Supplementary Information for

China Electricity Generation Greenhouse Gas Emission Intensity in 2030: Implications for Electric Vehicles

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Summary of Supplementary Information*:*

24 Supplementary Figures and 8 Supplementary Tables; 35 Pages including the cover sheet

Road transportation sector GHG emissions

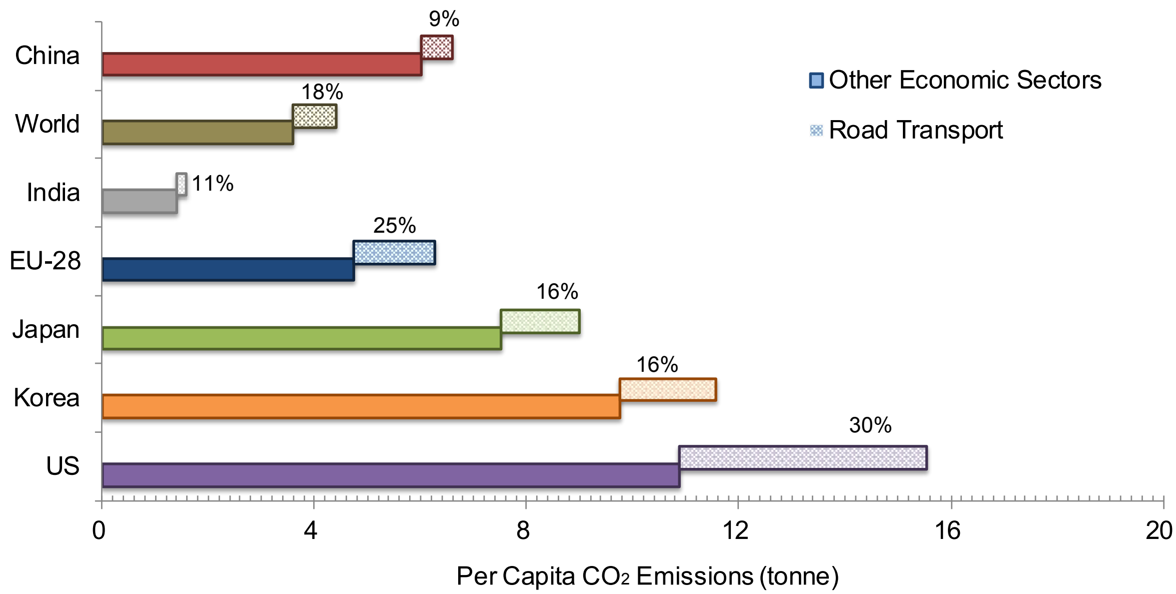

Figure S1. Fossil fuel CO_2 emissions in selected regions in 2015: Road transportation vs. other economic sectors

Data Source: IEA (International Energy Agency)

NEV (BEV + PHEV) and diesel vehicle trends in China

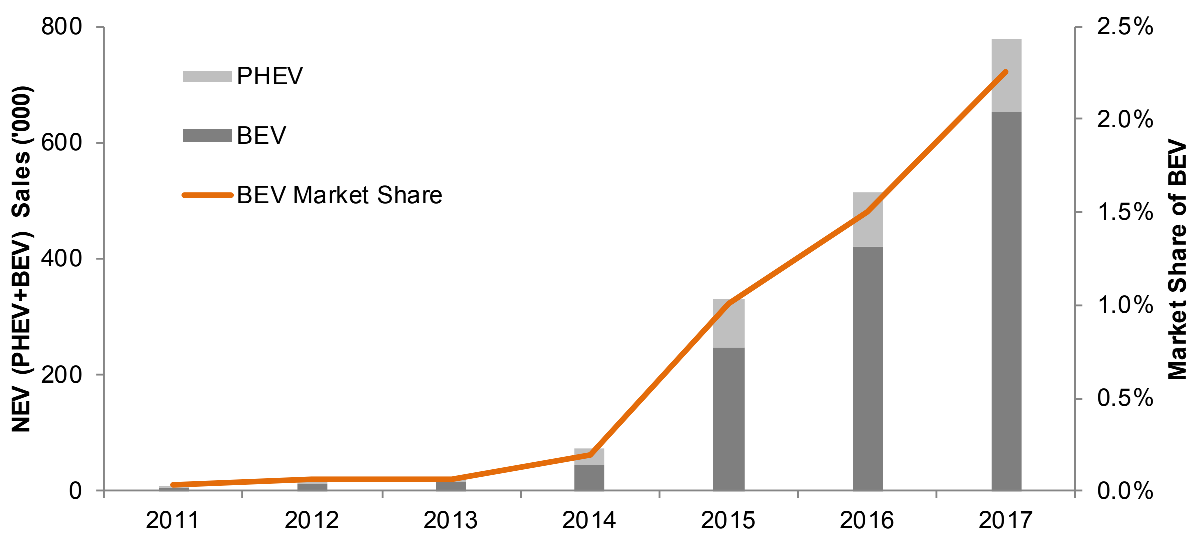

Figure S2. NEV (BEV+PHEV) sales in China
Data Source: China Association of Automotive Manufacturers

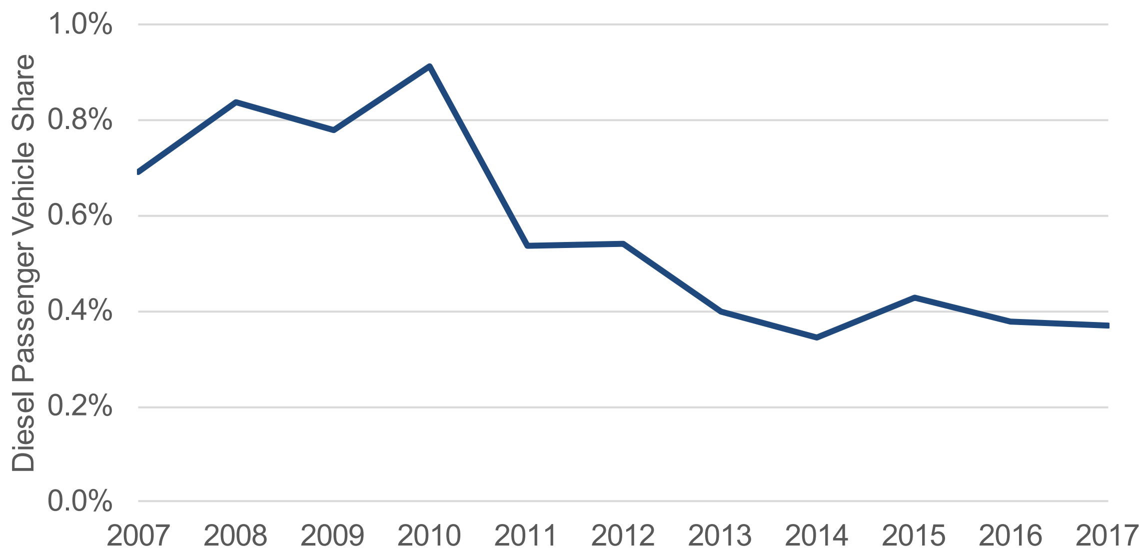

Figure S3. Diesel passenger vehicle market share in China
Data Source: China Association of Automotive Manufacturers

BEV electricity consumption rate

The Chinese government has a credit policy to encourage automakers to produce electrified vehicles. The credits incentivize automakers to achieve government fuel consumption goals for their products. The manufacturers' credits are based on the electricity consumption rate. Equation (1) shows the BEV electricity consumption rate, *e*, based on vehicle's curb weight, *m*. To qualify for the credit, the electricity consumption rate of a "common" BEV needs to be less than 95% of the value calculated from equation (1). If the electricity consumption rate is at least 25% lower than the value calculated from equation (1), the vehicle is considered an "advanced" BEV and gets 20% additional credit and 10% extra subsidy[1-2]. The thresholds for qualifying a vehicle as a common or advanced BEV are shown in Figure S4.

$$
\begin{aligned}
e &= 0.0126 \times m + 0.45 \ (m \leq 1000) \\
e &= 0.0108 \times m + 2.25 \ (1000 < m \leq 1600) \qquad (1) \\
e &= 0.0045 \times m + 12.33 \ (m > 1600)
\end{aligned}
$$

In our study, the 2015 BEV with a curb weight of 1,365 kg and 16 kWh/100 km satisfies the requirement of 16.14 kWh/100 km for a “common” BEV under the NEV credit policy. Our 2030 BEV with a curb weight of 1,275 kg and 12 kWh/100 km meets the 12.02 kWh/100 km efficiency requirement as an “advanced” BEV.

There is energy loss during charging of BEV. Real-world measurements show that losses for Level 2 (240V) charging are about 14%, slightly lower than the 16% loss for Level 1 (120V) charging[3]. Some LCA studies list charging loss separately[4], while others include it in the vehicle electricity consumption[5]. The electricity consumptions quoted in the present paper refer to electricity from the grid and include charging losses.

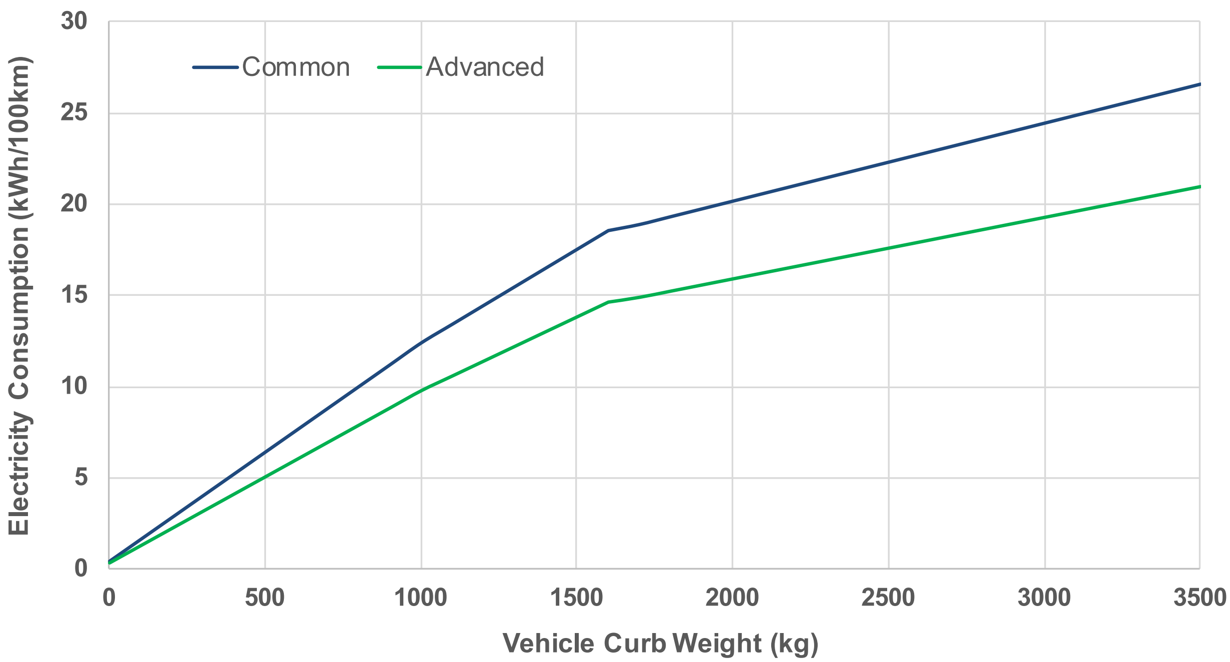

Figure S4. Vehicle electricity consumption requirement for BEVs in NEV credit policy

China's regional electricity demand growth

The regional power consumption growth trends during 2000 to 2015 are listed in Table S1. Based on expert opinions, we can make predictions on regional electricity demand growth[6-7]. Demand growth in the Northwest Grid would be significantly faster than the national average, while the growth in the North, South, East and Central grids will be slightly lower than the national average. We expect that demand growth will be the slowest in the Northeast Grid.

