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Research article

Energy revolution: From a fossil energy era to a new energy era☆

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Abstract

This paper aims to predict the future situation of global energy development. In view of this, we reviewed the history of energy use and understood that new energy sources will usher in a new era following oil & gas, coal and wood one after another in the past time. Although the fossil energy sources are still plenty in the world, great breakthroughs made in some key technologies and the increasing demand for ecological environmental protection both impel the third time of transformation from oil & gas to new energy sources. Sooner or later, oil, gas, coal and new energy sources will each account for a quarter of global energy consumption in the new era, specifically speaking, accounting for 32.6%, 23.7%, 30.0% and 13.7% respectively. As one of the largest coal consumer, China will inevitably face up to the situation of tripartite confrontation of the coal, oil & gas and new energy. The following forecasting results were achieved. First, the oil will be in a stable period and its annual production peak will be around 2040, reaching up to 45×10^8 t. Second, the natural gas will enter the heyday period and its annual production peak will be around 2060, reaching up to 4.5×10^{12} m^3, which will play a pivotal role in the future energy sustainable development. Third, the coal has entered a high-to-low-carbon transition period, and its direct use and the discharged pollutants will be significantly reduced. In 2050, the coal will be dropped to 25% of the primary energy mix. Last, the development and utilization of new energy sources has been getting into the golden age and its proportion in the primary energy mix will be substantially enhanced. On this basis, we presented some proposals for the future energy development in China. At first, we should understand well that China's energy production and consumption has its own characteristics. Under the present situation, we should strengthen the clean and efficient use of coal resources, which is the key to solving our energy and environmental issues. Then, under the low oil price circumstance, we should keep 200 million tons of annual oil production as “the bottom line” so as to ensure national energy security and to accelerate tight gas, shale gas and other unconventional resources development. In 2030, the annual natural gas production will reach up to more than 300 Bcm. Finally, the development and utilization of new energy resources should be further strengthened and non-fossil energy sources will be expected to reach as high as 20% of the primary energy consumption by 2030.

Keywords: Energy revolution; Fossil energy; New energy; Oil & gas; Coal; Renewable energy; Unconventional oil & gas; Shale gas; Tight oil; Nanotechnology; Graphene; Internet plus

Energy, water and food are three major elements to ensure human survival. The world energy development is entering a new historical period, when clean and low-carbon energy is inevitably required. Unconventional oil and gas revolution made the 40-year strategic dream of “energy independence” in the United States come true. The US government proposed the great energy strategy of “remaking America with green energy” in 2008, and especially, provided the revolutionary “four innovations” in unconventional oil and gas represented by shale oil and gas and tight oil, i.e. innovation in geological theory centering round continuous oil/gas accumulation, innovation in technologies with volume fracturing of horizontal wells as core, innovation in production methods for

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platform-type "factory" exploitation, and innovation in management centering around market competition mechanism. The unconventional oil and gas revolution in the United States is now changing the pattern of global oil and gas and even energy, exerting a profound impact on global political and economic development. The Chinese government has recently proposed an energy revolution strategy of "promoting energy consumption revolution to curb irrational energy consumption, promoting energy supply revolution to establish a diverse supply system, promoting energy technology revolution to drive industry upgrade, and promoting energy system revolution to open up a fast lane for energy development. The authors first summarized the general trend of world energy development by reviewing its history. Then, they analyzed the challenges to the energy development of China, and proposed relevant countermeasures.

1. The general trend of world energy development

1.1. Three transformations in energy development

Following the transformation from wood to coal then to oil & gas, the future will see the third major transformation from oil & gas to new energy. Since primitive humans first began to use fire, energy has become an essential resource for human survival. Easily accessible timber satisfied heating, cooking and other basic needs for the survival of primitive humans. With technological advances in coal mining, coal, which had higher energy density, was widely used. In 1769, Watt invented the steam engine. In 1875, the French built the first coal-fired power plant in the world. The progress of human civilization accelerated the development of the coal industry, and coal accounted for the largest share in primary energy mix in the 1780s, surpassing wood for the first time. This was the first transformation − from wood to coal. In 1886, Daimler invented the internal combustion engine, stimulating a great increase in the demand for oil and gas as efficient energy resources. Progress in geological theory, and drilling, completion and refining technologies drove oil and gas production to increase substantially. Accordingly, the share of oil and gas in primary energy mix grew rapidly to more than 50% in 1965. These energy resources replaced coal as the largest energy in the world, recording the second transformation − from coal to oil and gas.

With the sustained increase in the economic and social demand for energy and the advent of low-carbon society, the third major transformation from traditional fossil fuel to non-fossil new energy will become inevitable. In recent years, ecological and environmental problems caused by the use of coal, oil and other high-carbon energy resources have become increasingly prominent. The intensive use of coal and other high-carbon energy resources is the major reason for the fog in London in the early 20th century and the serious fog and haze in China now. With the increased demand for green ecological environment, natural gas and new energy as clean energy resources will take up a higher share in the primary energy mix.

Oil, gas, coal and new energy resources will each account for a quarter of global energy consumption. However, it is important to clearly realize that new energy can hardly play a vital role in quite a long time to come.

1.2. Three trends in energy development

In types, production methods and utilization methods of energy resources, the world energy development has shifted from high- to low-carbon, from simple production to technological production, and from one-time utilization to multiple one.

1) Energy types: from high- to low-carbon, or from fossil to non-fossil energy sources. The carbon content of calorific value per unit is 26.37 t/TJ in coal, 20.1 t/TJ in crude oil, and 15.3 t/TJ in natural gas. Hydropower, wind power, nuclear energy and solar energy are almost carbon-free. In the transition from coal to hydrocarbon and from hydrocarbon to new energy sources, pollutants and carbon emissions generated by various types of energy sources has been increasingly reduced which has met the needs of green development of ecological environment.
2) Production methods: from original to technological production. According to the general trend of energy development, primitive humans got wood from nature directly, and importance of engineering technology became increasingly prominent from coal mining to oilfield development. The development of nuclear, wind, solar and other new energy resources is technically intensive. The importance of technology is also highlighted in the development process of any type of energy. For example, in early years vertical well drilling was used for oil exploitation, and the application of horizontal well drilling and hydraulic fracturing technology enabled a large number of low-yielding wells to achieve effective development. In recent years, the application of staged fracturing in horizontal wells has promoted a "shale oil and gas revolution" in the energy sector.
3) Energy utilization: from direct use to energy transformations. Before the First Industrial Revolution, firewood and coal were used only for heating. With the invention of steam engine in 1769 and of internal combustion engine in 1875, energy was used for power generation. Following the discovery of electromagnetic induction by Faraday in 1831, energy was used for electric power, ushering in the era of energy use for electrification.

