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FEATURE ARTICLE

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Synergistic utilization of coal and other energy – Key to low carbon economy

Abstract In China, coal is a dominant component of energy mix, and it is expected to remain as such over the next 30 to 40 years. Coal is expected to be used even more in power generation. The direct combustion of coal already has been causing severe pollution and ecological degradation, and it is quite difficult to address the need to reduce greenhouse gas (GHG) given the direct combustion of coal. Therefore, the polygeneration system based on coal gasification, which is one of the major examples of synergistic utilization of coal, is proposed. It is a comprehensive solution to meet the energy challenges China is facing. Furthermore, the synergy of fossil fuels (especially coal) with renewable energy, the synergy of different kinds of energy for energy storage, the synergy of centralized and distributed supply of different kinds of energy, and the synergy of different kinds of energy in smart energy grid (power, gas, heat, and water) are the keys to making China a low-carbon economy. Carbon dioxide (CO_2) mitigation in China should begin from the coal-chemical industry given their accumulated relevant experiences. The mitigation process should gradually be transformed into the "IGCC + polygeneration + CCUS". The objectives of this paper are to describe the synergistic utilization of coal, and to analyze the synergy of coal with other energy resources, and to propose the scientific and technological problems to achieve these synergies.

Keywords synergy, clean and efficient utilization of coal, coal-based polygenration, CO_2 mitigation, energy storage

1 Introduction

As the world's population grows and as technology develops, everyone naturally desires to enjoy more and better energy services. Given this scenario, the world's total energy consumption will continue to increase. According to estimates, energy consumption will have increased by 40 percent in 2030. Supply of energy resources may continue to be available for some time, but the problem of climate change is urgent. Within a few decades, if humans failed to take decisive measures, a worldwide disaster would occur, and developing countries would be the first to bear the brunt. It may be said that humans could be losing the atmosphere faster than it is losing fossil resources, and that human-induced climate change would overshadow all his other efforts to cure diseases, reduce poverty, prevent warfare and preserve biodiversity.

Given this backdrop, the energy issue in the future is complex and multi-dimensional: economic development, environment, climate change, national security, and the demand and supply contradiction. These dimensions are not isolated, but mutually restrained and mutually influenced. This is a complex, time-varying, and nonlinear system with close integration of technical sciences and humanities. The solution should be perceived from the overall situation and from the point of view of the whole energy system. Due to industrial segmentation, solving the problem separately and locally is completely not suitable to the existing situation. In general, in addition to the strengthened energy conservation, more efficient, cleaner, and thorough utilization of fossil energy, and more rational utilization of renewable energy are required to mobilize the potential of all available energy.

It is true that

1) Traditional energy exploration and utilization are not sustainable, and are resulting not only in waste of resources, but also in serious environmental pollution.

2) New members are being added in the energy family — such as solar, wind, and biomass — and they provide intermittent and uncontrollable power, and depend on geographic locations. Their role will become increasingly important in addressing problems related to energy.

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3) There are new developments in energy conversion technologies, both in terms of products and manner of technology use. For example, polygeneration, based on coal gasification, could produce electricity, methanol, natural gas, liquid fuels, and chemical products through optimized and more thorough utilization of residual heat and residual pressure.

4) In the power industry, besides high-voltage and ultra-high voltage transmission, there are already several heavy railways for coal transportation, growth of gas and oil pipeline networks, and heat supply networks for shorter distances.

5) The end-users are characterized by diversification of energy supply and are varying significantly through time.

Under this new situation, this paper proposes that the synergistic utilization of coal and other energy resources can be an effective response to new challenges and is key to making China a low-carbon economy.

China, with its large population, is the first nation coming from a low level of development that ever attempted to modernize so quickly and desires to make fundamental changes in its growth strategy as a response to the environmental changes being experienced by the world. Coal continues to serve more than 70% of China's total energy needs, and this reliance on coal is not likely to change in the coming 30 to 40 years. Therefore, China, by historical circumstances, will be forced to become a global explorer and pioneer at the frontier of sustainable development. There is no precedent to follow; there is no existing example to copy. China should develop its own innovative strategy and technologies that could benefit it and the rest of the world.

Synergy entails the use of various energy resources, taking into account characteristics of each resource and combining them to achieve maximum effectiveness. Synergy has a very comprehensive connotation, covering different energy resources (coproduction of various products), conversion processes (pyrolysis, gasification, combustion), transportation and distribution (electrical transmission, pipelines, and various networks), and end-users (diversified supply to meet differentiated needs). This paper mainly focuses on describing the synergistic utilization of coal and analyzing the synergy of coal with other energies. To achieve better synergy, smart energy grid should be established with the integration of advanced information and energy technologies.

2 Coal is dominant in the energy mix in China [1]

2.1 Renewable energy could not solve the main energy problems of China in the coming 20 to 30 years

Due to the rapid growth of energy consumption in China, the use of renewable energy (mainly wind, solar, and biomass) will not be enough to solve the country's energy problems before 2020. China's situation is different from that of European countries, whose total energy consumption is no longer increasing (or is increasing very slowly) and renewable energy would gradually substitute fossil fuels. China is at the stage of rapid increase in energy consumption. The newly installed power generation capacity grows by nearly 100 GW per year (mainly coal-fired power generation), and renewable energy plays a very limited role in this. The following is an analysis of the future development of several main renewable energy resources in China.

2.1.1 Wind power

The cumulative installed capacity of wind power in China nearly doubles each year. In 2009, China's cumulative wind power capacity reached 25.80 GW, among which 16.13 GW was connected to the grid, accounting for 1.85% of the total installed capacity of electric power (until the end of 2009, the total installed capacity of electric power had reached 874 GW); and the electricity generated by wind power was 26.9 TW·h, only 0.737% of the total electricity production (in 2009, the total electricity production was 3650.6 TW·h) [2]. If the installed capacity of wind power in 2020 reaches 100 GW and the annual equivalent operating time is 2000 h, the estimated total power consumption will reach 6600 TW·h by 2020. However, wind power will account for approximately 3% of the total electricity consumption in an ideal condition, the biggest share of renewables apart from that of hydro power.

2.1.2 Solar energy

Take photovoltaic power as an example. By 2020, with the objective that the total installed capacity of photovoltaic power will be 20 GW [3] and the annual equivalent operating time is 1500 h, the electricity generated by photovoltaic will have reached 30 TW·h, less than 0.5% of the total power generation. The total PV production capacity of China can satisfy the world's requirements. At the time being, more than 95% of the PV products of China are used for export, and domestic demand is still quite limited due to their high price. Meanwhile, energy consumption and environment pollution should be carefully considered because the polycrystalline silicon-production industry is energy intensive.

2.1.3 Biomass energy

The potential biomass resource is quite limited and estimated to be 0.5 Gtce (Gtce: gigaton coal equivalent, 1 kgce = 29271 kJ = 7000 kcal). Since the arable land per capita is small (1/15–1/10 hectare per rural resident) and the biomass is highly scattered, biomass energy should mainly be used to solve the energy problem in rural areas.

According to a study on China's renewable energy development strategy [3], comprehensively considering the energy resources, environmental constraints, and total life cycle cost, the potential of the renewable energy, including hydro power, could optimistically be forecasted at approximately 600 Mtce/a by 2020 (Fig. 1).

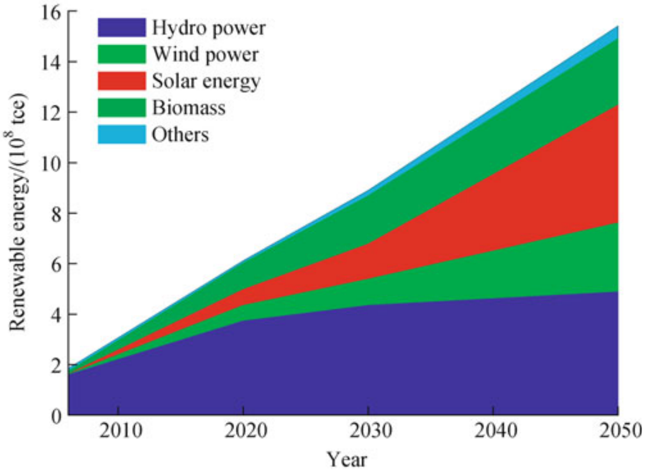


Fig. 1 Renewable energy development trend in China

2.2 Coal continues to serve as a major supply of energy, and consumption of it is expected to remain significant in the coming 40 years

In 2009, the primary energy consumption of China amounted to 3.05 Gtce, of which coal accounted for –70.1%; petroleum, –18.7%; and natural gas, –3.85% [4]. Summarizing the forecasts of studies conducted by different organizations, Figs. 2–4 present the development of nuclear power, natural gas, and oil.

The forecast on the overall energy consumption of China takes into account the abovementioned development of renewable energy, nuclear power, oil, and natural gas.

In the United States, per-capita energy consumption is approximately 11 tce. In medium energy-consuming countries, represented by European countries and Japan, per-capita energy consumption is 5 to 6 tce. Considering the concept of sustainable development and the objective that China would reach medium-level, developed countries in 2050, its energy consumption per capita should be controlled to a relatively low level, such as 4 tce. Since the population of China is estimated to reach around 1.5 billion by 2050, total energy consumption is estimated to hit around 6 Gtce/a by the same time. Figure 5 presents the structure of the energy mix, with a constraint of 6.35 Gtce/a in 2050.

