Supplementary Information *for*

Decarbonization scenarios and carbon reduction potential for China's road transport by 2060

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Supplementary Note 1. Energy conservation and emission reduction and NEVs promotion policies of China's transport sector

In the 19th National Congress of the Communist Party of China, General Secretary Xi Jinping proposed "building a strong transportation country", "advocating a green and low-carbon lifestyle", and encouraging everyone to travel green. In the future, there is an urgent need to promote energy conservation and emission reduction in the field of transportation and promote the electrification and cleaning of urban public transport and vehicles. The support policies of NEVs have covered industrial planning, industry management, financial subsidies, tax incentives, charging facilities construction, convenience measures, etc., for forming a policy system to support the development of new energy vehicles. Through the review of relevant policies, it can be found that in recent years, China's road transport sector has dramatically improved comprehensive efficiency, strengthened scientific and technological innovation, and promotion of low-carbon technology. Significantly, the relevant policy system has continuously promoted and applied in new energy and clean energy vehicles (See Supplementary Figure 1 and 2).

Supplementary Note 2. Cross-city difference in NEVs diffusion and emissions.

The development of NEVs presents a significant combined effect at the regional level. There were only 4 cities surpassing the threshold of 50,000 NEVs in 2016, and the number increased to 15 in 2019. Except for Chengdu, Chongqing and Liuzhou, these cities are all located in the eastern and central regions. The demand of Beijing, Shanghai and Guangzhou ranks first, and the growth rates of Zhejiang Province and Jiangsu Province are noticeable. However, under the influence of the restricted purchase policy, the sales growth of NEVs in some first-tier or new first-tier cities is relatively slow. The most typical representative is Beijing, followed by Tianjin, Guangzhou, Hangzhou, and other places. Shanghai is a particular case among the purchase-restricted cities, primarily because it has not implemented the new energy license auction policy. In addition, considering population density, economic development level, and related supporting infrastructure, such as charging piles[1], Zhengzhou and Chongqing are cities with enormous market demand for NEVs in the central and western regions.

Regarding CO_2 emissions, the top 10 cities in terms of carbon emissions, except Chengdu and Chongqing, are all located in the central and eastern regions. Beijing has the largest emissions at 18.88 Mt. Although Beijing ranks first in the country in terms of vehicle stock (more than 6 million vehicles in 2020), since the implementation of relevant policies, such as travel restrictions (2007) and a car purchase lottery (2011), its motor vehicle stock has increased at a lower speed than that in other cities, leading to the continued slowdown of the growth rate of its carbon emissions. Chengdu and

Chongqing currently have more than 5 million motor cars. Suzhou, Shanghai, Zhengzhou, and Xi'an have more than 4 million motor cars, which provides a reasonable explanation for the high emissions and high carbon emission growth in these cities. Notably, as a new first-tier city, Zhengzhou has seen significant growth of its vehicle stock. Its passenger car stock ranks sixth in China and first among the capital cities of the six central provinces. In recent years, the construction of transportation infrastructure in Zhengzhou has grown significantly, citizens find travel more convenient, and the purchase of private cars has increased substantially. Moreover, Zhengzhou has a well-developed logistics industry and is a transportation hub in the central region. These factors have led to a rapid increase in Zhengzhou's CO_2 emissions from road traffic. At a similar level to that in the central region, Chongqing's CO_2 emission growth rate is the most obvious in the western region. Apparently, China's first- and second-tier cities show more "stock" characteristics due to their early development, mature automobile markets, and near-saturated demand. Nevertheless, driven by economic growth in the central and western regions, there is much room in the consumer market, and the expected increase in carbon emissions is substantial.

Supplementary Note 3. Supplementary analysis on time trends of NEVs diffusion and the associated CO2 emissions.