1.3. Three patterns of energy development

With the advances in social civilization and science and technology, a new pattern of coordinated development between "oil" and "natural gas", "conventional energy" and "unconventional energy", and "fossil energy" and "non-fossil energy" is taking shape [1].

1) A new pattern of "oil" and "natural gas". Based on the international energy development and the exploration and development trends of oil companies, the general trend is to "stabilize oil production and increase natural gas supply". Natural gas will come as the "first revolution" on oil; an era of natural gas development is just around the corner.
2) A new pattern of "conventional energy" and "unconventional energy". Both conventional and unconventional energy resources have been focused in the development strategies of major oil companies, which remain concentrated on exploration of conventional oil and gas, and work thoroughly on critical technologies and theories concerning unconventional energy for progressive and effective development. In the long run, shale gas, shale oil, natural gas hydrate (hereinafter referred to as "NGH") and other unconventional resources entail huge potential. Once technological breakthroughs are made, the "second revolution", especially "the NGH revolution", will greet conventional oil and gas, and it is likely to be more radical than shale gas revolution.
3) A new pattern of "fossil fuels" and "non-fossil fuels". Traditional fossil energy is not renewable, while renewable non-fossil energy resources will complete the "ultimate revolution" on conventional energy. If it is acknowledged that the oil industry has a development cycle of 300 years, it has been 150 years from the starting of the world oil industry in 1859, and now the remaining 150 years may be the life cycle of fossil energy. Wind, solar, geothermal energy, stored energy and hydrogen energy that develop rapidly are showing good prospects. Maybe the "new energy revolution" will come before the depletion of fossil energy.

1.4. Two driving forces for energy development

Development of social civilization drives energy demand. Energy was mainly used to meet the needs for survival in the primitive society. The demand for energy was greatly increased due to the improved quality of human life and primary industrial production in the feudal society. Owing to the accelerated development of social civilization since the industrial revolution, human demand for transport, information and cultural entertainment has been significantly increased and modern industry demand for energy has reached an unprecedented level. In recent years, with a series of ecological and environmental problems arising from wastewater, waste gas and waste residue generated in the development and utilization of high-carbon energy, the ecological demand for energy production and consumption has been included in the energy development process.

Scientific and technological progress drives energy revolutions. For example, the history of oil industry is a history of scientific and technological development. The constant innovations in oil and gas geological theory and technology inject inexhaustible power to sustainable economic and social development. In the 150-year history of oil and gas industry, there were two major innovations in oil and gas discovery theory [1]. The first innovation was to discover conventionally trapped "reservoirs", and the second was to discover unconventional "sweet spots". The petroleum scientific and technological revolutions that pushed the transition from conventional to unconventional oil and gas, which included conventional trapped reservoir theory, unconventional oil and gas continuous accumulation theory, conventional oil and gas vertical well drilling, and nanotechnology and gas drive to enhance oil and gas recovery, have promoted the continuous development of the oil industry and resulted in steady growth of the world oil and gas reserves and productions. In 2014, the remaining proven recoverable reserves of oil and gas in the world were 2398×10^8 t and 187×10^{12} m^3 respectively, and the yield was about 73.5×10^8 t of oil equivalent (toe) [2]. Scientific and technological progress has promoted the discovery and utilization of oil and gas resources to meet the demand of human and social development for oil and gas.

2. New world energy map

Due to the differences in crust formation and evolution, fossil energy resources are distinctly distributed in regions around the world, with great imbalances in exploration and development, production and consumption. Along with the advance of social civilization, human demand for renewable energy, hydropower, nuclear power, and biomass fuels is increasing. In recent years, owing to the rapid development of unconventional oil and gas, China, India and other developing countries have presented fast growing demand for energy, which greatly influences the traditional energy pattern in both supply and demand. Four regions for oil and gas and four regions for unconventional oil and gas have been shaped. Coal is distributed in three regions: Asia–Pacific, North America and Europe, while new energy development is ongoing in Europe, North America and Asia–Pacific.

2.1. Fossil fuel energy

2.1.1. Fossil fuel energy resources

Global fossil fuel energy resources include oil, gas and coal. Along with the deepening of theoretical knowledge and dramatic progress in exploration skills, the new layout of global fossil energy resources has been reshaped.

The development of unconventional oil and gas resources has reshaped the traditional layout of oil and gas resources. The recoverable amount of conventional oil and gas in the world is 4878×10^8 t and 471×10^{12} m^3, respectively, and they are mainly concentrated in four regions: the Middle East (35%), Russia (14%), North America (13%) and South America (9%) [1,3]. Since 2000, with understanding and technological levels increasing, large-scale development of unconventional oil and gas has been realized, with North America as the representative. The potential of unconventional oil and gas has been re-recognized. According to the latest estimate, the recoverable amount of global unconventional oil resources is 6200 × 10^8 t, roughly the same as conventional oil resources; the recoverable amount of unconventional gas resources is about 4000 × 10^{12} m^3, roughly eight times that of conventional gas resources, and it is mainly concentrated in four regions with rich unconventional oil and gas resources, i.e. North America (34%), Asia−Pacific (23%), South America (14%) and Russia (13%) [1,3].