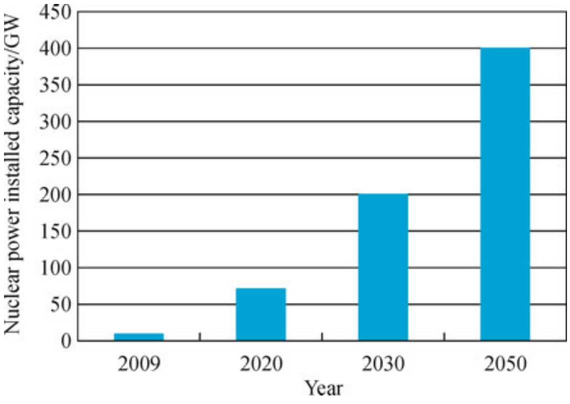


Fig. 2 Nuclear power development forecast for China

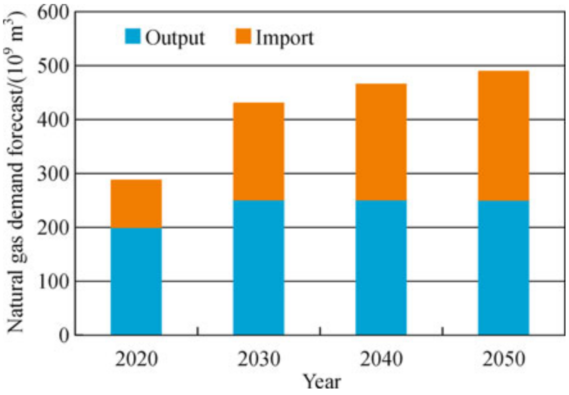
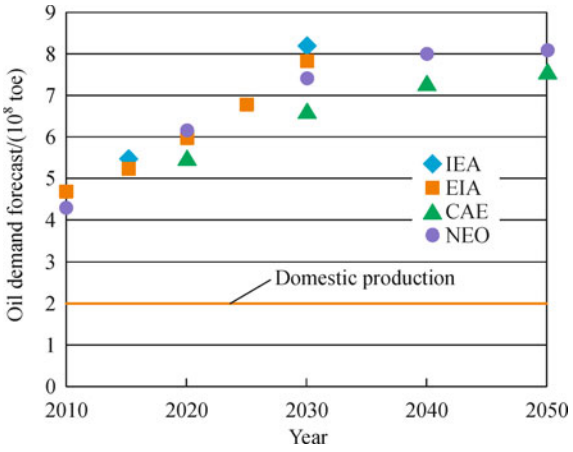
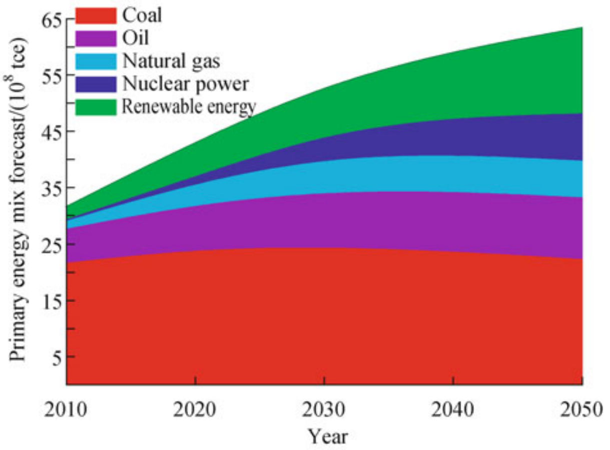


Fig. 3 Natural gas demand forecast for China



IEA – International Energy Agency; EIA – Energy Information Administration; CAE – Chinese Academy of Engineering; NEO – former National Energy Office

Fig. 4 Oil demand forecast for China



Data source: Consulting Report of "China's Medium- and Long-term Development Strategy Research" (from the Chinese Academy of Engineering, 2010)

Fig. 5 Primary energy mix forecast

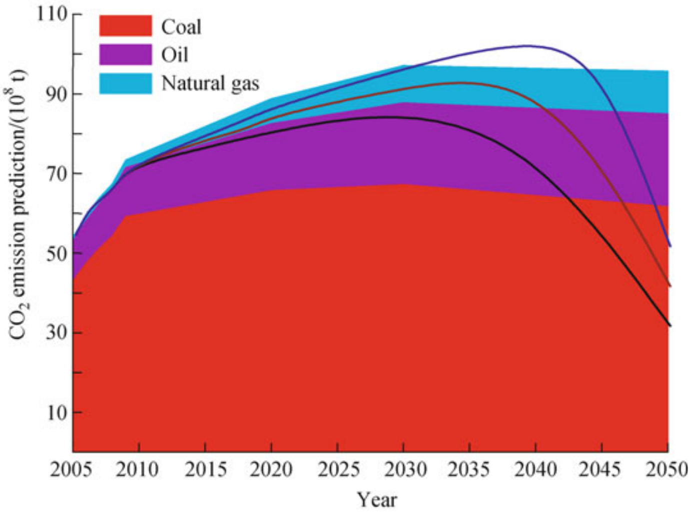
Although rapid development of renewable energy, nuclear power, natural gas, and oil, strengthened energy conservation, and frugal lifestyle are taken into consideration, coal consumption would still be more than 35% to 40% of the primary energy mix, and the annual demand for coal would be no less than 2 Gtce/a. Moreover, the accumulative coal consumption in the coming 40 years would amount to over 90 to 100 Gtce (see Fig. 5). The reality of natural resources and the requirement of environmental protection call for clean, highly efficient, and low-carbon utilization of coal.

3 Clean and synergistic utilization of 90 to 100 Gtce of coal is key to making China a low-carbon economy

Currently, China's annual CO_2 emission is approximately 6 Gt. At the Copenhagen Conference, China committed that by 2020, it will have reduced its CO_2 emission per unit gross domestic product (GDP) by 40% to 45% of the 2005 level. The international community wants to know the exact peak value of China's CO_2 emission, 8, 9, or 10 Gt, and when China will reach the peak value. To achieve the goal of limiting the increase in global temperature to below 2°C, the world's CO_2 emission by 2050 needs to be less than 50% of that in 1990. By then, the total global CO_2 emission space will only be 10.4 Gt (20.8 Gt in 1990). Given the climate change experienced globally, the acceptable CO_2 emission capacity for China is very small. Therefore, China should quickly and seriously act to mitigate its CO_2 emission.

Corresponding to the development scenario in Fig. 5, contributions to China's CO_2 emission from coal, oil, and natural gas are demonstrated in Fig. 6. Natural gas is a low-carbon energy resource with low CO_2 concentration in the exhaust gas, and it is not economical to capture CO_2 from natural gas combustion.

Because of scattered CO_2 emission sources of oil utilization, large-scale CO_2 collection is difficult. Furthermore, CO_2 emission from the utilization of natural gas and oil takes a relatively small share of the total CO_2 emission. Therefore, the burden of CO_2 mitigation falls on coal. Assume three scenarios of peak time and absolute peak value of China's CO_2 emission: 8 Gt by 2030, 9 Gt by



Peak time of CO_2 emission	2030	2035	2040
Peak value of CO_2 emission (10^8 t/a)	80	90	100

Fig. 6 CO_2 emission predictions

2035, and 10 Gt by 2040. These are shown by the three curves in Fig. 6. The parts above these curves represent the amount of CO_2 reduction even under the condition of strengthened energy conservation and the rapid development of nuclear energy and renewable energy. In the coming 40 years, accumulative coal consumption in China will be 90 to 100 Gtce. Ensuring the rational use of this 90 to 100 Gtce is a serious challenge for energy scientists and engineers in China. Innovative ideas and detailed planning are needed to address this issue. Coal used in power, chemical, metallurgy, building materials, and other industries needs comprehensive analysis and strategic planning, such as in terms of the choice and development of appropriate power generation technology, particularly from the perspective of carbon capture, utilization, and storage (CCS or CCUS), with the increase of coal used for power generation.

3.1 Coal-fired ultra-supercritical steam power plant (USC) is not the sole focus of highly efficient utilization of coal

In recent years, countries belonging to the European Union have focused on the development of ultra-supercritical steam generation (USC) and launched AD700 plan (37.5 MPa/ 700°C/720°C, η = 52%–55%) [5] in 1998. However, no commercialization plan has been developed, and the AD700 plan may have to be delayed.

Currently in China, the materials P91 and P92 used in ultra-supercritical boilers with parameters 28 MPa and 600°C mainly rely on imports. The 1000 MW boiler costs about 5 million RMB, of which 250 million is spent on importation of the materials for boilers with high steam parameters. The fundamental reason for the high cost of alloy materials is that the high temperature flue gas has to heat the working fluid through the wall of tubes of the boiler. Some corrosion problems have already occurred on the steam side of the tube wall of the superheater, but up to now, the mechanism has not been identified.

Therefore, further increase in steam temperature (such as 720°C or above) and corresponding pressure would propose even higher requirements in terms of materials. Since the amount of advanced alloy used for installed capacity per unit is relatively great, the cost of boiler constitutes a major problem.

Meanwhile, the cost of removal of pollutants from flue gas is rising with the increasingly stringent environmental requirements, which now include the removal of SO_2, NO_x, Hg, $PM_{2.5}$, and of more GHG. In direct combustion conditions, according to the present technology, carbon capture and storage (CCS) will reduce the thermal efficiency of power plant approximately by 11 percentage points and double the cost of electricity generated.

Thus, concerning the perspective of technology and economy, and the cost of conventional pollutants removal and CO_2 mitigation, in the long-term coal-fired ultra-supercritical steam power generation has a certain congenital defect, and the position of its “main sole” in power generation might be challenged.

3.2 IGCC has the advantages of significant improvement of more efficient and cheaper CO_2 mitigation

Natural gas combined cycle (NGCC) power generation technology has made great progress in recent years, rising from the Class E, Class F, Class G, and to Class H. The initial gas temperature increased from 1100°C to 1430°C, and is still advancing. The thermal efficiency of NGCC has improved from 50% to 58% to 60%. In a sense, gas turbine is a thermal engine with internal combustion. The chemical energy of the fuel can be directly transferred to the working fluid temperature without the intermediate heat transfer process, so the increase of the working fluid temperature is nearly unrestricted (theoretically up to 2000°C). Therefore, gas turbines have the greatest potential in enhancing the maximum temperature of the thermal cycle. If the initial gas temperature is raised to 1700°C, NGCC power generation efficiency could reach 62% or more.

