“十二五”江苏省高等学校重点教材

Renewable and Advanced Power Generation Technologies

新能源和高新发电技术

Jiufa CHEN Changdong SHENG
陈九法 盛昌栋

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Preface

This book provides a solid, quantitative and up-to-dated coverage for a wide range of sustainable low carbon electricity generation technologies. Three types of technologies are presented, renewable energy, advanced technologies, and clean coal, tackling the problems of pollution, energy shortage and climate change.

Eleven chapters are constructed, with Chapter 1, 5, 7 and 11 contributed by Dr Changdong Sheng, with Chapter 2, 3, 4, 6, 8, 9 and 10 contributed by Dr Jiufa Chen. Chapter 1 introduces electricity generation related energy and environment issues. Although renewable energy is crucial and promising, clean coal technologies still have indispensable importance to achieve sustainable energy supply in the coming decades. Since solar energy is the dominant renewable, Chapter 2 presents solar energy fundamentals: its formation, trajectory, atmospheric attenuation and solar energy distribution. Chapter 3 introduces solar PV technology, wafer or thin film based, from materials (silicon, metal compounds or organic materials) to PV cell, module and power plants. Chapter 4 dedicates to concentrating solar thermal power technologies, with solar heat receivers made of parabolic troughs, Fresnel reflectors, tower collectors, or dish collectors; using various types of heat transfer fluids and heat storage systems; elaborated hybridization and operation strategies. Chapter 5 is about hydropower, with three topologies of hydropower plants introduced, impoundment, run-off-river, and pumped storage, with different turbine technologies. Chapter 6 deals with wind energy, wind distribution, wind energy capture system, turbine control strategies, onshore and offshore wind farms. Chapter 7 is about biomass, from various biomass resources to their utilization technologies, including energy recovery from municipal wastes. Chapter 8 tells about geothermal energy, its formation, distribution, resource survey, elaborated with three types of geothermal power plant technologies based on dry steam, flash steam and binary cycle. Chapter 9 presents advanced fuel cell electricity generation technologies, from five type fuel cell configurations to fuel cell stack and power generation system. Chapter 10 presents clean and high efficiency coal electricity generation technologies, from reducing pollution and emission to improving efficiency, from retrofiting existing coal plants, to constructing advance systems, such as supercritical and ultra-supercritical conditions, pressurized fluidized bed combustion, and integrated gasification combined cycle. Chapter 11 focuses on technologies for reducing greenhouse gas emission from fossil fuel power plants, CO_2 capture, storage and utilization.

For each topic, the theoretical background is introduced, practical engineering considerations associated with designing systems and predicting their performance are provided, and methods to evaluate the economics of these systems are presented. The book is intended for a mixed audience of engineering and other technology-focused individuals, undergraduate, postgraduate students. The book has been designed to encourage self-teaching by providing completely worked case studies, typical parameter values and design guidance. Each chapter ends with a set of exercises that provide added practice for the student, which should also facilitate the preparation of homework assignments by the instructor.

The authors wish to express their thanks to School of Energy and Environment of Southeast University for the publication funds. Appreciations are given to Nari Group Corporation and to Trina Solar China for sharing the PV technology data. The authors also wish to thank Miss Nan Wang and Mr Kunming Zhuang for their assistance in editing Chapter 2, 3, 4, 6, 8, 9 and 10.

Contents

Chapter 1 Energy and Environment

1.1 Sustainable Development and Mitigation of Climate Change

1.1.1 Sustainable Development

Sustainability is the capacity to endure. The word "sustainability" is derived from the Latin *sustinere* (*tenere*, to hold; *sus*, up). Dictionaries provide more than ten meanings for *sustain*, the main ones being to "maintain", "support", or "endure". Accordingly, "sustainable" generally means "maintainable" and "supportable". However, since the 1980s *sustainability* has been used more in the sense of human sustainability on planet Earth and this has resulted in **the most widely quoted definition of sustainability as a part of the concept "*sustainable development*"**, that of the Brundtland Commission of the United Nations on March 20, 1987:

"sustainable development is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

In essence, "*sustainable development* is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations."

At the 2005 World Summit, it was noted that sustainable development requires the reconciliation of *environmental*, *social equity and economic demands*—the "three pillars" or "triple bottom lines of sustainability"—which have served as a common ground for numerous sustainability standards and certification systems in recent years. Definitely, all three dimensions are equally important for sustainable development. It means that sustainable development of any human activity achieves a continuing and adaptive process of trade-offs between ecological, economic and social objectives including, the least but not the last,

- **Enhancing economic benefits**: economy growth, globalization, national security, resource ownership, balance of trade, etc.;
- **Environmental managements**: strict emission conditions, greenhouse effect, Kyoto Protocol, renewable targets, etc.;
- **Social capita benefits**: employment, quality of living, health, regional development, etc.

After it was proposed, sustainable development had been laid as just a concept on the platforms of discussions in academic institutions and international communities. However, with the wide recognition of the threat of global warming and the resulting climate change to the development of human society, sustainable development is now turning to be real global actions.