Coal is the most abundant fossil energy in the world, with a total amount exceeding 100 trillion tons. It is mainly distributed in three regions: Europe and Eurasia, Asia−Pacific and North America (Fig. 1). By the end of 2014, the proven coal reserves in the world were 8915 × 10^8 t (or 4457.5 × 10^8 toe). Coal reserves in Europe and Eurasia, Asia−Pacific and North America account for 34.8%, 32.3% and 27.5%, respectively. The United States has the most abundant coal reserves totaling 2373 × 10^8 t, followed by Russia (1570 × 10^8 t) and China (1145 × 10^8 t) [2].

Table 1
World vs. China energy production and consumption in 2014 Unit: 10^8 toe.

Energy	Item	World		China	
Oil	Production	42.21	32.3%	2.11	8.4%
	Consumption	42.11	32.6%	5.20	17.5%
Natural gas	Production	31.27	24.0%	1.21	4.8%
	Consumption	30.66	23.7%	1.67	5.6%
Coal	Production	39.34	30.1%	18.45	73.8%
	Consumption	38.82	30.0%	19.61	66.0%
Nuclear power	Production	5.74	4.4%	0.29	1.2%
	Consumption	5.74	4.4%	0.29	1.0%
Hydropower	Production	8.79	6.7%	2.41	9.6%
	Consumption	8.79	6.8%	2.41	8.1%
Renewable	Production	3.17	2.4%	0.53	2.1%
	Consumption	3.17	2.5%	0.53	1.8%
Total	Production	130.52	100.0%	25.00	100.0%
	Consumption	129.29	100.0%	29.71	100.0%

Note: data from BP.

2.1.2. Fossil fuel energy production

The unconventional oil and gas revolution driven by technological advances is pushing profound adjustments in the world oil and gas production pattern. In the past 10 years, the world oil production has grown steadily, and natural gas production has increased rapidly. Compared with 2004, 2014 harvested global oil production of 42.2 × 10^8 t (Table 1), 8.1% up, and natural gas production of 3.46 × 10^{12} m^3 [2], 27.6% up. The yields in three conventional oil and gas producing areas, namely the Middle East, Russia and South America, grew steadily − by 11.7%, 15.3% and 6.0% for oil [4] and by 102.6%, 0.9% and 29.9% for gas [2,4]. In 2014, oil production in the Middle East, Russia and South America as three conventional oil and gas producing areas accounted for 31.7%, 12.7% and 9.3% of the world total production, respectively, while natural gas production accounted for 17.3%, 16.7% and 5.0%. In the past 10 years, major breakthroughs have been made in the exploration and development of unconventional oil and gas in North America. The rapid development of unconventional oil such as tight oil and tar sands oil rapidly promoted oil production increase in North America by 31.0% and it became a major growth point in global oil production. The rapid development of unconventional gas such as shale gas and tight gas rapidly promoted natural gas production increase in the United States by 38.4% and set off a wave of unconventional oil and gas development around the globe. Two major production territories, the Western Hemisphere for unconventional oil and gas and the Eastern Hemisphere for conventional oil and gas, are forming.

Affected by the expansion of coal production capacity in China and other emerging economies, the imbalances in the world coal production are increasing and the dominant position of coal in the Asia−Pacific is reinforced. Despite the abundant coal resources in North America and Europe, their productions take on a downward trend. Coal production in Asia−Pacific increases fast, making the region a major producer. China contributes nearly a half of the world total coal production. In 2004, the world total coal production was

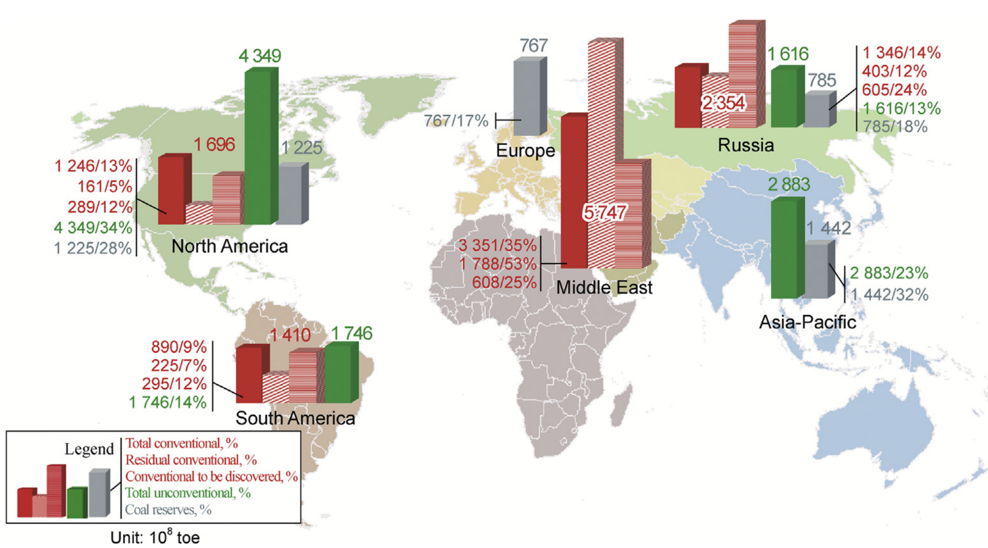

Fig. 1. Layout of global fossil energy distribution.

55.9×10^8 t (28.4×10^8 toe) [4], and Asia−Pacific, North America and Europe accounted for 56.1%, 21.5% and 15.8%, respectively. In 2014, the world total coal production was 81.65×10^8 t (39.3×10^8 toe) (Table 1) [2], and Asia−Pacific, North America and Europe accounted for 69.2%, 14.0% and 11.2%, respectively. Compared with the figures in 2004, the total coal production grew by 38.4%. China was the main contributor of coal production and accounted for 67.0% of global production growth.

2.1.3. Fossil fuel energy consumption

The strong growth of energy demand in emerging economies and the approaching to ecological environment carrying limit have forced humans to make a choice between different energy resources. This choice will impact and reshape the new layout of the world fossil energy consumption.