Most of the incumbent IGCC units in the world are Class E, with an initial gas temperature of 1100°C, a capacity of 250 MW, and a power generation efficiency of 40% to 42%. In the case of Class F IGCC units, with a larger unit capacity (450 MW) and a higher initial gas temperature, the power generation efficiency can be improved to approximately 45%. In the light of current trends, Class G and Class H IGCC units are already available and are in the process of commercialization. These IGCC units are predicted to achieve a generation efficiency of 48% to 50%. If the initial gas temperature can be further increased to 1700°C, the power generation efficiency of IGCC could be as high as 52%.

Gas turbines with large unit capacity and high initial gas temperature are the key components of IGCC. A lot of scientific and technological problems should be solved to achieve an initial gas temperature of 1700°C. The problems have to do with the following: stable operation of compressor with high compression ratio (30–40), flow separation and surge boundary control, and blade vibration control; stable combustion of various synthesis gas (especially gas with high hydrogen content), synergy of premixed combustion and catalytic combustion to ensure stable combustion and low NO_x emission at a high temperature; and extremely high temperature resistant alloy material, its enhanced cooling, and thermal barrier coating.

Despite the current development trend of IGCC, there is still much room for improvement, such as in terms of gasifier (multiple nozzles and dry powder pump), oxygen preparation (oxygen nitrogen separation by ion-exchange membrane), purification process (high temperature desulfurization, dust removal), and sensible heat utilization (combination of chemical and physical utilization, respective treatment in different temperature zones). As a result of these improvements, thermal efficiency can be increased by 4 to 5 percentage points. The greatest advantage of IGCC lies in CO_2 capture through conversion process at a relatively high CO_2 concentration and a higher pressure (4–7 MPa). The generation costs with and without CO_2 capture are presented in Table 1 [6].

Compared with the increase in cost due to use of pulverized coal-fired power (PC) units, the increase in construction cost and generation cost due to CO_2 capture for IGCC is much lower.

With the development of gas turbine technology, coal-based near-zero CO_2 emission energy system is emerging and will be the strategic solution for China's energy issue after 2020, that is advanced gas turbines with initial gas temperature higher than 1700°C, compression ratio higher than 35, decarbonization of synthesis gas, and hydrogen content in fuel gas higher than 60%. The captured CO_2 can be sequestrated or utilized, thus coal as a high-carbon fuel could be utilized with low carbon emission.

3.3 Coal-based polygeneration is an important strategic direction of synergistic utilization of coal in China

Synergistic utilization of coal includes synergy of products (such as power, liquid fuels, and chemical products), synergy of technical processes (such as pyrolysis, gasification, combustion, and synthesis), and synergy of suitable CO_2 removal points and CO_2 utilization.

After years of demonstrations and commercial practices, the availability of IGCC gradually increased to 90%, but the main problem is that the capital investment per unit capacity is larger (approximately 50% higher than pulverized coal-fired power plants) and it is not suitable for frequent changes in off-design operation. Coal, as primary energy, has a "nature" of realizing "full value" utilization and synergistic process routes can be chosen based on the demand of products, by complementing each other, simplifying the processes and equipment, reducing costs and improving efficiency. Considering the cost, such synergy would complement the power generation with chemical products, thereby overcoming the disadvantages of pure IGCC power generation.

Polygneration energy system based on coal gasification takes coal, residual oil, and petroleum coke as raw materials. The syngas ($CO + H_2$), via coal gasification after cleaning, is used for production of chemicals, liquid fuels (F-T liquid, methanol, dimethyl ether, etc.), electric power, heat, gas, etc. Figure 7 illustrates one of the possible coal-based polygeneration systems [7].

Coal-based polygeneration breaks the boundaries of different sectors of industry, such as power, chemical, and metallurgy. It optimizes energy flow, material flow, and exergy flow of the production processes, and is an important strategic direction to solve China's problems related to the environment, and energy and liquid fuel shortage.

One of the key technologies for polygeneration system is the slurry reactor. In slurry bed, the solid catalyst is suspended in liquid (some kind of oil). The heat released during reaction is very easy to be removed. The thermal conversion efficiency of such kind of once-through synthesis reactor could be improved, and the mechanical wear of catalyst could be reduced as well. It is characterized by its low cost, small-flow resistance, and high once-through conversion rate. It is suitable for large-scale hydrocarbon production and polygeneration. After passing the once-through synthesis reactor, the purge gas directly enters into the combustion chamber of the gas turbine. It has fast dynamic response and can quickly adjust the ratio of power and chemical production.

In a polygeneration system, all the energy flow, material flow, and exergy flow of these processes are coupled together and optimized. Compared with those of a stand-alone production system, the benefits of polygeneration system in terms of capital investment, cost of unit product, and pollutant emission (sulfur, Hg, and particulates) are very significant. At the same time, polygeneration is a highly flexible system. It can adjust the production of the power, chemical products, and liquid fuels according to market demand, and can adapt the "peak-valley" fluctuation of power. The IGCC currently used for power generation requires higher unit capital investment, but a combination of IGCC and polygeneration can result in better economic benefits.

Polygeneration based on coal gasification is the sustainable, technically consistent, technologically realistic, economically beneficial, and ecologically friendly way for CO_2 mitigation, especially for lower cost of CO_2

Table 1 Generation costs with or without CO_2 capture provided by some American research institutes

Research institutes/Generation cost	Generation cost without CO_2 capture		Generation cost with CO_2 capture	
	PC units	IGCC units	PC units	IGCC units
MIT (2007)	1	1.05	1.60	1.35
GE Energy (2007)	1	1.06	1.58	1.33
AEP (American Electric Power) (2007)	1	1.08	1.84	1.52
DOE/NETL (2009)	1	1.22	1.868	1.676

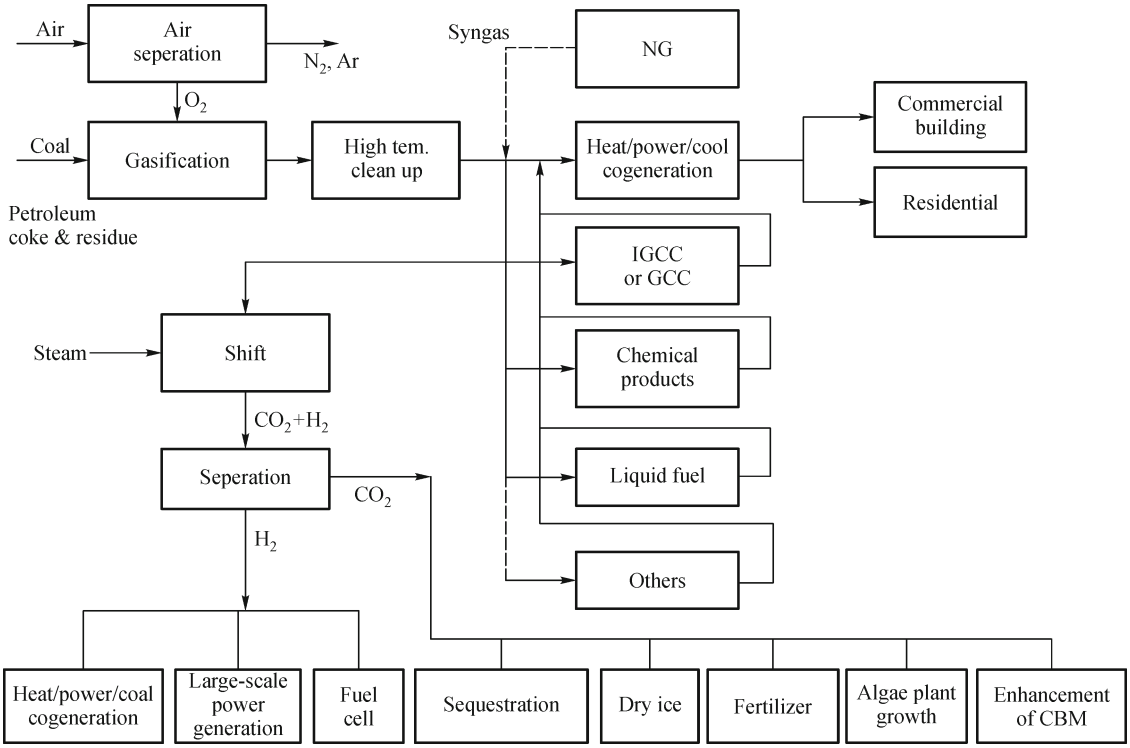


Fig. 7 Block diagram of polygeneration system

capture. It is considered the most important strategy to address energy-related problems in China and even the world.

The coal gasification-based polygeneration, as described above, has a wide range of chemical-production capability: extraction of useful substances before gasification from coal volatiles; full utilization of tar; and production of methanol, its subsequent products (such as olefin, propylene, and dimethyl ether), synthetic natural gas, and high-quality gasoline and diesel from F-T process, and so on. All these synergistic system has great potentials for further system optimization and energy efficiency improvement. These include lining up the system with chemical and power generation in a series or in a parallel form, properly raising gasification pressure to match the downstream gas turbine, better recovering the process heat and pressure, choosing the right catalyst to increase reaction temperature to raise quality of steam, and organizing and minimizing the CO shift process, and others.

Making synergistic use of coal is a good case in point when the H_2-rich coke oven gas and CO-rich synthesis gas are used to synthesis chemical products, in which the hydrogen/carbon ratio satisfies the major synthesis process requirement without the shift process. In addition, a large amount of coke oven gas in China can be purified and used directly as vehicle fuel. So far, a lot of laboratory tests and real vehicle applications have indicated that methane with hydrogen has significant advantage in both combustion efficiency and emissions performance. Compared with the strategy of using coke oven gas for methanol production, this approach has fewer intermediate conversion processes and higher added value. Another promising utilization direction is the production of fertilizer (K_2CO_3), in which part of the upstream gas with high CO_2 content could be used in the downstream so that CO_2 emission reduction can be achieved as well. Furthermore, utilization of coal can be in synergy with steel industry, which is consuming large amount of coal (more than 200 Mt), where the syngas from gasification can be used to produce high-quality sponge iron or to integrate coal gasification with COREX ironing process.

Because of the diversity of the coal composition and the great dispersion of different, volatile sulfur content, ash content, ash melting point, water content, etc, there is no uniform answer to the question of how to use coal synergistically. It depends on specific local conditions. Coal-based polyegeneration provides great opportunity for the utilization of high-sulfur coal, while its direct combustion will cause serious pollution.

