Pet. Sci. (2016) 13:370–383
DOI 10.1007/s12182-016-0089-2

ORIGINAL PAPER

A scenario analysis of oil and gas consumption in China to 2030 considering the peak CO_2 emission constraint

Xi Yang[1] · Hong Wan[2] · Qi Zhang[1] · Jing-Cheng Zhou[2] · Si-Yuan Chen[1]

Received: 22 October 2015 / Published online: 19 April 2016

Abstract China is now beginning its 13th five-year guideline. As the top CO_2 emitter, China has recently submitted the intended nationally determined contributions and made the commitment to start reducing its total carbon emissions in or before 2030. In this study, a bottom-up energy system model is built and applied to analyze the energy (mainly coal, oil, and gas) consumption and carbon emissions in China up to 2030. The results show that, the total energy consumption will reach a peak of 58.1 billion tonnes of standard coal and the CO_2 emissions will get to 105.8 billion tonnes. Moreover, in the mitigation scenario, proportion of natural gas consumption will increase by 7 % in 2020 and 10 % in 2030, respectively. In the transportation sector, gasoline and diesel consumption will gradually decrease, while the consumption of natural gas in 2030 will increase by 2.7 times compared to the reference scenario. Moreover, with the promotion of electric cars, the transport electricity consumption will increase 3.1 times in 2030 compared to the reference scenario. In order to fulfill the emission peaking target, efforts should be made from both the final demand sectors and oil and gas production industries, to help adjust the energy structure and ensure the oil and gas supply in future.

✉ Qi Zhang
zhangqi@cup.edu.cn; zhangqi56@tsinghua.org.cn

1 Academy of Chinese Energy Strategy, China University of Petroleum (Beijing), Changping, Beijing 102249, China

2 Policy Research Office, China National Petroleum Corporation, Beijing 100007, China

Edited by Xiu-Qin Zhu

Keywords Energy system planning · Oil and gas consumption · China-ESPT model · Carbon mitigation · Transportation sector

1 Introduction

With the targets of the 12th five-year plan being successfully fulfilled, China is now starting its 13th five-year plan. In April 2014, the National Development and Reform Commission of China claimed that it is crucial to correctly handle the relationship between the government and market, also scientific planning objectives should be set in the 13th five-year period. At present, China is facing pressures from both economy development and carbon mitigation. On one hand, China is experiencing a transition to the new normal economy. The economic growth is slowing down, with the GDP growth rate decreasing from 10.4 % in 2010 to 7.4 % in 2014. On the other hand, parallel challenges from carbon mitigation and environmental protection are emerging and drawing the attention of China's government. The emission of sulfur dioxide and carbon dioxide has been strictly controlled since last year, by multiple related regulations. In addition, recently in 2015, China has submitted the intended nationally determined contributions (INDCs), and made the commitment that by 2030, the carbon dioxide emissions per GDP should decrease by 60 %–65 % compared to the level of 2005; China's carbon dioxide emissions should reach a peak in or before 2030. The non-fossil fuel consumption should achieve 20 % of the total primary energy consumption (State Council of China 2015).

According to the BP Statistical Review of World Energy (2015a), China is the world's largest energy consumer, with the total energy consumption of about 4.3 billion tonnes of coal equivalent, which accounts for about 23 %

of the world's total energy consumption. Although coal consumption still accounts for an absolutely dominant proportion, about 66 % of the total energy consumption, oil consumption accounts for 17.5 %, and natural gas accounts for 5.6 % in 2014 (BP 2015a). Plans aiming to adjust China's energy structure are already on schedule. The State Council of China has claimed that by 2020, natural gas consumption is planned to account for 10 % of the primary energy consumption, the proportion of non-fossil fuel consumption would be more than 15 %, and the proportion of coal consumption should be controlled to below 62 % (State Council of China 2014). To successfully achieve the goal, it is urgent to take effective actions to reduce carbon emissions, to fully explore the potential of natural gas and non-fossil energy, and to have clean energy sources as feasible alternatives.

Among all the final demand sectors, the transportation sector, covering road, air, railway, and waterways, is the main sector for oil consumption, responsible for 59 % of the total oil consumption in 2011. According to the prediction of the Organization for Economic Co-operation and Development (OECD) and International Energy Agency (IEA), the oil consumption of the transportation sector will continue to increase, with a predictable rise to 63 % of all oil demand by 2040. For developing countries, the proportion of oil consumption from transportation sector is around 65 % of all the sectors, as shown in Fig. 1. Given the oil consumption for transportation sector, it can be found that less than 40 % of oil consumed in 2040 will be from the other sectors. The petrochemical and other industries account for approximately one-quarter of the total oil consumption in 2040. Residential and agricultural consumption, together with some consumption in the commercial sector, contributes only to 10 % of the total consumption. Thus, the transportation sector is the most critical final demand sector, when we are analyzing future oil and gas consumption in China. Besides, in China's road transport long-term planning, it is clearly claimed that the number of electric vehicles, as well as plug-in hybrid electric vehicles, should reach at least 5 million in 2020. Technological progress plays an important role in promoting the optimization of energy consumption structure, especially fuel standard upgrading and the improvement of natural gas consumption. Thus, in this paper, the effect of technological improvement on the energy consumption of the transportation sector is studied, according to the transportation long-term planning.

During the last decade, the traditional methods for predicting the final energy consumption, especially oil and gas consumption, mainly include time series, regression, econometric modeling, autoregressive integrated moving average model, and soft computing methods, such as fuzzy logic, genetic algorithm, and neural networks, are also being extensively used for final demand side management. In recent years, the support vector regression, ant colony, and particle swarm optimization have been new methods adopted for energy demand studies. Besides, bottom-up models such as MARKet ALlocation (MARKAL; energy technology systems analysis program, ETSAP 2013) and the Long-range Energy Alternatives Planning System (Stockholm Environment Institute, SEI 2013) are also being used at the national and regional levels for final energy demand analysis. There have been studies on the consumption of conventional energy in India, and one of them is carried out based on three time series models, namely the Grey–Markov model, the Grey model with a rolling mechanism, and singular spectrum analysis (Kumar and Jain 2010). Besides, a logistic function is used to characterize the peak and ultimate production of global crude oil and petroleum-derived liquid fuels (Gallagher 2011). Using a curve-fitting approach, a population-growth logistic function was applied to complete the cumulative production curve. An idealized Hubbert curve is defined as having properties of production data resulting from a constant growth rate under fixed resource limits.

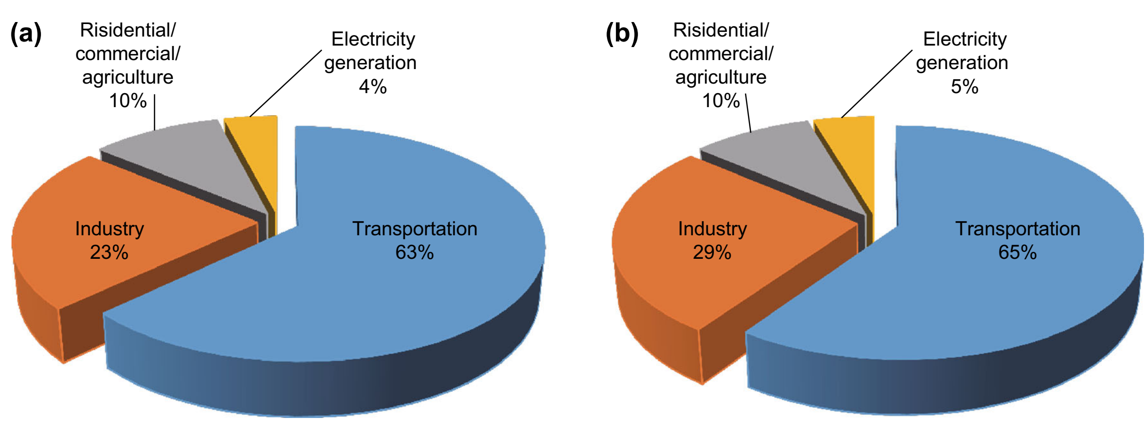

Fig. 1 Percentage of oil demand by sector in 2040, for the world and developing countries (%). *Data source* OECD/IEA Energy Balances of OECD/Non-OECD Countries (2013) and OPEC Secretariat calculations