Global energy consumption depends on the level of socio−economic development and the accessibility to resources. The energy demand in the United States, Europe and other developed countries remains stable while the demand in Asia−Pacific emerging economies grows rapidly. The world energy consumption has shifted from tripartite confrontation of North America, Europe and Asia−Pacific to polarization of the Eastern and Western Hemispheres. In 2004, the global fossil energy consumption was 90.1×10^8 toe [4], and North America, Europe and Asia−Pacific accounted for 27.1%, 27.6% and 33.0%, respectively. In 2014, the global fossil energy consumption reached 111.6×10^8 toe (Table 1), and North America, Europe and Asia−Pacific accounted for 21.3%, 20.1% and 43.1%, respectively [2]. Compared with the number in 2004, the global fossil energy consumption grew by 23.8%. The energy consumption in North America and Europe grew by −2.7% and −9.7%, respectively, showing a negative growth trend. From 2004 to 2014, the total energy consumption in the Asia−Pacific region increased from 29.7×10^8 t to 48.2×10^8 toe [2,4], 62.3% up. Coal, oil and natural gas consumption increased by 81.9%, 29.5% and 79.3%, respectively.

2.2. New energy

2.2.1. Renewable energy

Power generation has been a major purpose for utilization of renewable energy and leads the future of renewable energy development. With continuous scientific and technological progress in the development and utilization of wind, solar and other renewable energy, Europe, Asia−Pacific and North America have initially become three major producing regions of new energy. In 2014, the total installed capacity of wind power was 51.477 GW [5], and the installed capacity of solar power was 177 GW [5]. The total power-generating capacity of renewable energy was 3.17×10^8 toe [2], and Europe, North America and Asia−Pacific accounted for 39.3%, 23.2% and 29.7%, respectively.

The production of biomass fuels is highly region-specific and is affected by the production of agricultural products like sugar cane. It develops slowly and two major producing regions, North America and Latin America, have been initially shaped. In 2004, the production of biomass fuels was 0.16×10^8 toe [6], of which North America and South America accounted for 39.4% and 44.5%, respectively. In 2014, the total production increased to 0.71×10^8 toe [5], of which North America, Central and South America, Europe and Asia−Pacific accounted for 44.1%, 28.7%, 16.3% and 10.6%, respectively.

2.2.2. Hydropower

The world hydropower technology matures, and the industry development is mainly controlled by the distribution of water resources. Four producing regions, i.e. Asia−Pacific, Europe, North America and Latin America, have been generally established. In 2014, the global installed capacity of hydropower was 1036 GW and the total power generation was about 3900 TWh (8.79×10^8 toe) [2,7]. Asia−Pacific, Europe, North America and Latin America accounted for 38.9%, 22.3%, 17.5% and 17.7%, respectively. The United States and Canada are world leaders in hydropower development, with hydropower installed capacity of 79.6 and 77.6 GW (excluding pumped storage), respectively [7]. The US government encourages the development of hydropower and promulgated two bills in 2014 which simplifies the approval processes of building small hydropower projects on existing water infrastructure and increased the permitted capacity from 5 to 10 MW of hydropower projects built on existing water facilities or sites with hydropower potential. Hydropower accounted for 63% of the total power generation in Canada and the installed capacity of hydropower projects under construction was 4000 MW.

2.2.3. Nuclear power

Affected by the Fukushima nuclear disaster, the world nuclear power development tends to be cautious. There are two major producing regions − Europe and North America. In 2014, the total installed capacity of grid-connected nuclear power generating units was 4763 MWe [8], and the total generating capacity fell to 5.74×10^8 toe, of which Europe and North America accounted for 46.3% and 37.6%, respectively. In 2014, there were 70 units under construction, with a total installed capacity of approximately 74 GWe [8,9]. In 2014, four power reactors for grid-connected operation were added, one in Argentina (ATUCHA-2 Unit, PHWR, 692 MW) and three in China, i.e. No.1 Unit (PWR, 1000 MW) in Fangjiashan, No.1 Unit (PWR, 1000 MW) in Fuqing, and No.2 Unit (PWR, 1018 MW) in Ningde.

3. New energy map of China

As the largest developing country in the world, China has experienced earth-shaking changes after years of rapid socio−economic development. The current status of abundant coal resources but relatively deficient oil and gas resources determines that energy production and consumption has its special characteristics. From 2004 to 2014, China's GNP grew by 298%, reaching RMB 63.6 trillion [10], energy consumption was more than doubled from 21.3×10^8 to 42.6×10^8 tce (metric tons of standard coal equivalent) [10], and energy resource production increased by 72.6% from 19.7×10^8 to 34×10^8 tce (ton of standard coal equivalent) (29.7×10^8 toe) [2,10].

3.1. Fossil fuel energy in China

The fossil energy industry in China develops steadily. Coal occupies the dominant position in fossil energy, oil production is stabilized, and natural gas production is increased rapidly. In 2014, the total fossil energy production in China reached 21.77×10^8 toe [2,10], in which coal, oil and natural gas accounted for 84.7%, 9.7% and 5.6%, respectively.

3.1.1. Fossil fuel energy resources in China

There are abundant fossil energy resources in China. On the whole, coal resources are rich, while oil and gas resources are deficient. Coal resources total 5.0×10^{12} t, more in the west and north regions than in the east and south regions. The total coal resources in Shanxi, Inner Mongolia, Shaanxi, Xinjiang, Guizhou and Ningxia are 4.19×10^{12} t, accounting for 84% of the total coal resources in the country. The total recoverable oil and gas resources are approximately 1370×10^8 toe [1,3], with relatively low proven oil and gas recovery and extraction levels. The recoverable conventional oil resources amount to 212×10^8 t and the recoverable unconventional oil resources amount to about 200×10^8 t [3]. The recoverable conventional natural gas resources amount to 20×10^{12} m^3, and the recoverable unconventional natural gas resources amount to 80×10^{12}−120×10^{12} m^3 [3]: the latter is almost five times that of the former. With deepened theoretical understanding and innovation and development of engineering technology, there is more room for further growth of the potential oil and gas resources.