Table S1 Historical and forecast of regional electricity grid growth

	NATIONAL	NORTH	NORTHEAST	NORTHWEST	EAST	CENTRAL	SOUTH
2000-2005	16.6%	17.3%	10.5%	15.7%	18.5%	16.2%	17.0%
2005-2010	11.1%	11.7%	8.2%	12.7%	11.2%	11.4%	10.3%
2010-2015	6.1%	6.6%	3.0%	10.5%	5.5%	5.2%	6.2%
2015-2030	**3.2%**	**3.0%**	**1.8%**	**5.0%**	**3.0%**	**3.0%**	**3.0%**

Coal-fired electricity capacity and unit efficiency

China is the largest coal producer, accounting for 45% of global production. Coal-fired power generation has been the backbone of China's electricity supply and is China's largest coal demand sector. The proportion of coal consumed by power generation to the country's annual coal consumption has held steady at around 45% over the past decade[8]. China's capacity of coal-fired power generation has been growing. It reached 980 GW at the end of 2017[9]. On the other hand, the proportion of coal-fired electricity generation (the solid line in Figure S5) has declined from an all-time high of 81% in 2007 to 66% in 2017 with the introduction of more renewable energy into the grid. The actual power generation for coal-fired plants accounted for a much higher proportion than the capacity share (the dotted line in Figure S5). The utility factor for coal-fired generating units, although down substantially due to overcapacity recently, is still much higher than for renewable power generation[9].

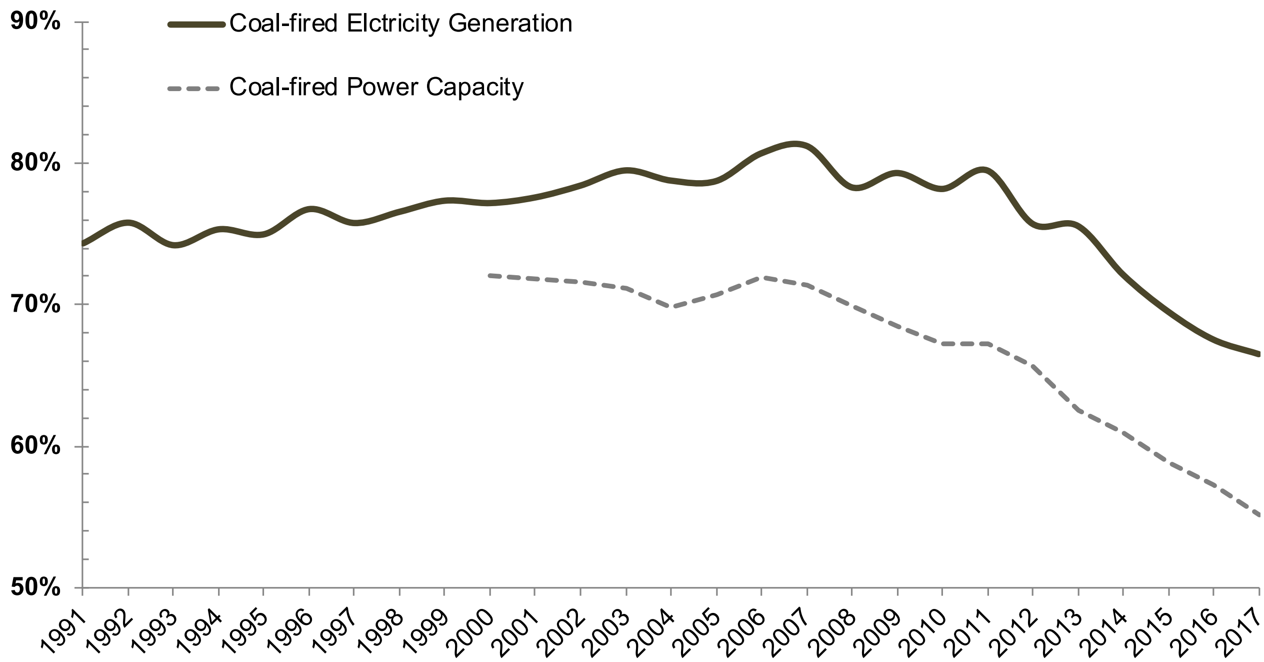

Figure S5. Coal-fired electricity generation and coal-fired power capacity share in China

After the coal price plunge in 2014, the profitability of coal-fired power plants increased significantly in China. Meanwhile, the approval authority for coal-fired power projects was delegated to the provincial governments. Under the pressure of economic downturn in the "new normal" status, the local government's enthusiasm for investment in energy infrastructure has been unprecedentedly high, resulting in a serious overcapacity of coal-fired plants. The capacity factor (CF, actual electricity output to the designed maximum output) of the coal-fired generating units has fallen to a 50-year low of 48%[9-10]. Several reports show that, as of the end of 2016, in addition to the 946 GW coal-fired capacity already in operation, 310 GW is under construction or has been approved, and another 480 GW to 560 GW is in different stages of planning[10-12]. This investment bubble of coal-fired power generation runs counter to the target of reducing coal consumption, which is the key part of the government's energy strategy of 2030[13]. This also makes it difficult for achieving the government's target – limiting coal-fired capacity below 1100 GW by 2020. In response to the bubble, the central government clearly stated that at least 150 GW of coal-fired power projects under construction or approved must be suspended or cancelled before 2020[14]. A detailed list of a total of 178 GW coal-fired projects in 20 provinces was released by the China National Energy Administration (NEA) in late 2017[14-15]. Another 20 GW of outdated generating units will be phased out within three years. Based on this publicly available information and private exchanges with government consultants and industry experts, we believe that China's capacity of coal-fired power generation will stabilize at around 1100 GW during 2020-2030, in line with the projection of the "New Policy Scenario" in IEA's World Energy Outlook (WEO).

China's coal-fired power generation technology has improved over the past three decades, with the commissioning of efficient and advanced generating units. The mainstream coal-fired units have been transformed from high-pressure (HP) and very-high-pressure (VHP) units to subcritical units (SubC), supercritical (SC) units and ultra-supercritical (USC) units. The unit capacity has been expanded from 50MW-100MW to 600MW-1000MW power generation units and 350MW-600MW combined heating and power (CHP) units. By the end of 2015, USC, SC and SubC units accounted for 10%, 37%, and 39% of China's total coal-fired capacity, respectively. The proportion of HP and VHP units was less than 15% and decreasing with decommissioning[16], as shown in Figure S6.

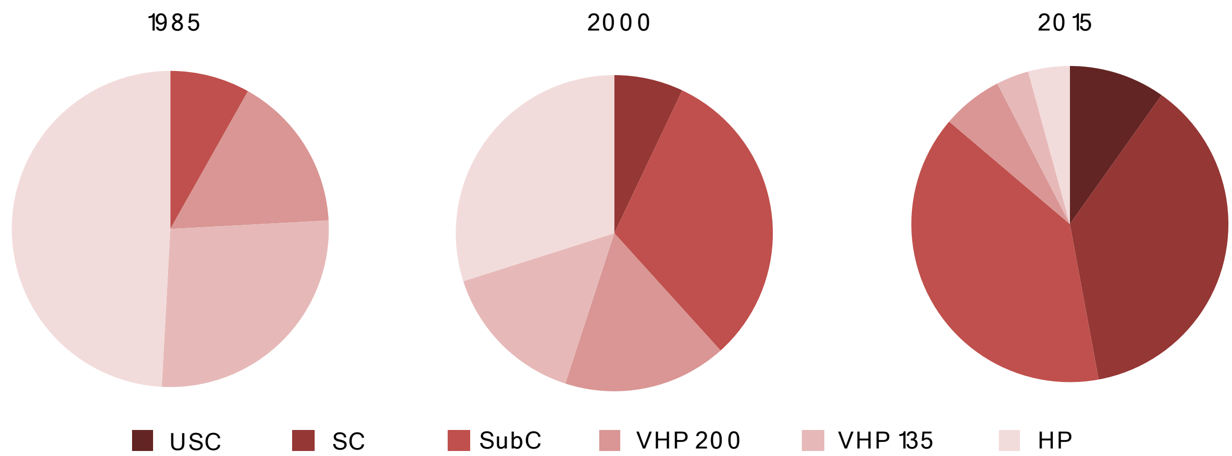

Figure S6. Market share of mainstream coal-fired power generation technologies: 1985-2015. VHP-135 represents very high pressure units with a capacity between 100MW and 150MW; VHP-200 represents very high pressure units with a capacity between 200MW to 225MW.

With the large-scale commissioning of advanced units, the CO_2 emission intensity from coal-fired power plants has been reduced substantially. The average emission intensity from coal-fired power plants dropped by more than 200 grams per kWh between 2000 and 2017, according to official statistical data[9]. We collected operational data from more than 900 existing generating units to simulate coal consumption levels in 2010 and 2015. The results show the average CO_2 emission level is around 960 g/kWh in 2015, 6% higher than the official statistics, as shown in Figure S7.