A bottom-up model can forecast future energy supply and demand, and analyze the impacts of the energy system on the environment, using various engineering technology models and by simulating the modes of energy consumption and production. The typical representatives of the bottom-up model are the MARKAL, EFOM, and the integrated MARKAL–EFOM system (TIMES; ETSAP 2013). Many studies have been undertaken in recent years to evaluate energy system planning, and these works offer good references for the possible future development pathways (Adams and Shachmurove 2008; Kypreos and Bahn 2003; Cox et al.1985; Lund 2010; Manne et al. 1995; Krewitt and Nitsch 2003; Bollen et al. 2009; Budzianowski 2012; Gillingham et al. 2008; da Graça Carvalho 2012; Messner and Schrattenholzer 2000; Klaassen and Riahi 2007; Klaassen et al. 2004; Nordhaus 1993; Paltsev et al. 2005; Tu et al. 2007; Rafaj and Kypreos 2007). For example, the US Energy Information Administration (EIA) presents long-term annual projections of energy supply, demand, and prices through 2040 based on results from EIA's national energy modeling system (2015). According to the BP Energy Outlook 2035 (2015b) and Joint IEA–IEF–OPEC report (OPEC 2015), global demand for energy is expected to rise by 37 % from 2013 to 2035, with an average increase of 1.4 % per year. Demand for the world's natural gas will grow faster among the fossil fuels over the period up to 2035, with a rate of increase of 1.9 % per year, driven mainly by the high demand from Asia. Meanwhile, the IEA declares that the energy use worldwide is expected to grow by one-third to 2040 in their central scenario, and the change of China's energy demand is estimated to be over 900 million tonnes of oil equivalent by 2040, with a total energy demand of nearly 4000 million tonnes of oil equivalent worldwide. Moreover, the natural gas demand of Asia is claimed to increase by approximately 700 billion m^3 by 2040 (IEA 2015). As well, the Grantham Institute for Climate Change at Imperial College London analyzed China's energy system based on the sector-specific and energy consumption bottom-up model for the transport, buildings, and industrial sectors based on the IIASA mix scenario and the IIASA HCB scenario (Gambhir et al. 2013). Besides, studies about China's energy system optimization have been carried out based on enenrgy model analysis (Jiang et al. 2010; Yin and Chen 2013; Cai et al. 2008; Dai et al. 2011; Zhang et al. 2011; Zhou et al. 2013a,b; De Laquil et al. 2003; Chen et al. 2007).

The paper mainly focuses on analysis of oil and gas consumption in future, the effect of road transport technology improvement on fuel consumption, and the optimization of China's energy system. Quantitative analysis has been carried out based on the China energy system planning and technology (China-ESPT) evaluation model. In Sect. 1, the background of the 13th five-year plan and the critical role of the transportation sector for oil and gas consumption are stated, with a literature study. In Sect. 2, the China-ESPT model is introduced for the structure, the main parameters, and the scenario design. Section 3 shows the main results based on scenario analysis, mainly focusing on the change of the energy system and the transportation sector. Section 4 concludes the analysis and further discusses relevant recommended policy.

2 Methodology

In this study, we introduce the China-ESPT evaluation model, an energy optimization model based on TIMES-VEDA (ETSAP 2013), and review a large amount of literature to quantitatively analyze and predict energy consumption up to 2030. Furthermore, the China-ESPT model is based on the reference energy system (RES) to describe the process of energy extraction, energy conversion, and energy distribution. Also RES is helpful for better describing the main characteristics, complex internal relations, and external constraints of the energy system. The model is driven by the future energy demand, considering the capacity of the related equipment, the characteristics of the future optional technology, and the constraints of the current and future energy supply. The model is based on the simulation of investment and operation, primary energy supply, and greenhouse gas emission reduction constraints. Scenario analysis is an important and widely used tool for the long-term simulation of energy and economic systems.

The objective function of this model is to minimize the total cost of the energy system while meeting the energy demand and constraints. The investment and dismantling costs are transformed into streams of annual payments, computed for each year of the horizon. Using China-ESPT, a total net present value (NPV) of the stream of annual costs is then computed, discounted to a user-selected reference year. The objective function of the model is listed in Eqs. (1)–(2):

$$\mathrm{OBJ}(z) = \sum_{r \in \mathrm{REG}} \mathrm{NPV}(z, r), \tag{1}$$

$$\mathrm{NPV}(z, r) = \sum_{y \in \mathrm{YEARS}} (1 + d_{r,y})^{\mathrm{REFYR}-y} \times \mathrm{COST}(r, y) - \mathrm{SAL}(z, r), \tag{2}$$

where NPV is the net present value of the total cost for all regions, $d_{r,y}$ is the general discount rate, REFYR is the reference year for discounting, YEARS is the set of years for which there are costs, R is the set of regions in the area of study, COST(r, y) is the total annual cost in region r and year y, and SAL is the residual value of the assets. The total cost includes several elements: the capital costs incurred for investment, fixed and variable annual operation and maintenance costs, the fuel cost for domestic production and import, transport cost, tax and subsidies, revenues from export, and so on.

The main constraints of the model mainly consist of the constraints of span-time capacity transfer, technical activities, flow balance, etc. First, the equation of capacity transfer balance is shown in Eq. (3):

$$\mathrm{CAPT}(r,\ t,\ p) = \sum_{t_n} \mathrm{NCAP}(r,\ t_n,\ p) + \mathrm{RESID}(r,\ t,\ p), \tag{3}$$

$$t - t_n < \mathrm{LIFE}(r,\ t_n,\ p),$$

where $\mathrm{CAPT}(r,\ t,\ p)$ is the total installed capacity of technology p, in region r and period t, $\mathrm{NCAP}(r, t, p)$ stands for new capacity addition (investment) for technology p, in period t and region r, and $\mathrm{RESID}(r,\ t,\ p)$ is the (exogenously provided) capacity of technology p due to investments that are made prior to the initial model period and that still exists in region r, at time t. The total available capacity for each technology p, in region r, in period t (all vintages), is equal to the sum of investments made by the model in the past and current periods, and whose physical life has not yet ended, plus capacity in place prior to the modeling horizon that is still available.

The equation of technical activities constraint is given in Eq. (4):

$$\mathrm{ACT}(r,\ v,\ t,\ p,\ s) = \sum_{c} \mathrm{FLOW}(r,\ v,\ t,\ p,\ c,\ s) / \mathrm{ACTFLO}(r,\ v,\ p,\ c), \tag{4}$$

where $\mathrm{ACT}(r, v, t, p, s)$ is the activity level of technology p, in region r and period t (optionally vintage and time-slice s), $\mathrm{FLOW}(r,\ v,\ t,\ p,\ c,\ s)$ is the quantity of commodity c consumed or produced by process p, in region r and period t (optionally with vintage v and time-slice s), and $\mathrm{ACTFLO}(r, v, p, c)$ is a conversion factor (often equal to 1) from the activity of the process to the flow of a particular commodity. As shown in Eq. (2), the quantity of commodity c consumed or produced equals the activity level of technology p times a conversion factor.

The equation of use of capacity is given in Eq. (5):

$$\begin{aligned}\mathrm{ACT}(r,\ v,\ t,\ p,\ s) = {} & \mathrm{AF}(r,\ v,\ t,\ p,\ s) \\ & \times \mathrm{CAPUNIT}(r,\ p) \times \mathrm{FR}(r,\ s) \\ & \times \mathrm{CAP}(r,\ v,\ t,\ p),\end{aligned} \tag{5}$$

where $\mathrm{AF}(r,\ v,\ t,\ p,\ s)$ is the availability factor, which serves to indicate the nature of the constraint as an inequality or equality. $\mathrm{CAPUNIT}(r,\ p)$ is the conversion factor between units of capacity and activity (often equal to 1, except for power plants). $\mathrm{FR}(r,\ s)$ parameter is equal to the duration of time-slice s, such as the proportion of daytime and nighttime. $\mathrm{CAP}(r,\ v,\ t,\ p)$ constraints mainly describe the relationship between the capacities of technology p with its activity level.

For the energy system analysis, first, the production of oil and gas must meet the demand for energy in future, and the development of the future energy system needs to meet the requirements of the low-carbon development path. Second, from the point of view of the supply of oil and natural gas, there are many factors influencing the energy production, such as exploitation of China's energy reserves, import–export ratio, unconventional gas development, etc. In addition, two factors determining the energy supply curve, which are average production and transportation costs, should be taken into account. Third, it is significant to set different scenarios according to different energy plans.

The model (China-ESPT model) is based on full economy sectors, including resource supply, electricity generation sector, transportation sector, industry sector, building sector, and other sectors. The electricity generation sector in this paper mainly focuses on power generation technology, nuclear generation technology, and renewable-energy generation technology. Coal and gas power generation are the main constituents of the power generation technology. In this model, the coal generation includes the traditional subcritical generation technologies, circulating fluidized bed furnace, and supercritical and ultra-supercritical technologies. In addition, the integrated gasification combined cycle (IGCC) technology and cogeneration technologies are also considered.