1.1.2 Climate Change and Greenhouse Gases Emissions

The Earth's global mean climate is determined by incoming energy from the Sun and by the properties of the Earth and its atmosphere, namely the reflection, absorption and emission of energy within the atmosphere and at the surface. Although changes in received solar energy (e.g., caused by variations in the Earth's orbit around the Sun) inevitably affect the Earth's energy budget, the properties of the atmosphere and surface are also important and these may be affected by climate feedbacks. Observed changes have occurred in several aspects of the atmosphere and surface that alter the global energy budget of the Earth and can therefore potentially cause the climate to change. Among these are the increases in greenhouse gas (GHG) concentrations in the atmosphere that act primarily to increase the atmospheric absorption of outgoing radiation, resulting the increase of global average air and ocean temperatures, i.e., *global warming*.

"*Warming of the climate system is unequivocal*, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." (see Fig 1.01). Moreover, heaps of observations and new findings around the world provide plenty of evidences for global warming and climate change.

The dominant factor in the radiative forcing of climate in the industrial era is the increasing concentration of various anthropogenic (man-made) GHGs in the atmosphere. As defined by Kyoto Protocol, the main GHGs include:

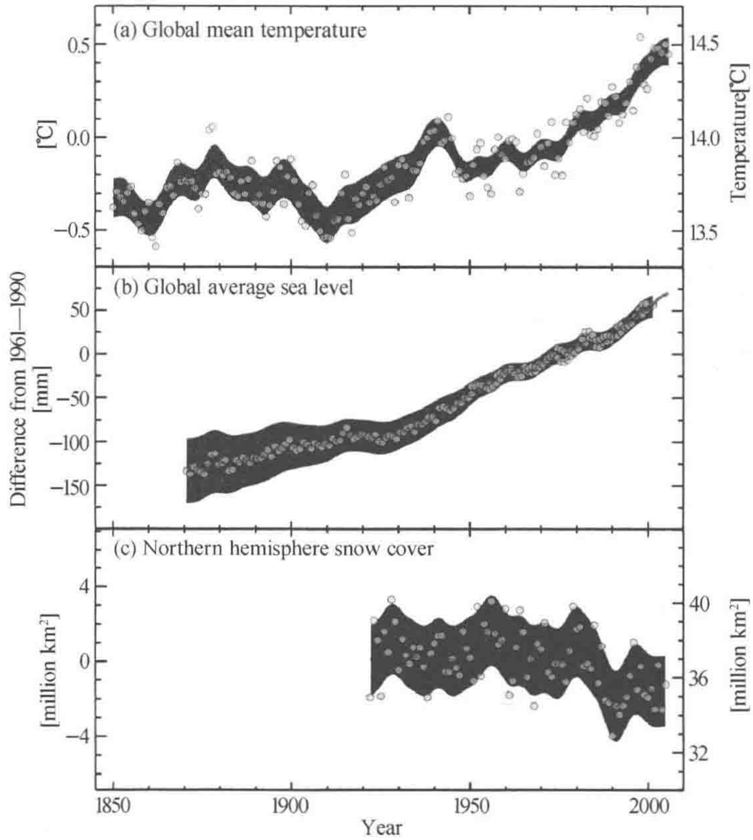


Fig 1.01 Observed changes: (a) global average surface temperature, (b) global average sea level from tide gauge and satellite data and (c) Northern Hemisphere snow cover for March-April.

- Carbon dioxide (CO_2);
- Methane (CH_4);
- Nitrous oxide (N_2O);
- Hydrofluorocarbons (HFCs);
- Perfluorocarbons (PFCs);
- Sulfur hexafluoride (SF6);
- Nitrogen trifluoride (NF3).

Among them, CO_2 is the most important one. The global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280 ppm to 387 ppm in 2009, 389.8 ppm in 2010 and 397.7 in 2014, exceeding by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores (see Fig 1.02). Recently, the annual growth rate of CO_2 concentration is larger (average: 1.9 ppm per year during 1995—2005) than it has been since the beginning of continuous direct atmospheric measurements (1960—2005 average: 1.4 ppm per year) although there is year-to-year variability in growth rates.

