO and its factors in Fujian from 1978 to 2017

	LVP	PCDIU	PCDIR	TRP	UR	PCGDP	HM	PH	PT
Pearson	0.93	0.95	0.97	0.71	0.88	0.98	0.88	0.72	0.53

Notes: SPVO was estimated by the following section 3.3.1, the indicators for its factors were calculated on the data from Fujian Provincial Bureau of Statistics. LVP, local vehicle production; PCDIU, per capita disposable income of urban residents; PCDIR, per capita disposable income of rural residents; TRP, total resident population; UR, urbanization rate; PCGDP, per capita GDP; HM, highway mileage; PH, passengers by highway; PT, passenger turnover.

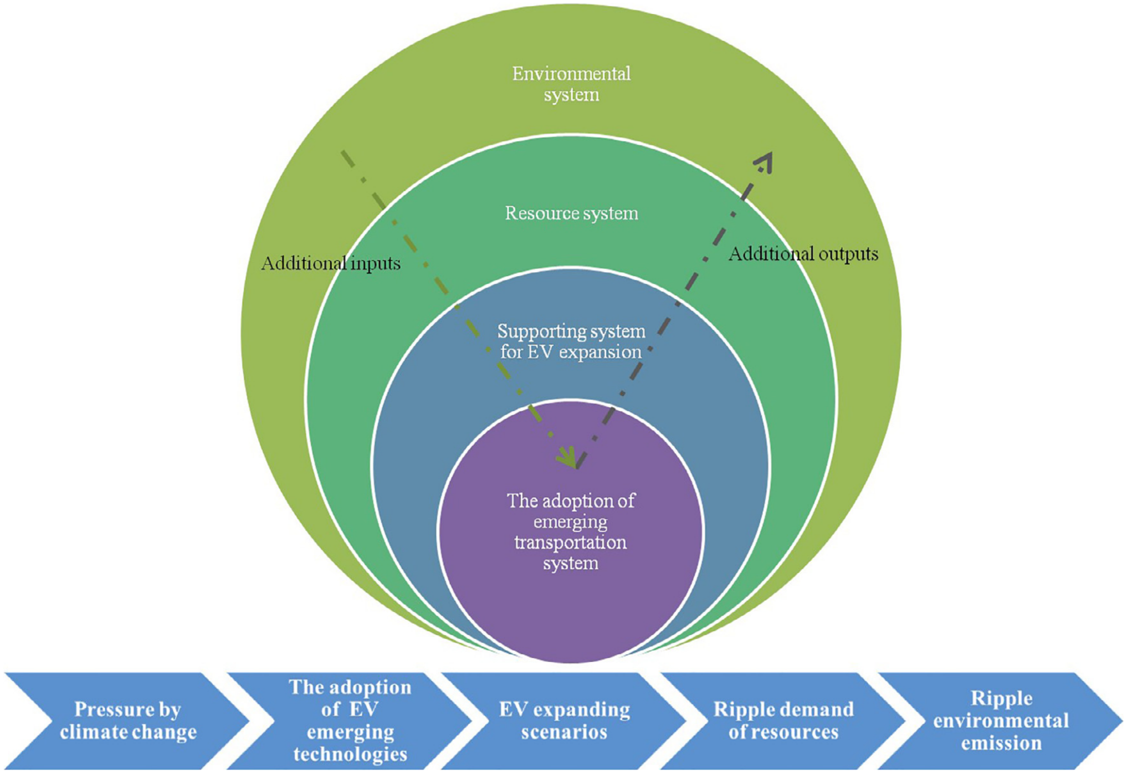

Fig. 1. A framework for analyzing ripple effects of emerging transportation system in resource use and its environmental emission

e.g. implementation intensity of policies related to EV industry in Fujian province, China. Due to more copper demand induced by an EV and its supporting facilities compared with an FV, increasing EV share in PVO indicated more copper demand for the same PVO or mileages. Then, the EV-induced copper demand trend from 2018 to 2050 in Fujian was extrapolated based on its EV sale scenarios. Next, copper-induced ripple effects can be estimated by lifecycle assessment results of copper's resource demand and environmental emissions according to a framework (Fig. 1). Thereafter, countermeasures can be formulated for reducing the ripple effects to promote the sustainability of copper use.

3.2. Modeling and scenario design

3.2.1. Standardization of PVO

In order to estimate copper demand for the expanding fleet and its EV share, it is necessary to convert various types of passenger vehicles as a type of standard passenger vehicle for predicting PVO by a unified model. The converting coefficient can be estimated on copper use per type of vehicle, as the material compositions of conventional vehicles within specific classes are sensibly constant on a percent-by-weight basis (Sullivan et al., 2010). Thereafter, the conversion factor of the PVO into light-duty standardized passenger vehicle ownership (SPVO) can be calculated as 2.855 for FV and 1.439 for EV. Details can be seen in the section 1 of Supporting Information 1 (mmc1).

3.2.2. Future SPVO

The change of vehicle consumption was affected by many factors (Table 1), which were also affected by many other factors. The interaction mechanism is very complex and uncertain. To make the forecast of vehicle consumption reliable, the DMFA combined with ARIMA was applied in this study. Base on the standardization results of PVO of FV and EV from 1978 to 2017, SPVO after the reference year 2018 can be predicted by Eq. (1), i.e. ARIMA (2,3,7) with 0.755 stationary R^2 indicating a sound modeling, after several times of model calibration (See Supporing information 2 (mmc2) and the section 2 of mmc1).

$$y_t = \mu + \sum_{i=1}^{p} \alpha_1 y_{t-i} + \epsilon_t + \sum_{i=1}^{q} \beta_i \epsilon_{t-i} \tag{1}$$

where, y_t, amount of PVO in the t year y_{t-i}, amount of PVO in the t-i year
μ, constant
P and q, order number
α_1, autocorrelation coefficient
β_i, partial autocorrelation coefficient
ϵ_t, error in t year
ϵ_{t-i}, error in t-i year

3.2.3. Material Flow Analysis of passenger vehicles based on quantity balance thinking

The change of in-use passenger vehicle stock, i.e. PVO, in the estimated year is the PVO difference between the estimated year and the year before the estimated year, which is also the difference between inputted vehicles and outputted vehicles in Fujian in the estimated year by DMFA (Fig. S1). Material flow analysis was usually based on mass balance principle (Brunner and Rechberger, 2004; OECD, 2008; Huang et al., 2012; 2014a; 2014b), while in this study DMFA of vehicles will be based on quantity balance thinking. The inputted vehicles are the sum of new sales and recycled number of vehicles in the estimated year, while the outputted vehicles are the scrapped vehicles in the estimated year. Then, some indicators such as recycling rate and scrapping rate of passenger FV ownership in 2015 and 2016 can be calculated on DMFA results and used in estimating future EV standardized passenger vehicle (SPV) sales.