The improvement of gas power generation technology is mainly based on gas-boiler and gas-steam combined cycle units. The gas-based power generation technologies are of higher efficiency and more environmental friendly than coal-based power generation technologies. The investment cost of gas boiler and combined cycle is much lower than that of the coal-fired generation unit. The cost of a gas boiler plant is around 1350–1780 RMB/kW, and the investment cost of natural gas-fired combined cycles (NGCCs) is around 3700–4230 RMB/kW on average, which is far below the cost of coal-fired units. Besides, the power generation based on biomass sources mainly includes biomass direct combustion power generation and biomass gasification power generation technology. The average efficiency and cost of power generation technologies are summarized in Table 1.

As the main oil product consumption sector, and also the main end-use sector of oil and gas products, the transportation sector is further studied in this paper. For the transportation sector, the final demand is related to the passenger or freight task and the fuel efficiency of vehicles.

Table 1 Efficiency and cost of power generation

Power generation	Technology	Efficiency, %	Investment per unit, RMB/kW
Coal-based	Ultra-supercritical (U-SUC)	45–47	3600–3800
	Supercritical (SUC)	41–42	3700–3850
	Subcritical	38–39	4400–4600
	Coal circulating fluidized bed	35–40	4500–6000
	Integrated gasification combined cycle (IGCC)	40–43	8000–10,000
Gas-based	Gas boiler	Below 35	3100–3400
	Natural gas combined cycle (NGCC)	55–67	3282–3350
Oil-based	Oil boiler	Below 25	3300–3500
	Oil circulating fluidized bed	37	4500–6000
Biomass	Biomass-fired	23	6500–8500
	Biomass gasification	36	6500–12,000

In the model structure, the output is calculated in Eqs. (6) and (8), with the total demand of the transportation sector shown in Eqs. (7) and (9):

$$\mathrm{TUR\_}P_i = \sum_m \mathrm{AR\_}P_{i,m} \times \mathrm{STOCK\_}P_{i,m} \times \mathrm{LOAD\_}P_m, \quad (6)$$

$$\mathrm{DEM\_}P_i = \sum_m \mathrm{FEUL}_{i,m} \times \mathrm{TUR\_}P_{i,m}, \quad (7)$$

$$\mathrm{TUR\_}F_i = \sum_m \mathrm{AR\_}F_{i,m} \times \mathrm{STOCK\_}F_{i,m} \times \mathrm{LOAD\_}F_m, \quad (8)$$

$$\mathrm{DEM\_}F_i = \sum_m \mathrm{FEUL}_{i,m} \times \mathrm{TUR\_}F_{i,m}, \quad (9)$$

where $\mathrm{TUR\_}P_{i,m}$ is the passenger task of the transport mode m in year i and $\mathrm{TUR\_}F_{i,m}$ stands for the freight task of the transport mode m in year i. $\mathrm{AR\_}P_{i,m}$ and $\mathrm{AR\_}F_{i,m}$ are, respectively, the average annual transport distance of transport mode m in year i for the passenger and freight transport. $\mathrm{STOCK\_}P_{i,m}$ and $\mathrm{STOCK\_}F_{i,m}$ are the stock of vehicles in year i for different modes m. $\mathrm{LOAD\_}P_m$ and $\mathrm{LOAD\_}F_m$ are, respectively, the carrying capacity for different kinds of vehicles m, for the passenger transport, where the carrying capacity is the number of persons, and for the freight transport, where the carrying capacity is expressed in tonnes of freight. $\mathrm{FEUL}_{i,m}$ is the fuel efficiency of the regular vehicles per kilometer, with the unit of L/km, and $\mathrm{DEM\_}P_i$ and $\mathrm{DEM\_}F_i$ are the final demand of the transportation sector, with the unit of million tonnes of coal equivalent. Among them, the data of the traffic department are mainly from the China Statistical Yearbook on Transportation (China Transportation Association 2011), the data of carrying capacity of the vehicle are obtained from Compilation of National Highway and Waterway Transportation Survey Data of China (China Ministry of Transport 2010), and the data of the average mileage of vehicles are from the setting of the GREET model (Argonne National Laboratory 2015).

According to different transport modes m, the transport sector includes passenger transport and freight transport, further divided into road transport, railway transport, water transport, air transport, and other transport. The road transport includes two- and three-wheeled small vehicles, ordinary vehicles, buses, trucks, and other transport modes. Furthermore, in this model, the road transportation technologies are defined referring to both different fuel consumption and the national emission standards. The main modes and technologies of transportation sector are listed in Table 2.

On the premise of meeting energy demands, the China-ESPT model aims at system cost optimization, the future development of oil and gas, as well as the proportion changes of application in some typical terminal sectors. The main economic assumptions for the model are shown in Table 3.

3 Results and analysis

3.1 Energy consumption and effect of key policies in the mitigation scenario

First of all, we set the mitigation scenario referring to the objectives of the "Thirteenth Five-Year Plan," including total targets and branch targets, and the long-term development plan for different sectors. The main constraints include the following: (1) the CO_2 emission intensity per GDP in 2020 should decrease 40 %–45 % compared to the year 2005; (2) the proportion of the non-fossil energy accounted in primary energy consumption should rise to 15 %; (3) according to the latest submitted INDC, the carbon dioxide emissions per GDP should decrease by 60 %–65 % and also start to decrease in 2030. Based on

Table 2 Main transport modes and technologies of the transportation sector

Transport modes	Modes and technologies	Final demand	Units
Road transport	Two- and three-wheeled small vehicles (oil product/electricity)	Passenger/freight task	MPkm/MTkm
	Vehicles (gasoline/diesel/hybrid/plug-in hybrid/electricity/fuel cell/others)	Passenger task	MPkm
	Buses (gasoline/diesel/natural gas/hybrid/electricity/others)	Passenger task	MPkm
	Trucks (mini truck/small truck/medium truck/heavy truck)	Freight task	MTkm
Railway transport	Railway (passenger/freight)	Passenger/freight task	MPkm/MTkm
Water transport	Shipping (passenger/freight)	Passenger/freight task	MPkm/MTkm
Air transport	Airplane (passenger/freight) aviation kerosene	Passenger/freight task	MPkm/MTkm
Others	Pipeline and others	Freight task	MTkm

The gasoline- and diesel-based transport modes are further grouped by the national emission standard of China (GB18352.3-2005: limits and measurement methods for emissions from light-duty vehicles)

Table 3 Assumptions of economy development for China-ESPT model

	2010	2020	2030
Population, millions	1360	1440	1470
GDP per capita (10^4 RMB/capita, 2010 price level)	2.95	5.74	9.88
Urbanization ratio, %	51.1	58.2	67.1

the above targets, we compare carbon dioxide emission reduction between the reference scenario and the mitigation scenario as shown in Table 5.

In the mitigation scenario, carbon dioxide emissions will peak in 2030 and then decrease to achieve a significant reduction in total emission. Compared to the reference scenario, the total reduction of carbon dioxide emissions will reach 13 million tonnes, which is a decrease from 118.8 million tonnes of emissions for the reference scenario to 105.8 million tonnes, with an average decrease rate of around 2.4 %. The average annual growth rate of carbon emissions before 2030 is about 1.5 %, which is 0.6 % lower than the reference scenario (Table 4).

Moreover, the emissions per GDP in 2020 is significantly lower than that in 2005, decreasing by 46 %–50 % in 2020, which is consistent with the target of carbon emission intensity in 2009; and the emissions per GDP will continue to decline by 30 %–40 % until 2030 on the basis of 2020. Compared to 2005, emission intensity per GDP will decrease to about 60 %–68 %, and the decline of the carbon emissions in 2020 is between 40 % and 45 %. The reduction of carbon emissions in 2030 is in accordance with the targets in China's latest submitted INDC documents. Based on the mitigation scenario analysis, the commitments are achievable in 2030 for China.

The main primary energy consumption is shown in Figs. 2 and 3 which show that China's total energy consumption will reach 4.95 billion tonnes of standard coal and 5.81 billion tonnes of standard coal, respectively, in 2020 and 2030.

In Fig. 3, the primary energy consumption structure of the mitigation scenario is compared with that of the reference scenario. After 2020, the coal-dominant energy structure in the process of electric power production and industry sectors will be improved gradually, but the consumption of fossil fuels will still account for a significant proportion. The oil consumption accounts for about 23 % in 2020 and about 25 % in 2030, on average 3 % lower than that in the reference scenario. Non-fossil energy accounts for more than 15 % after 2015 and will reach more than 20 % in 2030.