At present, due to the characteristics of resources in China, its modern coal chemical industry advances rapidly, and the merger of new processes, new technologies, and new catalysts provides new drive and technical support for the synergistic use of coal. China should lead the world in the synergistic use of coal.

3.4 CO_2 mitigation in China should begin from the coal-chemical industry and gradually transfer to the "IGCC + polygeneration + CCUS"

It is quite difficult and energy-consuming to capture CO_2 from flue gas in direct combustion of coal because of the low CO_2 concentration in flue gas (13% to 14%), low pressure, and large volumetric flow rate. Based on current technology, CO_2 capture and storage will reduce the coal-fired power generation efficiency by approximately 11 percentage points. If the original power generation efficiency is 45%, after CCS, it would be reduced to 34%. To get the same power output, more coal should be consumed, resulting in a vicious cycle. In the IGCC polygeneration system, CO_2 capture is characterized by high concentration and high pressure. CO_2 capture from the IGCC polygeneration system would still reduce the efficiency by 6 to 7 percentage points, much less than in direct combustion. On the other hand, the IGCC polygeneration system has a variety of products which can complement each other in cost and can achieve comprehensive utilization of energy. Therefore, "IGCC + polygeneration + CCUS" is a strategic direction for CO_2 reduction in China (CCUS stands for carbon capture, utilization, and storage).

At present, during the production process of coal-derived chemicals, the high concentration and pressure CO_2 (so called "ready-made" CO_2) is directly vented to the atmosphere. Now the annual methanol production in China is about 15 Mt, and the CO_2 vented per ton methanol is approximately 2.5 t. The annually vented CO_2 only from methanol production would be approximately 40 Mt. Therefore, CO_2 mitigation in China should start from the coal-chemical industry, and corresponding policies should be made, such as imposition of carbon taxes and granting of subsidies, etc. During this period, CO_2 treatment experience would be accumulated (chemical and physical utilization, transportation, storage, etc.). Considering the future clean coal power generation, "IGCC + polygeneration" should be demonstrated as soon as possible to build several large-scale polygeneration power plants and to allow gradual progress to using the "IGCC + polygeneration + CCUS" system according to the CO_2 mitigation requirement.

The research and small-scale demonstrations of CCS from direct combustion of coal-fired power plants are also needed, but large-scale commercial implementation has to be observed for a period of time. At the same time, the in-depth studies on the physical properties of CO_2, corrosion, and geological structure of storage, and long-term monitoring of the possible leakage, etc. should be conducted. Basic research on broadening the use of CO_2 (such as for enhanced oil recovery and enhanced coal-bed methane recovery) and permanent solidification through utilization should be conducted from now on. Generally speaking, the actual condition of China should be taken into consideration in CO_2 mitigation, beginning from easier processes to more difficult ones, accumulating experiences step by step.

3.5 Urgent actions should be taken to implement the "IGCC + polygeneration" strategy

In recent years, supercritical, ultra-supercritical power generation units are basically adopted in the newly-built thermal power plants. If the development of the IGCC + polygneration is not considered, it means that the next period of technology development path of China's coal-based electric power generation will be locked in the direct combustion of coal. It takes years for any new energy system to develop from demo to commercial use. If efforts are not made now to promote IGCC polygeneration demonstration, higher cost is to be paid for retrofitting in the future.

Liquid fuels produced by polygeneration, especially methanol and dimethyl ether (DME), are suitable alternative fuels for vehicles and can significantly address the shortage of oil in China. Furthermore, methanol could be used to produce other conventional oil-derived chemicals (MTO and MTP). DME is similar to liquefied petroleum gas (LPG) in physical nature, and could be used as clean residential fuel. Furthermore, according to the operation experience in a special bus route in Shanghai, DME is an excellent fuel for diesel engine, whose emission of NO_x is lower by 60% compared with that of conventional diesel oil. On April 8 and May 18, 2009, the National Standards Committee promulgated a "vehicle fuel methanol" and "car gasoline with methanol (M85)" national standard, and implemented it from November 1 to December 1, 2009.

The majority of technologies in polygeneration system are mature, such as large-scale coal gasification units, various chemical reactors, and corresponding catalyst, syngas fueled gas/steam combined cycle, etc. In 2006, Yanzhou Mining Group in Shandong Province launched one coal-based methanol-power polygeneration plant. This is the first polygeneration unit with a stable operation already lasting for three years. The overall energy efficiency of coal-based methanol-power polygeneration reached 57.16%, and was 3.14 percentage points higher than that of the stand-alone methanol and power production systems [8]. The operation data show that this kind of unit has great potential to improve energy efficiency and reduce environmental pollution.

4 Synergy of fossil fuels with renewable energy

With the world's dwindling fossil fuel resources and worsening environment, more attention has been paid to renewable energy, particularly solar and wind. In recent years, countries all over the world drafted ambitious plans on renewable energy development. As the share of renewable energy in total energy consumption increases every year, energy diversification is the future trend. Since 2005, China's wind power-installed capacity has doubled, reaching 25.8 GW in 2009, ranking second highest in the world. If this momentum continues, China's installed capacity of wind power would be the first in the world within two to three years. According to statistics, 30% of these installed wind turbines are not connected to power grids. Even for those which have been connected, the power output is restricted for various reasons, resulting in a dreadful waste. China's wind resource-rich regions (Xinjiang Uighur Autonomous Region, Inner Mongolia Autonomous Region, Gansu Province, Ningxia Hui Autonomous Region, etc.) are basically remote areas that have small electricity demand and are far from the load centers, but the planning of wind power in these areas are usually more than several GW. The main constraints of the large-scale application of wind power are that the local power grid structure is weak and the power capacity is small; wind power has the characteristics of randomness, and large-scale access of wind power to power grid will inevitably lead to the instability of power grid. Some special control equipment, additional spare capacity, and in some cases, energy storage devices are needed, thus requiring higher amounts of investment. Currently, difficulty in accessing the power grid is the major bottleneck for the development of wind power.

If the so called "bundling" output for wind power is adopted, many coal-fired power plants have to be constructed at those remote, water-short, and ecologically fragile areas. The unit cost of constructing special transmission lines for wind power would be very high since operating hours of wind turbines at full load is less than 2000 h per year. Using large-scale electricity storage, such as hydro pumped storage, to balance the intermitted output of wind power is only possible in some areas with special geographical conditions, and the cost is also fairly high. Other batteries (like vanadium flow battery) have limited capacity, and the unit cost is high as well. The abovementioned methods will lead to higher cost and drag the economic benefit of wind power. How to utilize the large-scale wind power in remote areas is a hard nut to crack in China. Is it the only way for large-scale wind farms to be connected to the power grid? China has a great number of energy-consuming industries, such as chlor-alkali (3000 kW·h consumption per ton) and electrolysis of aluminum (15000–16000 kW·h/t), whose electricity demand is met by the power grid, through the process of step-down and rectifier to convert the high-voltage alternating current into low-voltage, direct current. The synergistic use of wind power and grid power has been proposed under the national "973" Plan "basic research on large scale non-grid-connected wind power system". Actual situations may show that wind power can be the main supplier, while grid electricity can act as a supplement. In addition, there might be other possible ratios between these two forms of electricity supply. The possible ways are:

1) Electrolytic aluminum industry (adopting thermal insulation and regulating electrolyte composition).
2) Chlor-alkali industry.
3) Seawater desalination.
4) Electrolysis of water for obtaining hydrogen and oxygen.
5) Oil extinction devices in oil fields.

Other uses of wind power can also be examined and explored. As long as electricity consumers have no strict requirements on the fluctuation of the electricity, grid power can be used to complement and support wind power. For instance, in northern regions, abundant winter wind could be utilized to drive heat pumps, upgrading low-grade heat from other heat sources for heating or other use, since heat pump systems have relatively large thermal inertia, which could afford certain range of fluctuations.

The synergy of the rapid development of wind power and coal-chemical industry is worthy of further discussion. Some remote areas abundant in wind power are very rich in coal resources, and it is the rational way to produce clean energy and upgrade local economy.

Synergy of wind power and methanol production is a case in point. The stand-alone wind power and methanol production systems are illustrated in Fig. 8, and the synergy of the wind power and methanol production systems is shown in Fig. 9. Table 2 lists the calculation results [9].

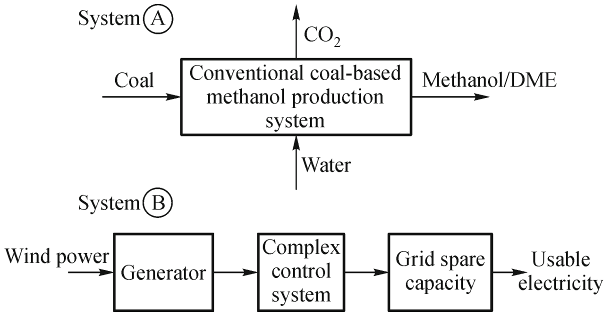


Fig. 8 Stand-alone systems of methanol production and wind power

The calculations show that by adopting the synergy process, the yield of methane doubles while the emission of CO_2 drops by 60% from the same amount of coal. The emission of CO_2 per ton methane of the synergy process drops to only 20% of that of the traditional process, a good example of synergizing modern coal-chemical industry and wind power, and a more rational application of wind power that solves the problem of heavy CO_2 emission in coal-chemical industry. However, the problem of intermittent wind power and production of methane, which needs a relative stable operation, remains unresolved.