The proportion of battery electric vehicles (BEVs) gradually increased by vehicle type, and hybrid vehicles gradually decreased (Fig. 3b). The largest NEV sales volume in 2019 was for BEVs, whose sales accounted for 24.7% and 39.9% more than those of HEVs and PHEVs, respectively. This is directly reflected in the stock structure of NEVs. Among the NEVs in 2019, BEVs, HEVs and PHEVs accounted for 58.61%, 24.68% and 16.71%, respectively. This is directly related to the promotion of NEVs and the stickiness of consumer habits. In the early stage of the promotion of NEVs, considering the critical position of traditional fuel cars in consumers' car-buying habits, the National Development and Reform Commission advocated the priority promotion of oil and gas or electric hybrid vehicles. However, in the later period of the promotion, considering the goal of energy conservation and emission reduction and the development requirements of green and low-carbon transportation, the Ministry of Industry and Information Technology vigorously promoted pure electric vehicles.

Auto sales declined due to a combination of factors, such as the transformation of the auto industry, US–China trade frictions, changes in environmental standards, and COVID-19. However, given China's "dual carbon" target, the recognition of NEVs has improved among consumers, and NEVs will show a significant growth trend in the future, especially in the second- and third-tier cities in the central and western regions. It can be expected that the carbon emission reduction potential and contribution of road transportation electrification will continue to increase.

Supplementary Note 4. Evidence of stock-CO2-economic relations on the city level

The cases of Beijing and Guangzhou re remarkable. In 2019, its passenger car stock and CO_2 emissions were the highest among all cities, but its per capita GDP growth rate (21.91%) and CO_2 emissions growth rate (23.6%) were both more extensive than the stock growth rate (5.7%). This is mainly because, as the capital, it has faced severe traffic congestion and air pollution situations in recent years. Thus, its traffic control and environmental governance are relatively strict. In particular, the rapid expansion of motor vehicles is restricted by policies such as lottery and driving restrictions. As a result, the high emissions growth is closely linked to a large fuel vehicle stock and robust economic activity. In addition, Guangzhou's CO_2 emissions and stock increased the most in 2019, reaching 94.7% and 59.9%, respectively, while its per capita GDP increased by only 10.3%. The per capita GDP growth rates of Shenyang, Hangzhou, Tianjin, and Jinan are lower than the average in eastern China, but the CO_2 emission growth rate and stock growth rate are more prominent. In particular, Jinan's per capita GDP growth in 2019 was only 0.46% compared with that in 2016, but the increase in CO_2 emissions and stock was 76.7% and 38.67%, respectively. Therefore, it is interesting to pay some attention to the relationship between economic development and carbon emissions in these cities.

Supplementary Note 5. Comparisons with transition pathways under the SSPs

We conducted a comparative analysis of China's road traffic emission paths under typical SSP scenarios. Compared with the SSP5-34OS scenario, in which emissions peaked in 2040, the three scenarios in this paper present reductions of 18.9%, 43.0%, and 43.3% in the peak level. The SSP3-LowNTCF scenario calls for road traffic emissions to peak in 2030, with emissions as low as 1043.55 Mt. The SSP1-19 scenario, which corresponds to the 1.5-degree temperature control target, requires a carbon emissions drop beginning immediately. Evidently, compared with these scenario results, our path is higher both at the peak and overall path levels, but this does not affect the reliability of the low-carbon path in this paper. First, this paper adopts a bottom-up microaccounting method based on high-frequency big data. However, the historical accounting data we select are low-level high-frequency data, which are more authentic than the public macro data statistics. In particular, fuel economy and average mileage per month are sampled from big data (millions) monitored in real time. Second, the data of the SSP scenario are mostly from the IEA and were estimated by the top-down method. Nevertheless, the accounting of relevant departments in China is more extensive than that of the IEA[2,3-5].