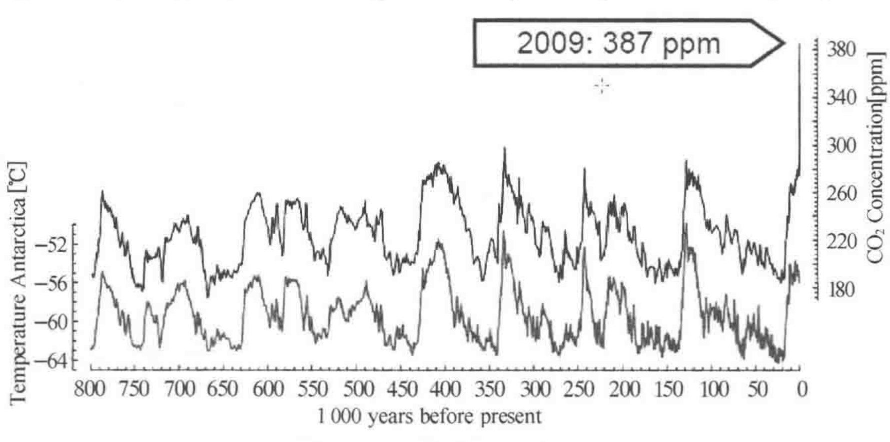
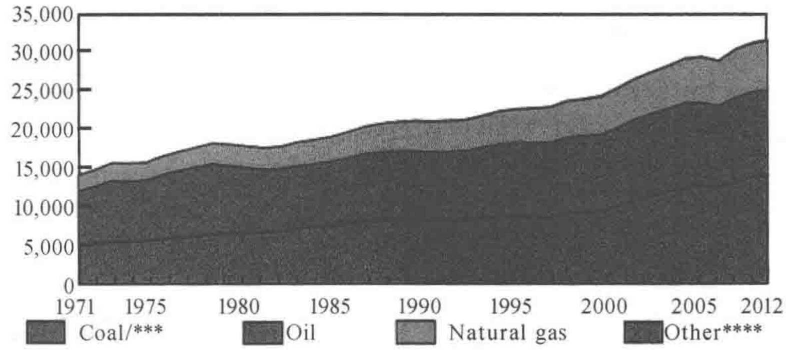
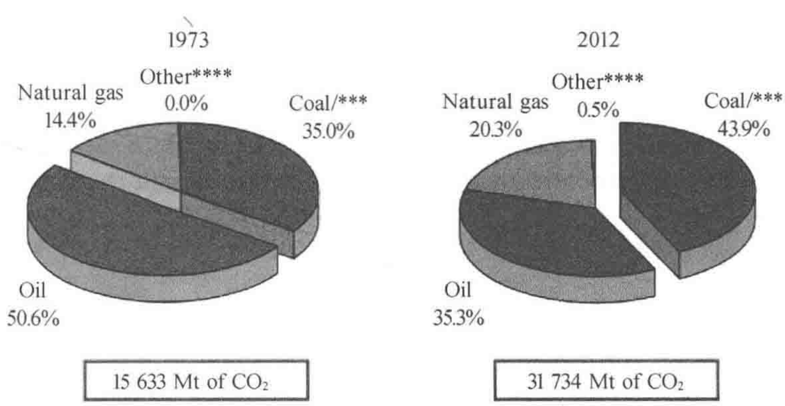


Fig 1.02 CO_2 concentration in the atmosphere

The primary source of the increased atmospheric concentration of CO_2 since the pre-industrial period results from fossil fuel (mainly coal, oil and natural gas) uses, with land-use change providing another significant but smaller contribution. In recent decades, the emissions of the man-made CO_2 have been continuing to increase. While CO_2 emissions associated with land-use change are estimated to be 5.9 Gt CO_2 per year over the 1990s, global annual fossil CO_2 emissions increased from 15.6 Gt CO_2/year in 1973 to 29.0 Gt CO_2/year in 2009, and energy-related CO_2 emissions to 31.7 Gt in 2012 (see Fig 1.03).



(a) CO_2 emissions from 1971 to 2012 by fuels [Mt of CO_2]



(b) 1973 and 2012 fuel shares of CO_2 emissions

Fig 1.03 World CO_2 emissions by fuel (Mt of CO_2). *** Other includes industrial waste and non-renewable municipal waste.

Greatly reducing man-made CO_2 emissions is central to meeting the challenge of global warming to sustainable development. Intergovernmental Panel on Climate Change (IPCC) estimates that CO_2 emissions must be reduced 50% ~ 85% by 2050 compared to 2000 levels. That reduction will keep the global mean temperature rise below 2.0℃, where severe impacts begin. To achieve this goal, an agreement called Paris Agreement was drawn on 12 Dec 2015 by the Parties to the United Nations (UN) Framework Convention on Climate Change on UN Climate Change Conference 2015. It stated that "holding the increase in the global average temperature to well below 2℃ above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5℃ above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."

To cope with global warming and climate change, first of all, we need *mitigation of GHG emissions*. Moreover, the emission reduction needs to start right now. Even if we start the actions on mitigation of CO_2 emissions now, it is still not sufficient to stop global warming. So, on the other hand, we also need *adaptation to global warming*. Namely, the step needs to be taken to adjust to the inevitability of climate changes.

There is a broad international acceptance that stabilizing the atmospheric concentration of greenhouse gases at below 450 parts per million (ppm) of carbon-dioxide equivalent (CO_2-eq) is consistent with a near 50% chance of achieving the 2 ℃ target, and that this would help avoid the worst impacts of climate change. Fig 1.04 demonstrates that, without further action, by 2017 all CO_2 emissions permitted in the 450 Scenario will be "locked-in" by existing power plants, factories, buildings, etc. This calls the immediate global actions to mitigate CO_2 emissions while any delay of the actions is unacceptable.

To achieve the 450 ppm goal, the scale of the required reduction in CO_2 emissions is enormous. Human activity globally currently releases about 30 $GtCO_2$ per year into the atmosphere (Figure 1.04). Cutting this in half or more would bring emissions down to 14 $GtCO_2$ or below by 2050. This is a reduction of at least 48 $GtCO_2$ below the 62 $GtCO_2$ projected for 2050 under current trends. Cumulatively, at least about 600 $GtCO_2$ will have to be cut over the entire period from now.

As described above, man-made CO_2 mainly results from utilizing fossil fuels. Therefore, using renewable energy to replace fossil fuels can directly reduce CO_2 emissions. However, it is well-known that fossil fuels are being fundamental energy for human development and they will stay in the center of energy utilization at least in the foreseeable future. It determines that we also have to use fossil fuels in sustainable ways. Considering that the reduction of CO_2 emissions for keeping the increase in global temperature below 2 ℃ is huge, while any individual option for GHG reduction is impossible to achieve this heavy task at all, the only way for mitigating global warming is to establish the system of sustainable energy.