3.2.4. Scrapped rate of SPVO

Given that scrapped rates of SPVs, including FVs and EVs, are constant for reference and all forecast years, scrapped rate of SPVO in a forecast year can be calculated by Eq. (2).

$$R_i = (y_i^{FV} \times r^{FV} + y_i^{EV} \times r^{EV})/y_i \tag{2}$$

$$r^{FV} = \frac{R_i \times y_i}{y_i + 4y_i^{EV}} \quad (3)$$

$$R_i = (y_i^{EV}/y_i + 0.25) \times 4r^{FV} \quad (4)$$

where,

R_i, scrapped rate of SPVO in the *i* year. R_i in 2015 and 2016 can be estimated on DMFA results (Fig. S2, Table S7).

y_i^{FV}, SPVO of FV.

y_i^{EV}, SPVO of EV. y_i^{EV} for the years of 2013-2018 is estimated from production and sales of EV (ETC, FD, STD, and DRC in FJ, 2014; FJPPG, 2014; 2018).

r^{FV}, scrapped rate of SPVO of FV based on vehicle mileage life which can be assumed to be constant across all years as suggested by MCC (2012). The arithmetic mean of r^{FV} for 2015 and 2016 can be calculated as 0.02565 which was assumed to be a constant for following EVs' estimation in forecast years.

r^{EV}, scrapped rate of SPVO of EV, which is 5 times of r^{FV} based on the average real-world FV's and EV's mileage life expectancy which are 600 000 km and 120 000 km, respectively (MCC, 2012; BJSTC, 2015). Thus, Eq. (2) can be changed as Eq. (3), based on that y_i is the sum of y_i^{FV} and y_i^{EV}.

y_i, the amount of SPVO in the i year. y_i for 2015 and 2016 is the values modeled from SPVO in 2015 and 2016 by ARIMA (2,3,7).

The detailed calculation process for parameters in 2015 and 2016 in Eq. (2-4) was explained in the section 3.2.4 of mmc1.

3.2.5. Future SPV sales of EV

In order to lower GHG emissions and help mitigate the causes of climate change caused by on-road FV, many countries issued the timetables of the bans on the FV sale (Table S2). After the ban year, EV adoption rates, i.e. the rate at which EV will replace FV, depends on the FV abandonment rate and the growth rate of social civil vehicle demand. However, before the ban year, according to literature overview (Shafiei et al. 2012; Sierzchula et al. 2014; Li et al., 2019; Al-Alawi and Bradley, 2013), EV sales could be affected by many factors with complex interaction, it could be difficult to forecast it by various factors, see the section 4.1 of mmc1. As a viable option, it would be a better way to estimate EV sales by using DMFA indicators (Eq. (4)) (Huang et al., 2012).

3.2.5.1. Total SPV sales. Based on DMFA framework (Fig. S1), future SPV sales can be estimated by Eq. (5).

$$N_i^{sale} = N_i^{scrapped} + \Delta^{stock} - N_i^{recycling} \quad (5)$$

Where,

N_i^{sale}, total SPV sales, i.e. the sum of sales of EV and FV in *i* year.

$N_i^{scrapped}$, the sum of scrapped vehicles of EV and FV's PVO in *i* year, which can be estimated on y_i and R_i. R_i is the rate of scrapped vehicles to y_i, and can be calculated on y_i^{EV} by Eq. (4). y_i^{EV} denotes the product of the total SPVO (y_i) and the proportion of EV's SPVO (y_i^{EV}) to the total SPVO (y_i) in *i* year. There are two scenarios of the proportion, see scenario design of the proportion in mmc1.

Δ^{stock}, the change of PVO, i.e. the difference between PVO in *i* year and *i-1* year, which can be sourced from previous prediction results of future SPVO.

$N_i^{recycled}$, the amount of recycled vehicles of PVOs of EV and FV in the *i* year, which can be estimated on y_i and $R_i^{recycled}$, i.e. the rate of recycled vehicles to y_i, which is calculated on DMFA results (Fig. S2), see the analysis on $R_i^{recycled}$ in mmc1.

3.2.5.2. The share of EV in total SPV sales. (1) Baseline scenario

In baseline scenario (BS), EV's market share of total SPV sales can be estimated on market penetration rate of EVs for the years from 2018 to 2050 by Eq. (6). Market penetration rate of EVs in *i* year is the plus of the EV market penetration rate in *i-1* year and 0.369% which is the average annual increasing rate of EV's market penetration rate during the reference years 2013-2018.

$$N_i^{sale-EV} = N_i^{sale} \times R_i^{EV} \quad (6)$$

where,

$N_i^{sale-EV}$, the sales of standardized passenger EVs in *i* year.

N_i^{sale}, total SPV sales, i.e. the sum of sales of EV and FV in *i* year.

R_i^{EV}, market penetration rate of EVs in *i* years.

(2) Aggressive scenario

In aggressive scenario (AS), after 2018, at least 12% of the market penetration rate was assumed in 2025, considering the following facts: 1) global EV penetration rate need to reach to 12% in order to comply with environmental regulatory targets by 2025 (Hamilton et al., 2018); 2) a new round of policy measures involving parking discounts and electricity price concessions will be issued in Fujian before the end of 2019 (Wei et al., 2019);and 3) the first provincial-level new energy vehicle policy in China was introduced in Fujian province and '*Fujian driven by Electricity*' was promoting (Huang, 2017). Similarly, according to the time of the bans on the FV sale in several countries (Table S2), if the Fujian provincial government would enforce the promotion of EVs and ban FV sale in 2040, 100% of the EV penetration rate can be assumed in 2040. Then, the average annual increasing rate of market penetration rate of EVs during the periods of 2018-2025 and 2025-2040 can be calculated on market penetration rates of the reference years 2018, 2025, and 2040. So, market penetration rate of each scenario year from 2019 to 2050 can be estimated on the average annual increasing rate. Finally, the AS sales of standardized passenger EV can also be calculated on Eq. (6).

3.2.6. Copper demand of the expanding EV fleet

3.2.6.1. Additional copper demand for vehicle manufacturing caused by copper content difference between EV and FV. Consumption-based EV-induced copper demand was estimated on the following assumptions. (1) Current copper use per vehicle in manufacturing phase keeps constant in future years. (2) The BS and AS copper demand for vehicle production in future years can be estimated by the scenario results of EV's market share of total SPV sales, as waste EV batteries were currently few and its reuse technologies is mostly in the experimental stage (DECCU, 2019), and reused amount only accounted for 7.4% of total waste EV in 2018 (Ma, 2019). (3) The lifetime of copper used in vehicle can last till the end of vehicle. (4) Copper loss wouldn't occur during the operation phase of vehicle on road.

Copper use per FV was calculated as 12.081 kg if we considered the difference of copper content between EV and FV (Table S3), based on the discussion on copper use in vehicle (See mmc1) and the data of new energy vehicles' production (80% for passenger in which EV accounts for 74%) and their copper demand in China in 2018 (CBRI, 2019; WOR, 2018). Considering the purpose of estimating minimum environmental effects of increasing copper demand for this study, we applied the data of 12.081 kg per FV (Table S3) and 83 kg per EV (Shanghai Nonferrous Metals, 2018; Hamilton et al., 2018; China Industry Information, 2018). Then, future additional copper demand for vehicle manufacturing can be calculated on the sales of standardized passenger EV and FV in future years by Eq. (7).

$$y_i^{EV-FV} = (S_{EV} \times C_{EV} + S_{FV} \times C_{FV}) - (S_{EV} + S_{FV}) \times C_{FV} \quad (7)$$

Where.

y_i^{EV-FV}, additional copper demand for vehicle manufacture due to replacing FV with EV in the expanding fleet.

S_{EV} and S_{FV}, annual sales of EV and FV in each year, see the section 3.2.5.2.

C_{EV} and C_{FV}, copper content per vehicle, i.e. 83 kg per EV and 12.081 kg per FV.