As a relatively clean energy, the future consumption of natural gas will significantly increase. It is estimated that the gas consumption will grow up to 304.4 billion m^3 by 2020, and increase to 483.3 billion m^3 by 2030, due to the structural adjustment of the power generation sector and industry sector. In the mitigation scenario, the proportion of natural gas will increase to 7 % in 2020 and to 10 % in 2030. However, the growth rate of the use of natural gas will slow down after 2030. The main reasons include the

Table 4 Comparison of carbon dioxide emissions between the reference scenario and the mitigation scenario (million tonnes)

Years	2010	2015	2020	2025	2030	2035	2040
Reference scenario	78.36	89.32	108.77	112.15	118.84	122.59	128.74
Mitigation scenario	78.36	89.46	104.37	105.42	105.77	99.65	99.63

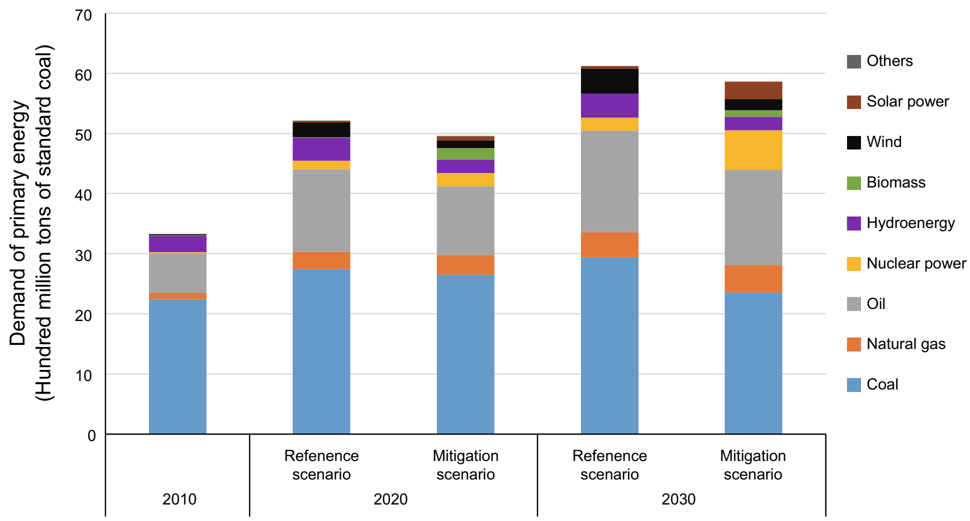

Fig. 2 Comparison of the primary energy consumption between the reference scenario and the mitigation scenario

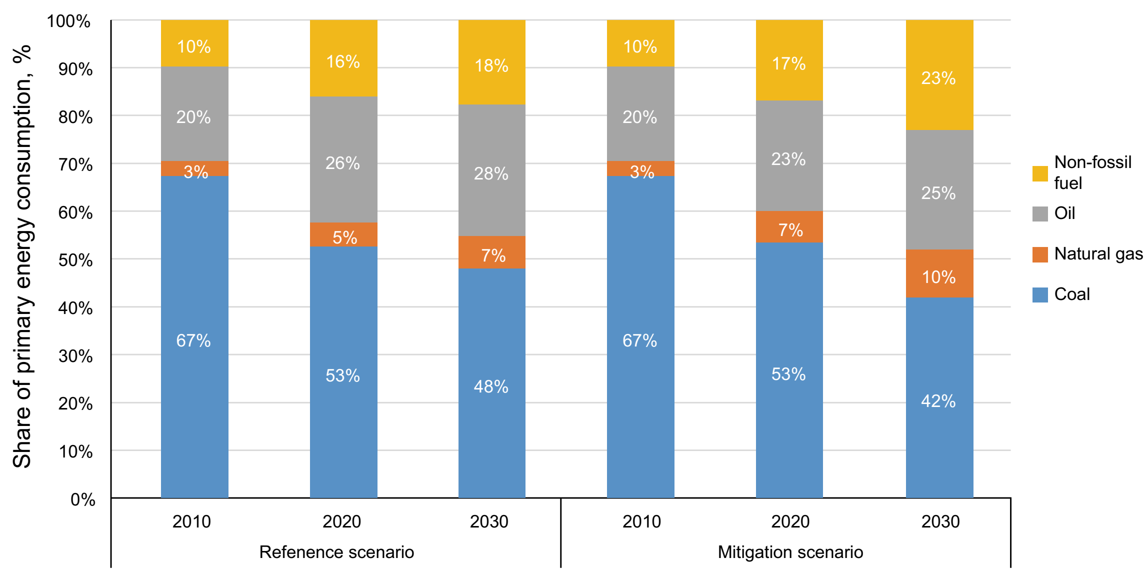

Fig. 3 Comparison of structure of the primary energy between the reference scenario and the mitigation scenario

following: first, the amount of China's natural gas imports continues to increase, while the growth rate is slowing down; second, the new pipelines being put into operation are limited by the resources and efficiency; third, the use of gas in some industries is especially sensitive to the fluctuation of gas prices; last but not least, the energy demand increase is also gradually slowing down.

In order to analyze the effect of key policies, we take the power generation sector as an example. In the power generation sector, several technology options are adopted in the mitigation scenario. Firstly, the cleaner use of fossil fuels will be promoted. All the newly installed coal-based power plants after 2020 will be supercritical, ultra-supercritical, or IGCC power generation technologies. Natural gas power generation technologies should be applied in an appropriate place and act as an important back-up technology for intermittent generation technologies. About 90 % of coal power plants and 80 % of natural gas power plants will be equipped with carbon capture and storage facilities. Secondly, the renewable power generation technologies will become more cost competitive in the future and enjoy a rapid growth. The generation cost of wind power and solar photovoltaic technologies will decrease gradually and will be lower than that of fossil fuel power generation technologies in the future. The biomass power generation will not see an apparent growth after 2020 due to limited resources. Next, the nuclear power will see a large increase and all new nuclear plants should be built in accordance with the third-generation standard.