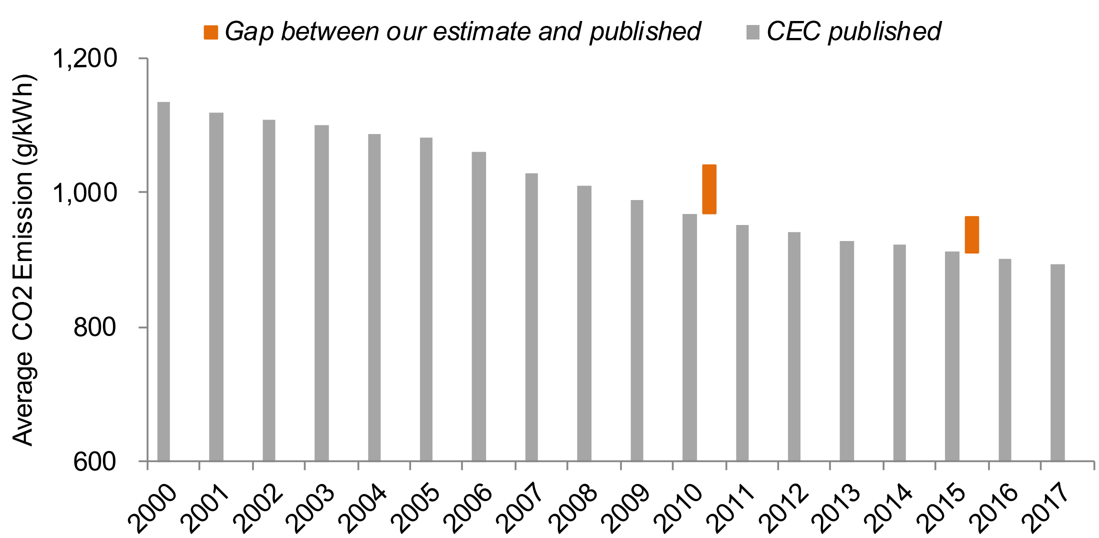

Figure S7. Average CO_2 emission from coal-fired electricity generation in China

NG-fired and oil-fired electricity

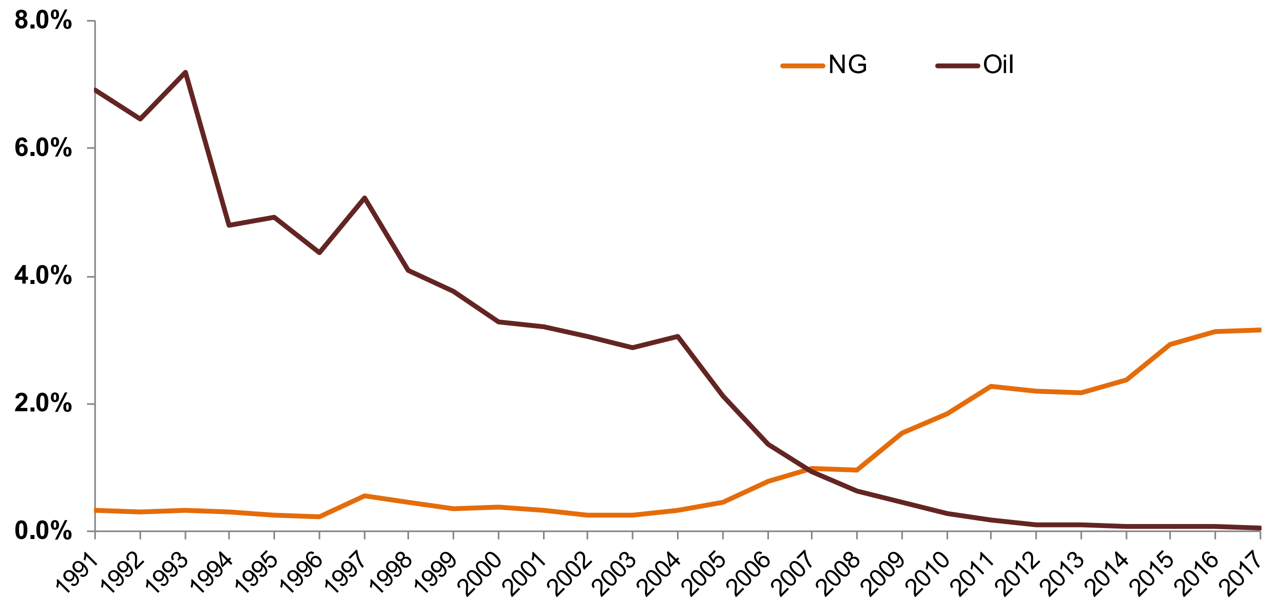

Figure S8. NG-fired and oil-fired electricity generation share in China

The proportion of electricity generation from two other fossil fuel based technologies, oil-fired and NG fired power generation, is shown in Figure S8. Like coal, the proportion of more CO_2-intensive oil-fired electricity has fallen, from around 7% in the early 1990s to less than 0.1% presently[16]. Most of the existing units are backup for large enterprises in the southern coastal provinces. As a relatively clean and efficient fossil energy, NG-fired power generation is encouraged by the government. With the completion of the two phases of the West-East gas pipeline, the proportion of gas-fired capacity increased rapidly during 2004-2011. In 2013, NG-fired power generation development became part of the air pollution control action in the northern and eastern China[17]. The total gas-fired capacity reached 76 GW by the end of 2017, doubled from five years earlier. 350 MW and larger natural gas combined cycle (NGCC) units account for 90% of the total gas-fired capacity. Others are 180 MW NGCC units and new distributed NG-fired power stations. Total NG consumption increased by approximately an order of magnitude from 24.5 billion cubic meters (bcm) in 2000 to 237.3 bcm in 2017. The proportion of NG used for power generation has also increased from 3% to more than 17%[7]. However, due to overcapacity in the whole industry and the relatively high cost of NG-based power generation, the CF of gas-fired generating units has declined significantly to around 30% in the recent years, limiting the growth of the electricity generated from NG (slightly above 3% in 2017)[9].

Hydro-electricity

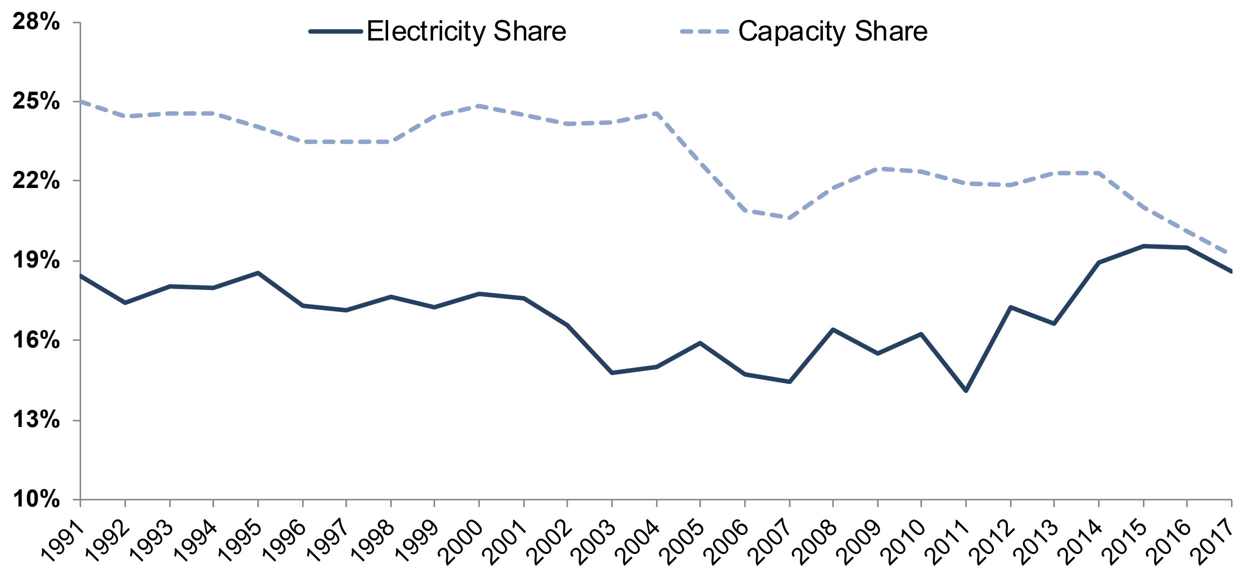

Figure S9. Hydro-electricity generation share and hydropower capacity share in China

Hydropower is China's second largest source of electricity generation after coal. The hydropower capacity increased nine-fold since 1990 and reached 341GW in 2017[9]. The proportion of hydropower in the total capacity was basically stable in the 1990s. However, although a series of large hydropower stations have been put into operation in the Three Gorges and other areas in the southwest China, the hydropower capacity share has declined significantly since 2004, as shown in Figure S9, due to the capacity increase of variable renewable energy (VRE, such as wind and solar). In the first decade of this century, as the CF of coal-fired power generation was high, the proportion of electricity generated from hydropower has been limited. With the CF of coal-fired generating units declined due to the overcapacity of coal-fired power plants and weak electricity demand, the proportion of hydropower generation rebounded to a record high level. However, as the economic growth stabilized and hydropower construction slowed down, the trend reversed again in 2017.

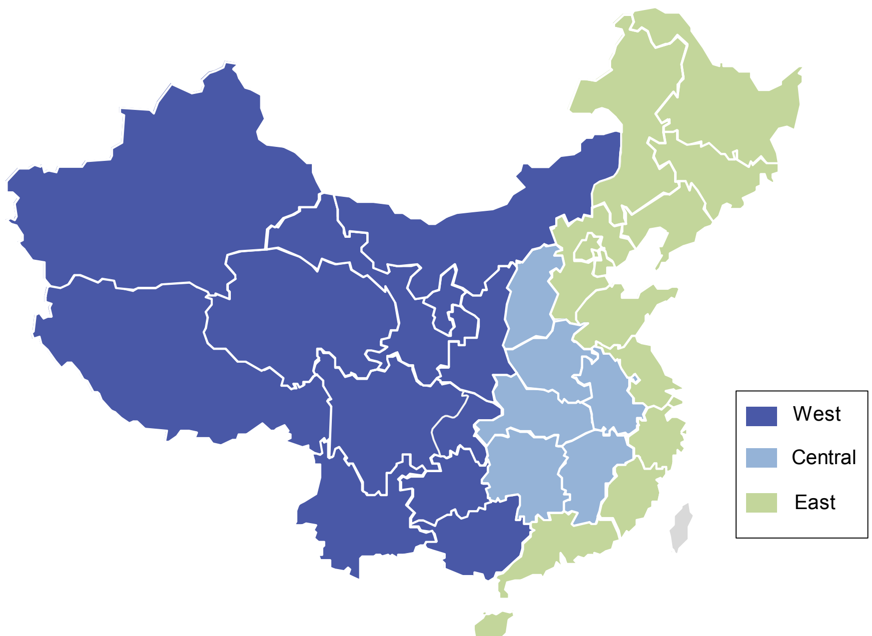

Figure S10. Geographical hydropower development regions used in the analysis. Map constructed by authors.