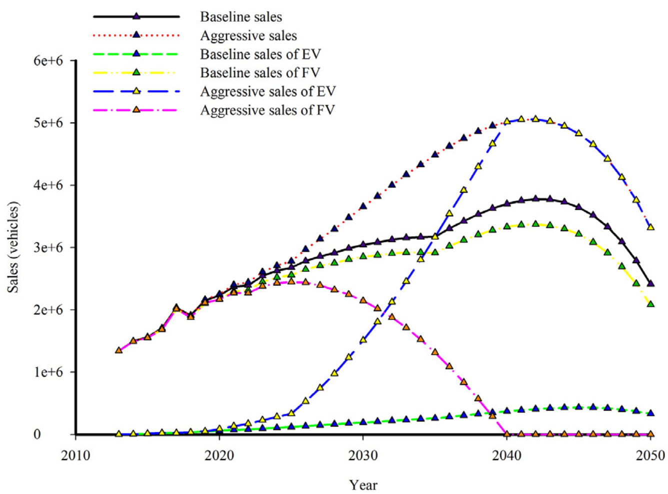

Fig. 2. The trend of sales of FV and EV in baseline and aggressive scenarios. Unit: vehicles.

3.2.6.2. Copper demand for charging facilities due to increasing passenger EV sales

$$y_i^{pile} = S_{EV} \times C_i \times r_i \tag{8}$$

Where.

y_i^{pile}, copper demand for charging piles, *i* refers to alternating current (AC) or direct current (DC).

S_{EV}, annual EV sales in each year, see the section 3.2.5.2.

C_i, copper content per charging pile, i.e. 5.05 kg per AC pile and 59.09 kg per DC pile (See mmc1).

r_i, the rate of AC or DC piles to total charging piles, i.e. 90% for AC or 10% for DC (WOR, 2018).

Based on literature data and the discussion on charging facilities (See mmc1), copper demand for charging piles can be estimated by Eq. (8). While, total copper demand for EV charger can calculate on 0.7 kg and 8 kg of copper use per EV charger for AC and DC charging piles, respectively (Shanghai Nonferrous Metals, 2019).

3.2.6.3. Copper demand for grid upgrade for EV charging. Grid infrastructure is heavily reliant on copper for wiring, transformers and motors with only overhead transmission lines dominated by lighter-weight aluminum owing to the need to minimize pylon supports. Of course, this segment is the largest copper consumer in the world, e.g. China's State Grid consumed up to 10% of global copper in any given year (Hamilton et al., 2018). Obviously, there is an extraordinary amount of copper wiring needed to transmit the electricity from the grid down into the EV charging stations. Copper demand of grid upgrades for EV charging accounted for 74% of all copper demand growth to 2025, equivalent to 5.5 mt per year, while transportation driving 18% of copper demand growth through 2025, or 1.33 mt per year (Hamilton et al., 2018). Given that these two percentages were the same as grid upgrades and the EV expansion's copper demand shares in total copper demand growth in Fujian, i.e. 74% is for 1,594 charging stations and 12 power change stations excluding charging piles (POFJPPG, 2019), and 18% is for increasing EV and charging piles and chargers calculated in the above sections, copper demand for grid upgrades can be estimated.

3.2.7. Ripple effects caused by increasing copper demand from a lifecycle aspect

Both primary and secondary copper will be used to meet EV expansion's copper demand. The system boundary of lifecycle assessment on the potential environmental impact of both primary copper and secondary copper production technologies covered the major production processes, including mining, beneficiation, smelting, converting, fire refining and electrorefining for primary copper, and disassembling, separation, fire refining and electrorefining for secondary copper. The potential environmental impacts include the inputs of resources, raw materials and energies for each process, and the outputs of pollutants and residues from each process.

The proportion of secondary copper production was approximately 30% of copper use in China (Chen et al., 2019), so we can assume that secondary recycling copper accounted for 30% of total copper use for vehicle manufacturing in Fujian in estimating environmental impacts of additional copper input due to automobile industry transition. Thus, Eq. (9) can be used to estimate total environmental impact of EV expansion's additional copper input in any given future year.

$$E_i = 70\% \times C_j \times e_{ip} + 30\% \times C_j \times e_{is} \tag{9}$$

Where,

E_i, total environmental impact of additional copper input for increasing EV market share in any given future year, *i* means one of resource inputs or pollutant outputs.

C_j, copper demand for increasing EVs and EV's supporting facilities in Fujian.

e_{ip}, environmental impact of additional primary copper input for increasing EV market share in any given future year, see Table S6 (Chen et al. 2019).

e_{is}, environmental impact of additional secondary copper input for increasing EV market share in any given future year, see Table S6 (Chen et al. 2019).

4. Results and discussions

4.1. The future passenger vehicle demand and its EV share in Fujian province

According to ARIMA (2,3,7) modeling results, the SPVO in Fujian will grow and peak at 52.25 million vehicles in 2042, with 3.34 times of increase since 2018, and then fall down to 43.99 million vehicles in 2050 (Table S8, Fig. S3). In line with both the SPVO modeling results (Table S8 and Fig. S3) and EV's share in total SPV sales calculated on DMFA results (Fig. S2), scenario analysis showed that the 2013-2050 trends of total BS sales, total AS sales, the BS sales of FV and EV are similar, with an increase of 2.0, 2.6, and 1.8 and 11.9 times from 2018 to their peak years, respectively (Fig. 2). Except for the BS sales of EV which peaked at 0.43 million vehicles in 2045, the first three will in order peak at 3.78, 5.06, and 3.37 million vehicles in 2042, respectively, and then decrease (Fig. 2). The peak values indicated that 1) the increasing rate of total AS sales is 1.3 times of that of total BS sales, and 2) the increasing rate of EV sales is 6.6 times of that of FV in BS.

Since 2018, AS sales of EV will rapidly increase and peak at 2042 with 5.06 million vehicles, then decrease in the following years; correspondently, AS sales of FV will gradually increase to 2.45 million vehicles in 2025 from 1.87 million vehicles in 2018, then rapidly fall down to 0 in 2040 when it will be banned (Fig. 2). The peak AS sales of EV and FV are 139.4 and 1.3 times of their sales in 2018, indicating that the increasing rate of AS EV sales is 107 times of that of AS FV sales.

The proportions of EV sales in total sales will gradually increase to 100% in AS peak year 2040 and 11.9% in BS peak year 2045 from 1.9% in 2018. The actual proportion would majorly depend on local governmental policy due to GHG emission reduction pressure.

It is difficult to accurately predict the expansion speed of PVO and its EV share which is affected by complex and changing factors including income change, policy regulation, charging infrastructure development and consumer acceptance. Nevertheless, the simulation results of Fujian's PVO and its EV share in the next 30 years by the ARIMA are credible, because the model was based on the long-span local 40-years' passenger vehicle data and had been verified (mmc2), and modeling results was consistent with the government's PVO policy

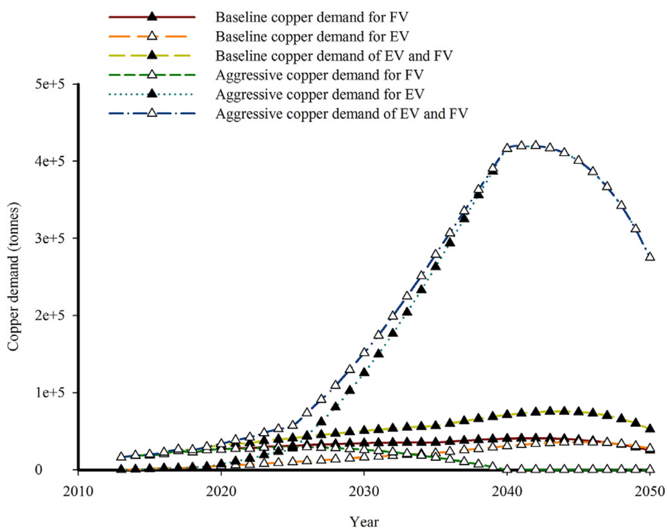

Fig. 3. Annual copper demand for annual sales of EV and FV in baseline and aggressive scenarios. Unit: tonnes. Note: The data in the figure was calculated on the SPV sales of EV and FV.

orientation and the growth trend of population, passenger vehicle production, per capita GDP, and per capita disposable income in Fujian which are the most relevant factors to the PVO expansion based on Pearson correlation analysis from 1978 to 2017 (Table 1). The actual trends of sales of FV and EV in both scenarios mentioned above will depend on the implementation of local government's policies and the change of those PVO expansion-related factors.