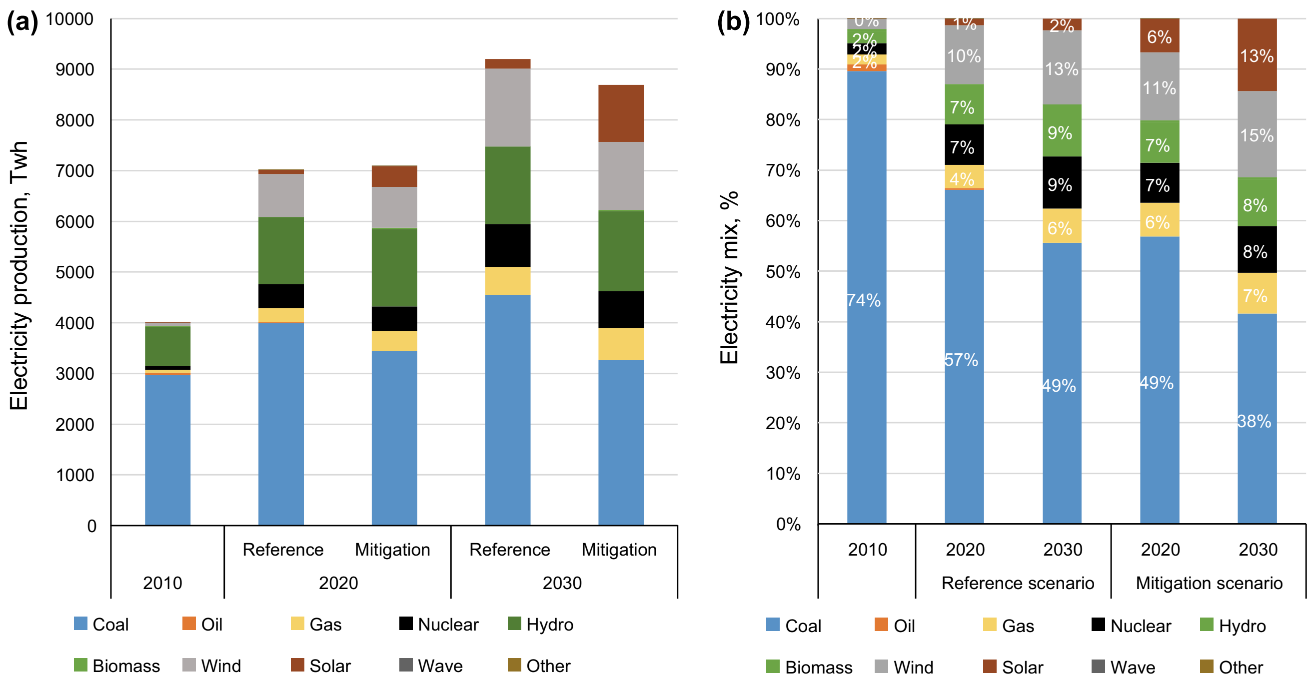

Fig. 4 Electricity production (TWh) and electricity mix (%) during 2010–2030

The most important measure for the carbon emission reduction will be the extension of the use of natural gas, renewable, and nuclear energy, replacing a large amount of coal-fired power generation. Also, the high-percentage combination of carbon capture facilities with coal-fired and gas-fired power generation units also has an effect on the carbon mitigation. The electricity generation and structure are shown in Fig. 4. First, due to energy conservation measures in the final demand sectors, the total electricity needed for the final demand in 2030 is about 8692 TWh, which is 2.17 times of that in 2010, and a 6.78 % reduction compared to the reference scenario in 2030. Second, for the structure of electricity production, the proportion of power generated by fossil energy will reach to 45 % in 2030, with a 31 % reduction compared to that in 2010, and a 10 % reduction compared with the reference scenario in 2030. Third, although the total power generation ratio is decreasing, the relevant clean gas-fired power generation shows an increasing trend. Gas-fired power generation will reach 6 % in 2020 and continue to increase to 7 % in 2030 in the mitigation scenario, compared to 2 % in 2010, 4 % in 2020, and 6 % in 2030 of the reference scenario.

3.2 Impact of technological improvement on the transport sector

According to the model, the main fuel consumption of the transportation sector is still oil products. The consumption of gasoline and diesel accounts for 74 % of the total fuel consumption in 2030, decreasing from 79 % in 2010. The total fuel consumption of transport sector will increase to 397 million tonnes of standard coal in 2030, while it is 272 million tonnes in 2010.

Based on the increase of electric vehicles and hybrid electric vehicle, which is estimated to reach 5 million in 2020, and the improvement of fuel economy, the change of main oil products consumption in the transport sector is studied using the model. Also, the contribution of different transport modes to passenger and freight service is calculated with the model. At the same time, the model takes into consideration the full life cycle of the main transport mode of China. The average life expectancy of the vehicles is 16.5 years, while a truck's average life expectancy is 11 and that of a train is 19. In addition, the annual inventories of vehicles must meet the demand for passenger and freight service, which can be proved by the average carrying rate and annual average driving distance of all transport modes.

Apart from the common hybrid technology, pure electric vehicles, plug-in hybrid vehicles, and fuel-cell vehicles are also considered. Due to the limitations of technical maturity, costs, infrastructure, and other factors, the future development of these technologies is full of uncertainty. From the perspective of technology costs, the model assumes that the annual costs of conventional vehicles will remain constant during the calculation period, and costs of hybrid electric vehicles will annually reduce by 2.5 % on average, while costs of electric vehicles and fuel-cell vehicles will reduce by 4.5 %.

First, for the road transportation, this paper mainly considers three different modes, namely light-duty vehicles

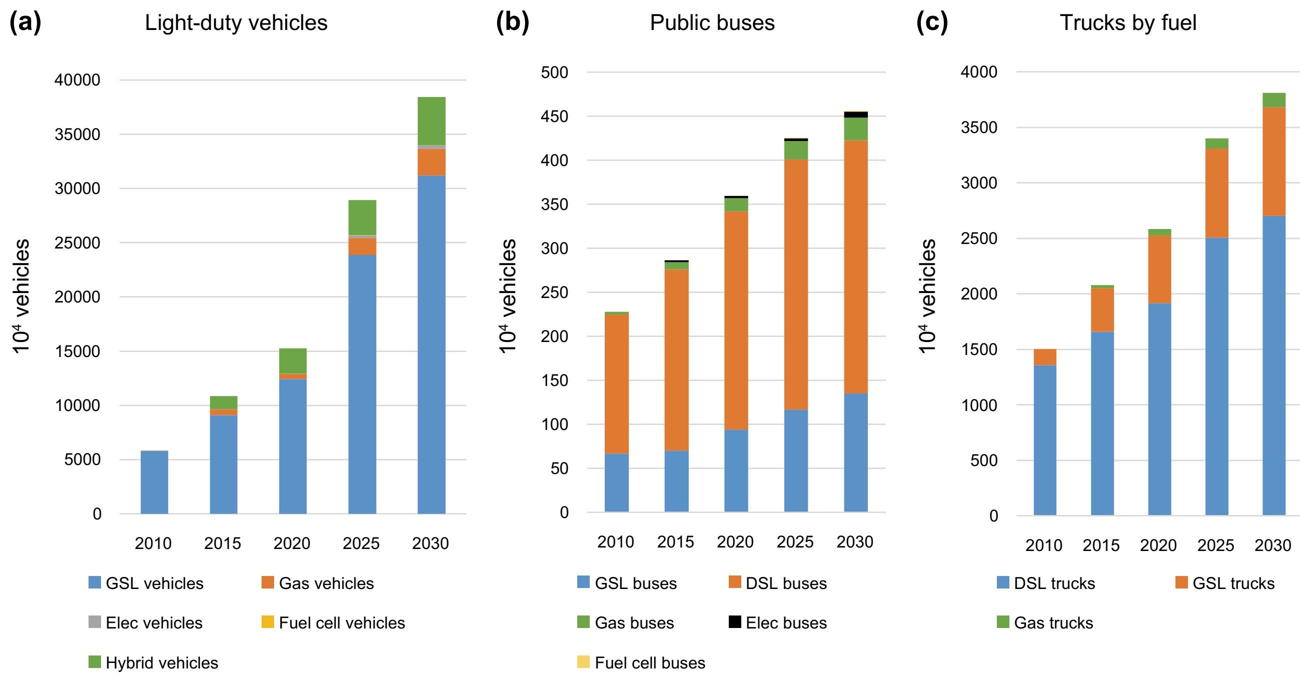

Fig. 5 Numbers of light-duty vehicles, public buses, and trucks during 2010–2030 (10^4 vehicles) (*DSL* diesel, *GSL* gasoline)

(LDVs), public transportation for passengers (mainly buses), and freight transportation (which is mainly by truck). In the reference scenario, when focusing on road transportation, the main vehicle stocks are shown in Fig. 5. Among the private cars, gasoline cars are still the dominant vehicles with 58.1 million vehicles in 2010 and will increase to 311.7 million vehicles in 2030. The gas-fuel vehicles also will increase from 0.19 million in 2010 to 24.5 million in 2030. The electric vehicles in the reference scenario will increase to 3.5 million in 2030, while it is 5.1 million in the technological improvement scenario. For the public buses, generally, the gasoline buses account for the dominant proportion and will increase from 0.67 million in 2020 and to 1.35 million in 2030. The expansion of gas buses and electric buses in recent years cannot be ignored, and the number will increase to 253,000 and 70,000, respectively, in 2030 according to the current policies. The trucks are mainly diesel based, with the diesel trucks increased from 13.6 million in 2010 to 27.1 million in 2030, while the proportion of diesel is decreasing from 90.3 % in 2010 to 70.9 % in 2030. At the same time, the number of gas trucks will increase to 1.30 million with the proportion of 3.7 % in 2030.

When focusing on different modes of road transport, besides the vehicle stocks, the contribution of different vehicles to the road passenger turnover task or freight turnover task is much more important when analyzing the final demand of the transportation sector. In the technological improvement scenario, the fuel efficiency is supposed to improve according to the China national standard, and the electric vehicles stock is encouraged to be more than 5 million with China national subsidy policies. Besides, the elimination of old vehicles and the technological improvement of new vehicles according to their life expectancy are also considered.

For LDVs, the main technology structure and the share rate of passenger transport of the passenger car are shown in Fig. 6. It can be seen that the proportion of the hybrid vehicles takes second place (gasoline car takes first place), with the contribution to the passenger service being about 17.3 % in 2020, and further expanding to 18.9 % in 2030. On the other hand, the electric vehicles and fuel-cell vehicles only account for 2.1 % in 2020 for the reference scenario and 4.3 % for the technological improvement scenario.

From the point of view of road passenger transport (mainly buses), the main technologies used and the contribution of different fuel-based buses are shown in Fig. 7. The main fuels of road passenger transport include diesel and gasoline. The proportion of buses based on natural gas is gradually increasing as the technology improves, accounting for approximately 8.7 % in 2020 and further increasing to 11.2 % in 2030. In addition, the proportion of electric buses is also gradually growing, reaching 3.5 % in 2020 and further rising to 4.6 % in 2030.