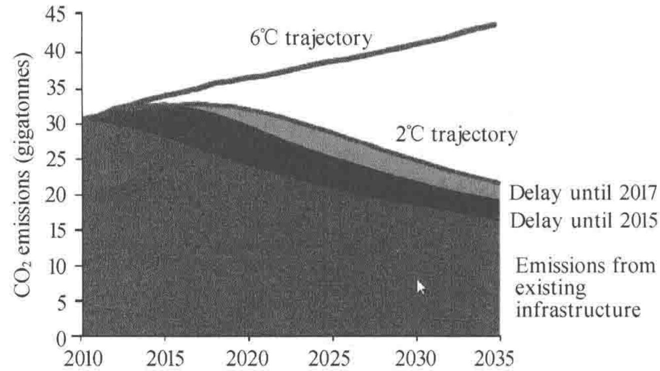


Fig 1.04 To keep the increase in global temperature below 2 ℃ requires immediate global action for mitigating CO_2 emission

1.2 Sustainable Energy

1.2.1 Sustainable Energy

Sustainable energy refers to the sustainable provision of energy that meets the needs of the present without compromising the ability of future generations to meet their needs for energy. Under this definition, sustainable energy embraces a number of practices, policies and technologies which seek to provide us with energy we need at the least financial, environmental and social costs. It can be divided into two major groupings:

1) Energy efficiency;

2) Renewable energy.

They are said to be the twin pillars of sustainable energy future. Energy efficiency means using energy as efficiently as possible. Moving towards energy sustainability will require changes not only in the way energy is supplied, but in the way it is used, and reducing the amount of energy required to deliver various goods or services is essential. Opportunities for the improvement on the demand side of the energy equation are as rich and diverse as those on the supply side, and often offer significant economic and environmental benefits. Renewable energy technologies are essential contributors to sustainable energy as they generally contribute to world energy security, reducing dependence on fossil fuel energy, and providing opportunities for mitigating GHGs. Because of the fact that fossil fuels is most likely to remain as important sources of the world's energy for several decades to come, sustainable energy also embraces sustainable utilization of fossil fuels but with avoiding significant CO_2 emissions.

Electricity is one of the most important energy carriers for supporting modern economic and social development. It can be generated from both conventional fossil fuels and new/renewable energy sources. Therefore, utilizing fossil energy with high efficiency and exploiting renewable energy sources are also applicable for electricity generation. Indeed, sustainable energy is virtually the drive force for developing and utilizing new/renewable energy sources and developing and deploying advanced electricity generation technologies with high efficiency.

1.2.2 World Energy Trends

According to the projection of International Energy Agency(IEA) , the world energy demand expands by 35% between 2010 and 2035—an average rate of an increase of ~1.5% per year. Oil remains the leading fuel though natural gas demand rises the most in absolute terms (Fig 1.05). Over the past decade, coal accounted for nearly half of the increase in global energy use, with the bulk of the growth coming from the power sector in emerging economies like China, India, and Indonesia (Fig 1.06). However, driven by the requirements of sustainable development and particularly CO_2 emission reduction, the share of fossil fuels in global primary energy consumption falls slightly from 81% in 2010 to 75% in 2035 (Fig 1.05). In 450 Scenario, the share of fossil fuels in the global energy mix even falls further to 62% in 2035.

It is expected that global demands for both coal and oil will peak before 2020, and then decline by 30% and 8% respectively by 2035, relative to their 2009 levels. In contrast, natural gas demand will grow by 26%, though it plateaus by around 2030. Natural gas is the only fossil fuel to increase its share in the global energy mix over the period to 2035. Renewable energy and natural gas collectively are projected to overtake coal and oil to meet almost two-thirds of the incremental energy demand in 2010—2035 (Fig 1.07).

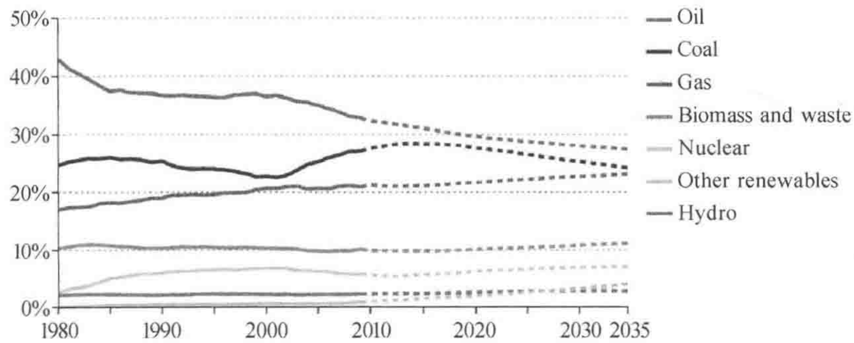


Fig 1.05 Shares of energy sources in world primary energy demand between 1980 and 2035