4.2. Copper demand for expanding fleet and its EV share

4.2.1. Vehicle copper demand for annual sales of EV and FV

The future expanding SPVO fleet and its growing EV share would lead to the growing flows of various vehicle-related materials and resources such as copper into automobile industry. According to the SPVO modeling results, if EV were not adopted in future years, the peaks of annual BS and AS copper demand will be reached at 45635 and 61077 tonnes in 2042, respectively. However, due to the EV adoption (Fig. 2), annual BS and AS copper demand will gradually increase and respectively peak at 75445 tonnes in 2044 and 419617 tonnes in 2042 (Fig. 3). The BS and AS copper demand of EV fleet in peak years will increase 1.65 and 6.87 times respectively, compared with no EV fleet.

Annual BS copper demand will peak at 40724 tonnes for FV in 2042 and at 35907 tonnes for EV in 2045, copper demand for EV will surpass that for FV in 2048. Its peak year's annual copper demand will increase 10.9 times for EV and 1.9 times for the sum of FV and EV since 2018. Annual AS copper demand will peak at 29547 tonnes for FV in 2025 and at 419617 tonnes for EV as well as the sum of FV and EV in 2042, while copper demand for EV will surpass that for FV in 2026. Since 2018, its peak year's annual copper demand will increase 138.4 times for new EV sale and 15.4 times for the sum of FV and EV sales.

In short, the rapid copper demand increase is caused mainly by the electrification of the fleets, indicated by the trends of copper demand for the sale sum of EV and FV in both scenarios are similar as that of EV's copper demand (Fig. 3). The electrification contributed 65% and 587% of copper demand increase in peak years respectively for BS and AS, compared with no EV in the fleets. The key reasons for the contribution include not only more copper demand for EV fleet than that for FV fleet, but also the difference in mileage lifespan between EV and FV, that is, the scrapped rate of EV is five times that of FV based on mileage lifespan. Therefore, the copper demand caused by EV adoption would accordingly increase more than five times due to more copper demand per EV than that per FV, which would stir up serious systematic environmental effects. The consideration of significant mileage life expectancy difference between EV and FV can possibly lead to a contrary result in comparing the environmental effects of EV and FV, which were usually assessed based on vehicle weight, vehicle model, and driving time or distance of vehicle in the previous studies.

The rapid copper demand increase in Fujian may be unlikely met by foreseeable limited available copper in the world. Firstly, the peak years of copper demand in Fujian will almost overlap with that in China where the highest peak of copper in-use stocks will be possibly achieved around 2045 (Zhang et al., 2015). Even worse, as the largest copper consumer in the world, the copper demand-supply gap for China has enlarged greatly in the last two decades (Zhang et al., 2012), and will be continuously enlarged with its rapid economic growth and societal development. In addition, in 2025, Fujian's new copper demand for the BS and AS sales of passenger vehicles will respectively reach to 3.1% and 4.3% of 1 330 000 tonnes of new copper use driven by global transportation excluding supporting facilities (Hamilton et al., 2018). However, Fujian's permanent residents accounted for only 0.52% of the global population in 2017 (FJBS, 2018; https://countrymeters.info/cn/World). In other words, the share of copper demand of Fujian's passenger vehicles in new copper use for global transportation is about 6-8 times the share of Fujian's population in the world, which leads to a significant violation of the principle of fairness in sustainable development in adaption to the global shortage of resources. Worse, in 2042 AS peak of copper demand would account for 31.55% of global new copper use for transportation in 2025. The results on the proportions are reasonable, considering that the growing rate of population in Fujian is 7.3 times of that in the world. Thus, if rapidly increasing copper demand in Fujian were met, the global copper supply gap will significantly expand, assumed that current trends of copper supply and demand keep in other areas in future years. Thus, BS may be more likely to be implemented from the perspective of sustainable copper supply.

4.2.2. Additional copper demand caused by replacing FV with EV

The ongoing electrification has intensified the use of copper in transport industry. Due to the electrification in Fujian, calculated on the copper use gap between FV and EV, the vehicle-induced additional copper demand accounted for only 11.1% of copper demand from total sales of no EV SPV in 2018 for both scenarios, then, the rate will rapidly increase to 70% in 2045 for BS and 587% in 2042 for AS (Fig. 2-4). Furthermore, total amount of additional copper demand from both EVs and their supporting facilities excluding grid upgrade will increase about 12 times for BS and 139 times for AS from the reference year 2018 to their respective peak years, i.e. 2045 and 2042 (Fig. 4).

In both scenarios, 79% of total additional copper demand is contributed by EV's more copper demand during manufacturing in contrast to FV. While, based on assumptions in the section 3, given that each EV is equipped with a AC charger and a DC charger, only about 21% of total additional copper demand is from EV's supporting facilities, in which copper demand for AC charging pile, DC charging pile, AC charger, and DC charger accounted for 5.0%, 6.6%, 0.8%, and 8.9% of total additional annual copper demand, respectively.

Although 90% of charging piles is AC slow piles, total copper demand for AC will still be lower than that for DC. In addition, copper demand for DC chargers is also much more than that for AC chargers. Thus, in order to reduce environmental impacts from developing EV industry, it is necessary to encourage the use of home and public AC chargers, according to the fact that the home AC charger has the lowest cumulative energy demand and global warming potential, followed by public AC and DC chargers, and the public mix chargers (integrating both AC and DC) (Zhang et al., 2019). However, total copper demand for all piles and chargers accounts for a very small percentage of that for grid upgrade for EV operation in both scenarios, although the proportion will increase from 0.63% in 2018 to 2.39% and 3.91% respectively for BS and AS in 2050 (Fig. 5). While, the rate of annual copper use

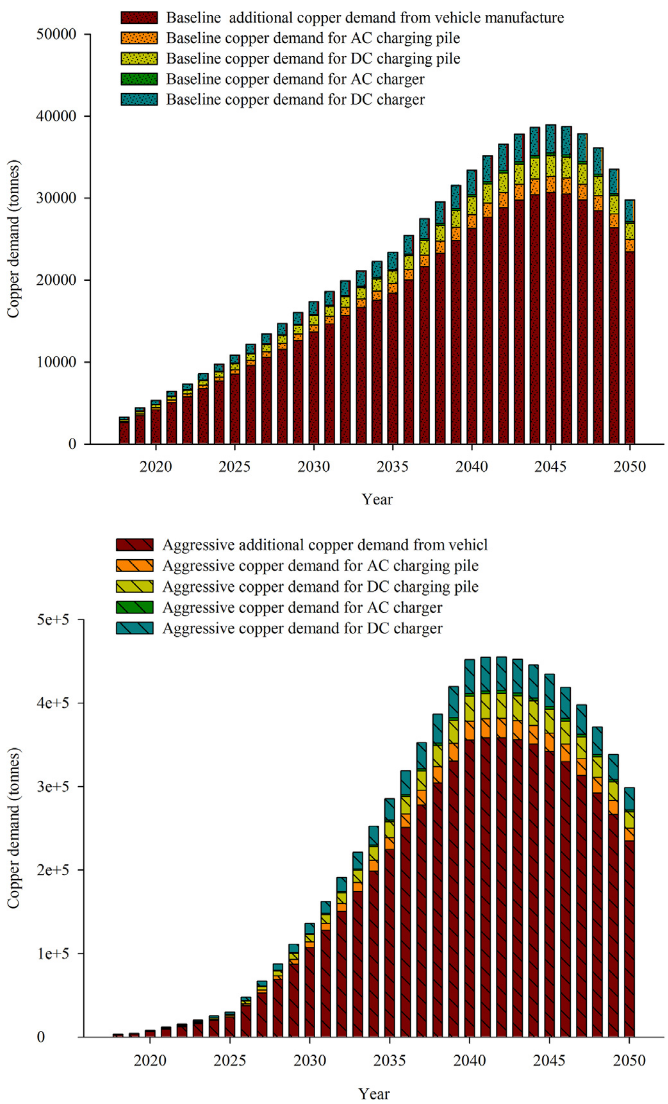

Fig. 4. Additional copper demand caused by replacing FV with EV. Unit: tonnes. Note: Copper demand of grid upgrades for EV charging was not considered here.