For the road freight transport, the main technologies and the contribution of various trucks to freight transport are shown in Fig. 8. The road freight mode is divided into mini trucks, small trucks, medium trucks, and heavy trucks, and the main fuel consumed is diesel, especially for the

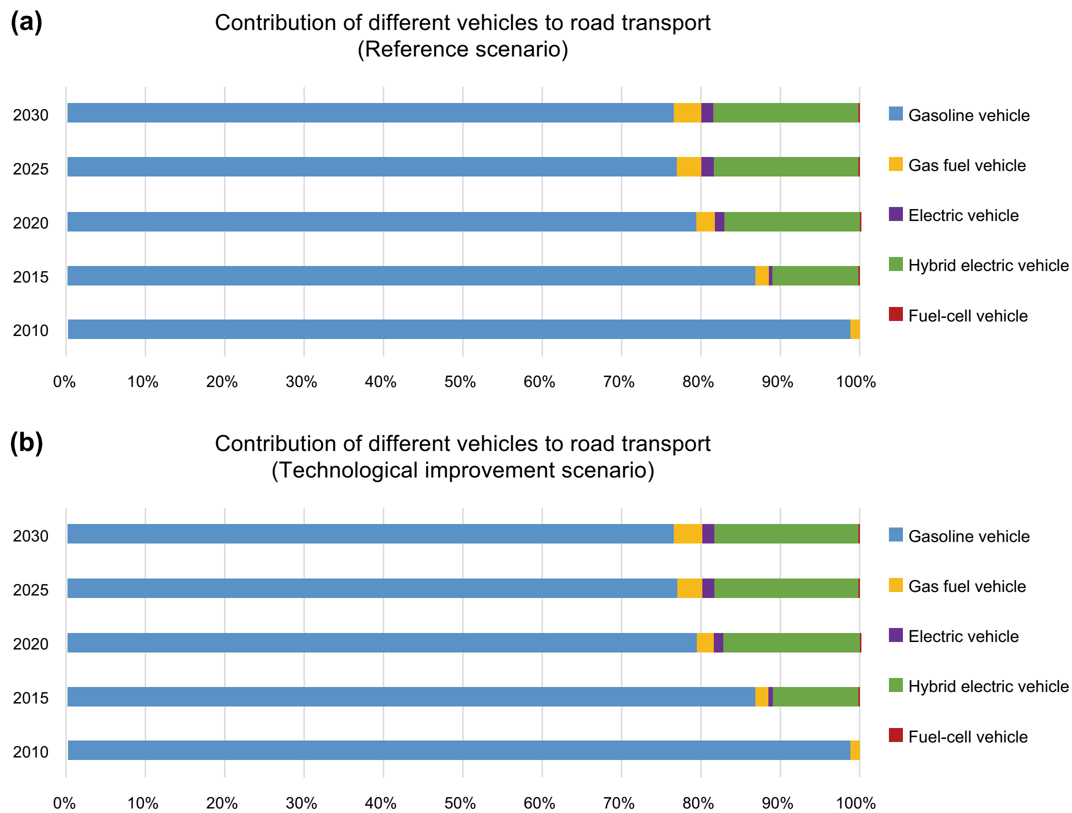

Fig. 6 Contribution of different vehicles to road passenger transport

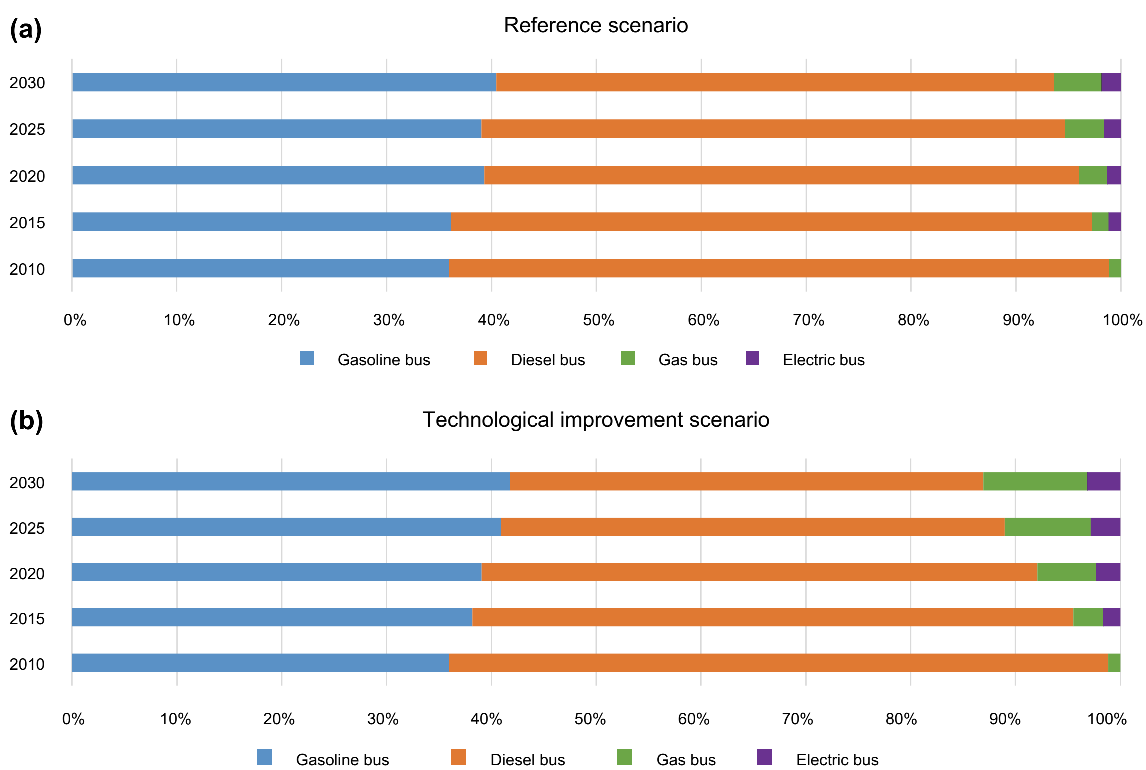

Fig. 7 Contribution of different buses to road passenger transport

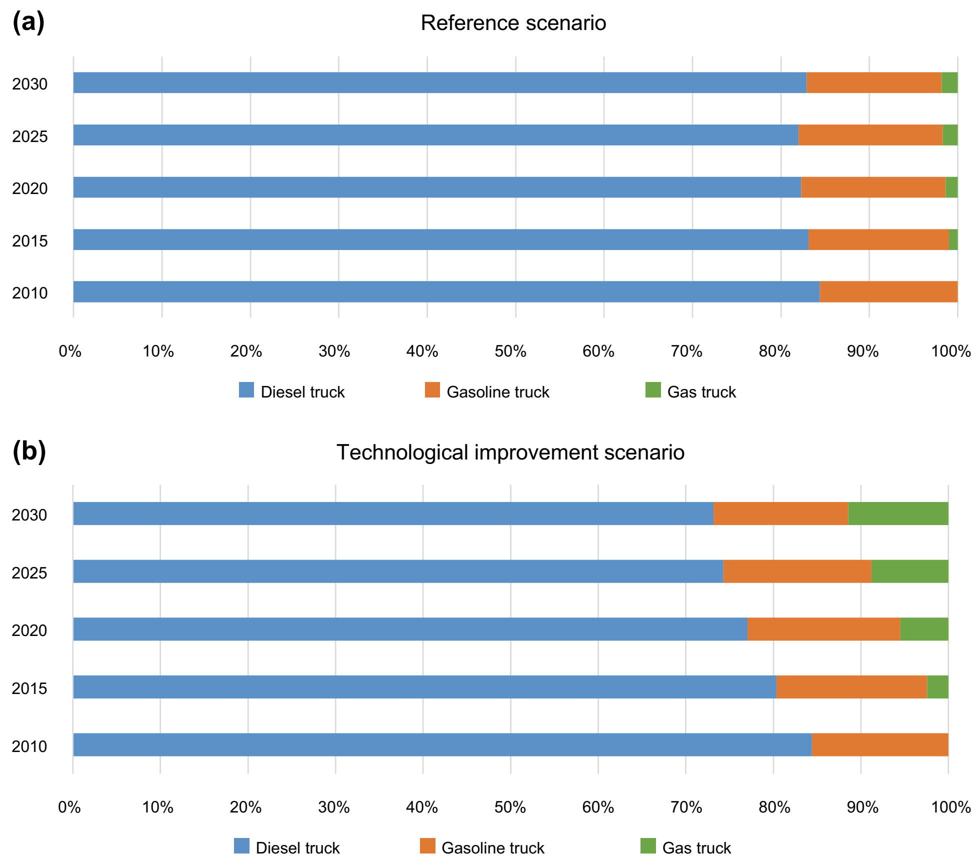

Fig. 8 Contribution of different trucks to the road freight task

medium truck transportation. Also gasoline cars account for a small proportion. In the technological improvement scenario, the contribution of gasoline trucks to freight transport will be more than 5.5 % in 2020 and over 11.7 % in 2030.