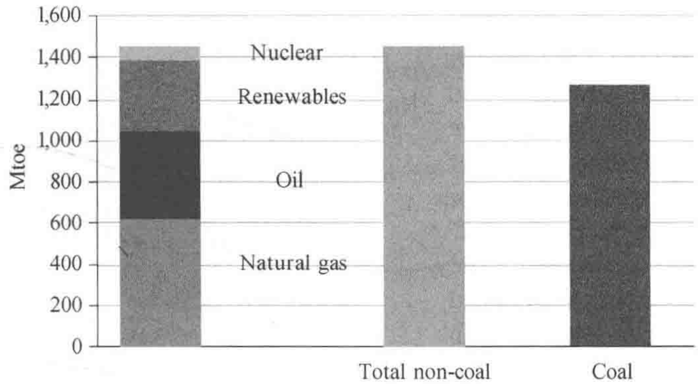


Fig 1.06 Growth in global energy demand between 2000 and 2010

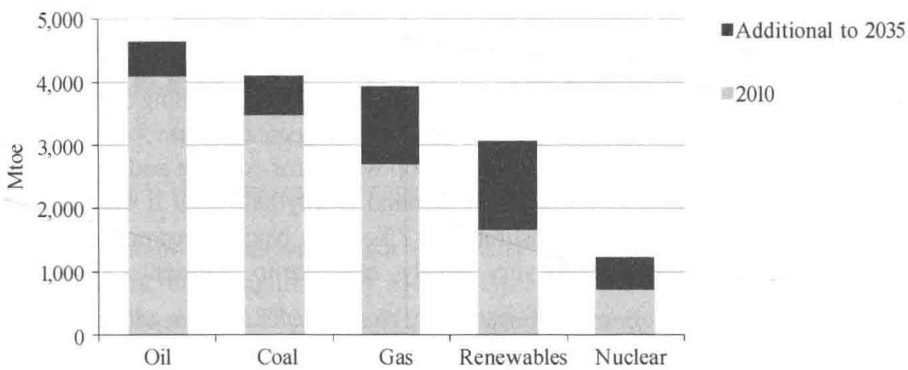


Fig 1.07 World primary energy demand for major primary energy sources

Locating in the center of energy production and consumption, electricity generation also undergoes continuous growth. In the sustainable development regime, more renewable energy is used to replace conventional fossil fuels for electricity generation. According to the estimation of IEA World Energy Outlook (2011), renewable energy, led by hydropower and wind, accounts for half of the new capacity installed worldwide to meet growing demand through to 2035 (Fig 1.08). The parts of renewables taking in the growths of global energy demands (Fig 1.07) and electricity generation (Fig 1.08) all demonstrate the significance of the roles renewable energy plays in the future energy production.

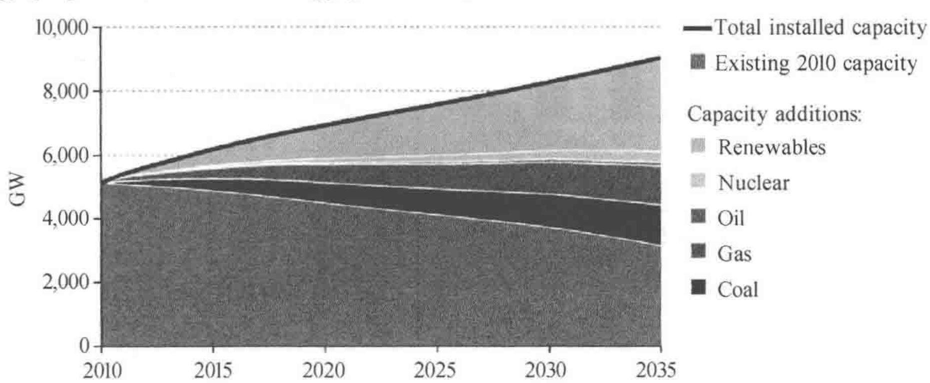


Fig 1.08 Global installed capacity of electricity generation and its additions by various technologies between 2010 and 2035

1.2.3 Energy Trends in China

In less than a generation, China has moved from being a minor and largely self-sufficient energy consumer to becoming the world's fastest-growing energy consumer and a major player on the global energy market. Soaring energy use is both a driver and a consequence of the remarkable growth in the country's economy. For many years, China was able to meet its rapidly growing energy needs entirely from domestic sources, and consequently its impact on global markets was minimal. However, that has changed dramatically in the last decade and the national concern about energy supply security has grown in parallel. In 2009, China overtook the United States to become the world's largest energy user.

Fig 1.09 shows the total energy demand in China in 2008 as an example. It can be seen that coal is the backbone of China's energy system, accounting for over 60% of the country's primary energy needs and providing most of the fuel used by power stations and much of the final energy used by industry, commercial businesses and households. In fact, coal's importance in the overall fuel mix has been growing in recent years, due to the booming demand for electricity, which is almost 80% coal-based. China is both the largest consumer and producer of coal in the world and, until recently, was an important net exporter. In 2009, it was a net importer of coal, as the domestic supply struggled to keep up with the high demand growth and the logistical constraints meant that the imports were often the cheaper option. However, coal net imports totaled only 1% of the demand (nonetheless, volumetrically large by the standards of global steam coal trade).