Supplementary Note 6. Road transport stock under different scenarios and CO_2 emission under BAU scenario (2020-2060)

The development paths of the vehicle under different scenarios are shown in Fig. S4a. Under the BAU, the motor vehicle of road transport in China increases and will be about 638.65 million in 2060. Vehicle ownership will reach its peak in 2049, with a peak level of 599.25 million under the CPS. The TPS can advance the peak time of the possession to 2047, and the corresponding peak level is 591.26 million. Furthermore, the EPS can further extend the peak time to 2045 and reduce the corresponding peak time to 559.05 million. By 2060, compared with the BAU, the retention of the three scenarios will decrease by 29.85%, 37.15%, and 49.32%, respectively. Fig. S4b shows that carbon emissions generated by the passenger transport sector firstly increased and then decreased, reaching a peak of 1044.88 Mt in 2050 and decreasing to 1013.67 Mt in 2060. On the other hand, the carbon emissions of the freight sector will continue to increase and reach 1548.26 Mt in 2060. Although the carbon emission of passenger transport is slightly greater than that of freight transport before 2023, freight transport will overtake passenger transport and become the main force of road transport emissions from 2024. This is mainly because industrialization and urbanization in China are continuing, and the demand for freight transportation is still in the stage of rapid growth, mainly in bulk commodity transportation. At the same time, with the prosperity and development of the e-commerce economy, the demand for express transportation is also rising, which also brings challenges to the low-carbon transition of freight transportation.

The United States, the European Union, Japan, and other developed countries are pioneers in low-carbon transport development. Therefore, the evolution of the development characteristics of their transport industry can provide an essential reference for the formulation of China's low-carbon transport development strategy[6-8]. In typical economies, the historical trends of road transport energy consumption (emissions) and GDP show a precise "S" shape. Moreover, the S-shaped peaks occur at different times, depending on the population size. In general, energy consumption for road transportation declines after a period of high growth and then tends to stabilize[9]. In 2016, the United States transportation sector surpassed the electric power sector as the largest carbon emitter for the first time. In 2018, carbon emissions from the transport sector in the United States and the United Kingdom accounted for 33.1% and 33% of total carbon emissions[10]. Developed economies have completed urbanization and industrialization, and private car ownership is growing slowly. As a result, the energy consumption and emissions of the transport sector have reached an S-shaped peak and began to decline. In contrast, China's industrialization and urbanization process continue, and car ownership has yet to peak. The energy consumption and emissions of the transport sector are still in the stage of rapid growth. As a result, the energy consumption and road transport emissions have not reached the S-shaped peak, and their proportion is still significantly lower than that of developed countries. This further indicates that the contribution of stock adjustment to emission reduction is more significant than that of transportation electrification. At present, China needs to take strong policy measures to make the transport sector achieve a carbon emission peak as soon as possible.

Supplementary Note 7. Emission reduction calculation of electrification
Battery electric vehicle (BEV):

$$\Delta R_{BEV} = E_{tf} - E_e \qquad (1)$$

where, ΔR_{BEV} represents the CO_2 emissions reduction of BEV, E_{tf} represents the CO_2 emissions of traditional fuel vehicles, and E_e represents the CO_2 emissions of BEV.

$$E_e = \sum(VS_i \times \omega_i \times AVT_i \times EF)/(1-k) \qquad (2)$$

Where $\boldsymbol{\omega_i}$ represents the power consumption for 100 km of type i (kWh/100km), k represents the transmission loss rate from output to input region (The default value is 6%, MEPC[11]).

Hybrid electric vehicle (HEV) and Plug-in hybrid electric vehicle (PHEV):

$$\Delta R_{HEV(PHEV)} = E_{tf}\lambda_i - E_{HEV(PHEV)} \qquad (3)$$

Where, $\Delta R_{HEV(PHEV)}$ represents the CO_2 emissions reduction of HEV (PHEV), E_{tf} represents the CO_2 emissions of traditional fuel vehicles, and $E_{HEV(PHEV)}$ represents the CO_2 emissions of HEV (PHEV).

Regional power emission factors are shown in Supplementary Table 4.