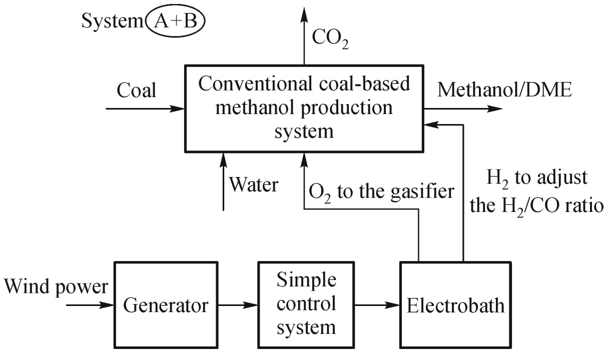


Fig. 9 Synergy system of methanol production with wind power

Table 2 Material flows of different cases

Systems	Syngas: $H_2/CO = 0.623$	
	Ⓐ	(A+B)
Methanol production/(10^9 kg·a^{-1})	0.500	0.963
Coal consumption/(10^9 kg·a^{-1})	0.678	0.678
Water consumption/(10^9 kg·a^{-1})	5.000	5.994
CO_2 emission/(10^9 kg·a^{-1})	1.085	0.464
Wind power consumption/(TW·h·a^{-1})	–	3.976

Large containers for hydrogen and oxygen are essential, and the technology involved becomes the new barrier. The expedient solution is the hybrid version, in which 70% to 80% of the process uses the traditional cryogenic air separation unit for oxygen production and a shift reactor to adjust H_2/CO, while only 20% to 30% of the process uses hydrogen and oxygen from the electrolysis of water, hence, the need for hydrogen and oxygen storage is much less. A 75 MPa and 10 m^3 hydrogen storage tank is recently under demonstration. The high pressure decreases the size of the storage tank, but it takes a lot of energy to pressurize the hydrogen to 75 MPa (0.15–0.2 kW·h to pressurize 1 m^3 hydrogen from 3.0 to 70 MPa, or 1.5–1.8 kW·h for 1 kg hydrogen at the current technology). This amount of energy consumption seems tolerable. With the development of technology and the solution of hydrogen storage, making hydrogen by electrolyzing water with the wind power becomes more applicable.

Recently, as many big cities are eager to get more clean energy, the remote areas with plentiful coal resource (especially Xinjiang Uighur Autonomous Region) are now paying attention to synthetic natural gas (SNG) process. Coal is gasified and transformed to SNG at mining places, and the CO_2 separated from the process could be utilized or stored in neighboring regions. The SNG is then transported through natural gas pipelines to cities in the east as clean energy. Although the efficiency from coal to SNG is only 50% to 55%, cheaper long-distance transportation, and highly efficient power or cogeneration plants on the demand side can be realized because SNG is the best clean fuel. Taking the entire technological chain into account, higher efficiency and less emission of CO_2 are achievable. The emission and treatment of CO_2 during the coal-SNG process is still the key problem. If SNG process is synergized with wind power like methanol production, the yield of SNG per ton coal may double and CO_2 emission can be greatly mitigated.

Synergy of fossil fuels with solar energy is considered in this section. The merits and demerits of polycrystalline silicon and thin film photovaltaics (PV) is not the focus of this paper as each technology develops along its own pathways. Currently, the high cost of PV is still a barrier to its widespread use in China. Use of solar thermal power, among renewable energy resources, is another direction being looked at by policymakers. Presently, there are several hundred-megawatt-class demonstration power plants in the world, and similar power plants are also being built in China. High cost, likewise, is a main constraint. This technology utilizes the high-temperature range of solar thermal, usually raising the temperature above 550°C to 600°C by highly focusing the solar radiation. The efficient concentrate of solar energy, the efficient transfer of heat to working substance, and the utilization of molten salt to store high-temperature heat are problems requiring further research. Comparing with other ways of solar thermal utilization, low/medium-temperature range of solar collectors is the simplest and most effective one. The low energy density solar thermal can heat the working substance to 70°C to 80°C (low temperature)/ 140°C to 200°C (medium temperature) at low costs. Low-temperature technology is mature and is used worldwide. In Beijing, heat provided by one square meter of solar vacuum collector per year is equivalent to the heat of 120 to 130 kg of coal for producing hot water. It is a highly cost-effective way of solar energy utilization. In recent years, the research team in Tsinghua University has done intensive research on medium-temperature solar heat collector (140°C) in close cooperation with an enterprise (Shandong Linuo Solar Thermal Group Co., Ltd), and has realized scale-production, opening up a new field for synergistic utilization of solar thermal with other types of energy.

1) In synergy with different types of heat pump for air conditioning and heating, and in combination with natural gas or grid electricity, the required operating conditions are obtained.

2) In synergy with direct coal-fired power generation, solar thermal energy is used to heat the feed water, hence reducing steam extraction for feed water heating, and consequently increasing the power output. After preliminary calculation and experiments, incremental power output of this kind of synergy produces nearly three times more

electricity in comparison with PV covering the same area, and the cost is much lower. Solar thermal also can be used in CO_2 capture. After absorbing CO_2 in flue gas, the absorbent-NH_3 would be regenerated by solar thermal at 120°C, reducing the loss due to less steam extraction.

3) In synergy with huge amounts of small- and medium-sized industrial boilers, many energy services are provided in the form of heat. Currently, there are more than 500000 industrial boilers of different capacity in China, most of which are used for heating, for processing, and other purposes (the average efficiency is only 65%). These boilers consume approximately 300 to 400 Mtce of coal and emit nearly 700 to 800 million tons of CO_2 annually. As the capacity of these boilers is relatively low, the cost for pollution removal is higher than that for large power stations. Since these boilers have no desulfurization and denitration equipment, environment pollution caused by per unit coal fired is quite serious. According to rough statistics, the SO_2 emission from coal-fired industrial boilers is 6 million tons per year, accounting for 1/3 of the total SO_2 emission in the country, close to the current total SO_2 emission from coal-fired power plants (8.9 million tons). Therefore, the solar thermal for feedwater heating will play a significant role in this important field of coal utilization.

With the development of medium-temperature range solar collector and further improvement of the advanced full-spectrum absorbing coating, the temperature will reach 200°C. In synergy with other types of energy, this technology becomes a major direction for solar thermal utilization, and has very wide spectrum in industrial and civil applications.

The biomass also can be synergistically utilized with other energy resources, such as through direct cofiring with coal. Another way is for biomass to be first converted into peat, which is higher in energy density, and then cofired with coal. The original volume per unit weight of biomass could be reduced and made easier to collect and transport.

5 Synergy in energy storage and complementary use of energy

5.1 Increasingly large difference between peak and valley requires efficient peak-shaving and valley-filling technology

With the rising standard of living, especially in large and medium-sized cities, the difference between peak and valley of electricity load increases as well, sometimes reaching 50%. To ensure a reliable supply of electricity, the need for peak shaving and valley filling in power systems and power grid should be addressed. In recent years, hydro pumped storage system develops rapidly and is a good way for peak shaving. However, this method needs large investment and depends on geographical location. Considering the development of electricity from a future perspective, which calls for improvement in power-generation efficiency and pollution reduction, the current policy is to construct large-capacity power plants, shut down small ones, and develop supercritical and ultra-supercritical generating units. Considering China's present power structure, the share of 600 to 1000 MW ultra-supercritical power plants would become larger and larger, which are suitable for base load operation, and off-design operation would overshadow the advantages of large units in efficiency and pollution reduction.

In addition, nuclear power generation in China is developing rapidly (by 2020, installed nuclear power capacity would be 60 to 80 GW, approximately seven times higher compared with current installed capacity), and basically it requires stable and full-load operation. When the external demand (valley power) changes, problems on how to store surplus power and how to find suitable energy carrier should be solved. Is the use of valley electricity to produce hydrogen a solution? If so, how can hydrogen be used? Distributed small-scale fuel cell is one of the possible ways, but it is constrained by the cost of the fuel cell itself and the complicated and expensive infrastructure problems.

5.2 Rapid development of renewable energy requires small-, medium- and large-scale energy storage systems

With the development of renewable energy, non-grid-connected utilization of renewable energy and energy storage become increasingly important. Although great efforts have been made in electric power storage in recent years, no fundamental breakthroughs have been achieved in large-scale storage. In the future, as a result of utilization of renewable energy, a number of small- and medium-sized grids of distributed power system will take their places in the whole power system. In that case, energy storage devices and carriers will also be key problems worth solving.

According to conditions in each country, all kinds of energy should be synergistically developed from the perspective of sustainable energy systems to make the best use of their advantages and avoid their weaknesses. Transformation of energy, with their random characteristics (such as surplus electricity of large generating units, wind power, and solar power), into a highly efficient and controllable energy is the major strategic issue that modern power systems are facing. Technical progress and breakthroughs of highly efficient small-, medium-, and large-scale energy storage systems are urgent. In large-scale energy storage systems, in addition to hydro pumped energy storage, compressed air energy storage (synergy with wind and solar power) and integrated system of Brayton and Rankine Cycle have great potential (synergy with excessive nuclear power and valley power of ultra-supercritical power units).

5.3 Compressed air energy storage system [10]

Compressed air energy storage system (CAES) [11] stores air under pressure in underground cavities or aquifers in periods of excess electricity supply. During periods in which demand exceeds supply, additional external heat (such as that from natural gas combustion) is used to heat the air. Then, air is released to drive a turbine to generate electricity. CAES can be roughly divided into non-adiabatic compressed air energy storage and adiabatic compressed air energy storage.

The non-adiabatic compressed air energy storage system involves injection of additional fuel to the system to heat the compressed air released from the air storage chamber. Built in 1978, Huntorf Power Station in Germany is typical example of this system. It has energy-storage efficiency (power input/power output) of approximately 42% [12]. If waste heat recovery device is added before the high pressure combustion chamber to heat the cold air released from the air storage chamber, the efficiency could be even higher. Built in 1991, McIntosh Power Plant in the US is a typical representative of this kind. Its energy storage efficiency is approximately 54%.

The adiabatic compressed air energy storage system is a relatively new concept. The heat generated during the compression process is absorbed by the thermal energy storage device and is used to heat the cold air released from the air storage chamber, avoiding the heat loss during the cooling-down process. The diagram of the adiabatic compressed air energy storage system, including single-stage compression and single-stage expander, as illustrated in Fig. 10, is compatible with low-pressure systems. The maximum storage pressure of the compressed air storage chamber is 40 bars. When the storage pressure of the air storage chamber reaches 200 bars, multi-stage compressors and multi-stage expanders are required. The energy storage efficiency of an adiabatic compressed air energy storage system theoretically could reach 70% [13].