difference between the vehicle fleets with and without EV to annual copper demand for grid upgrade will increase from 2.3% in 2018 to 8.8% and 14.5% in 2050, respectively for BS and AS (Fig. 5). Thus, copper demand for the EV-induced grid upgrade is dominant in total copper demand for the transportation electrification. Optimizing grid layout in the future is the key to reduce copper use during the expansion of EV fleets.

4.3. Additional resources and emissions needed for increasing additional copper demand

The Fujian case showed that the growth of GDP and per capita disposable income of urban and rural residents will lead to the expanding fleet which will surely result in the input increase of resources including copper demand in the manufacturing of vehicle and its supporting facilities (Fig. S6-S8). With the increase of EV-induced annual additional copper demand (Fig. 3, 4), the annual input flows of various raw materials and resources required for copper processing will consequently expand and peak at 2045 and 2042, and have about 12 and 139 times of increase since 2018, respectively for BS and AS (Fig. S6-S8).

To meet refined copper demand growth from EV industry excluding grid upgrade, the annual input of copper ore and scrap accordingly increase, respectively peak at 5.37E + 06 and 2.17E + 04 tonnes in 2045 for BS, and respectively at 6.28E + 07 and 2.54E + 05 tonnes in 2042 for AS, and then fall down (Fig. S6). Similarly, to process these copper ore and copper scrap, the annual consumption of energy resources also causally increase to the BS peak at 1.19E + 03 tonnes for crude oil, 3.30E + 04 tonnes for hard coal, and 7.20E + 06 m^3 for natural gas in 2045; the AS peak at 1.39E + 04 tonnes for crude oil, 3.86E + 05 tonnes for hard coal, and 8.42E + 07 m^3 for natural gas in 2042, and then fall down (Fig. S7). Other important resources required for copper smelting and refining include fresh water, butyl xanthate, pine camphor oil, etc. (Chen et al., 2019), the input flows of these resources would also grow with expanding copper demand induced by EV. Based on the above mentioned, it was found that annual copper demand in peak years can lead to the processing of hundreds of times of copper ore and other resources in both scenarios through industry chain.

While, the expanding input flows of resources required for EV-induced copper consumption will also inevitably lead to larger-scale resource extraction and processing which would correspondingly contribute to growing emissions of environmental pollutants (Fig. S9-S11). Just like the increase in EV-induced resource consumption, EV-induced annual emission flows of various pollutants will also expand and peak at 2045 and 2042 with 12 and 139 times of increase since 2018, respectively for BS and AS (Fig. S9-S11).

Therefore, the demand change of end-products with long production chain could incur large-scale ripple interference in resource and environmental systems through the industrial chain. This indicates that whether to promote an emerging end-product on a national or global scale need a systematic assessment of its resource and environmental ripple effects.

4.4. Is fleet electrification an opportunity for sustainability?

Although other materials-induced costs caused by EV production and consumption weren't included in this assessment, copper-induced additional resource and environmental cost during EV manufacturing can significantly offset on-road EV's better environmental benefits in comparison to FV (Table 2).

4.4.1. Sustainability of resource supply

According to current recycling rate of copper scrap in China, to replace each FV with EV, copper-induced additional inputs of copper ore, copper scrap, hard coal, fresh water, soften water, and industrial oxygen during each vehicle manufacturing were estimated to be 48898 kg, 198 kg, 300 kg, 7496 kg, 834 kg, and 260 m^3, respectively (Table 2). If other EV materials-induced additional resource demand due to the replacement was included, these values will rocket up.

Accumulative copper ore demand induced by the BS and AS EV sales from 2013 to 2050 will respectively reach to 3.95 times and 40.43 times of the national resource reserve in China in 2016 (NBSC, 2017). In the peak years, even without considering copper demand from grid upgrade, BS EV-induced annual copper ore demand will be about 21% of the Chinese copper resource reserve and 862% of Fujian's copper basic reserve in 2016, while in AS the two proportions will be about 240% and 10072% (Table 3). Some of EV-induced other resource demand in peak years would also take considerable share of the national or the provincial resource reserve and emissions in 2016 (Table 3). These ratios indicate that the EV-induced potential consumption of many resources in Fujian do not meet the principles of sustainability and commonality of sustainable development.

4.4.2. Environmental sustainability

With the input of resources for copper refining, CO_2 emissions induced by the refining of additional copper demand would correspondingly reach to about 819 kg per vehicle, excluding emissions from other processes required for the refining-related resources (Table 2). In

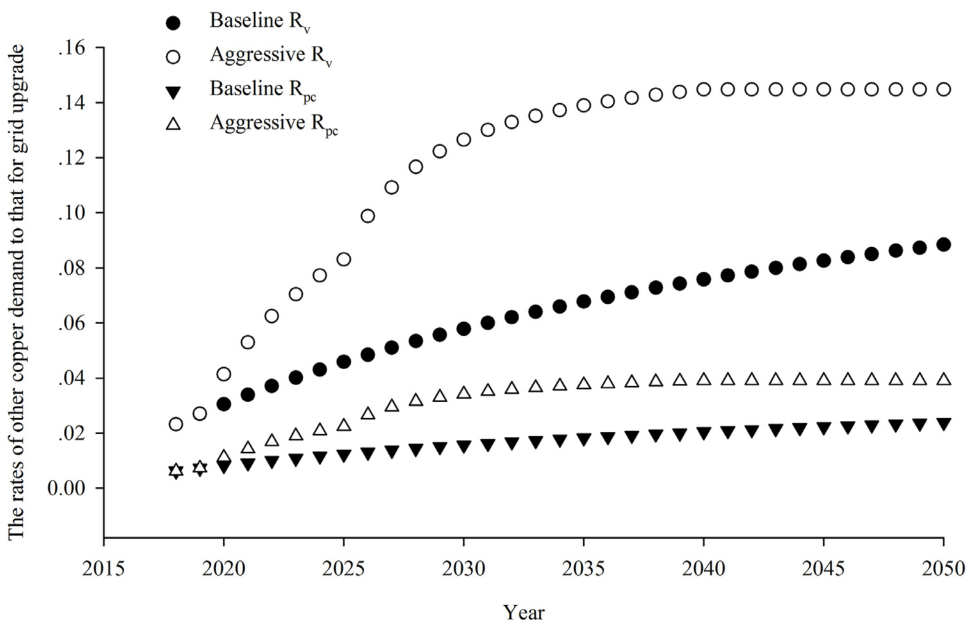

Fig. 5. The rates of other copper demand to that for grid upgrade for electrifying the fleets. Notes: R_v is the rate of additional copper demand for vehicle to that for grid upgrade, R_{pc} is the rate of copper demand for piles and chargers to that for grid upgrade, details see in the section 3.2.6..

contrast, only 12865 kg CO_{2eq} would be reduced during 600 000 km mileage which is an FV's or five EVs' mileage lifespan, calculated on power supply structure in China (Chen et al., 2019; Ding et al., 2017) and the emission data of different types of vehicles (Van Mierloet al., 2017; Nordelöf et al., 2014; Edwards et al., 2014). In short, even if we consider only copper refining emissions, 6.4% of on-road CO_{2eq} reduction by replacing FV with EV will be offset by CO_2 emission from the refining of the replacement-induced additional copper demand. This offset will rise up to 21.1% (14.7% + 6.4%) in 2050 and 61.6% (55.2% + 6.4%) in 2018, if we include copper-induced CO_2 emission from charging facilities, although copper use in facilities for each EV will fall down, to 821 kg in 2050 from 3077 kg in 2018 in BS, with the improvement of the facility network.