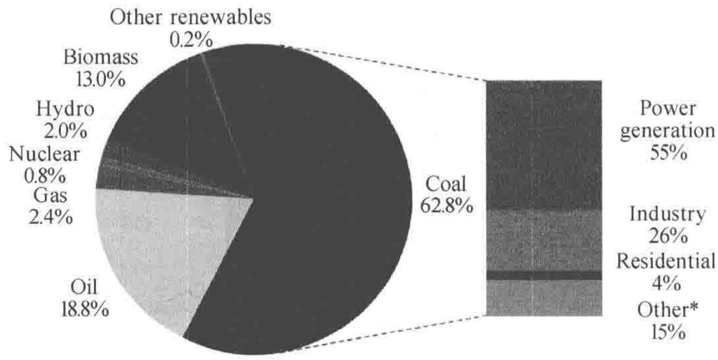


Fig 1.09 Primary energy mix in China (Total energy demand in 2008 was 2 131 Mtoe)

Oil demand has been growing quickly, with its share of the primary demand reaching 19% in 2005. China, which was a net oil exporter in the early 1990s, has become the world's second-largest oil importer. Because of the continued use by so many rural households of fuel wood and crop wastes for cooking and heating, biomass remains an important source of energy. Still, its share of the primary demand is only half what it was two decades ago. Natural gas and the country's many hydropower projects constitute just 2% each. Nuclear power provides less than 1% of the primary energy. Other renewables, while growing very rapidly, continue to represent a small share.

In the global growth in primary energy demand between 2010 and 2035, China alone accounts for more than 30% (Fig 1.10), consolidating its position as the world's largest energy consumer. According to the prediction of IEA World Energy Outlook 2011, in 2035, China consumes nearly 70% more energy than the United States, the second-largest consumer, even though, by then, per-capita energy consumption in China is still less than half the level in the United States. The rapid growth in primary energy demand and particularly the rising fossil-fuel use has worsened already acute local pollution and driven up GHG emissions, casting doubts on the sustainability of China's pattern of development. Therefore, establishing sustainable energy is the priority for both achieving sustainable development and securing energy supply in China. The development and deployment of renewable energy and advanced electricity generation technologies are the key to the sustainable development of our country as well as our energy industries.

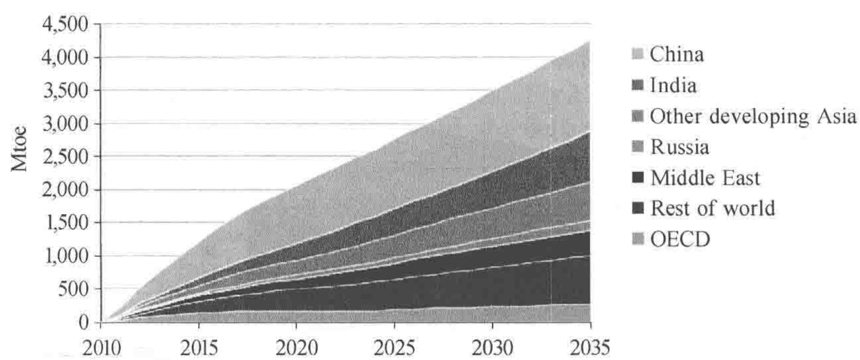


Fig 1.10 Growth in the primary energy demand of countries and regions

Due to the rapid increase in fossil fuel demand, the share of the renewable energy resources in the primary energy mix decreased slightly before 2010. In 2010, the renewables took a part of 8.9% in the primary energy consumption. However, with the strengthening on energy saving and emission reduction as the national priorities, the utilization of renewable energy is encouraged and promoted on all policy levels. It is planed to have the share of renewables in primary energy consumption reaching 11.4% by 2015[11]. Considering the huge quantity of total energy demand and rapid development and utilization of renewable energy in the past decade in China, it is indeed a big step to move towards energy sustainability.

To fuel the fast growth of the economy and meet the demand of increasingly improved quality of living, electricity generation in China rapidly increases particularly after 2004 (Fig 1.11). The installed power generation capacity totaled 1360 GW in 2014, dominated by fossil fuels particularly coal-based generation. For a long time, about 75% of the total installed capacity was based on fossil fuels. However, this share decreased gradually after 2007 and reached 67.3% in 2014 mainly due to the significant increase in the installed capacity of electricity generation from renewable energy sources (mainly hydropower). It was planned that the total installed capacity of electricity generation from renewables will increase by 160 GW from 2011 to 2015, in which hydropower is 61 GW, wind power 70 GW, solar power 20 GW and biomass electricity 7.5 GW. As such, renewables are planned to generate 20% of the total electricity in China by 2015.