3.1.2. Fossil fuel energy production in China

The production of fossil energy grows steadily, with overcapacity of coal production, stabilized oil production, and rapid growth of natural gas production. In 2014, the total capacity of coal industry was 43.7×10^8 t and total production was 38.7×10^8 t (18.45×10^8 toe) [2]. Major coal producing areas such as Shanxi, Shaanxi, Ningxia, Henan, Inner Mongolia and Xinjiang have been established. After 60 years of development, six oil production bases have been initially built in China, with annual outputs over 1000×10^4 t. They are Bohai Bay Basin, Songliao Basin, Ordos Basin, Junggar Basin, Tarim Basin, and Pearl River Mouth Basin. Moreover, three natural gas production bases have been established, i.e. Ordos Basin, Tarim Basin, and Sichuan Basin, with annual outputs of more than 100×10^8 m^3. Oil production exceeded 2×10^8 t in 2010 and reached 2.11×10^8 t in 2014. Natural gas production exceeded 500×10^8 m^3 in 2006, 1000×10^8 m^3 in 2011, and 1306.8×10^8 m^3 in 2014.

3.1.3. Fossil fuel energy consumption in China

For a long time, coal has occupied an excessively high proportion in the energy mix in China, while oil and natural gas have occupied low proportions. In 2014, coal accounted for 66.2%, oil 18.4%, and gas 5.6% [2,10] in the primary energy mix in China. The total share of oil and gas was only 24%, far less than the world average (56%) [2]. The recent continuous deterioration of ecological environment has desperately called for adjustments in the primary energy mix to greatly increase the proportion of clean energy consumption such as natural gas while efficient and clean coal utilization is strengthened.

3.2. New energy sources in China

In recent years, the new energy industry in China has evolved thriftily with increasing share in the primary energy mix, becoming an important part of energy. In 2014, the total production of renewable energy, nuclear power and hydropower in China reached 3.22×10^8 toe [2,10], accounting for 10.9% of the primary energy consumption. The proportions of renewable energy, nuclear power and hydropower in the total production of new energy were 16.5%, 8.9% and 76.6%, respectively [2].

3.2.1. Renewable energy sources

As a vast country, China provides inherent advantages for the development and utilization of renewable energy, ranking the first in the world in terms of installed capacity of wind energy, solar energy and other renewable energy. In 2014, the new installed capacity of wind power in China reached 2335.1×10^4 kW [5] and the installed capacity of grid-connected solar energy units reached 26.52 GW (according to the National Energy Administration, 2015), 25.5% up and 67% over the previous year, and their power generation amounts were 1563×10^8 and 231×10^8 kWh, respectively [5,6]. The total power generation amount of renewable energy in China reached 0.51×10^8 toe, accounting for 1.8% in the primary energy consumption. Affected by the supply of raw materials, the biomass fuel production in China still develops slowly, with the production in 2014 being 208×10^4 t, 3.3% up over the previous year.

3.2.2. Hydropower

Hydropower resources are rich in China and hydropower development is accelerating. In 2014, the total installed hydropower capacity was 282 GW and the hydropower generating capacity was 10661×10^8 kWh (2.41×10^8 toe) [7], 19.7% up, accounting for 19.2% of the total power generation in the country. In 2014, the new hydropower capacity was 21250 MW [7], in which the new hydropower capacity contributed by Sichuan and Yunnan was about 80%. Supplementary power generation with hydropower and renewable energy is the new direction of future development. In 2014, Longyangxia Power Station, the largest hydro-PV supplementary power station in the world, was connected to grid for power generation. This hydropower station was perfectly integrated with a 320 MW photovoltaic power plant.

3.2.3. Nuclear power

In recent years, China has accelerated its nuclear power construction ranking the first in the world for t its nuclear power capacity under construction. In 2014, the total nuclear power capacity reached 20290 MW [2,8] and the total power generation amount reached 1262×10^8 kWh (0.29×10^8 toe) [2,8], an increase of 1.6 times from 2004. At present, there are 26 nuclear power units under construction in China, with an installed capacity of 28500 MW. In February 2015, No.2 Unit in Fangjiashan, No.2 Unit in Yangjiang, No.3 Unit in Ningde, and No.3 Unit in Hongyanhe began to generate power by connecting to grid, and 23 nuclear power generating units were put into operation, with a total installed capacity of 21386 MW.

4. Forecasts of energy development in the world and China

According to the general development trend, the world energy industry is undergoing a transition from oil and gas to new energy, and will enter a new era in which oil, gas, coal and new energy each account for a quarter of global energy consumption. The following predictions were made. First, development of oil industry has already been in a stable period. Second, that of natural gas industry will enter the heyday period. Third, that of coal industry will enter a transitional period. Fourth, that of new energy will gradually get into the golden age. The unique characteristics of energy resource production and consumption in China determine that its resource development should be based on domestic and multiple sources for safety and environmental protection in the development process.

4.1. The steady period of oil

4.1.1. The world annual oil production peak will be around 2040

By virtue of innovations in theories, techniques and methods, the “peak theory” suggested by Hubbert in 1956 has been subverted. The peak of oil production in the world is increasing and the time for peak keeps extending, probably into the mid-21st century. The life cycle of world oil industry is likely to be more than 300 years. Since 1986, the world oil production has shown a general steady growth. The forecast that allows for multiple factors shows that the peak of oil production will be around 2040 at about 45×10^8 t (Fig. 2).