Nevertheless, if calculated on power supply structure in Fujian where thermal power (dirty energy) supply proportion was lower than the national average in 2018 (FJBS, 2019), the same emission data of different types of vehicles mentioned above, the CO_{2eq} reduction will rise to 32644 kg during an FV's mileage lifespan. Correspondingly, the offset in the BS will fall to 8.3% in 2050 and 24.3% in 2018 (2.5% from vehicle, 5.8% in 2050 and 21.8% in 2018 from supporting facilities). Thus, if we consider nothing but CO_{2eq} reduction for environmental sustainability, environmental benefits of the replacement would depend on local availability of clean power, as well as its energy types and power plant location landscape (Gao et al., 2019a). Fortunately, in China which is the world's largest CO_{2eq} emitter based on emissions from coal power-generating units which is a primary cause of global emissions (Oberschelp et al., 2019), the emission from coal power plants have substantially reduced after the introduction of ultra-low emissions standards since 2014 (Tang et al., 2019). In short, EV-induced pollution can be considerably less severe, depending on the charging source, the energy intensity and structure of EV manufacturing (Holdway et al., 2010).

Apart from CO_2, other pollutant emissions should not be ignored, e.g. accumulative pollutant emissions of arsenic, mercury, and lead in Fujian from 2013 to 2050 will equal to 15.88%, 158.90%, and 3.50% of national emissions in China in 2017 for BS, and to 162.39%, 1625.31%, and 35.79% of the national emissions in 2017 for AS (NBSC, 2018). Thus, in addition to copper, if we consider the emissions caused by processing the resources, total environmental cost of the fleets with EV adoption will likely surpass the cost without EV adoption.

In summary, it is not prudent enough to judge whether EV adoption is environmentally friendly by relying on one aspect of environmental performances of on-road vehicle, e.g. such as GHG emission during the on-road phase. Thus, if an industrial transformation were enforced by top-down policy rather than spontaneously driven by down-top industry development, it is necessary to carefully balance the speed and scope of transformation advancement by systematically evaluating the resource efficiencies and environmental effects of the whole vehicle industry chain.

4.5. Ripple effects of end product on environmental sustainability

According the number of processes received, human-made products can be roughly divided into the following categories: raw resource such as ore, processed resource such as ore concentrate, raw material such as primary metal, processed material such as refined metal, semi-finished product such as auto parts, end product such as vehicle. Some resource-intensive end products can be called pyramid tip product, e.g. EV, as they are assembled by many semi-finished products which are made up of various processed materials, some of which must consume huge amounts of various resources. In other words, pyramid tip product's material footprint from the beginning to the end of its production chain is much more intensive than other products. Material processing along each level of the chain would correspondently result in associated environmental emissions. Ripple effects of end product on environmental sustainability comprise both materials extracted from the environment and its associated emissions. The ripple effects of pyramid tip products could be much more significant than other products, as confirmed by EV in this study.

Due to the expanding EV fleets in Fujian, the peak year's 3.34 times of SPVO increase since 2018 could induce about 12 times and 139 times of increase of annual additional copper demand, respectively for BS and AS. The increase in additional copper use will inevitably lead to a correspondingly significant increase in copper processing-related resources and emissions along the copper processing chain (Fig. S4; Fig. S6-S11), mainly the use of raw materials in its upstream processes verified by that the accumulative input of primary or pre-processed resources required for copper refining such as copper ore, fresh water, and hard coal, were orders of magnitude of times more than further processed products such as gelatin, thioureas, and casein (Fig. S4,

Table 2
Copper-induced additional cost per vehicle contributed by replacing FV with EV. Units: m^3 for natural gas and industrial oxygen, kg for others.

	Crude oil	Hard coal	Natural gas	Copper ore	Copper scrap	Fresh water	Butyl xanthate	Pine camphor oil	Limestone	Quartz sand	Soften water
Input	10.9	300.2	65.5	48898.7	197.9	7496.1	2.0	1.2	53.0	128.6	834.0
	Industrial oxygen	Refractory material	Hydrochloride acid	Sulfuric acid	Gelatin	Thioureas	Casein	Spray mold	Sodium hydroxide	Sodium chlorite	Sodium hypochlorite
Input	260.4	4.1	0.1	2.3	0.0	0.0	0.0	0.5	0.0	0.1	0.0
	Carbon dioxide	Sulfur dioxide	Nitrogen oxide	Carbon monoxide	Methane	Nitrous oxide	Sulfuric acid mist	NMVOC	Particulate matter	Mercury	
Output	818.90	3.48	0.20	0.83	2.21	0.01	0.14	0.02	2.88	0.00	
	Lead	Zine	Nickel	Arsenic	Chemical oxygen demand		Biochemical oxygen demand	Solid suspension		Ammonia nitrogen	Solid waste
Output	0.00	0.00	0.00	0.00	0.03		0.00	0.33		0.09	26452.43

Notes: The copper-induced cost from EV grid upgrade is excluded here. The cost per vehicle includes resource input or pollutant emission, is the product of the cost per kg copper (Chen et al., 2019) and EV-induced additional copper use which is the difference of 5 EVs' copper use minus 1 FV's copper use, based on the mileage life difference between EV and FV (Section 3.2.4.). "Copper use per vehicle" sees the section 3.2.6.

Table 3
The share of Fujian's EV copper-induced resource demand or emission in peak years in total reserve of resources or total emissions in China or Fujian in 2016.

	AS Rate A %	Rate B %	BS Rate A %	Rate B %
Energy resources	0.002	21.536	0.000	1.843
Copper ore	239.59	10071.57	20.50	861.84
Sulfur dioxide	0.041	2.363	0.003	0.202
Nitrogen oxide	0.002	0.100	0.000	0.009
Particulate matter	0.037	1.557	0.003	0.133
Mercury	138.25	38520.62	11.83	3296.28
Lead	1.54	204.24	0.13	17.48
Arsenic	7.87	878.38	0.67	75.16
Ammonia nitrogen	0.008	0.225	0.001	0.019
Solid waste	1.10	76.36	0.09	6.53

Notes: The copper-induced resource demand or emission from Fujian's EV fleet and its supporting facilities excludes that from grid upgrade. Rate A and B denote the rates of Fujian's EV copper-induced demand/emission in peak year to the national and Fujian's values in 2016. The aggressive scenario (AS) and baseline scenario (BS) peak years are 2042 and 2045, respectively. The demand of energy resources was estimated by standard coal values of crude oil, hard coal, and natural gas. The national and provincial particulate matters refer to smoke (powder) dust. The national and provincial solid wastes denote general industrial solid waste. The national and provincial data are sourced from NBSC (2017).