The geographical definitions of eastern, central and western regions, commonly used by the Chinese government, are shown in Figure S10. Conventional hydropower resources are concentrated in the western mountainous and plateau regions. Hydropower in the central and eastern plains accounts for only about 20%, and 80% of these easily accessible resources in the eastern and central regions have already been developed for hydropower plants. The hydropower resources to be developed in the next decade are located in remote mountainous areas where the cost of construction, electricity transmission, resident relocation, and ecological protection are high and the cost-effectiveness of the projects is questionable. There has been a slowdown in hydropower investment. For example, the "seven major hydropower bases" in the western provinces have planned a total capacity of 221 GW. However, the built capacity is only 122 GW as of 2015 and it is expected to add another 12% by 2020[18].

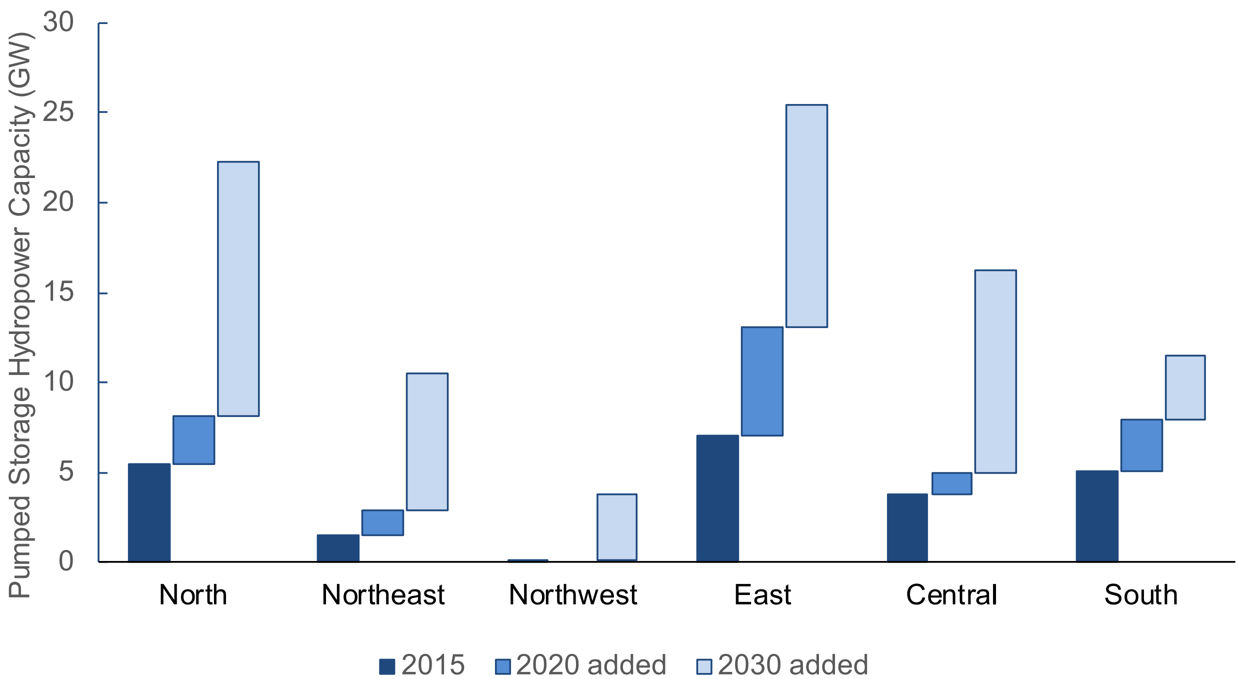

Figure S11. Pumped storage hydroelectricity capacity development in regional grids

China's hydropower development is shifting to pumped-storage hydroelectricity (PSH). PSH plants consist of upper and lower reservoirs and a hydropower generation system. The energy stored in PSH system comes from VRE sources such as wind and solar, or excess electric energy from base-load power sources such as thermal power or nuclear power, which can be used during peak load periods. The IEA expects China to require approximately 120-180 GW of PSH capacity to achieve the 2050 target of GHG reduction and a large-scale shift to renewable energy[19]. China's current capacity of PSH is less than 30 GW, accounting for only 8% of the total hydropower capacity[8]. We expect China to have about 90 GW of PSH capacity by 2030. The distribution of PSH capacity in each grid is shown in Figure S11.

Nuclear power

China's nuclear power development has gradually emerged from the shadow of the Fukushima disaster. Since 2013, 22 new reactors have been put into operation. The capacity reached 36 GW by the end of 2017, which was triple that in 2012. Although the nuclear capacity is only one-tenth of the VRE power generation, the proportion of electricity generated from nuclear power plants is still close to 4% of China's total electricity generation, which is similar to that of wind power and double that of solar power. This is mainly due to the much higher CF for nuclear than for solar and wind power plants[9].

Electricity generated from VRE

As the most promising VRE today, wind power and solar power are booming. The total capacity of wind power and solar power were 432 GW and 230 GW, respectively, at the end of 2015[20-21]. China ranks first in the world in terms of cumulative installed capacity and new added capacity of these two types of technologies. China's wind power capacity increased by 98GW, during its 12^{th} five-year plan (FYP, 2011-2015), and reached 129 GW in 2015. The electricity generated from wind power generators exceeded 300 TWh for the first time in 2017, accounting for 5% of the country's total power generation. China's solar power generation increased from less than 0.3 TWh to 118 TWh since 2010 and accounted for nearly 2% of the country's total power generation in 2017[9], as shown in Figure S12.

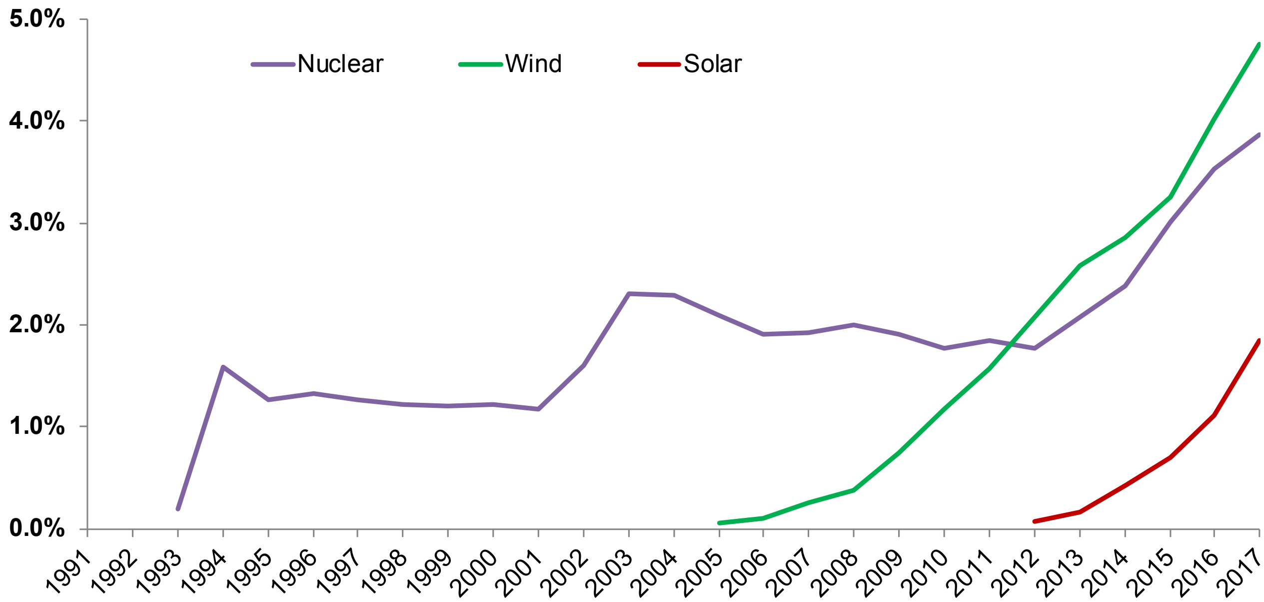

Figure S12. Wind power (green), solar power (red), and nuclear power (purple) generation share in China

Potential developable capacity of onshore wind energy (70 meters height) is more than 2,600 GW, and the potential capacity in the offshore area with water depth between 5 to 50 meters is about 500 GW. The current technically developable capacity is more than 1,000 GW[22-23]. The government plans to achieve 135 GW in the "Three North" regions by 2020 and 70 GW in other provinces. The detailed objectives for wind capacity of each province are included in a government document released by NEA[20]. Solar energy resources are concentrated in western China, with resource-rich provinces in the North and the Northwest grids[23]. Most provinces in Northwest Grid enjoy the richest of resources, with a radiation of 1700-1900 kWh m^{-2} yr^{-1}, and in some areas over 2000 kWh m^{-2} yr^{-1}.

According to above discussion, we summarize the regional capacity projections for different generation technologies in 2030 in Table S2.

Table S2 Capacity distribution of different generation technologies in 2030 (GW)

	NORTH	NORTHEAST	NORTHWEST	EAST	CENTRAL	SOUTH
COAL	284	82	174	234	186	126
GAS	48	5	4	71	10	32
NUCLEAR	20	12	0	55	0	49
HYDRO	25	19	47	47	178	136
BIOMASS	7	5	4	8	9	4
WIND	145	70	92	42	36	45
SOLAR	114	20	149	53	38	26
TOTAL	**643**	**213**	**470**	**510**	**457**	**418**

Capacity Factor

The capacity factor is generally measured by “working-hour” in the China power industry. Generally, the working-hour for power plants based on fossil (coal-fired and gas-fired), nuclear, and traditional controllable renewable energy (CRE, such as hydro) are relatively stable in the past several decades[16]. The working-hour data are shown in Table S3. As the economy reached a “new normal” lower growth, the working-hour of coal-fired plants declined from around 5,000 to 4,200 hour yr^{-1} during 2010-2017. Considering the government policy of energy transition[13] and air pollution control[17], the working-hours for coal-fired power plants is expected to remain at approximately 4,200 hour yr^{-1}, while that of gas-fired plants will increase to 3,500 hour yr^{-1} in 2030. The working-hours of nuclear and hydropower (including PSH) plants are expect to be 7,000 and 3,100 hour yr^{-1}, respectively. These assumptions are very close to the IEA WEO[24] and China State Grid report[6].