With the development of oil industry, the exploration of conventional oil in the world expands towards deepwater, deep layers and the Arctic region. From 2000 to 2012, the new proven crude oil reserves around the globe reached 698×10^8 t [3]. The new deepwater reserves accounted for 28%, mainly in Brazil, Australia, West Africa, and the Gulf of Mexico. The new reserves in deep layers accounted for 16%, mainly in the Middle East and Central Asia. In the Arctic region, 423 oil and gas fields have been found, with proven reserves of 380×10^8 toe, and the reserves to be discovered are measured 564×10^8 toe [3]. Moreover, concept innovations and technological breakthroughs drive the oil industry to shift their exploration focus from conventional to unconventional energy. In the United States, based on the

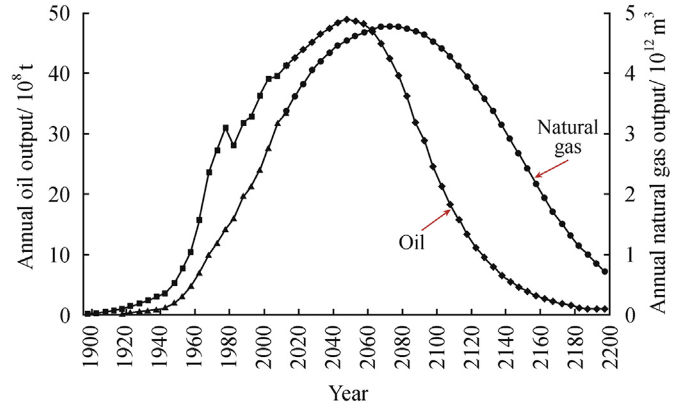

Fig. 2. Forecast of global oil and gas production growth trend.

theoretical technology and development experience in shale gas, tight oil has been developed and utilized on a large-scale basis. Tight oil production in 2014 was 2.09×10^8 t, accounting for 36% of the total oil production, decreasing the United States' dependence on foreign oil from 60% in 2005 to 26% in 2014 and offering the prospect of self-sufficiency by relying on itself [11]. According to the forecast of International Energy Agency (EIA) in 2013, the technically recoverable tight oil resources in 42 countries would amount to 449×10^8 t and unconventional oil and gas was expected to become a new area for future oil development.

On the whole, the global oil reserves are abundant, with a reserves−production ratio over 50, and especially in Central and Latin Americas and the Middle East (with the reserves−production ratios up to 120 and 78), showing a great development potential. Global oil production continues to grow steadily and the average growth rate in the past 10 years was 8.1%. Oil development has entered a “steady time” (Fig. 3).

4.1.2. The bottom line of annual oil production is 2×10^8 t

Compared with traditional resources s, oil production in China requires higher costs. As the global oil and gas supply is in a transitional period, the low crude oil prices exert a huge impact on China's oil production. In 2014, China's dependence on foreign oil was 59%. A substantial cut in production would significantly increase the dependence on foreign oil and raise national oil security risks. Thus, domestic oil production should allow for various factors and 2×10^8 t of annual oil production should be kept as “the bottom line”.

Unconventional oil resources will play an important role in oil production in China, especially tight oil. Great breakthroughs have been made in the exploration and development of tight oil in key basins. By far, 9 tight oil producing areas (including 3 areas with capacity of 10×10^8 t and 6 areas with capacity of 1×10^8 t) have been established. Moreover, 8 pilot tight oil development areas (e.g. Ordos Basin, Songliao Basin and Junggar Basin) have been set up, with designed annual output over 100×10^4 t. Till the mid-21st century, unconventional oil production represented by tight oil is expected to be about a quarter of the total oil production in China.

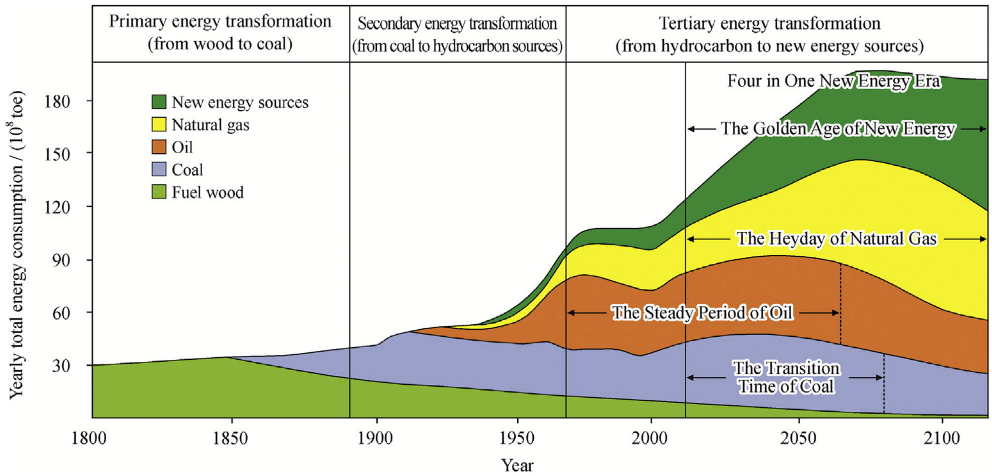

Fig. 3. Trends and forecasts of global energy consumption.

4.2. The heyday of natural gas

4.2.1. The world annual production peak of natural gas will be around 2060

As the cleanest fossil fuel, natural gas has entered a stage of rapid development and becomes a bridge of transition from fossil energy to new energy. It will play a pivotal role in the global sustainable energy development in the future. Natural gas is a practical, cheap, clean and green "3A energy" (available, affordable, and acceptable). Over the past 50 years, its share in the global primary energy mix has risen from 15.6% to 23.7%, proving to be the fossil fuel that grows fast in the world energy mix. According to the analysis of US Geological Survey (USGS), EIA, and CEDIGAZ, the global remaining recoverable resources of conventional gas and three types of unconventional gas (i.e. tight gas, shale gas and coal-bed methane) are over 800×10^{12} m^3 and will be exploited for about 250 years under the current production capacity.

Breakthroughs in unconventional natural gas are expected to drive the global gas production to substantially increase and extend the life cycle of the gas industry. Since the 1970s, tight sand gas, coal-bed methane and shale gas in the United States have developed rapidly to compensate for the decrease e of conventional natural gas production. Especially, the recent rapid development of shale gas has boosted a new record in gas production in the United States, making it the largest gas-producing country again, with the prospect to become a net gas exporter by 2017. This development is changing the energy supply pattern in the world.