Supplementary Table 1 | Quantification of impacts for different policy measures

	Scenario settings			
Scenario measures	**BAU**	**CPS**	**TPS**	**EPS**
Sales	Passenger car sales and truck sales will grow by 5% from 2020-2030, 3% from 2030-2040, 1% from 2040-2050, and 0.5% from 2050-2060, respectively.	In 2030 and 2060, passenger vehicle sales will reach 33 million and 25 million, while freight vehicle sales will reach 5.5 million and 3.5 million.	In 2030 and 2060, passenger vehicle sales will reach 36 million and 25 million, while freight vehicle sales will reach 6.5 million and 3.5 million.	In 2030 and 2060, passenger vehicle sales will reach 38 million and 25 million, while freight vehicle sales will reach 7 million and 3.5 million.
Electrification of vehicles	In 2030 and 2060, the NEVs in new passenger cars sales will account for 25% and 55%, and the NEVs in truck sales accounted for 4 % and 10 %.	In 2030 and 2060, the NEVs in new passenger cars sales will account for 40% and 80%, and the NEVs in truck sales accounted for 5 % and 17 %.	In 2030 and 2060, the NEVs in new passenger cars sales will account for 45% and 85%, and the NEVs in truck sales accounted for 7 % and 19 %.	In 2030 and 2060, the NEVs in new passenger cars sales will account for 55% and 100%, and the NEVs in truck sales accounted for 20 % and 80 %.
Stock adjustment	The vehicle stock will reach 370 million in 2030, 600 million in 2045, and 495 million in 2060.	The vehicle stock will reach 370 million in 2030, 600 million in 2045, and 495 million in 2060.	The vehicle stock will reach 390 million in 2030, 600 million in 2045, and 456 million in 2060.	The vehicle stock will reach 400 million in 2030, 600 million in 2045, and 384 million in 2060.
Technological development	Basic data	The fuel economy of traditional fuel vehicles decreases by 0.5 on the basic data in 2019. The average power consumption of NEVs reaches 12 Kwh / 100km.	The fuel economy of traditional fuel vehicles decreases by one on the basic data in 2019. The average power consumption of NEVs reaches 11 Kwh / 100km.	The fuel economy of traditional fuel vehicles decreases by 1.5 on the basic data in 2019. The average power consumption of NEVs reaches 10 Kwh / 100km.

Supplementary refs[12-15].

Supplementary Table 2 | Basic data for estimation of passenger sector CO_2 emissions in 2019

		Class	Vehicle stock (thousands)	Proportion (%)	Fuel type	Annual vehicle travel (km)	Fuel economy L(kWh)/100km
Passenger	**Traditional fuel Vehicle**	**Mini**	229.9198	100	Gasoline	13273.27	6.66
		Common	15302.9673	99.9851	Gasoline	19801.12	7.80
			2.2813	0.0149	Diesel	20283.16	5.57
		Middle	6267.4642	99.4223	gasoline	15570.97	9.67
			36.4148	0.5777	Diesel	21690.34	8.68
		Middle-high	73.9233	97.7529	Gasoline	18523.72	13.39
			1.6993	2.2471	Diesel	27667.21	11.15
		High	0.1008	100	Gasoline	23459.28	16.56
	NEVs	**BEV**	223.5542	100	Electricity	21424.02	15.71
		HEV	94.1239	100	Gasoline	21707.47	5.06
		PHEV	63.7477	100	Gasoline	24953.94	6.46

Source data are provided in Source Data file.

Supplementary Table 3 | Basic data for estimation of freight sector CO_2 emissions in 2019