The total energy consumption of transport sector is shown in Fig. 9. The growth rate of the total energy consumption in the reference scenario is gradually slowing down due to improvement of fuel economy. The proportion of compressed natural gas, liquefied petroleum gas, and fuel ethanol will increase to 5.1 % in 2030. Overall, although the proportion of oil fuel will decrease, it is still the main component of future energy consumption in the transportation sector, with large requirements for the future oil supply of China.

As shown in Table 5, the calculation results of China-ESPT are consistent with other models, like MESSAGE V.4 (IIASA 2013) and IMAGE 2.4 (PBL 2010). The total energy consumed by freight transport is about 55.7 % of the total energy consumption, and passenger transport accounts for 44.3 % of the total energy consumption. In addition, passenger vehicles account for 26.9 % of all modes of passenger transport, with an energy consumption of approximately 1/4 of total energy consumption.

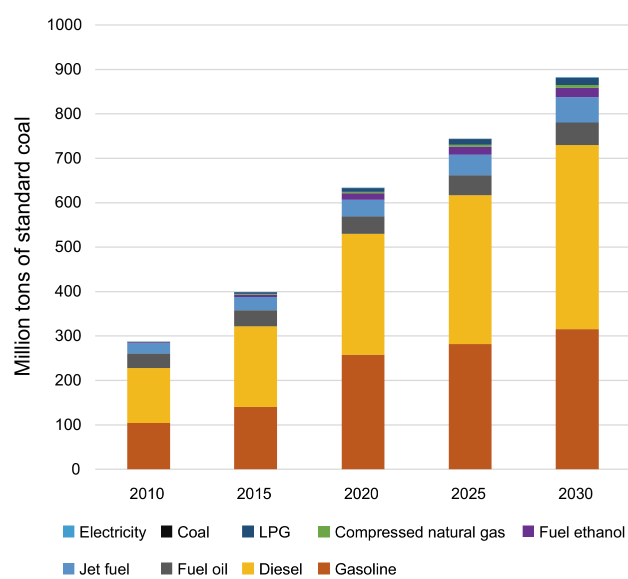

Fig. 9 Energy consumption of transport sector before 2030 (the reference scenario)

As shown in Fig. 10, in the technological improvement scenario, the total fuel consumption of the transportation sector will reduce by about 7.9 % in 2020, in which the

Table 5 Oil consumption of transportation (EJ)

	2010	2020	2030
China-ESPT	8.33	17.91	24.75
IMAGE 2.4 (PBL 2010)	6.58	15.70	24.59
MESSAGE V.4 (International Institute for Applied System Analysis, IIASA 2013)	7.99	18.40	28.34
REMIND 1.5 (PIK 2013)	7.47	15.74	23.29
ChinaTimes (Yin et al. 2015)	8.68	17.17	24.33

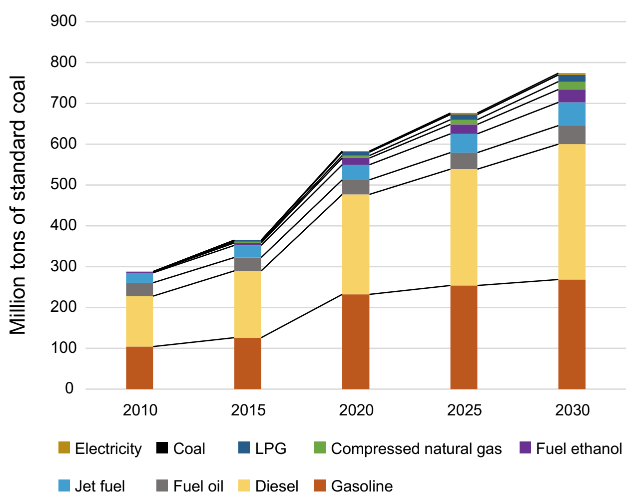

Fig. 10 Energy consumption of transport sector (technological improvement scenario)

consumption of diesel, gasoline, and fuel oil will reduce by 10.4 % compared to the reference scenario. In addition, it is estimated that the total fuel consumption will decline by 12.3 % in 2030, and diesel, gasoline, and fuel oil will, respectively, decrease by 19.1 %, 15.4 %, and 10.2 %. Moreover, in terms of fuel substitution, the consumption of natural gas will increase 1.8 times that of the reference scenario in 2020, and 2.7 times that of the reference scenario in 2030 as a result of technology improvement. Because of the increase of electric vehicles and fuel-cell vehicles, electricity consumption in transport will be 2.5 times and 3.1 times that of the reference scenario, respectively, in 2020 and 2030.

4 Discussion

According to the model analysis, in the mitigation scenario, the primary energy consumption will reach 4.95 billion tonnes of standard coal in 2020 and 5.81 billion tonnes in 2030, with CO_2 emissions limits of 105 tonnes in 2030. The consumption of fossil energy will still occupy a significant proportion. In the mitigation scenario, non-fossil energy consumption will reach more than 15 % in 2020 and more than 20 % in 2030.

The consumption of natural gas will significantly increase to 304.4 billion m^3 in 2020 and 483.3 billion m^3 in 2030. This is mainly due to an increase in final energy demand, especially in industry sector and transportation sector. Besides, China has launched a plan to control the total amount of coal consumption to ensure that carbon emissions will peak around 2030. The gas resource is cleaner than coal, and less expensive than renewables, thus has large development space. In addition, the development of nature gas is highly encouraged by the government. The oil consumption will keep increasing, but with the rate of increase decreasing. The main reason is the driving of the increasing demands from transportation sector. Thus, in this paper the transportation sector is further studied.

As a main consumer of oil products, the transportation sector is studied based on the reference scenario and technology improvement scenario. The design of the scenario mainly considers the fuel economy updates and technological improvement of hybrid cars, electric vehicles, and fuel-cell car. This paper analyzes changes in fuel, oil, and natural gas consumption, as well as changes in contributions of all types of vehicles to future passenger and freight service. Because of the technical maturity, technical cost, and infrastructure, the future development of these technologies has some uncertainty. In this study, we can predict the contribution rate of different types of vehicles to passenger and freight service, by assuming the service life of the vehicle, average carrying rate, annual distance, and changes in costs. The total energy consumption of the transportation sector is also analyzed.

Focusing on the oil and gas consumption, the consumption of diesel, gasoline, and fuel oil of the technology improvement scenario will reduce by 10.4 % compared to reference scenario. In addition, it is estimated that the total fuel consumption will decline by 12.3 % in 2030. The diesel, gasoline, and fuel oil will, respectively, decrease by 19.1 %, 15.4 %, and 10.2 %. In terms of fuel substitution, the consumption of natural gas will increase 1.8 times that of the reference scenario in 2020, and 2.7 times that of the reference scenario in 2030 due to technological improvement. With the increase of hybrid electric vehicles, electric vehicles, and fuel-cell vehicles, the transport electricity consumption in 2020 will increase 2.5 times that of the reference scenario, and 3.1 times that of the reference scenario in 2030.

According to the consumption of oil and gas in the transportation sector, on one hand, the consumption of refined oil is still the main component of the transportation sector. It is important to improve the fuel economy, under the premise of ensuring oil supply and energy security. Moreover, the development of electric vehicles, plug-in hybrid vehicles, and fuel-cell vehicles can effectively promote the achievement of goals due to energy structure adjustment and carbon dioxide emission reduction, and it is important to push forward the upgrading of oil standards and natural gas consumption.

Based on the results above, the oil and gas industry should also strengthen the implementation of relevant policies to achieve the target of peaking carbon emissions in 2030. First, it is important to promote the update of oil quality, especially the emission standard. Up to now, China's diesel product can achieve the national III standard and the gasoline product would be able to achieve national V standard. Second, it is necessary to ensure the clean energy, especially the natural gas supply. Based on the analysis, compared to the reference scenario, the proportion of natural gas consumption will increase by 7 % in 2020 and 10 % in 2030. Besides intensifying the domestic natural gas exploration, the importation of natural gas from Kazakhstan and Burma should also be encouraged, under the premise of ensuring energy security. Moreover, encouraging fuel substitution in transportation sector will help adjust the energy consumption structure. The promotion of electric or hybrid vehicles and natural gas buses will definitely improve the energy structure of the transportation sector, with an increase of electricity consumption by 3.1 times in 2030 compared to reference scenario. Thus, efforts should be made from both oil and gas supply industry and final demand sectors, to fulfill the emission peaking target in 2030.