Table S3 Working-hour trend of thermal, nuclear and hydro power (hour yr^{-1})

	COAL	GAS	NUCLEAR	CONVENTIONAL HYDRO	PSH
2010	4,966	2,937	7,097	3,420	572
2015	4,306	2,528	6,240	3,703	694
2016	4,170	2,686	6,336	3,746	1,030
2017	4,220	2,656	6,931	3,728	1,153
2030E	4,100	3,500	6,850	3,550	1,200

In contrast to traditional power plants, the capacity factors of VRE based power stations vary largely in different regions, especially during the fast development period. The national and regional working-hour values of wind power and solar power in recent years are listed in Table S4 and S5. Due to the policies of renewable energy subsidy and power purchasing protection, the actual growth of wind power and solar power capacity has greatly exceeded current market demand and interprovincial transmission capacity, resulting in an extremely low CF level during 2015-2017. To increase the CF, the central government suspended new project approval for wind power in six provinces and solar power in three provinces[25]. The government has proposed mandatory targets for working-hours of existing and new projects in key provinces[26-27]: 1,800-2,000 hour yr^{-1} for wind power and 1,300-1,500 for solar power. Considering the assumptions of IEA WEO[24] and experts' opinion, the working-hours for wind power is assumed to be 2,100 hour yr^{-1} nationwide in 2030. For solar power, working-hours of 1,300-1,500 hour yr^{-1} are used for different provinces in 2030.

Table S4 Historical working-hours of wind power (hours/year)

	NATIONAL	NORTH	NORTHEAST	NORTHWEST	EAST	CENTRAL	SOUTH
2010	1,613	1,674	1,626	1,319	1,893	1,510	1,413
2015	1,440	1,650	1,574	987	1,755	1,474	1,758
2016	1,623	1,805	1,689	1,214	1,919	1,755	1,849

2017	1,872	1,968	1,967	1,611	2,017	1,731	2,083

Table S5 Historical working-hours of solar power (hours/year)

	NATIONAL	NORTH	NORTHEAST	NORTHWEST	EAST	CENTRAL	SOUTH
2012	1,063	1,139	1,050	1,077	975	684	1,080
2015	917	910	1,005	1,075	599	581	690
2016	855	959	911	928	716	562	817
2017	908	958	815	1,152	754	658	755

Inter-regional electricity transmission

To balance the electricity supply and demand in electric grid operation, there are daily transmissions between regional grids. To simplify the scenarios, we regard the whole grid of each region as one "supplier" or "consumer" in the transmission network and we consider only the "net" annual electricity transmission (in TWh per year) between a supplier and a consumer. According to China Electricity Council (CEC) statistics[16], the "net" electricity transmission among regional grids were 106 and 261 TWh yr^{-1} in 2010 and 2015, respectively. The detailed transmissions are shown in Table S6 and S7. The Central and Northwest grids have become the largest inter-regional electricity suppliers by 2015. Currently, hydroelectricity generated from the west part of the Central Grid was transmitted to the East Grid, while coal-fired power from the Northwest Grid satisfied part of the demand in the North and Central grids. The Northeast Grid was also a supplier for the electricity consumers in the north Hebei province.

Table S6 Net electricity transmission among regional grids in 2010 (TWh yr^{-1})

	SUPPLIER:			
	NORTH	NORTHEAST	NORTHWEST	CENTRAL

CONSUMER:	NORTH		8.8	2.0	
	CENTRAL	2.7		12.4	
	EAST	16.6			39.8
	SOUTH				23.4

Table S7 Net electricity transmission among regional grids in 2015 (TWh yr^{-1})

		SUPPLIER:			
		NORTH	**NORTHEAST**	**NORTHWEST**	**CENTRAL**
CONSUMER:	NORTH		17.6	52.7	
	CENTRAL	3.0		29.1	
	EAST	16.2			130.8
	SOUTH				11.3

China's economic activities and related electricity demand are mainly concentrated in eastern coastal provinces, while energy, especially renewable energy resources, are mostly located in western provinces. The power industry has been constructing a nationwide transmission network with ultra-high voltage (UHV, 800-1000 kV) transmission lines to bring power from west to east. At present, there are more than 19 UHV lines in operation or under construction, as shown in Figure S13. After simulating the supply and demand in each region, we project that the "net" inter-regional transmission will exceed 400 TWh in 2030. The details are listed in Table S8. After the new nuclear, hydro, and coal-fired power plants under construction are put into operation, the South Grid is expected to be fully self-sufficient in 2030. Considering the fixed asset investment decline in the Northeast provinces and the west-to-east UHV network development, we expect the fast growing Northwest Grid will become the single inter-regional supplier to the North Grid in 2030. Renewable and coal-fired power sources in the Northwest Grid will also satisfy part of the demand of the East and Central grids. Hydroelectricity from the west part of the Central Grid will continue to supply Shanghai and other large cities in the Yangtze River Delta in 2030.

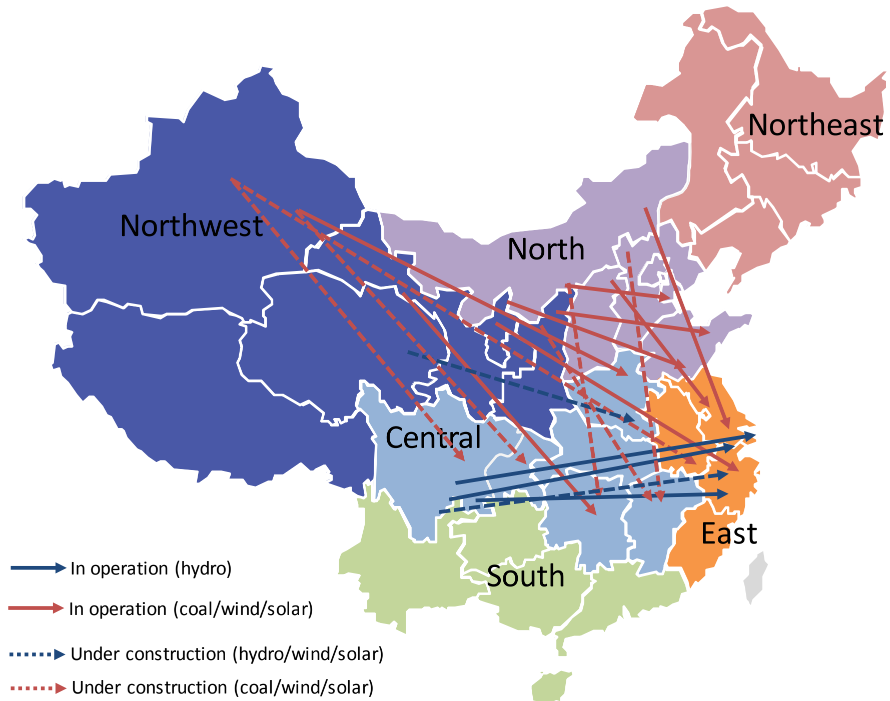

Figure S13. Inter-regional ultra-high voltage transmission lines among electricity generating regions used in the analysis. Map constructed by authors.

Table S8 Forecast of net electricity transmission among regional grids in 2030 (TWh yr^{-1})

		SUPPLIER:		
		NORTH	NORTHWEST	CENTRAL
CONSUMER:	NORTH		80	
	CENTRAL	15	103	
	EAST	20	63	130

Electricity mix transition of selected cities in China: 2015-2030

Beijing consumed 95 TWh in 2015 with local supply accounting for only 44%. Coal-fired power dominated the electricity mix (see left of Figure S14) with 53% of total electricity supply transmitted from coal-fired power plants in Shanxi and Inner Mongolia provinces (inside North Grid). To reduce air pollution, particularly PM2.5[17], the government shut down all the coal-fired power plants in Beijing by the end of 2015, and all the local electricity supply has come from NG-fired plants and renewable sources since 2016. Two new UHV transmission lines from west Inner Mongolia to Beijing were put into operation in the early 2018. Two other 500kV transmission lines between northern Hebei and Beijing are under construction. Integrating with coal-fired electricity, wind and solar electricity is expected to be transmitted to Beijing through these lines in the future. We expect that 90% of Beijing's local electricity supply will come from NGCC power plants in 2030, with the other 10% from local wind and solar power. Imported coal-fired and renewable electricity will account for about 40% and 30% of Beijing's total demand in 2030, aligned with the government plan of 70% electricity coming from long-distance transmission in the mid- to long-term future[28]. The electricity mix for 2030 is shown on the right of Figure S14.

For Shanghai, currently more than 50 TWh yr^{-1} of hydroelectricity comes from the upstream Yangtze River in the Central Grid through four dedicated transmission lines (three UHV and one 500kV)[16]. Meanwhile, Shanghai imports coal-fired electricity from Anhui province and nuclear power from Zhejiang province. A lot of new nuclear power units (10 in Zhejiang and 15 in Fujian province) are under construction or in the planning stage[29-30]. The nuclear capacity in this region will increase fourfold during 2015-2030. Shanghai consumed 140 TWh in 2015. Considering the low annual growth (average 1.8% in the last five years), we expect it will increase one-third by 2030[6]. The imported hydropower is expected to maintain at its current level[31], while nuclear electricity supply from other provinces will increase to 30 TWh in 2030, from 7 TWh in 2015[16].

For the Pearl River Delta (PRD), clean electricity makes a larger contribution than for any other city group in China. The cities in the PRD (e.g., Guangzhou) receive a large amount of hydroelectricity from Yunan and Guizhou provinces in the South Grid. With the new UHV lines development inside the South Grid, the input could be doubled by 2030. The nuclear power stations provide 47 TWh to PRD in 2015[16]. Considering 20 additional nuclear units (currently under construction or planned) and large-scale onshore windpower development[32-33], the nuclear and wind electricity supply for PRD in 2030 is expected to reach 220 TWh and 30 TWh, respectively.

Chongqing consumed 88 TWh in 2015, with 13 TWh hydroelectricity and 7 TWh coal-fired electricity coming from other provinces[16]. As a large industrial city in western China, Chongqing's electricity demand is growing very quickly. More than 4 GW of new coal-fired power plants have been put into operation since 2015, and we expect Chongqing will not continue to import coal-fired electricity. With the planned new transmission lines, the hydroelectricity imported from Sichuan and Qinghai provinces to Chongqing is expected to reach 50 TWh by 2030[34-35]. Another UHV line will transmit electricity from the Northwest Grid, with 1:1 ratio between renewable (wind/solar) electricity and coal-fired electricity[6].