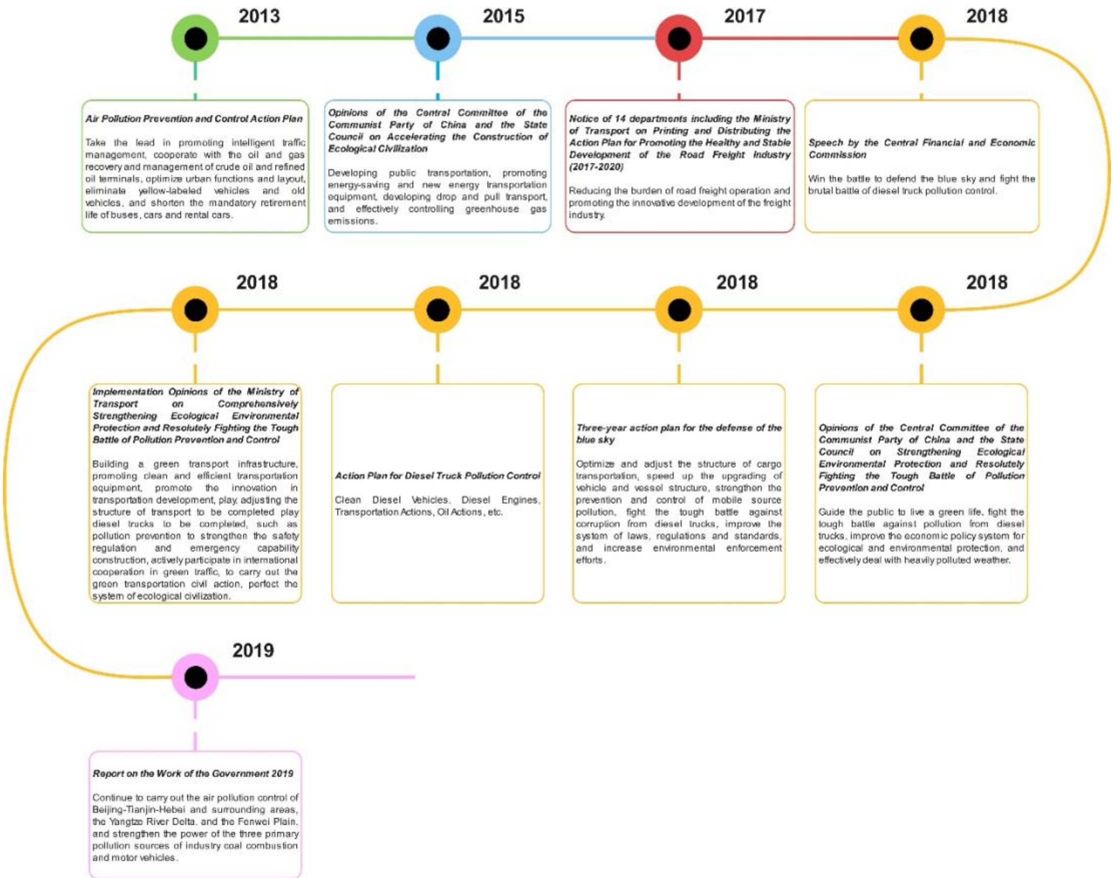
		Class	Vehicle stock (thousands)	Proportion (%)	Fuel type	Annual vehicle travel (km)	Fuel economy L(kWh)/100km
Freight	**Traditional fuel Vehicle**	**Mini**	7616.9	27.37	Diesel	75000	15
		Light	1162.5	4.18	Diesel	35000	18
		Medium	19007.5	68.3	Diesel	30000	21
		Heavy	41.3	0.15	Diesel	20000	25
	NEVs		410	0.015	Electricity	21424	15.71

Data source from Supplementary refs[16-19].