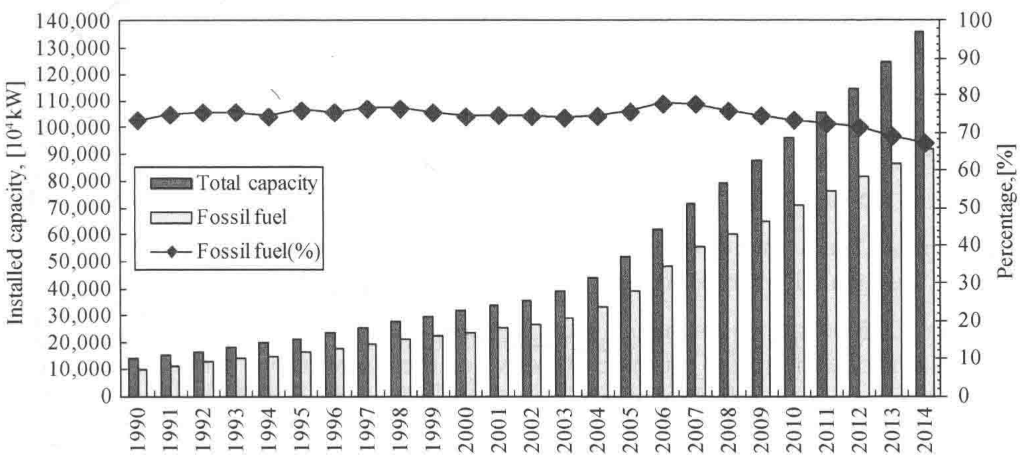


Fig 1.11 Total installed capacity of electricity generation in China

Besides remarkable development of renewables for electricity generation, thermal efficiency of existing fossil fuel-fired power plants also increased significantly in recent years in China. The state-of-the-art pulverized coal-fired power plants with ultra-supercritical steam parameters have achieved the net electricity generation efficiency of more than 45%. As a result, the energy cost for generating unit electricity decreases significantly. Fig 1.12 presents that the average energy cost, expressed as grams of standard coal equivalent required for supplying per kWh electricity, decreased steadily from 370 g/kWh in 2005 to 330 g/kWh in 2014. The increase in electricity generation efficiency not only achieved great energy saving but also substantially reduced CO_2 emissions.

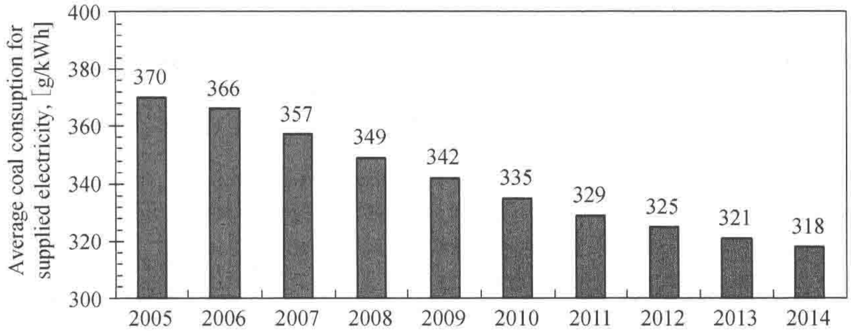


Fig 1.12 The energy cost for electricity supplied from power plants

1.3 Mitigation of CO_2 Emissions

1.3.1 Kyoto Protocol

The first action the international community took to tackle climate change is Kyoto Protocol.

Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change. It was adopted in Kyoto, Japan, on 11 December 1997. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and European Commission (Annex I countries or Parties) for GHG emissions. The main goals of Kyoto Protocol are:

- To cut the emissions of GHGs in Annex I countries by at least 5 percent below 1990 levels in the commitment five-year period from 2008 to 2012;
- To set rules for planting forests to soak up GHGs;
- To set a fund to aid poor nations adapting to climate change.

Kyoto Protocol entered into force on 16 February 2005. 182 Parties of the Convention have ratified the Protocol up to date. China ratified Kyoto Protocol in August 2002.

Kyoto Protocol has been amended in 2012. The Protocol is extended to cover the period of 2012—2020; Annex I countries commit an aggregate reduction of GHG emissions at least 25 to 40 percent below 1990 levels by 2020.

Under the Protocol, 37 Annex I countries must meet their targets primarily through national measures. Nevertheless, the Kyoto Protocol offers them an additional means of meeting their targets by way of three market-based mechanisms:

1) Emissions trading—known as the "carbon market";

2) Joint implementation;

3) Clean development mechanism (CDM).

Under the Convention, China, as a developing country, is not required to commit GHG emissions reduction, but can take part in through CDM to contribute to global GHG emissions reduction.

The purpose of the CDM shall be to assist countries not included in Annex I in achieving sustainable development and in contributing to the ultimate objective of the Convention, and to assist Parties included in Annex I in achieving compliance with their quantified emission limitation and reduction commitments.

Under the CDM, (a) Parties not included in Annex I will benefit from project activities resulting in certified emission reductions, and (b) Parties included in Annex I may use the certified emission reductions accruing from such project activities to contribute to compliance with part of their quantified emission limitation and reduction commitments. Many technical measures can be employed to achieve CDM, in general, including

- Energy saving;
- Energy substitution;
- Renewable energy sources;
- Tree planting and afforestation;
- CO_2 sequestration.

China is expected to account for more than half of all the credits to be generated by CDM projects to 2012. China's big market share means that it sets a *de facto* global price floor for Certified Emission Reductions (CERs, each of which corresponds to one tonne of CO_2). By August 2007, China had 737 CDM projects, which were expected to generate almost 1.2 billion CERs by 2012. Of these projects, 107 had already been registered, accounting for 391 million CERS in 2012.