Fig. 6). Accordingly, pollutants were emitted mostly from upstream processes of vehicle industrial chain (Fig. S9-S11). Thus, although downstream processes consumed very few resources and produce very slight environmental effects, EV can incur ripple effects from downstream to upstream of its production chain. The ripple effects would be greatly amplified, considering 1) other EV materials-induced effects through their multiple layers of processes (Fig. 7), e.g. growing NO_x emissions from Chinese iron sintering process (Gao et al., 2019b), as iron is one of critical metals (Al, Co, Cu, Fe, Li, Mn, Ni, Nd, Dy) for electromobility (Habib et al., 2020); and 2) the system-to-system effects from the processing of copper processing-related materials which consume resources and discharge pollutants before they can be used in copper refining from lifecycle perspective. Thus, the change in PVO structure can be the fuse or engine of future potential vast systemic environmental changes or serious resource shortage. Finally, the change can affect the infrastructure of the ecosystem which supports the development of human civilization.

To meet the transportation needs and promote environmental sustainability, on-road vehicles' energy consumption and GHG emissions are not the only problems that we should face. During the production phase of EVs and their supporting facilities, much more resources, materials, and energies input will be demanded than FV, as verified by copper in this case. Even worse, cumulative amount of the consumption of resources and emissions will increase by orders of magnitude, attributed to the ripple effects.

5. Conclusions and suggestions

Climate and energy security concerns make the electrification of transportation system inevitable. Since 2018, the BS and AS peak years' copper demand would respectively increase about 12 times and 139 times in response to the rapid increase of PVO and its EV share estimated by ARIMA integrated with DMFA. While, in peak years, annual BS and AS copper demand with EV in the fleet would be 1.65 and 6.87 times of that with no EV in the fleet. Correspondingly, copper-induced ripple environmental effects would increase significantly. Even worse, the effects will be amplified along the production chain if including resource and environmental load from producing resources/materials required for copper refining. Therefore, the road transportation mix would be the most possible solution in the near future, depending on a compromise between additional cost of EV-induced ripple effects and

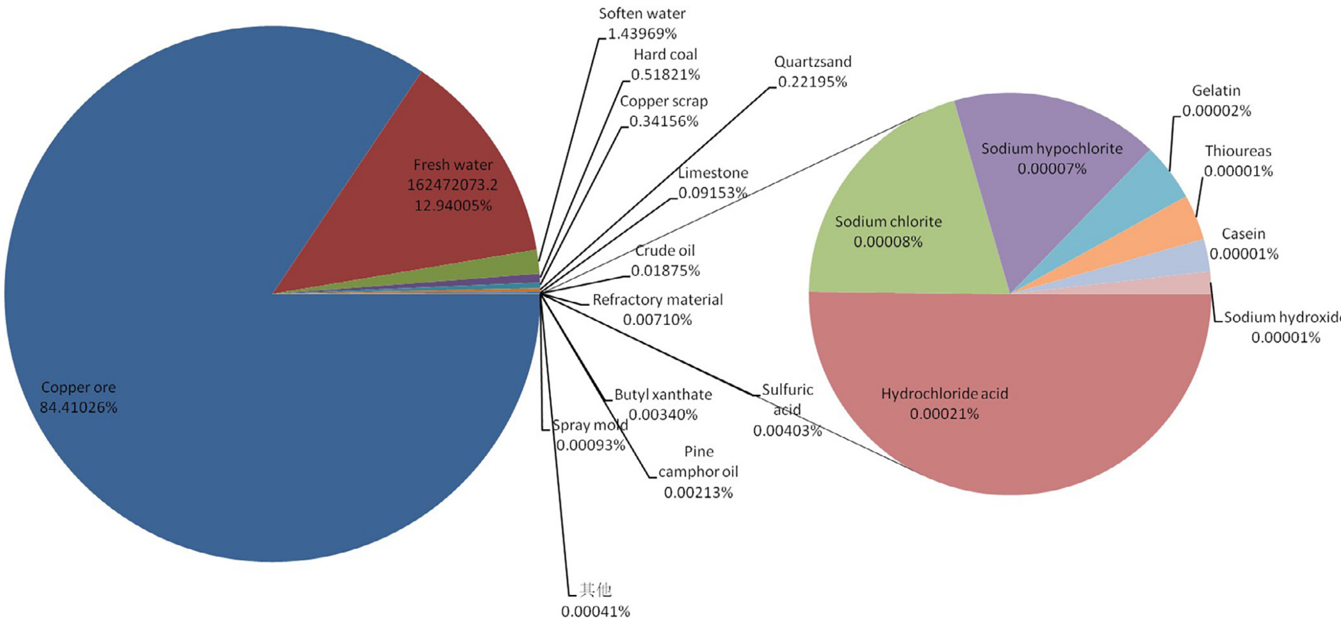

Fig. 6. The structure of accumulative input of resources for additional copper demand from 2013 to 2050, due to the expanding fleets and its EV share. Units: m^3 for industrial oxygen and natural gas, tonnes for other resources. Note: The resources or products in the percentage figure was required for copper refining, but without considering copper ore, natural gas, and industrial oxygen.

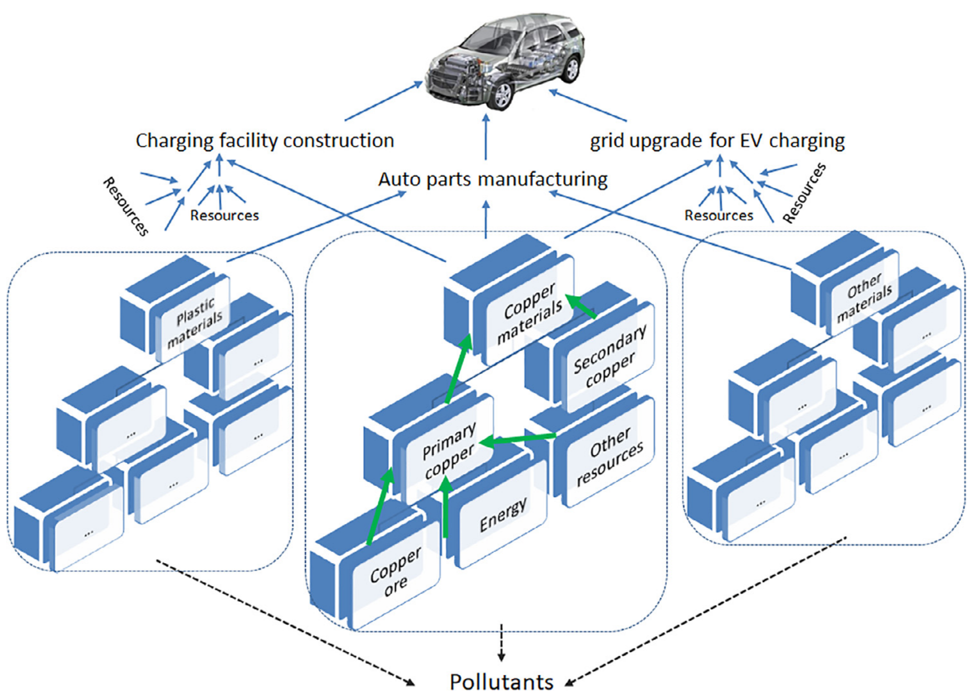

Fig. 7. Ripple effects of resource demand and pollutant emission from the expanding pyramid tip products

on-road EV's better environmental benefits, in contrast to FV.