In general, natural gas is huge in both resources and reserves. It will play a more important role in the energy mix. This most realistic and accessible clean energy can satisfy the market demand in the world for a long time. There are ample natural gas reserves in the world. By the end of 2014, the reserves−production ratio was 54.1. With a rapid growth of reserves and production, "a heyday period" of natural gas is about to come (Fig. 3). Transnational gas pipeline network and LNG facilities will be completed to adapt to long-distance transportation of natural gas, and the foundation for rapid growth of natural gas has been laid. The global gas production peak is expected to appear around 2060, with the peak production of about 4.5×10^{12} m^3 (or 40.5×10^8 toe) (Fig. 2).

4.2.2. China should accelerate the development and utilization of unconventional gas resources

A serious supply−demand imbalance has appeared as the natural gas industry in China just entered a rapid development period. To speed up the development and utilization of tight gas, shale gas and other unconventional gas resources becomes an inevitable choice. According to the estimates of National Energy Administration, the national demand for natural gas in 2020 will be 3700×10^8 m^3. In order to control excessive dependence on foreign gas supply, the domestic production of natural gas will have to reach 2300×10^8 m^3. To accomplish the natural gas production target in 2020, the Sichuan Basin, Ordos Basin, Tarim Basin, and the South China Sea should be treated as key areas to produce conventional gas. Key problems in science and technology should be tackled to strengthen exploration in low-grade sites in the western regions, deep layers in the eastern regions, and deep waters. Exploration and development activities should be intensified so as to make big breakthroughs and discoveries. Eight large natural gas production bases with annual production over 100×10^8 m^3 should be built to achieve the goal of conventional gas (including tight gas) production at about 1850×10^8 m^3 by 2020.

More supports should be given to the exploration and development of unconventional gas in order to motivate oil and gas companies to develop unconventional gas such as tight gas and shale gas. Financial subsidy should be implemented effectively for the development of low-grade tight gas. More studies should be conducted on the evaluation of shale gas sweet spots, shale gas drilling/completion and stimulation at reservoirs below 3500 m, and optimization of "factory" development of shale gas. The purpose is to drive and achieve rapid growth of shale gas production by making breakthroughs in key engineering technologies.

4.3. The transitional time of coal

4.3.1. Clean utilization of coal is the trend

The share of coal in the world primary energy mix will be further reduced and clean utilization of coal is the trend. In 2014, the world coal production was 81.65×10^8 t [2], 0.7% down over the previous year, and the world coal consumption increased by 0.4%, lower than the average level of 2.9% over the past 10 years. The share of coal in the world primary energy consumption dropped to 30.0%. Coal productions and consumptions in North America, Europe and Eurasia are all declining [12].

As the cheapest fossil fuel, coal will continue to play an important role in the world energy mix. With the increased demand for ecological and environmental protection, efficient and clean utilization of coal will be the trend (Fig. 3). Coal is mainly used for power generation, which will consume more than half of the global coal resources. Efficient and clean use of coal for power generation is expected. Now, coal-fired power generation with large capacity and high parameters, power generation with large-scale circulating fluidized bed, and integrated gasification combined cycle power generation can increase the thermal efficiency of coal generator units to be around 50%.

4.3.2. Efficient and clean use of coal is critical for solving environmental issues in China

The primary energy consumption mix in which coal is dominant will not be fundamentally changed in the short term in China. Accordingly, it is necessary to reduce direct combustion of bulk coal and strengthen the efficient and clean use of coal for purpose of environmental protection. With the progress of industrialization and the improvement in people's living standards, the demand for electricity grows quickly. Due to the limitations of the energy resource structure and distribution, coal is considered to be the main energy for power generation. In 2013, coal consumption in power generation and heating across the nation reached 20.6×10^8 t, accounting for 55.7% of total coal consumption. The primary energy consumption mix in which coal is dominant will not be fundamentally changed in the short term in China. Electricity sector is the major consumer of coal. Accordingly, efficient and clean use of coal for power generation is a principal part in low-carbon utilization of coal. To achieve low-carbon and clean use of coal, it is necessary to upgrade the existing units based on the local and factory conditions and to address the high consumption and excessive emissions of pollutants caused by long service time, aging of units, and backward design and manufacturing technologies.

Coal as end-use energy will result in low energy efficiency and serious environmental pollution. The emissions of sulfur dioxide, nitrogen oxide, and fine particulate matters from coal combustion account for 80%, 60% and 70% of the national total emissions, respectively. The emissions of sulfur dioxide and smoke resulting from direct burning of coal per 1 kg are 4 and 8 times higher than the emissions of coal used for power generation. Direct combustion of bulk coal leads to the most serious pollutions. In 2013, for example, the consumption of bulk coal directly burnt was about 9×10^8 t, accounting for 24% of the total coal consumption, which produced sulfur dioxide in an amount roughly equal to the combustion of 20×10^8 t of thermal coal, and emitted fine particles almost three times that from thermal coal. Inefficient direct combustion of coal can be reduced by (1) accelerating the elimination of backward production capacity in small iron and steel and cement industries in the country, namely, achieving industrial upgrading, and (2) speeding up the urbanization, materializing central heating and gas supply in rural and urban areas, and actively developing small renewable energy networks to achieve green development of urban and rural areas.

4.4. The golden age of new energy

4.4.1. “New energy revolution” may come earlier than expected

New energy is meaningful in achieving low-carbon development. The accelerated development and utilization of new energy has triggered the global energy to grow further. According to IEA statistics, the proportion of new energy such as nuclear energy, hydropower and renewable energy in the primary energy consumption mix reached 14.33% in 2014. With technological advancement, the costs for the development and utilization of new energy continue to decline, making new energy be highly competitive with fossil energy. According to Bloomberg New Energy Finance (BNEF), in the second quarter of 2015, the cost was USD0.083/kWh for onshore wind power, USD0.122/kWh for solar photovoltaic power, and USD0.066−0.105/kWh for coal power. Renewable energy resources (including hydropower) have become the main forces in global new energy development and they are developing more quickly. In 2013, the power generation capacity of renewable energy exceeded that of natural gas to become the second largest source of global electricity generation, accounting for 22% of the total power generation amount and reaching 5130 TWh. In 2014, renewable energy contributed 58.5% of the global generating capacity growth, 27.7% of the global power installed capacity, and 22.8% of power generation. The development of new energy is gradually entering into the Golden Age (Fig. 3).