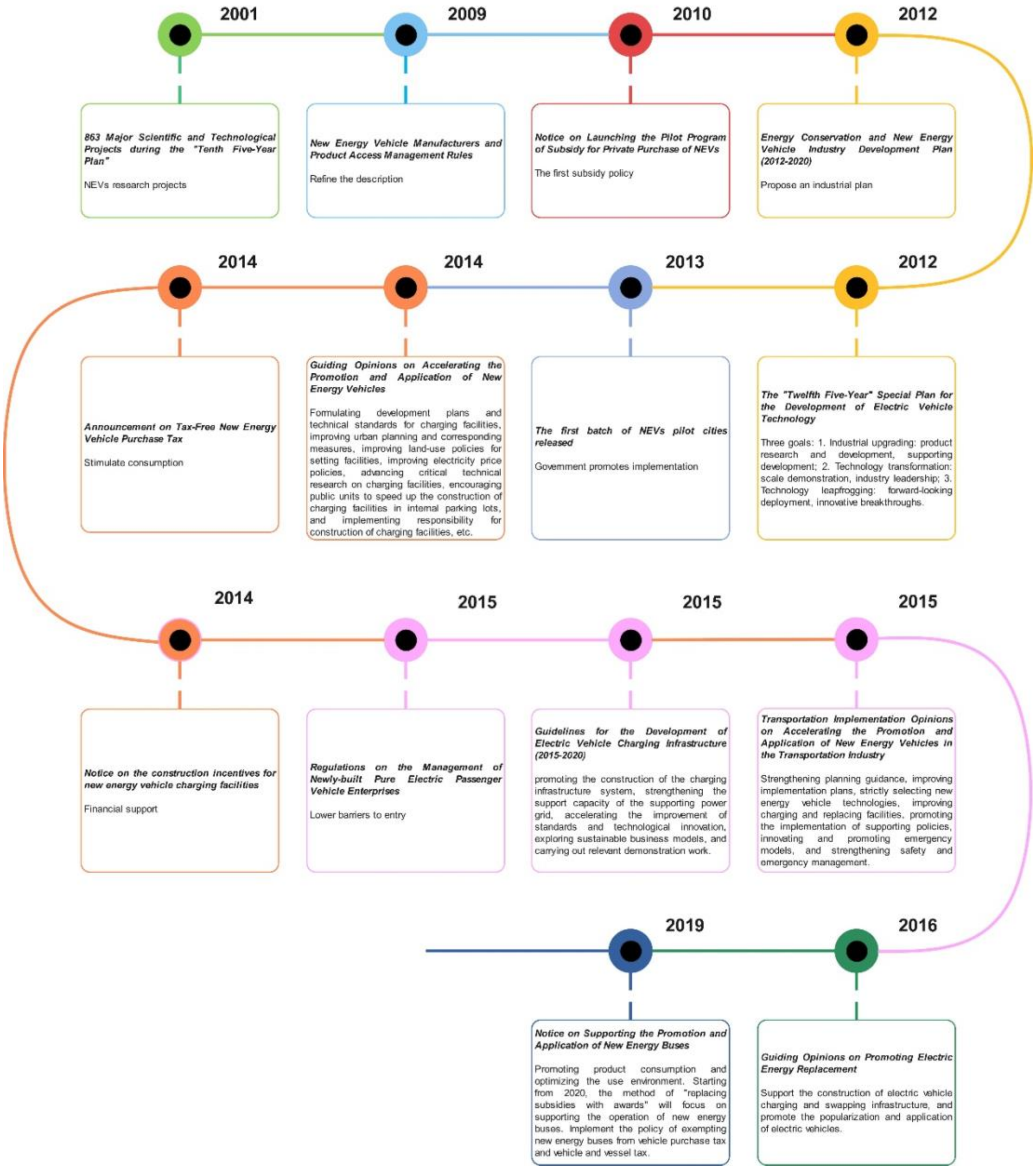
Supplementary Table 4 | Calculation results of OM emission factors of six regional power grids in 2019 (2015-2017 three-year weighted average)

Regional power grids	**OM emission factor（t CO_2/MWh）**			
	2015	**2016**	**2017**	**weighted average**
North	0.9590	0.9242	0.9437	0.9419
Northeast	1.0959	1.0634	1.0886	1.0826
East	0.7987	0.7894	0.7888	0.7921
Central	0.8767	0.8564	0.8444	0.8587
Northwestern	0.9178	0.8614	0.8990	0.8922
Southern	0.8080	0.7900	0.8139	0.8042