5.1. Copper

Along with the increase of population, per capita income, and local vehicle production since 1978, the expanding copper supply-demand gap in Fujian will accelerate with the electrification of local fleet driven by local governmental aggressive EV promotion plans such as the "Electric Fujian" program and increasing battery production by CATL. The copper demand increase contributed by the electrification was largely caused by battery manufacturing and grid upgrade. Thus, enhancing the recycle of copper scrap in these two sectors will play crucial role in reducing primary copper demand and slowing down the gap expansion, as current recycled scrap copper accounts for less than 30% of the total copper use in China where copper use is mostly met by imports (Table S1; Wang et al., 2019). However, the import won't be sustainable, as the global cumulative copper demand is expected to exceed its reserves and reserve base in most scenarios by 2050 (Elshkaki et al., 2016), but copper scrap will rapidly increase, as verified by about 60% of the copper consumed in the U.S. was transformed to scrap during the period 1900-2016 (Wang et al., 2018). Therefore, strengthening the recycling of secondary copper will play a more important role in alleviating future copper shortages. Other alleviating measures may comprise circular design, reduction and reuse of scrap copper from production-consumption processes, improving copper use technology, extending the service life of copper-containing products, improving power transmission and distribution efficiency of grid. In addition, material substitution is an effective way to reduce copper demand, e.g. aluminum for copper in power cable, electrical equipment, automobile radiators, and cooling and refrigeration tube; Titanium and steel for copper in heat exchangers; optical fiber for copper in telecommunications applications; plastics for copper in water pipe, drain pipe, and plumbing fixtures (USGS, 2018).

5.2. Additional resource and emission for additional copper demand

With increasing EV-induced additional copper demand, additional resources will be needed for additional copper refining, and the refining-related emissions will also be significantly enhanced. According to current copper refining technology, to replace each FV with EV, additional refined copper demand requires a much larger amount of various resources, e.g. additional copper ore and fresh water demand are 33 times and 5 times of the EV weight which is assumed to be 1500 kg. Thus, future EV-induced additional copper demand in Fujian would bring about serious resource and environmental consequences, verified by AS in which the 2013-2050 EV-induced accumulative copper ore use would be 40 times more than total copper ore use in China in 2016, and its associated mercury emission is 16 times of the national 2017 emission. Apart from copper-induced resource and environmental effects, EV-induced other materials' effects cannot be ignored either (Fig. 7), and their processing should apply resource saving technologies (Gao et al., 2019c; 2020). In short, EV-induced additional cost compared with FV can significantly offset its on-road benefits in environmental performance. Therefore, to reduce the electrification's negative effects would rely on the improvement of passenger capacity and transportation efficiency of the fleet by efficient use of in-use vehicles and extending vehicle life. After all, supporting value of the environment to human society, i.e. the value of all resources extracted from the environment consumed in an end-product's industrial chain and the environmental purification cost of pollutants from resource processing, can only be ultimately realized when the end product is used by consumers. Secondly, we should continue to improve copper production technologies, such as copper smelting and refining, and copper industry management efficiency to achieve resource-efficient copper production. In addition, because most of CO_2 emissions arise from energy use (Davis et al., 2018), we must continuously increase clean energy production and reduce the proportion of high-polluting thermal power in copper production, as well as enhance energy-saving during EV operation such as encouraging the employment of energy-saving charging facilities.

5.3. Ripple effects of a pyramid tip product

Analysis on the ripple resource and environmental effects of a pyramid tip product systematically provide a model for the development of a catalogue pedigree of various products from raw resource to pyramid-tip product from a lifecycle perspective. The pedigree is useful for systematically planning resource utilization and environmental protection from the planetary scale, based on pyramid tip product's significant leverage effect on reducing resource consumption and pollutant emissions. Firstly, the pedigree can emphasize the importance of efficient use of pyramid tip product in promoting environmental sustainability. This is verified by EV, i.e. the better the monitoring and use of EV, the higher passenger capacity and transportation efficiency per its lifecycle, the less EV-induced production, indicating the smaller its resource and environmental effects through its production chain. Secondly, the pedigree is helpful for the lifecycle management in producing pyramid tip product and its associated upstream products and check out the key technology to reduce resource use and emission across the scales of their industry chains. Thirdly, the pedigree facilitates the targeted sorting of waste components containing pyramid tip products, its recycling means recovering their embedded economic or environmental values and functions, based on the thinking on the water conservation significance of municipal solid waste management (Huang et al., 2016). Finally, the pedigree can facilitate promoting a discussion of the relationship between material use chain length and human civilization development degree for a better common future. Then, by building a comprehensive monitoring system across its production chain to extend local environmental responsibility to global responsibility and extend the focus on lifespan of end products to that of all products across the pedigree, the crisis of ripple effect of local EV expansion may be turned into an opportunity for sustainable development of global EV deployment.

The ripple effects of a pyramid tip product also indicated that more levels of a pyramid from raw resource extraction to end product manufacturing, the easier it is to discover the urgency and potentiality of efficient use of key resources. The more levels a pyramid chain, the more types of resources required, and the more technical accumulation and integration of efficient use of resources. Furthermore, although the accumulated waste in a longer pyramid chain may be more than that in a shorter one, the less the waste likely generated in a single link of the longer chain due to scientific and technological progress associated with the extension of the chain, the better the overall environmental benefits, in contrast to the corresponding link of the shorter one. Moreover, it also means that the longer a pyramid chain, the more jobs can be accommodated. Therefore, strengthening international cooperation in pyramid tip product management should be encouraged by governments around the world. The cooperation would promote the optimal allocation of resources on a global scale by inducing the flows of resources from a shorter to an efficient longer chain, thereby improve the overall utilization efficiency of global resources. It was also suggested that the governmental departments and enterprises and consumers should strictly control the consumption of pyramid-tip products, save them, and strengthen their reuse, as well as extend cleaner production to cleaner consumption for environmental sustainability (Fig. 8).

In conclusion, compared with the discussion of use efficiency of raw resources, it may be more important for environmental sustainability to explore the ripple effects of pyramid tip products. The exploration of the ripple effects is conducive to the sustainable use of resources and the top design of environmental protection.

6. Future research

Accurately, the service value of a passenger vehicle is reflected in the service mileage (mileage lifespan) rather than length of time from factory to end-of-life (duration lifespan). The average service mileage of FVs is five times that of EVs. Therefore, If considering the system-of-system effect, the ripple effects of resource demand and environmental emission of one FV should also be compared with that of five EVs. However, in many previous studies, the comparison between environmental effects of FV and EV usually focused on only the difference of the GHG emission effects of one FV and one EV within the same driving

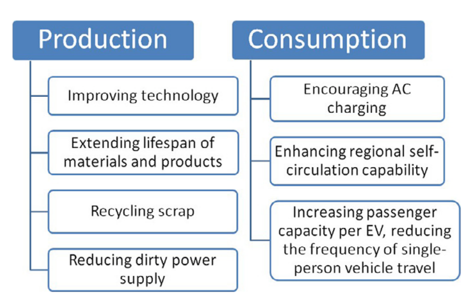

Fig. 8. Suggestions for sustainable replacement of FV by EV

distance, ignoring other pollutants rather than GHG, the different effects of the two types of vehicles during manufacturing, different mileage lifespan, different resource demand and environmental effects from their supporting systems. However, although this study considers the above-mentioned problems, it has not considered the resource and environmental effects of land, plant construction, and manpower training required for EV system. Thus, realization of the copper-induced additional ripple effects incurred by the expanding EV fleet could stimulate the discussion on the system-of-system effects of adopting emerging technologies at a global scale.

Credit author statement

Chu-Long Huang: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Validation; Visualization; Writing - original draft and review & editing

Ming Xu: Supervision; Writing - review & editing

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Declaration of interests

•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.

•The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.104861.

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