New energy has become a common subject in researches. The “new energy revolution” may come earlier than expected. Especially, the reduced costs of power generation with new energy and breakthroughs in battery energy storage technology will strongly promote the coming of “a new energy era”. At its 125th anniversary, *Science* published the top 125 challenging issues, including alternatives to oil and nuclear fusion. In 2015, McKinsey proposed *Outlook on 2025: 12 Disruptive Technologies: Advances that Will Transform Life, Business, and the Global Economy*, in which renewable energy and energy storage technologies were considered to be the two important disruptive technologies. On December 12, 2015, the 21st UN Conference on Climate Change adopted the “Paris Convention” which urges to control the increase of global average temperature above the pre-industrial levels within 2 °C and to achieve zero net greenhouse gas emissions in the second half of the 21st century. These goals put forward higher requirements for the development of new energy. The network big data system based on artificial intelligence will play an important role in the optimized configuration of the energy structure. To promote the construction of intelligent Internet + energy network through the development of distributed grid structure will fundamentally solve the existing grids' absorption of power generation from new energy and further enhance the development and utilization efficiency of renewable energy, thereby finally allowing humans to get rid of dependence on fossil fuels.

Nanotechnology emerges as a kind of new material. The application of nano meta-materials will accelerate the development of new energy technologies. The excellent performance of graphene will surely make it the second “black gold” after oil in the history of energy development. According to preliminary forecasts, by 2030, the technological advancement of nano materials will make the cost of solar power generation further reduce by 40%, proving solar energy a cheap source of energy. In addition, nanotechnology has accelerated breakthroughs in battery energy storage. Currently, the lithium-ion battery used in Tesla electric vehicles in the United States can endure for 400 km. BYD, a Chinese company, has successfully developed a battery life of 400 km in new energy cars. At the climate conference in Paris, Germany proposed the goal to fully ban gasoline and diesel cars by 2050. Important progress has been made in the study of battery materials based on grapheme and other meta-materials recently. If they can be used for mass production of batteries that can be charged quickly and have a long service and good durability, the new energy era will come sooner.

4.4.2. China should be fully prepared for the “new energy era”

Strengthening the development of renewable energy, hydropower and other new energy resources is the key to achieve low-carbon energy development. According to the *United Nations Framework Convention on Climate Change*, the Chinese government promised to control carbon dioxide emissions to be below 100×10^8 t/a during 2016−2020, and increase the proportion of non-fossil energy in the primary energy consumption mix to 20% by 2030 when the carbon dioxide emissions will have reached a peak. In 2014, non-fossil energy accounted for only 10.9% in the primary energy consumption mix in China. The 20% goal may bring both challenges and opportunities.

Potential for renewable energy development is huge in China. It is expected that, by 2020, the national wind power generation capacity will reach 4500×10^8 kWh, accounting for 5.3% of the total generation capacity, and the number is expected to exceed 10% in 2030; the national solar power generation capacity will exceed 1×10^8 kW and is expected to surpass that of the United States in 2030; the national hydropower installed capacity will reach 3.6×10^8 kW and even 4.5×10^8−5.0×10^8 kW in 2030. The conflict between rapidly increasing installed capacity of renewable energy for power generation and the inadequate grid capacity is a bottleneck that restricts development. The absorption of renewable energy in grids can be increased by optimizing and adjusting the grid structure and developing the portfolio of energy storage technology and multi-energy grid technology. The electricity storage technology is decisive to whether new energy can revolutionarily replace traditional fossil energy.

Furthermore, China will develop nuclear power moderately and orderly by adopting advanced and mature technologies on a safe basis. At present, there are 26 nuclear power units under construction around the country and the installed nuclear power capacity is expected to reach 5800×10^4 kW by 2020. At all events, safety is always the top priority in the development of nuclear power. This sector should be developed healthily and orderly within the overall strategic energy framework of China, with consideration to such factors as geography, energy demand, and technological level.

5. Conclusions and discussions

Following the transformation from wood to coal then to oil & gas, the future will see the third major transformation from oil & gas to new energy. The advances in social civilization and science and technology drive the efficient development of unconventional oil and gas resources and increasing the proportion of new energy consumption. Sooner or later, oil, gas, coal and new energy sources will each account for a quarter of global energy consumption in the new era. Although the fossil energy is still plenty in the world, great breakthroughs made in some key technologies and the increasing demand for ecological environmental protection both impel the third transformation. The following forecasting results were achieved. First, the development of oil industry has been in a stable period and its annual production peak will be around 2040. Second, the development of natural gas industry will enter its heyday and its annual production peak will be around 2060, which will play a pivotal role in the future energy sustainable development. Third, the development of coal industry has entered a high-carbon to low-carbon transitional period, and its direct use and the discharged pollutants will be significantly reduced. In 2050, coal will be dropped to 25% of the primary energy mix. Fourth, the development and utilization of new energy resources have been getting into the golden age. The strong development of new energy technology will promote the coming of a “new energy era”, and “new energy revolution” may come earlier than expected.

The energy production and consumption in China has its own characteristics. Accordingly, efficient and clean use of coal is essential for energy development and for solving environmental issues. China should keep 2×10^8 t of annual oil production as “the bottom line”. China should accelerate the development of unconventional resources such as tight gas and shale gas to achieve the goal − realizing gas production of more than 3000×10^8 m^3 by 2030, of which unconventional gas will account for about 60%. China should strengthen the development and utilization of new energy, with non-fossil energy accounting for 20% of the primary energy consumption mix by 2030. Battery energy storage technology shows good prospects. If it can be used for mass production of batteries that can be charged quickly and have a long service and good durability, the new energy era will come sooner. China should make strategic preparations for the coming of the "new energy era".

In addition, affected by the pace of technological innovation, political structure, economic growth rate and fluctuations in the prices of oil and gas, the energy revolution process may be prone to many uncertainties and the forecasts about production peaks of oil, gas and coal are subject to changes.

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