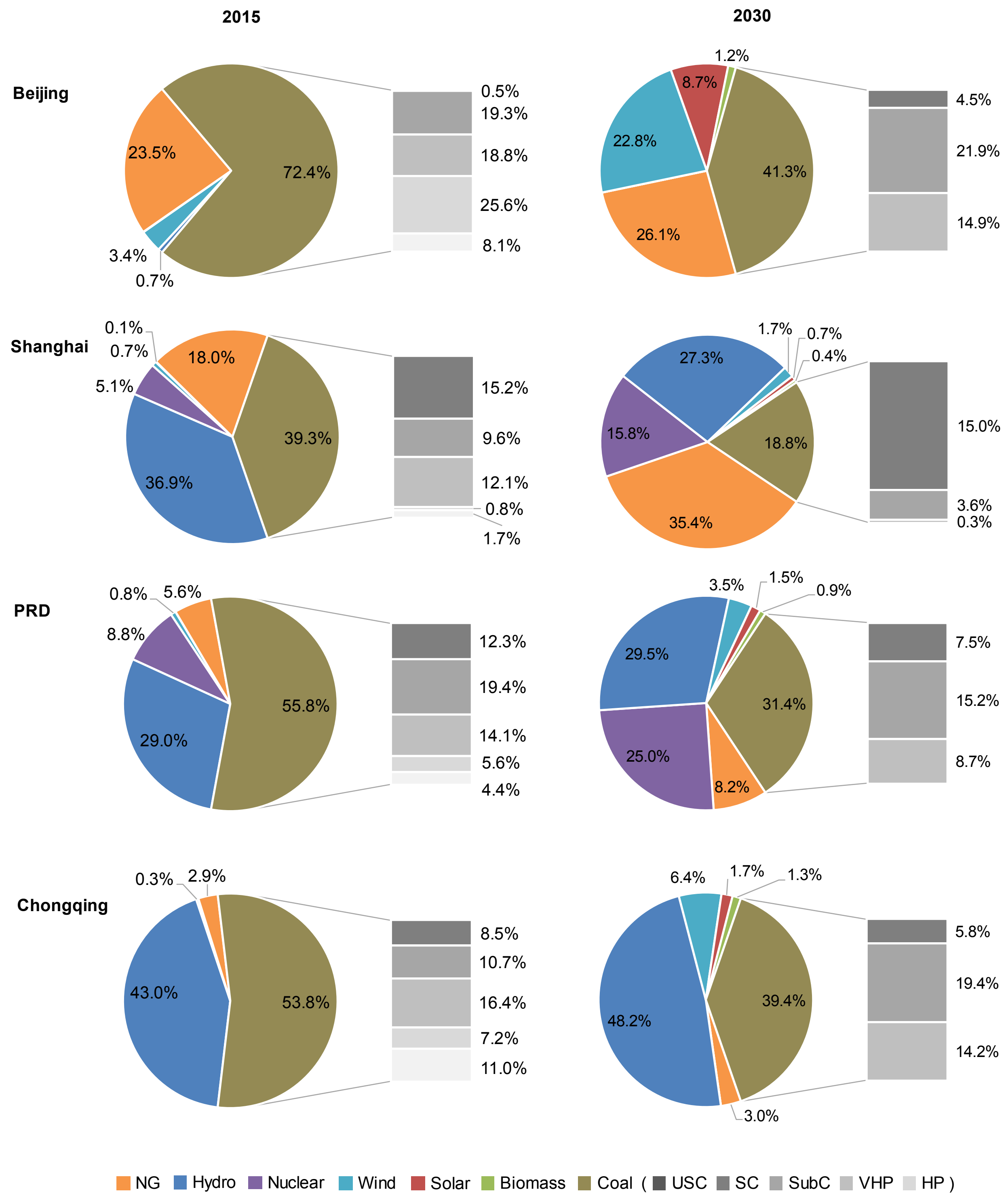

Figure S14. Electricity mix transition for Beijing, Shanghai, Chongqing, and Pearl River Delta city group (PRD), 2015-2030 (Coal plant types: USC, ultra-supercritical; SC, supercritical; SubC, subcritical; VHP, very high-pressure; HP, high-pressure).

Plug-in electric passenger vehicle sales in selected markets

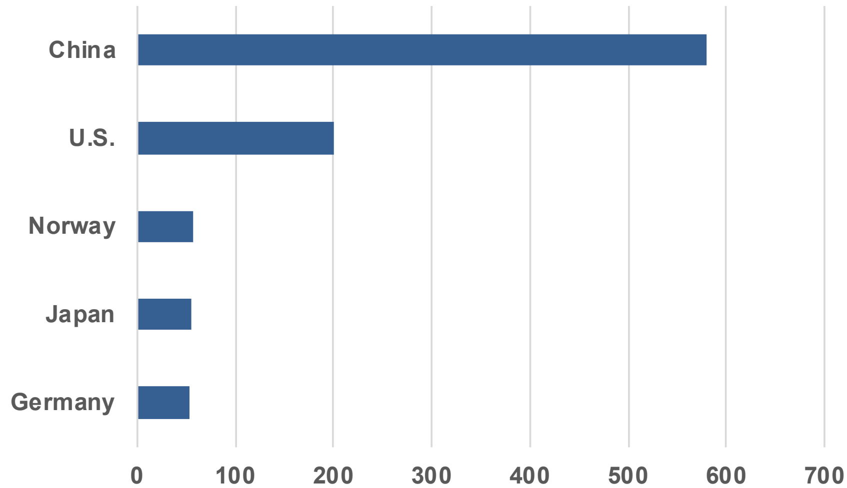

Figure S15. Plug-in electric passenger vehicle sales of global top five markets in 2017 (unit: thousand) [36]

U.S. regional electricity grids: status quo and future trend

Figure S16 shows the electricity consumption and grid mix of China and the U.S. in 2015. It is worth noting that the proportion of fossil electricity in the U.S. is 67%, only five percentage points lower than that of China. However, as U.S. gas-fired power generation accounts for half of fossil electricity consumption, the average GHG emissions of the U.S. power industry are significantly lower than those of China. The electricity grid of the contiguous United States has lines of a total length of approximately 190,000 kilometers and is operated by more than 500 companies. It is divided into eight large regional grids and more sub-regional grids[37], as shown in Figure S17 and Figure S18. The EIA provides statistical information for the eight grids in 2015 and an outlook for 2030 in its Annual Energy Outlook 2018, as shown in Figure S19 and Figure S20. The regional grid with the largest share of non-fossil electricity in the U.S. is NPCC (Northeast Power Coordinating

Council) in the northeastern states with non-fossil electricity accounting for more than 50%. The NPCC has the least coal-fired electricity consumption with only 2.5% in 2015. The proportion of coal-fired electricity in the grid for Florida (Florida Reliability Coordinating Council, FRCC) and the west coast grid (Western Electricity Coordinating Council, WECC) is also relatively low. The former is more dependent on natural gas for power generation, while the latter has the largest renewable power generation system in the U.S. Renewable electricity accounts for 32% of total power supply in the WECC. The EIA projects that the total amount of U.S. power generation in 2030 will increase by only 8% compared to that of 2015, but the power mix will change to low-carbon electricity. A large number of coal-fired power plants will be replaced by renewable generation systems, with the proportion of coal-fired electricity decreasing from 33% to 23%, while renewable electricity will increase from 14% to 25% during the same period[38]. Figure S21 shows the EIA grid mixes for sub-regional grids in the U.S in 2015 and Figure S22 shows the forecast for 2030.

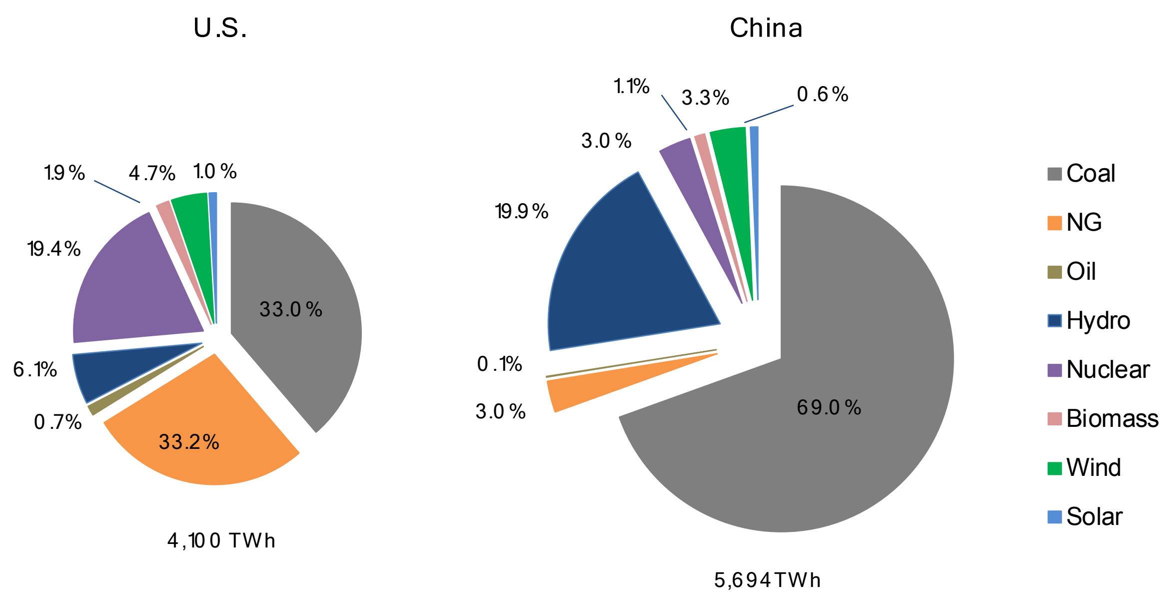

Figure S16. Electricity mix in the U.S. and China, 2015

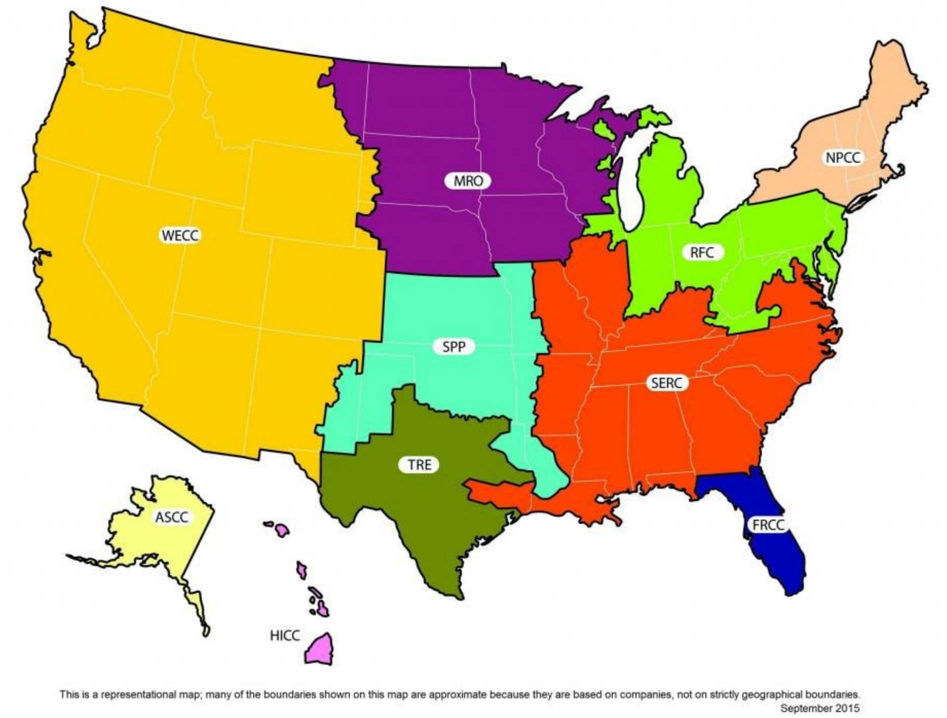

Figure S17. NERC (North American Electric Reliability Corporation) regions (Reproduced from reference 39)