Currently, rock is considered to be a substance for heat storage. The use of other better materials for heat storage is a topic for further study. Furthermore, instead of geological structure for underground storage of high-pressure air, some experts propose that specially made pressure vessels be used.

5.4 Integrated system of Brayton with Rankine cycle synergy of energy storage with coal-fired power and nuclear power

In the integrated system of Brayton and Rankine cycle, thermal energy utilization of coal and H_2 follows the principle of "cascade utilization of coal and H_2 according to their nature." The first half of the integrated cycle (Fig. 11, processes 4 to 6), the raising of the temperature of steam from feed water to 600°C, is the "responsibility" of coal through external combustion. The second half of the cycle (Fig. 11, processes 6–1), the raising of the temperature of superheated steam to 1400°C to 1500°C is done by internal combustion of hydrogen and oxygen in the combustion chamber. If hydrogen combustion device is added to the conventional steam turbine power generation system, according to preliminary analysis, the energy conversion efficiency H_2 can reach 62%, and the thermal efficiency of the entire system could reach 52%, higher than the 44% of conventional supercritical steam power generation. By so dong, it can be said that each fuel fulfills its own functions, and hydrogen is "standing on the shoulder of coal." This system combines external and internal combustions, overcomes the inherent disadvantages of the conventional Brayton and Rankine cycle, and gives full play to their capability. In this scheme, hydrogen is used even more effectively in comparison with fuel cells.

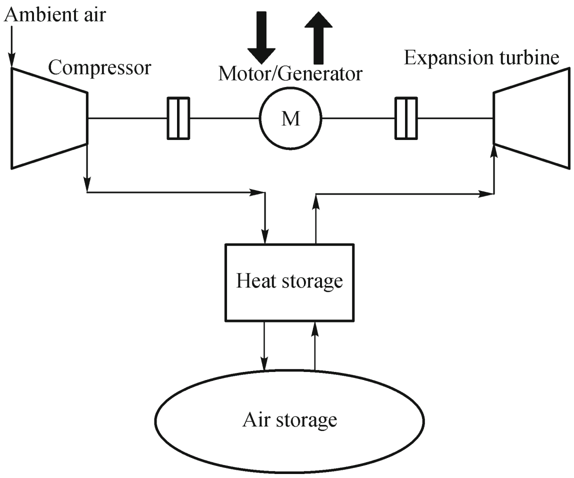


Fig. 10 Diagram of an adiabatic compressed air energy storage system

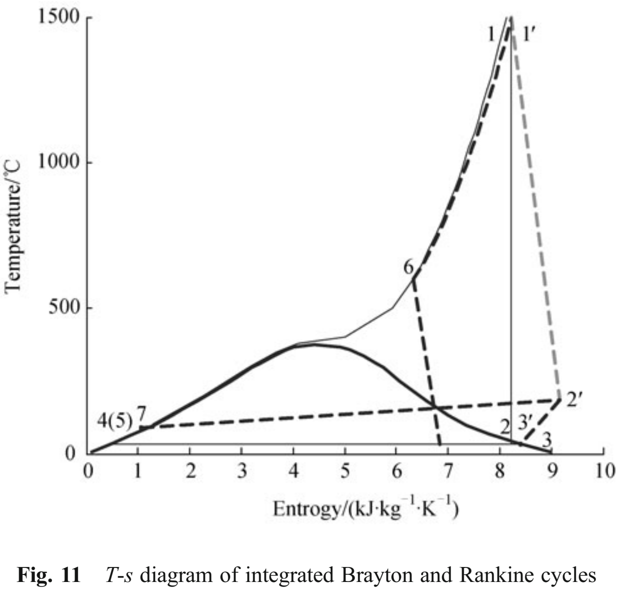


Fig. 11 *T-s* diagram of integrated Brayton and Rankine cycles

The thermodynamics of such cycle has been reported by Malyshenko et al. [14]. If improvement of efficiency is the only one considered, the problem related to storage of power, hydrogen, and oxygen would persist for continuous operation.

Therefore, from the perspective of application of large-scale electricity storage, the integrated cycle could be used as a power-boosting system in synergy with a conventional ultra-supercritical steam power generation system. During the peak load of power grid, the power-boosting system would begin to operate and enhance the power output by 100%.

Figure 12 depicts the principle of the integrated system. Under normal condition, only conventional steam turbine power generation is in operation; at valley demand for grid electricity, some power plants are still maintained at a high-load, high-efficiency operation regime. The extra electricity is used to electrolyze water to produce H_2 and O_2, which are stored in the respective buffers. At peak demand for grid electricity, the O_2 and the H_2 in the buffers are injected into the combustion chamber, and the ordinary superheated steam from the supercritical boiler (parameters are $p = 30$ MPa, $t = 600$°C) is heated to 1500°C. This flow of steam expands at a special high-temperature, high-pressure steam turbine to produce extra power, and the exhaust steam (temperature, pressure have reduced to an ordinary supercritical parameter steam) continues to expand through the conventional steam turbine. The part in stippled line in Fig. 12 is the conventional frame of the steam turbine. When there is no need for peak shaving, valve A is closed and B is open, the system is in normal operation. When peak shaving is needed, valve A is open and B is closed, and the high-temperature and high-pressure steam turbine goes into operation, doubling the output.

In the integrated system, many scientific problems have to be solved, such as high temperature and high pressure hydrogen combustion system, structural design of high temperature and pressure steam turbine, cooling of the turbine blade and cylinder, high speed and frequency regulation technology, large-scale hydrogen and oxygen storage, coupling and decoupling of rated and boosting operations, etc.

6 Synergy of centralized and decentralized energy supply systems

Historically, delivery of energy supply had transformed from using distributed systems to centralized ones. Energy efficiency, convenience of use, and pollution control were significantly improved with centralized power grids so that the centralized energy system was considered to be a crucial leap in technology and a milestone of modern society. However, diversity, efficient utilization, and clean energy supply are now becoming the new trends, and the centralized energy system alone cannot meet the requirements of modern energy systems, which require not only high efficiency but also adequate flexibility and supply safety. In addition, energy supply and demand should be closer in terms of form and distance to diminish conversion, transport, and storage processes as well as the energy lost in these processes. As a result, energy experts are now starting to shift their attention to the need

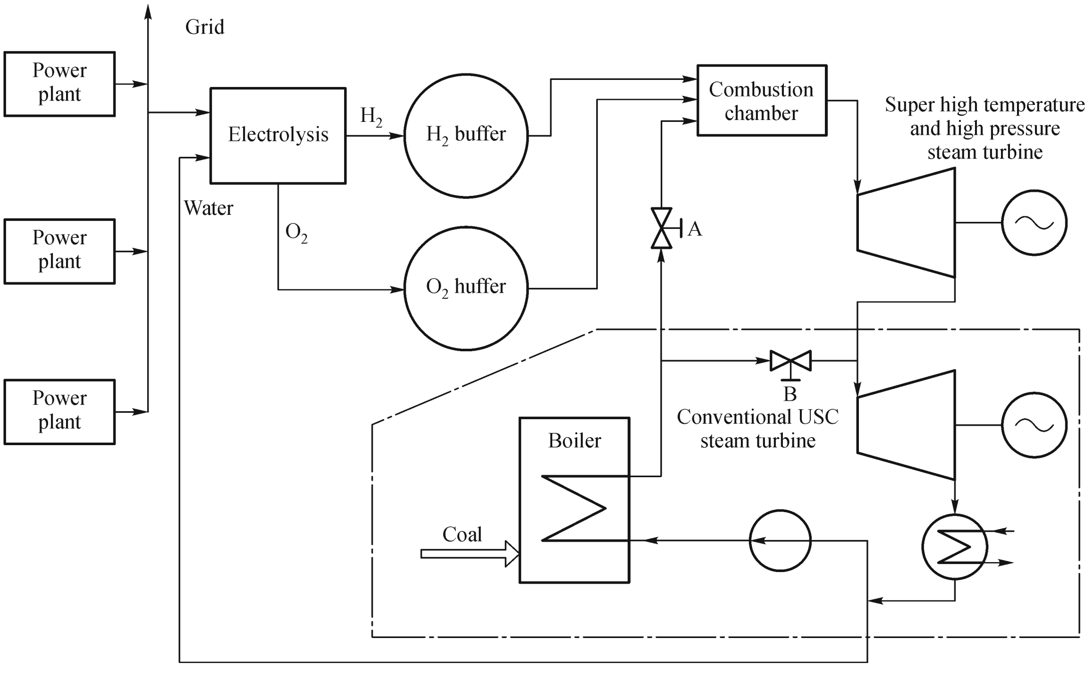


Fig. 12 Diagram of integrated cycle of Brayton with Rankine cycle

for transformation from centralized energy systems to a combination of centralized and distributed energy systems, and the need to explore the synergy of this new energy supply mode.

In contrast to centralized energy systems (large power plants and power grids), distributed energy systems are more disperse and are usually installed in the vicinity of the end-users. The onsite energy production supplemented by multiple control and optimization technologies can result in a cascaded utilization of energy and reduce the intermediate energy loss during the distribution processes. Generally, natural gas is the primary energy source of distributed energy systems, and various renewable and locally available energy resources can be integrated as well. Distributed energy systems adopt various energy conversion and storage technologies to meet the end-users' diversified demands, such as for electricity, heat, lighting, refrigeration, and ventilation.

Distributed energy systems have more merits compared with centralized energy systems. These are the following:

1) Considerable energy efficiency. Distributed energy systems are often based on natural gas combined cooling heat and power systems (CCHP), which can provide low temperature heat to nearby communities with the waste heat from the power plant. The overall efficiency of a CCHP plant mostly can surpass 80%, which is much higher than that of large power generation units.

2) Minimum energy loss during distribution. Large power grids lose a large proportion of generated electricity during transmission and distribution. In 2009, the electricity loss of the national grid was 219.1 TW·h, which accounted for 6.72% of the total electricity produced [15]. In contrast to centralized energy systems, energy produced is close to the end-users in distributed energy systems, thus minimizing the tremendous energy transmission losses during energy distribution.