5 Conclusions

In the present study, the energy consumption during the period of the "Thirteenth Five-Year Plan" and by 2030 was analyzed based on the developed bottom-up energy model. Three important constraints were considered in the analysis: (i) total CO_2 emissions will reach a peak value by 2030 as presented in INDC; (ii) CO_2 emission per GDP in 2020 should decrease 40 %–45 % from those in 2005; and (iii) the proportion of non-fossil energy in total energy consumption should reach 15 %. China's total carbon dioxide emission reductions and energy (mainly coal, oil, and gas) consumptions were calculated and analyzed subject to the constraints. Especially, the scenario analysis of oil and gas consumptions in transportation sector was conducted, and the importation roles of oil and gas were emphasized. Finally, in Sect. 4, the analysis results were reviewed and the improvement of fuel economy, quality of oil product, and fuel substitution in transportation sector were analyzed and discussed.

Acknowledgments This study is funded by the Project supported by China National Petroleum Corporation (Project Name: The development trend of oil and gas industry till 2030; Project Number: 20150114).

References

Adams FG, Shachmurove Y. Modeling and forecasting energy consumption in China: implications for Chinese energy demand and imports in 2020. Energy Econ. 2008;30:1263–78.
Argonne National Laboratory. Greenhouse gases, regulated emissions, and energy use in transportation model document. https://greet.es.anl.gov/. Accessed 10 Dec 2015.
Bollen J, Zwaan B, Brink C, et al. Local air pollution and global climate change: a combined cost–benefit analysis. Resour Energy Econ. 2009;31:161–81.
BP statistical review of world energy 2015. http://www.bp.com/en/global/corporate/ (2015a). Accessed 18 Jan 2016.
BP. BP energy outlook 2035. http://www.bp.com/content/dam/bp/pdf/ (2015b). Accessed 18 Oct 2016.
Budzianowski WM. Target for national carbon intensity of energy by 2050: a case study of Poland's energy system. Energy. 2012;46:575–81.
Cai W, Wang C, Chen J, et al. Comparison of CO_2 emission scenarios and mitigation opportunities in China's five sectors in 2020. Energy Policy. 2008;36:1181–94.
Chen W, Wu Z, He J, et al. Carbon emission control strategies for China: a comparative study with partial and general equilibrium versions of the China MARKAL model. Energy. 2007;32:59–72.
China Ministry of Transport. Compilation of national highway and waterway transportation survey data of China, 2010.
China Transportation Association. China transportation yearbook, 2011–2014.
Cox JC, Ingersoll JE, Ross S. An intertemporal general equilibrium model of asset prices. Econometrica. 1985;53:363–84.
da Graça Carvalho M. EU energy and climate change strategy. Energy. 2012;40:19–22.
Dai H, Masui T, Matsuoka Y, et al. Assessment of China's climate commitment and non-fossil energy plan towards 2020 using hybrid AIM/CGE model. Energy Policy. 2011;39:2875–87.
De Laquil P, Wenying C, Larson ED. Modeling China's energy future. Energy Sustain Dev. 2003;7:40–56.
EIA. Annual energy outlook 2015. Washington, DC: US Energy Information Administration; 2015.

ETSAP. Energy technology systems analysis program 2013. http://www.iea-etsap.org/. Accessed 10 Dec 2015.

Gallagher B. Peak oil analyzed with a logistic function and idealized Hubbert curve. Energy Policy. 2011;39(2):790–802.

Gambhir A, Schulz N, Napp T, et al. A hybrid modelling approach to develop scenarios for China's carbon dioxide emissions to 2050. Energy Policy. 2013;59:614–32.

Gillingham K, Newell RG, Pizer WA. Modeling endogenous technological change for climate policy analysis. Energy Econ. 2008;30:2734–53.

IEA. World energy outlook 2015. http://www.worldenergyoutlook.org/ (2015). Accessed 20 Jan 2016.

International Institute for Applied System Analysis (IIASA). http://www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MESSAGE.en.html (2013). Accessed 20 Jan 2016.

Jiang B, Sun Z, Liu M. China's energy development strategy under the low-carbon economy. Energy. 2010;35:4257–64.

Klaassen G, Riahi K. Internalizing externalities of electricity generation: an analysis with MESSAGE–MACRO. Energy Policy. 2007;35:815–27.

Klaassen, G, Amann M, Berglund C, et al. The extension of the RAINS model to greenhouse gases. An interim report describing the state of work as of April 2004. IIASA IR-04-015; 2004.

Krewitt W, Nitsch J. The German Renewable Energy Sources Act—an investment into the future pays off already today. Renew Energy. 2003;28:533–42.

Kumar U, Jain VK. Time series models (Grey–Markov, Grey Model with rolling mechanism and singular spectrum analysis) to forecast energy consumption in India. Energy. 2010;35(4):1709–16.

Kypreos S, Bahn O. A MERGE model with endogenous technological progress. Environ Model Assess. 2003;8:249–59.

Lund H. The implementation of renewable energy systems. Lessons learned from the Danish case. Energy. 2010;35:4003–9.

Manne A, Mendelsohn V, Richels R. MERGE: a model for evaluating regional and global effects of GHG reduction policies. Energy Policy. 1995;23:17–34.

Messner S, Schrattenholzer L. MESSAGE–MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy. 2000;25:267–82.

Nordhaus WD. Rolling the 'DICE': an optimal transition path for controlling greenhouse gases. Resour Energy Econ. 1993;15:27–50.

OECD. Energy balances of non-OECD countries 2013. http://www.oecd-ilibrary.org/energy/energy-balances-of-non-oecd-countries-2013_energy_bal_non-oecd-2013-en. Accessed 10 Sept 2015.

OPEC. Joint IEA–IEF–OPEC report 2015. http://www.opec.org/opec_web/en/publications. Accessed 17 Jan 2016.

Paltsev S, Reilly JM, Jacoby HD, et al. The MIT emissions prediction and policy analysis (EPPA) model, in, joint program on the science and policy of global change. Cambridge: Massachusetts Institute of Technology; 2005.

PBL Netherlands Environmental Assessment Agency. http://themasites.pbl.nl/models/ (2010). Accessed 20 Oct 2015.

Potsdam Institute for Climate Impact Research (PIK). https://www.pik-potsdam.de/research/sustainable-solutions/models/remind (2013). Accessed 20 Oct 2015.

Rafaj P, Kypreos S. Internalization of external cost in the power generation sector: analysis with Global Multi-regional MARKAL model. Energy Policy. 2007;35:828–43.

Stockholm Environment Institute (SEI). Long range energy alternatives planning system 2014. Joint IEA–IEF–OPEC report. http://www.opec.org/opec_web/en/publications. Accessed 20 Oct 2015.

The State Council of China. Enhanced actions on climate change: China's intended nationally determined contributions [EB/OL]. http://www.gov.cn/xinwen/2015-06/30/content_2887330.htm/. Accessed 21 Oct 2015.

The State Council of China. Strategic action plan for energy development (2014–2020). http://www.gov.cn/zhengce/content/2014-11/19/content_9222.htm. Accessed 21 Oct 2015.

Tu J, Jaccard M, Nyboer J. The application of a hybrid energy–economy model to a key developing country—China. Energy Sustain Dev. 2007;11:35–47.

Wicke L. Beyond Kyoto—a new global climate certificate system. Heidelberg: Springer; 2005.

Yin X, Chen W. Trends and development of steel demand in China: a bottom-up analysis. Resour Policy. 2013;38:407–15.

Yin X, Chen W, Eom J, et al. China's transportation energy consumption and CO_2 emissions from a global perspective. Energy Policy. 2015;82:233–48.

Zhang N, Lior N, Jin H. The energy situation and its sustainable development strategy in China. Energy. 2011;36:3639–49.

Zhou N, Fridley D, Khanna NZ, et al. China's energy and emissions outlook to 2050: perspectives from bottom-up energy end-use model. Energy Policy. 2013a;53:51–62.

Zhou S, Kyle GP, Yu S, et al. Energy use and CO_2 emissions of China's industrial sector from a global perspective. Energy Policy. 2013b;58:284–94.