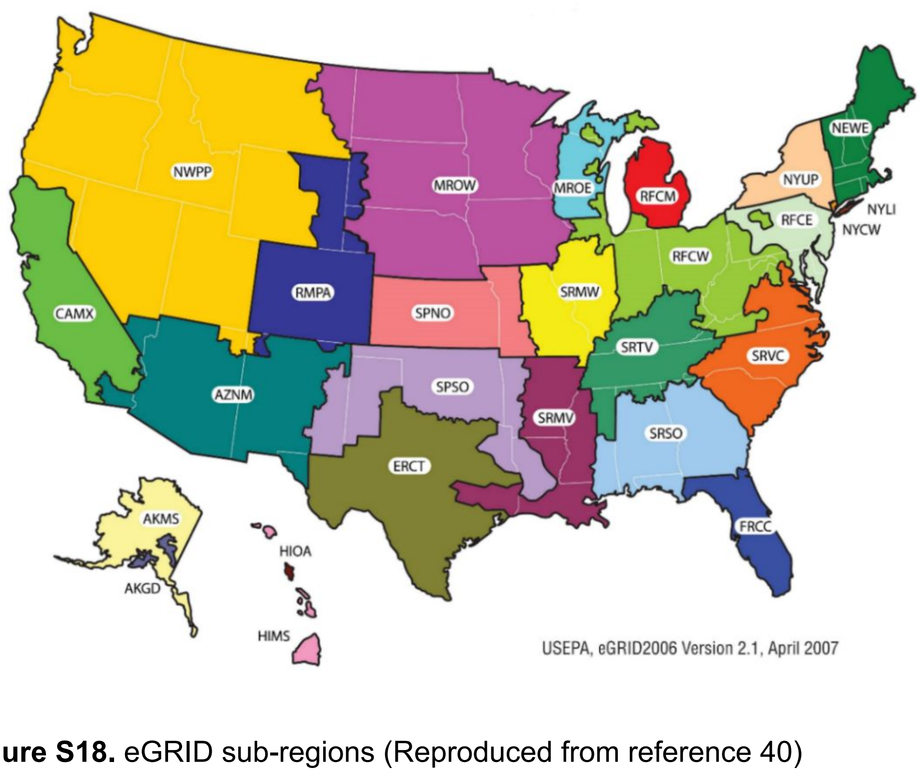

Figure S18. eGRID sub-regions (Reproduced from reference 40)

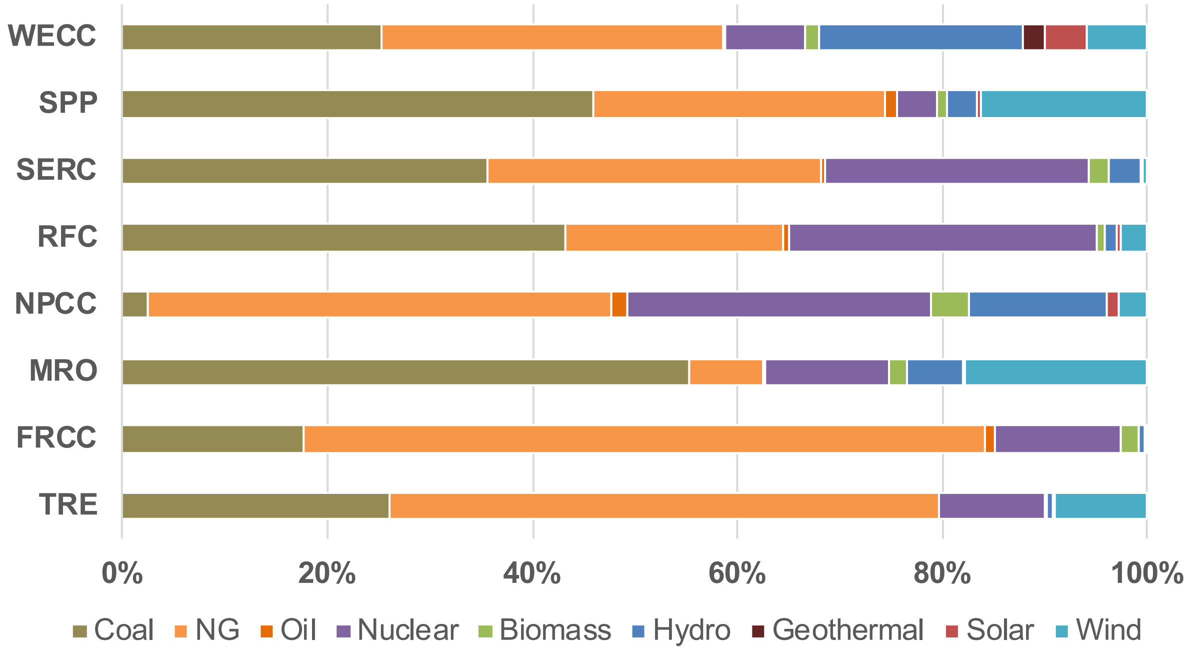

Figure S19. Electricity mix for regional grids in the contiguous United States in 2015
Data Source: Energy Information Agency.

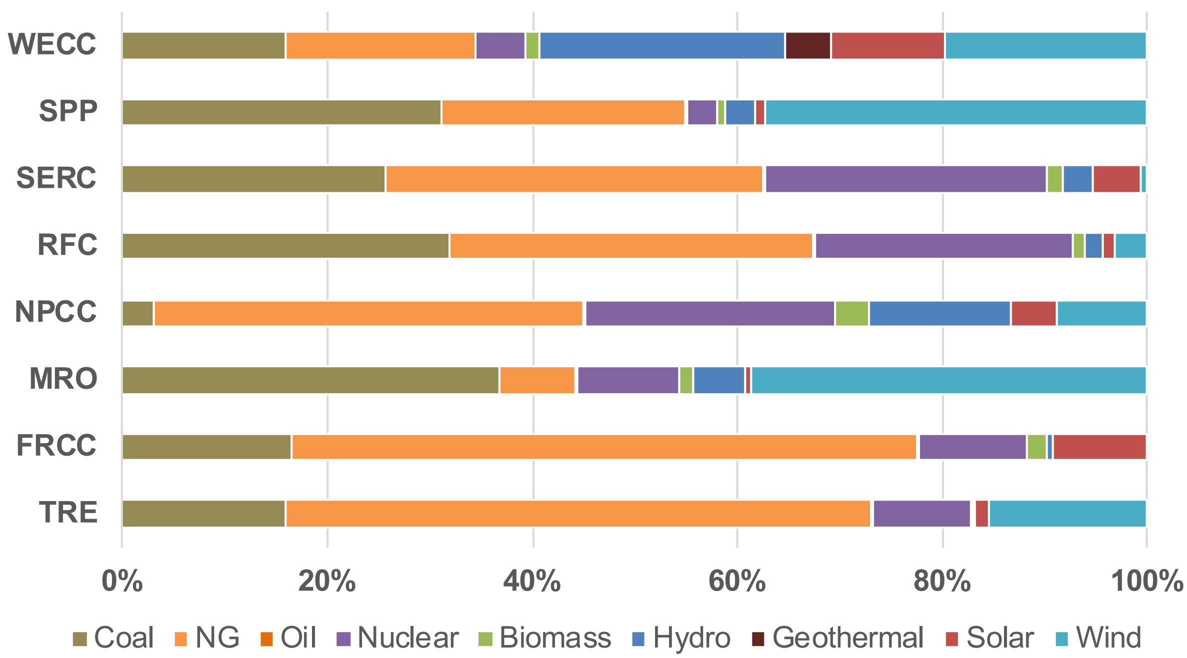

Figure S20. Projected electricity mix for regional grids in the contiguous United States in 2030
Data Source: Energy Information Agency.

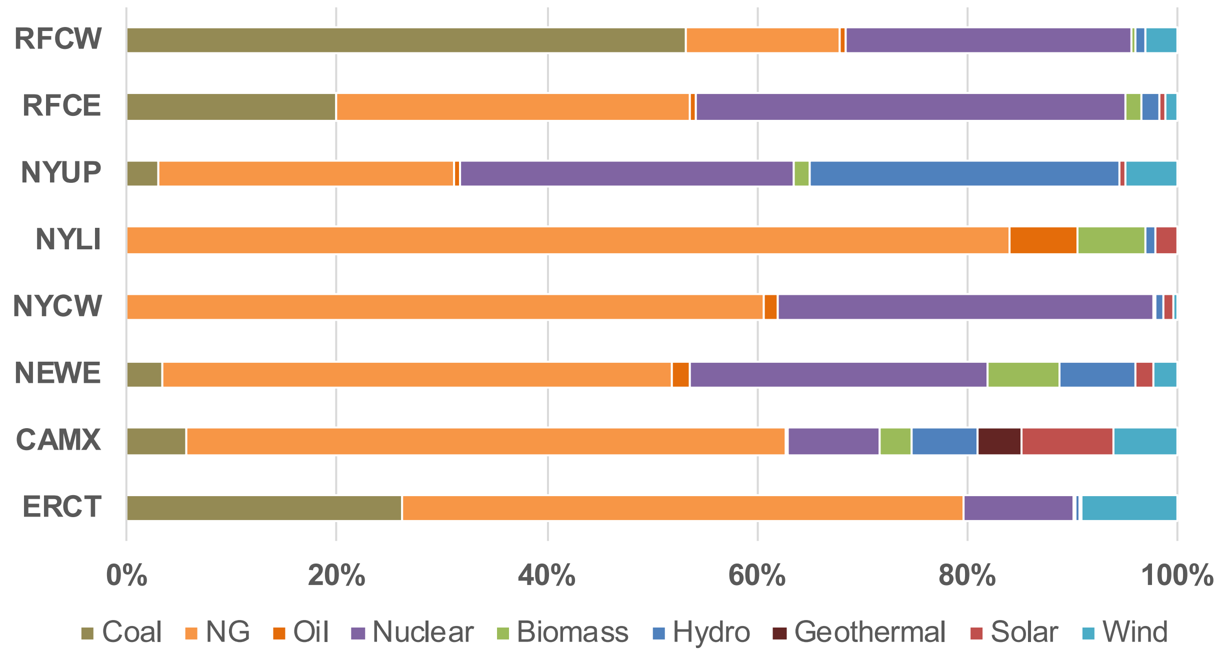

Figure S21. Electricity mix for grids in selected U.S. states and cities in 2015
Data Source: Energy Information Agency.