3) Synergy with various energy sources. Distributed energy systems are complicated, multi-input and multi-output systems. Through the integration of various energy sources and adoption of various electric power, heating, refrigeration, and energy storage technologies, the redundancy of all energy sources can be minimized despite the distributing and fluctuating features of renewable energy. From the demand perspective, the quality of energy should be differentiated. For instance, high-temperature should be distinguished from low-temperature heat, stable from unstable electricity, and continuous from discontinuous needs. Distributed energy systems can meet the differentiated requirements, thus avoiding the low-efficiency energy conversion processes.

4) High reliability. Distributed power generation device can continuously provide electricity to important users when the grid accidently collapses. If distributed energy systems are connected to the grid, its reliability will be further enhanced. When the grid fails, it can be automatically disconnected with the grid. When some users' system fails, it can also break up with the grid to minimize the negative effects on systems of other users.

Since the distributed energy systems could overcome the deficiencies of centralized energy systems on efficiency and reliability, future energy systems should include both centralized and distributed systems for accessing the various energy sources. Distributed energy systems have been developed for years in Europe, especially in Denmark, the Netherlands, and Finland, which are the leading countries in this domain. The capacity of distributed power generation in Denmark accounted for more than half of total domestic power generation, and the Netherlands, Finland, Latvia were also approaching 40% in 2005 [16]. The Danish government announced in July 2005 that it would construct the world's longest, intelligent grid infrastructures, which would enable distributed energy systems to be the main power source in Denmark [17]. The United States, Canada, UK, Australia, and other countries are also aware of the significance of developing distributed energy systems after experiencing series of widespread blackouts, and are enthusiastic in promoting this new concept.

There is still a big gap between China and above-mentioned countries in terms of the development of distributed energy systems. China lacks experience in the implementation of distributed energy technologies and tailor-made distributed energy system designs. However, there are already some successful cases of distributed energy systems highlighted by Beijing Gas Group's CCHP program, which provides heating, cooling, and electricity for a building with an area of 32000 m^2. Another successful case is Beijing South Railway Station's distributed system featured with its sewage source heat pump, solar power, and natural gas CCHP plant [18]. These successful experiences are essential intermediate milestones that have great importance for the development of distributed energy systems in China. China should exert more effort on the use of such systems and should consider exploration of optimization and control of the system as one of its priorities.

The core of the distributed system is the power source. According to experience, for capacity less than 200 kW, the reciprocating internal combustion engine is better than gas turbines because of higher efficiency and lower cost of the former. In recent years, for the combustion process, using the synergy of air-fuel mixing rate and combustion rate, the thermal efficiency could be increased by several percentage points and the emission could satisfy the Euro. VI and V standard without exhaust gas after-treating. It is also some kind of synergy of the combustion sub-processes.

The research on distributed energy systems can be divided into two levels: system level and component level. The current energy conversion technologies for distributed energy systems are mostly mature technologies, such as gas turbines, reciprocating piston engines, heat pumps, and turbine chillers. However, many components, such as photovoltaic cells, are still very expensive. Thus, on the component level, the main task is to reduce the costs of these system components. On the system level, the configuration and control of distributed energy systems are the most important issues. It is important to provide right solutions to meet the demands of a specific region because of the diversity of the inputs and outputs of distributed energy systems, and the volatility and fluctuation of various energy sources. It is also essential to study how to control such a complex system to meet the safety requirements and maximize the advantages of distributed energy systems.

7 Synergy of power, natural gas, heat (cooling), and water grids

Electricity is the best secondary energy. From the aspect of energy supply, the power grid technology is very mature. Many countries, including China, have constructed relatively reliable grids for the high-voltage transmission, power supply of cities, and power distribution of areas. How to fully utilize the grid to provide increasing energy service is a long-term need for social development. In recent years, smart grids, which originated in the United States, is quite “hot” in many countries. The purpose of smart grids is to offer an energy service that is not only safer, more environmental-friendly, economical, and convenient, but also more efficient. At the same time, it promotes interaction between power supply and user, and between power source points and grids. The major task is to make use of the widest range of various kinds of power sources, especially renewable energy, such as the GW-scale wind farms and small-scale individual roof power generation. In smart grids, different power generations using the “waste” pressure and heat, electricity cogeneration of different industrial processes, and distributed micro grids can play appropriate roles accordingly. The integration and interaction of user and power source are key trends in the future.

However, as mentioned before, demand for electricity is just one of the major aspects of the energy service. In addition, there are other demands for heat, cooling, gas fuel, and water. Therefore, with the development of the power grid, natural gas, heat supply, and water grids in cities are also being developed accordingly. In fact, these grids are in close synergy that they can be called ENERGY GRID. The development of smart grids will promote the intelligence of grids for natural gas, heat (cooling), and water supplies, making a smart integration of them.

In the aspect of heat supply grid, the heat supply for the towns in north China in winter can be taken as an example. The total building area for civil use is 0.75 billion square meters, which is 43% of the total building area in cities and towns. The energy consumption in winter is 0.15 Gtce, which is 40% of the total energy consumption in cities and towns. Now the heat supply is facing problem of the serious lack of heat sources and infrastructure capacity of heat delivery. One way [19] to solve the problems is to use 300-MW and larger-scale steam turbines to implement combined heat and power cogeneration and central heating. Another way is to increase the supply/return-water temperature difference with heat pumps (e.g., water supply temperature at 130°C and return-water at 15°C to 20°C), making use of waste heat that has been emitted to the atmosphere through the cooling water (about 20% to 50% of maximum heat supply of the steam turbine). At the same time, it can double the capacity of heat delivery for already constructed heat-pipe system, and form a new heat supply network.

Another example is the utilization of different industrial waste heat. Now the waste heat of a factory is only applied for water and building heating and some domestic use individually with low efficiency. It is desirable to connect several waste heat sources to an integrated system. However, doing so for the waste heat at different temperature level is very difficult. The development of heat pumps (compression and absorption types) provides possibility to increase the energy grade or lower the temperature. The invention of the electric transformer is a great progress for electrical engineering. The transformer helps control the voltage and makes electricity convenient for transmission and use. The heat pump system can adjust the temperature of different heat sources as the transformer can change the voltage of electricity. It can be viewed as a heat source transformer and expand the possibility of waste heat utilization, as shown in Fig. 13 [20].

Therefore, the temperatures of various waste heat sources can be regulated to 130°C for water supply and 15°C to 20°C for return-water, forming an integrated grid. Due to different sources, temperatures, and heat capacity, accurate and smart control is needed to fulfill the demand of users. The compression heat pumps are driven by power and should be in synergy with the power grid. The similar innovative synergy could be applied according to actual local conditions.

The demand for natural gas is dramatically increasing in China, while there are still no convincing scientific studies or definite descriptions about the highly effective application of natural gas. For large cities, the demand for electricity, heat, and gas is varying daily, and the disparity is even more apparent in different seasons. Figure 14 illustrates the power and natural gas consumption of a city over a year [21]. The two curves have obvious peak and valley difference, and the curve of electricity consumption reaches its peak when the other one reaches its valley. Meanwhile, there remains a problem on power and gas storage. Usually, natural gas is the domain energy source of distributed energy systems. The distributed energy system includes various energy demands, different kinds of renewable energy, and coproduction facilities. The

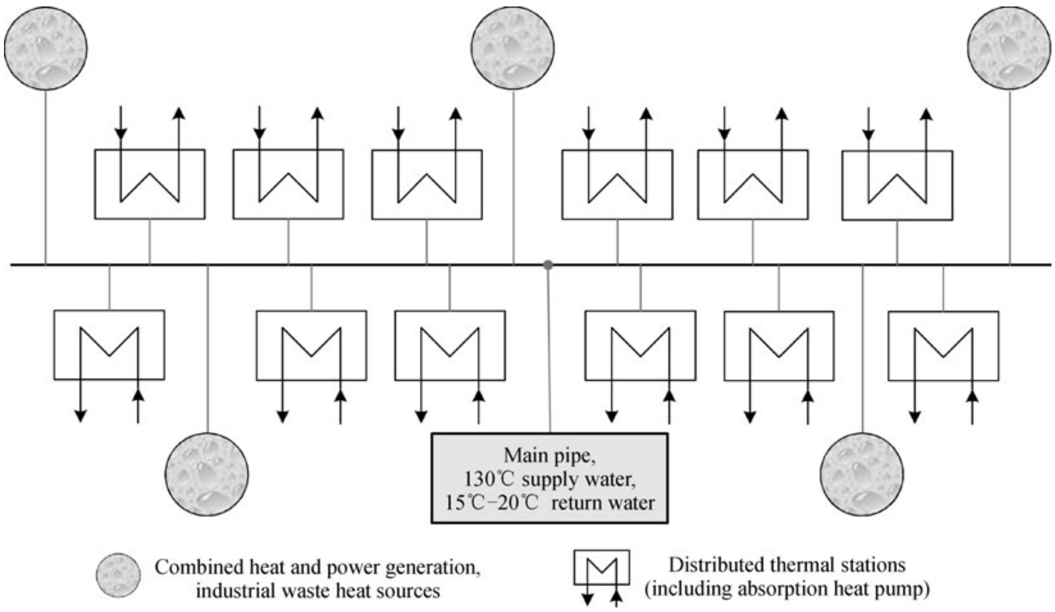


Fig. 13 Centralized heat supply networks in cities with various heat sources

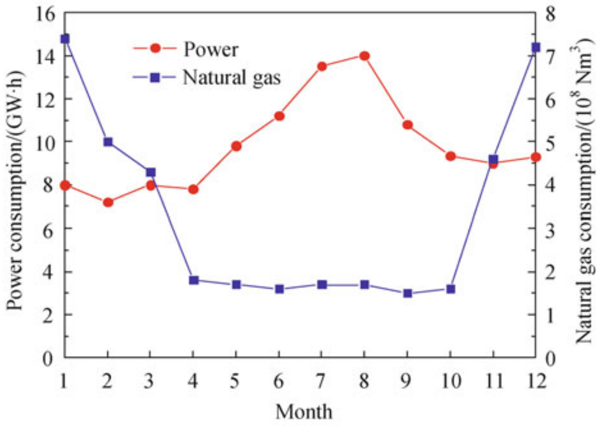


Fig. 14 Power and natural gas consumption of Beijing in 2007

optimized synergy of the system is significant, and the outward constraints of electricity and natural gas should be considered as well. If the natural gas utilization is divided into several levels, from the large-scale CHP to varied-scale distributed energy systems, and if these levels are optimized, interacted, and controlled, then formation of a smart-gas grid is possible in the future.