China's preferred categories of CDM projects are renewable energy, energy efficiency and methane recovery projects. However, the largest share of registered credits, 72%, comes from projects to reduce emissions of hydrofluorocarbon HFC-23 (see Fig 1.13). HFC-23 is a by-product of HCFC-22, which is a potent greenhouse and ozone-depleting gas used largely for refrigeration. China is well placed to provide these credits, because it is a big producer of HCFC-22 and cutting HFC-23 emissions is very cheap in China, at less than $1 per tonne of CO_2 equivalent, or less than a tenth of the value of the CDM credits generated. Projects that reduce N_2O (another powerful greenhouse

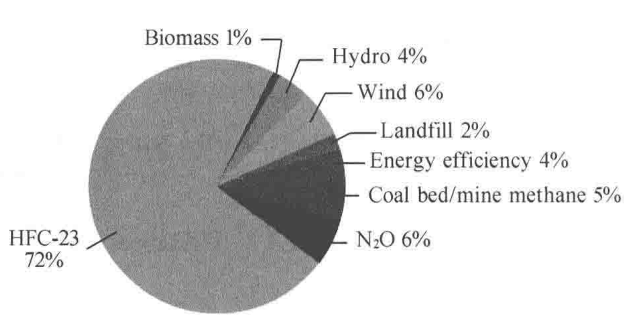


Fig 1.13 China CDM CO_2 reduction by project types registered by 2007

gas), hydropower and the collection of methane from coal mines and coal beds make up about 11% each of total expected 2012 credits, while energy efficiency in industries accounts for almost 10%, wind power for 6% and landfill gas for 3%.

1.3.2 Reduction of Energy-related CO_2 Emissions

As stated in Section 1.2.1, most man-made CO_2 emissions are from fossil fuel utilization. In other words, most CO_2 emissions are energy-related. Energy-related CO_2 emissions continue to form the greatest part of global anthropogenic GHGs emitted in the 450 Scenario, reaching 31.9 Gt CO_2 in 2020, or about 70% of total GHG emissions. Therefore, reduction of CO_2 emissions is the center to achieving energy sustainability.

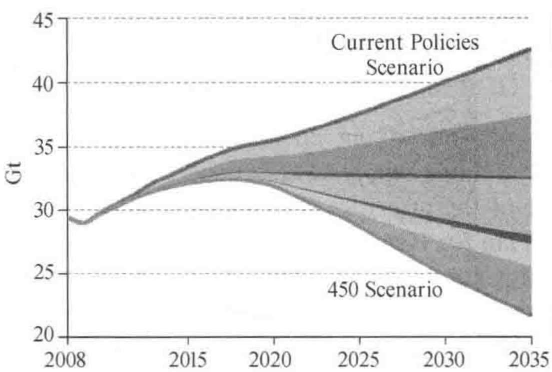
Specified for mitigating energy-related CO_2 emissions, many different technological measures can be applicable, generally including:

- Increasing energy efficiency in all sectors;
- Utilizing renewable energy sources;
- Switching from high-carbon fuels (e. g. coal and oil) to low-carbon fuels (e. g. natural gas) or no-carbon fuels (e. g. nuclear, biomass, solid wastes);
- Implementing CO_2 capture and storage (CCS) associated with fossil fuel utilization.

In order to keep the increase in global temperature below 2 ℃, i. e., to stabilize the concentration of the GHGs in the atmosphere at 450 ppm CO_2-equivalent, as can be seen in Fig 1.14, GHG emissions should be kept at 31.9 Gt in 2020 and decline to 21.7 Gt in 2035, 20.9 Gt or 49% lower than in the Current Policies Scenario. As roughly estimated, 1 Gt CO_2 emissions reduction is equivalent of:

- Building 1,036,000 MW of wind farms;
- Applying CCS to 137 coal-fired power plants, each 1,000 MW;
- Increasing efficiency of the world's 500 million automobiles by 7.3 km/liter;
- Reforestation of 90,000,000 hectares, about 10% of the area of Brazil; or
- Biomass plantations on 48,000,000 hectares, about the area of Spain.

Accordingly, 20.9 Gt CO_2 means a huge quantity of reduction, which is impossible to achieve by any individual measure. It implies that all the above measures are of significant importance for CO_2 abatement.



	Abatement		
	2020	2030	2035
Efficiency	71%	49%	48%
End-use(direct)	34%	24%	24%
End-use(indirect)	33%	23%	23%
Power plants	3%	2%	1%
Renewables	18%	21%	21%
Biofuels	1%	3%	3%
Nuclear	7%	9%	8%
CCS	2%	17%	19%
Total(Gt CO_2)	3.5	15.1	20.9

Fig 1.14 World energy-related CO_2 emission savings by policy measure in the 450 Scenario

The contribution made by different abatement measures to the 450 Scenario may change over time, as cheaper options are exhausted and more expensive options have to be taken up (see Figure 1.14). End-use efficiency accounts for 71% of the 3.5 Gt abated in 2020, vis-ὰ-vis the Current Policies Scenario, but its share declines to 48% by 2035. Over time, the contribution made by energy efficiency is evenly split between abatement achieved through greater efficiency in direct combustion of fossil fuels (e. g. through the increased efficiency of coal combustors) and abatement achieved as a result of lower electricity demand attributable to greater efficiency in end use (e. g. more efficient appliances) which reduces the combustion of fossil fuels in the power generation sector.

Renewables, including biofuels, account for a slightly increasing share of CO_2 savings over time, their share growing from 19% in 2020 to 24% in 2035 (Figure 1.14). Faster deployment of renewables, which reduces their capital costs, and higher electricity prices due to rising prices of CO_2 mean either that renewables become competitive earlier, or that they require a lower level of support per unit of energy. Nonetheless, the