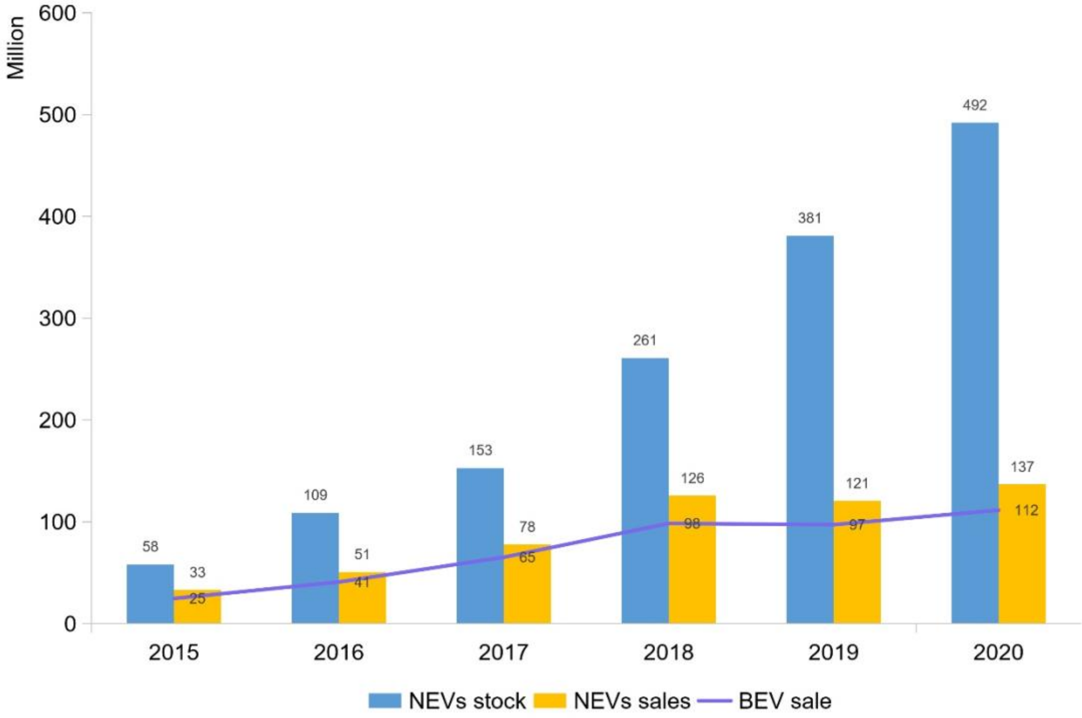
Data source: Ministry of Ecology and Environmental Protection, PRC "2019 China Regional Power Grid Carbon Dioxide Baseline Emission Factor OM Calculation".



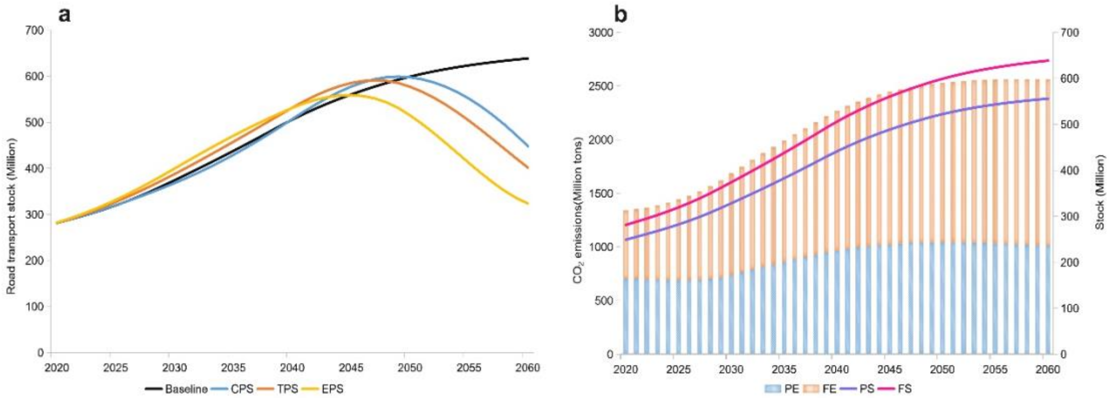
Supplementary Figure 1 | Road transportation energy conservation and emission reduction policies in China



Supplementary Figure 2 | New energy vehicles (NEVs) policies in China



Supplementary Figure 3 | NEVs stock and sales (2015-2020) Figure based on data from refs[20].



Supplementary Figure 4 | Road transport stock under different scenarios and CO_2 emission under BAU scenario (2020-2060) a. Road transport stock under different scenarios (2020-2060); **b**. CO_2 emission under BAU scenario (2020-2060) (PE=Passenger emissions; FE=Freight emissions; PS=Passenger stock; FS=Freight stock). Source data are provided in Source Data file.

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