Water is the scarcest resource in China. In the future, water shortage will become a new bottleneck to sustainable development. The issues on how to save water, how to optimally distribute and use water (pure drinking water, water for residential use, for industrial use, and irrigation, etc.), and how to exploit water resource with proper technologies (seawater desalination, reclaimed water treatment) are important at present and more so in the future. The supply and recycling of water, which are highly relevant to energy issues, will definitely form an intelligent network in mutual promotion and restriction.

According to the law of energy conservation, energy consumed by mankind is eventually dissipating as low-grade heat to the surroundings. Approximately 10% to 20% of dissipated heat goes to waste water. Part of this low-grade heat could be used via heat pumps. Such kind of utilization of water, heat and electricity is the synergy of water grid, heat grid, and electricity-grid as well.

In conclusion, to utilize the widest range of energy sources, the natural gas network, heat (cooling) network, and water network should be developed in similar direction just as smart electric grid is. The synergy of four networks (or more) will form a smart-energy network, within which, smart electric grid will play a dominant role [22].

8 Establish sustainable energy system based on “IDDD + N” principle for synergy of all kinds of energy [23]

8.1 Integration of the processes

Integration means breaking of the boundaries between different sectors of the industry, and integrating mass flows and energy flows of power generation, chemical process, etc. The traditional processes should be changed to achieve overall system optimization from the perspectives of energy, environment, and economy.

Typical systems, such as coal gasification-based poly-generation, realize multi-dimensional, cascade use of energy as follows:

1) Cascade utilization of coal vitalities and tar.

2) Cascade utilization of gas composition (H_2/CO): make differential use of chemical composition of syngas

($H_2 + CO$).

3) Cascade utilization of the pressure: to recover the pressure difference between the process by expanders.

4) Cascade utilization of substances: to minimize unnecessary chemical exothermic processes, such as steam shift process.

5) Cascade utilization of the temperature: thorough and efficient utilization of process heat.

6) Cascade utilization of fuel quality: fine energy, such as natural gas, should be used most sophistically and efficiently, for instance in distributed cogeneration system.

7) Cascade utilization of the physical exergy and chemical exergy by temperature matching, pressure matching, and right ingredients matching.

In the synergistic energy systems, each energy source should play its specific role, especially, the use of renewable energy must be considered based on concrete conditions, which may vary from place to place, from time to time, and may depend on the applications. It is important to insert renewable energy as a considerable share of primary energy to the whole energy system and to put it properly in the entire energy system in a strategic manner. Examples of synergy are that between wind energy and coal chemical industry, and between solar thermal energy and a variety of fossil fuel-fired equipment.

8.2 Differentiation of the demand

The energy requirements of end-users are quite diversified. The different levels and dynamic changes of the energy demand could provide information and guidance for the energy supply and planning. For instance, demand for the heat, electricity, gas, and liquid fuels for vehicles and so on should be carefully differentiated and analyzed. Use the diversified supply to meet the differentiated demand.

8.3 Diversification of the supply

Each energy source has its own characteristics; the focus is not on what they can do, but what they should do in the whole energy system in a synergistic manner to meet the various needs of end-users with relatively less cost.

Basic principles are as follows:

1) Large-scale conversion of high-density and centralized energy production, and connection with end users by the existing infrastructure, such as power, natural gas pipeline network, etc.; distributed use of scattered and low-density energy, such as use of biomass mainly to satisfy the energy demand in rural areas.

2) High-quality energy should be used for power generation; low-quality energy should be used in a cascading manner, and unnecessary energy conversion process should be avoided.

3) Due to its randomness and low-energy density, renewable energy should be used according to specific local conditions, and should be synergized with fossil fuel and other more stable energy sources.

8.4 Decentralized grid in synergy with centralized ones

1) Energy closely matches and connects with end-users in both form and the distance, resulting in high efficiency and low energy loss.

2) Small-scale energy systems (micro-turbines, internal combustion engines, heat pumps, wind power, solar photovoltaic, solar collectors, etc.) should work together with diverse energy storage system (medium- and small-scale power storage, heat storage, gas storage, etc.).

In a sustainable energy system, distributed energy system should be applied based on local conditions. Centralized power grid, distributed power grid, and off-grid operation should collaborate in a complementary manner to improve safety, efficiency, and flexibility of energy supply. The current traditional power grid should be transformed into “smart grid” and then into “smart energy grid” in big cities.

8.5 Network of control and management

Flexibility, controllability, reliability, and online optimization both statically and dynamically are new challenges to energy systems. The rapid development of information technology could be used to promote newly emerging sustainable energy systems, such as data collection, network sensing, online monitoring, data analysis, data mining, data prediction, etc, especially for renewable energy, which has strong randomness and instability. The energy information platform and multi-level optimization network with a wide coverage is necessary.

Abovementioned (integration of the processes, differentiation of the demand, diversification of the supply, decentralized grid in synergy with centralized ones and network of control and management) can be referred to as “IDDD + N.” With the growing awareness of climate change, energy technology (ET) is expected to immensely develop within 30 to 50 years. Situation in various countries are not the same, and China has no example to copy. In addition to advances in energy technology, use of information technology (IT) in addressing energy-related issues is essential. Developing the ideal energy system is an enormous endeavor, and the integration of ET and IT, which may be called energy information technology (EIT), is an inevitable trend to pursue such endeavor.

Establishing the sustainable energy systems with sub-level synergy of various energy sources and implementing the principle of IDDD + N entail gradual processes. However, the goal and the policy must be clear, and measures should be decisive. The principles and requirements of IDDD + N should be broken down into implementation details for various sectors and regions, with demonstration projects of different sizes as templates and benchmarks to be followed. The government should figure out a road map toward IDDD + N, stage by stage and level by level, through institutional changes, regulations, price policies, various state-funded projects and capital investment, establishment of research and engineering centers, capacity building, guidelines for private investments, and so on.

9 Conclusions

1) Energy issues have entered a new era with multi-dimensional and severe challenges.

2) Energy conservation is the fundamental way to achieve sustainable energy development. Therefore, human beings should control appetite for depleting energy, and make energy conservation part of their culture and social morality.

3) From now to 2050, cumulate coal consumption in China will amount to 90 to 100 Gtce, so the strategic arrangements for top-level design should be made to realize the best use of such large amount of coal.

4) The main strategy to meet the energy-related challenges that the world faces is diversity by accessing the widest range of energy sources, competition by bringing out the best way of finding, producing, and distributing energy, and efficiency by making the most of each unit of energy.

5) China, by historical circumstances, will be forced to become a global leader of sustainable development. China should develop its own innovative policies and technologies that could benefit it and the rest of the world.

6) Concerning the status of energy resources and the energy-related challenges faced by China, synergistic utilization of coal and synergy of coal with other energy types are the key to making China a low-carbon economy. Moreover, "IGCC + polygeneration + CCUS" is an important strategic direction for the development of a sustainable energy system.

7) The guiding principle of synergy is "Put the Right thing at the Right place, use the Right system, implement the Right synergies of different kinds of energy, and perform the Right role" (5R).

8) Synergy will open new ideas, create new thinking, and open up a broad scope of innovation in basic research, applied research, and industrial demonstration in the energy system.

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Prof. Ni entered Tsinghua University as an undergraduate in 1950 and was sent to Bauman Polytechnic Institute of Moscow in 1951–1957, and got his Master's Degree. After that, he become an assistant professor in Tsinghua University, and got his PhD at Kalining Polytechnic Institute of Leningrad, USSR (1960–1962). Then he became an associate professor, full professor, Chairman of the Department of Thermal Engineering and Chairman of the Department of Automobile Engineering in 1963–1987. Prof. Ni Weidou was Vice President of Tsinghua University in 1988–1994, Chief Scientist of State "Climbing B" Project in 1995–1999, Chairman of Science and Technology Committee, Ministry of Education in 2000–2010, and Academician of Chinese Academy of Engineering in 1999.

Prof. Ni is a famous scholar in the field of the modeling, simulation, control and diagnostics of turbo-machinery and thermal power systems. He has systematically developed the new theory and method for the modeling and control strategy of complex thermal systems, has attained creative achievement in online monitoring and diagnostics of large power plants, has developed the first training simulator of the gas/steam combined cycle, and has resolved a lot of key problems concerning the application of advanced gas turbines in China.

Prof. Ni is also an important and influential scientist in the field of energy and power in China. As a member of the Consultant Group of State Fundamental Research and the Co-chairman of Energy Group of China Council for International Cooperation on Environment and Development (CCICED), he continues giving consultation on state energy policies as well as on the planning and approving of important research and engineering projects in the energy field in China.

Prof. Ni is now devoted to the sustainable development of energy and energy conservation in China, and has proposed the idea that polygeneration based on coal gasification is the key strategy for the sustainable development of China and has been making a lot of efforts in promoting the research and implementation of polygeneration and methanol and DME as alternative vehicle fuels in China. He also attaches much importance to the research of renewable energies especially wind power in China.

Besides, he has lead many national and international co-operations and research projects in the past 7–8 years and has achieved remarkable results, such as the cooperation of Tsinghua University with British Petroleum (BP) to set up "Tsinghua BP Clean Energy Research and Education Center", devoted to the research on "China Energy strategies and new energy systems; and the cooperation of Tsinghua University with Mitsubishi Heavy Industries (MHI) to set up "Tsinghua University-Mitsubishi Heavy Industries Research and Development Center", dedicated to the research on key technologies of advanced power generation systems.

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