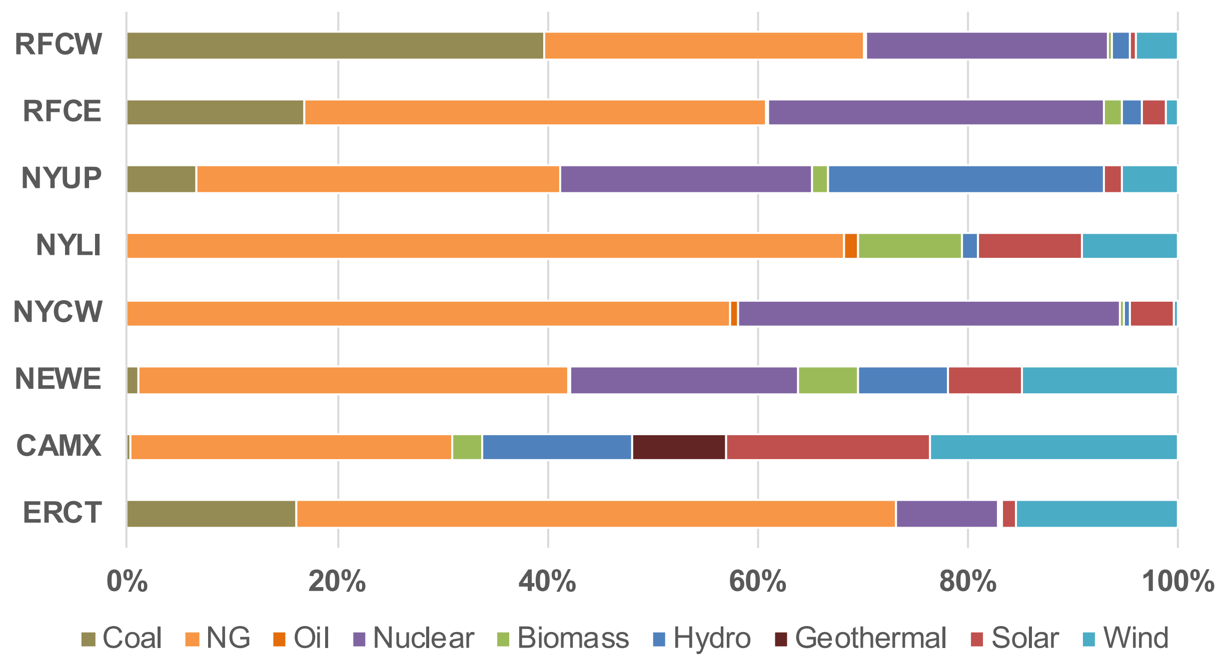

Figure S22. Projected electricity mix for grids in selected U.S. states and cities in 2030
Data Source: Energy Information Agency.

PHEV's parameters and WTW GHG emissions

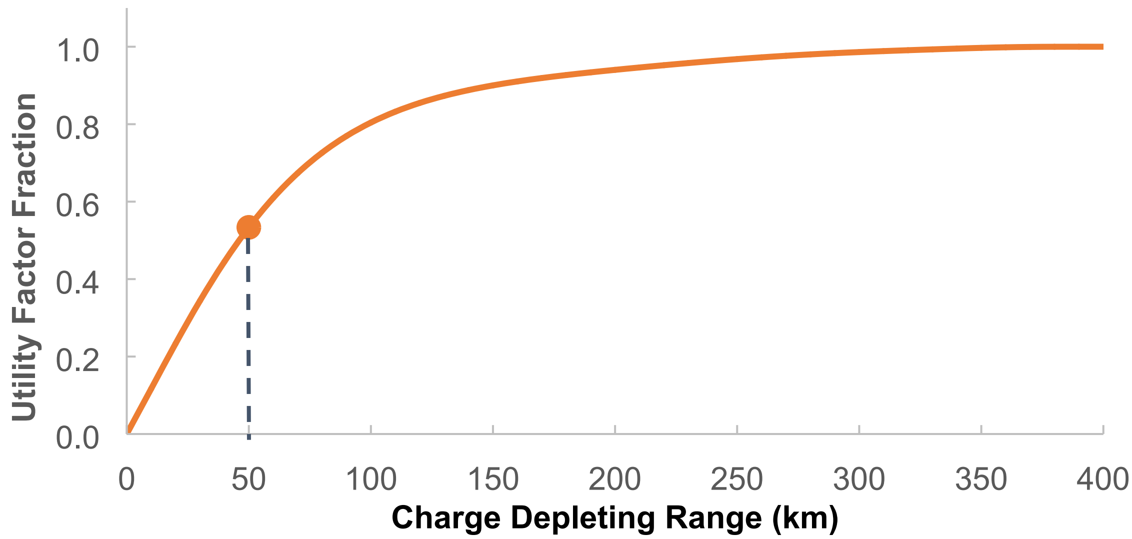

Figure S23. Utility factor curve and UF determination for 50 km AER PHEV in China

The Chinese government regulations currently require at least 50 km AER for PHEVs and at least 150 km for BEVs[41-43]. We assume 50 km AER for PHEVs in 2015 and 2030. PHEVs have two driving modes – charging depleting (CD) and charging sustaining (CS). In the CD mode, the vehicles use electrical energy stored in the battery until the battery's state-of-charge (SOC) reaches a predetermined level. For some PHEVs, the CD mode can be a blended operation in which ICE will assist the electric motor when it is required in high speed or high load. In this study, we assume the CD mode is all-electric. When the battery SOC reaches the predetermined level, the vehicle switches to the CS mode, in which the vehicle operates as a gasoline-powered HEV. Calculating the fuel and electricity consumption of a PHEV is very challenging because the energy consumption varies greatly depending upon the travel distance between charge events. Previous regulations in China were based on European standard ECE R101 where the calculation of PHEV electrical energy consumption is based on a weighted average of CD and CS operation, assuming that, between charges, the vehicle travels 25 km in CS mode after all electric operation in CD mode[44]. The new regulation adopts the concept of “utility factor” (UF) in SAE standards to describe the fraction of the PHEV driving in each mode. The Chinese UF curve is based on the daily travel data of more than 550,000 Chinese light-duty vehicles in 2015[45]. The curve creation method comes from SAE J2841[46]. As shown in Figure S23, the UF is 0.53 when the AER of a Chinese PHEV is 50 km. In other words, we assume that the PHEV operates like a BEV for 53% of its annual mileage and like a HEV for the other 47%. We assume that PHEVs, during CD mode, have electricity consumption rates identical to BEVs.

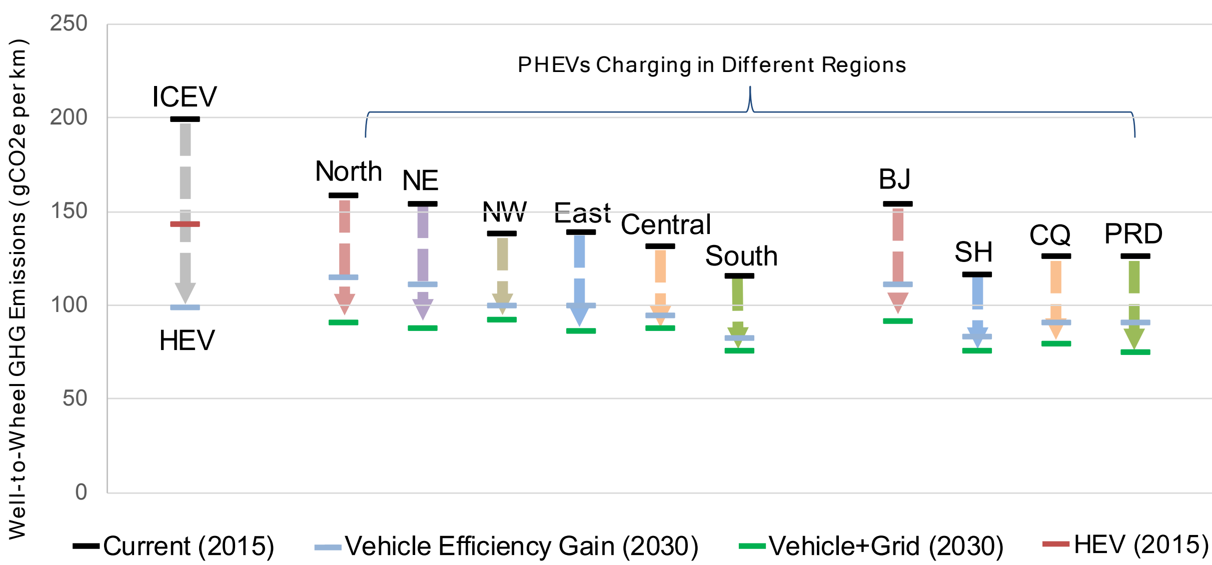

Figure S24. Potential WTW GHG reductions from plug-in hybrid electric vehicles

Figure S24 shows that currently (black bars) the geographically-relative ranking of PHEV WTW GHG emissions is similar to that for BEVs (Figure 3, main paper). While the emissions of BEVs in North and Northeast China are higher than those of HEVs, the emissions of PHEVs in these two grids are somewhat lower than from HEVs. Currently, PHEVs charging in North and Northeast grid have approximately 6%-8% lower emissions than BEVs. In other regions of the country, PHEVs have higher WTW GHG emissions than BEVs. This is particularly clear in South Grid, where the WTW GHG emissions of PHEVs are 27% higher than those of BEVs. By 2030, following the large deployment of renewable energy in all regional grids, WTW GHG emissions from PHEVs (green bars) are expected to be lower than from advanced HEVs in all regions, like BEVs. WTW GHG emissions from PHEVs will be 6%-37% higher than from BEVs when they charge in the same regional grid.

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