**ESMAP and EASEG TECHNICAL PAPER**
**011**

# *Technology Assessment of Clean Coal Technologies for China: Environmental and Energy Efficiency Improvements for Non-Power Uses of Coal*

## Volume II

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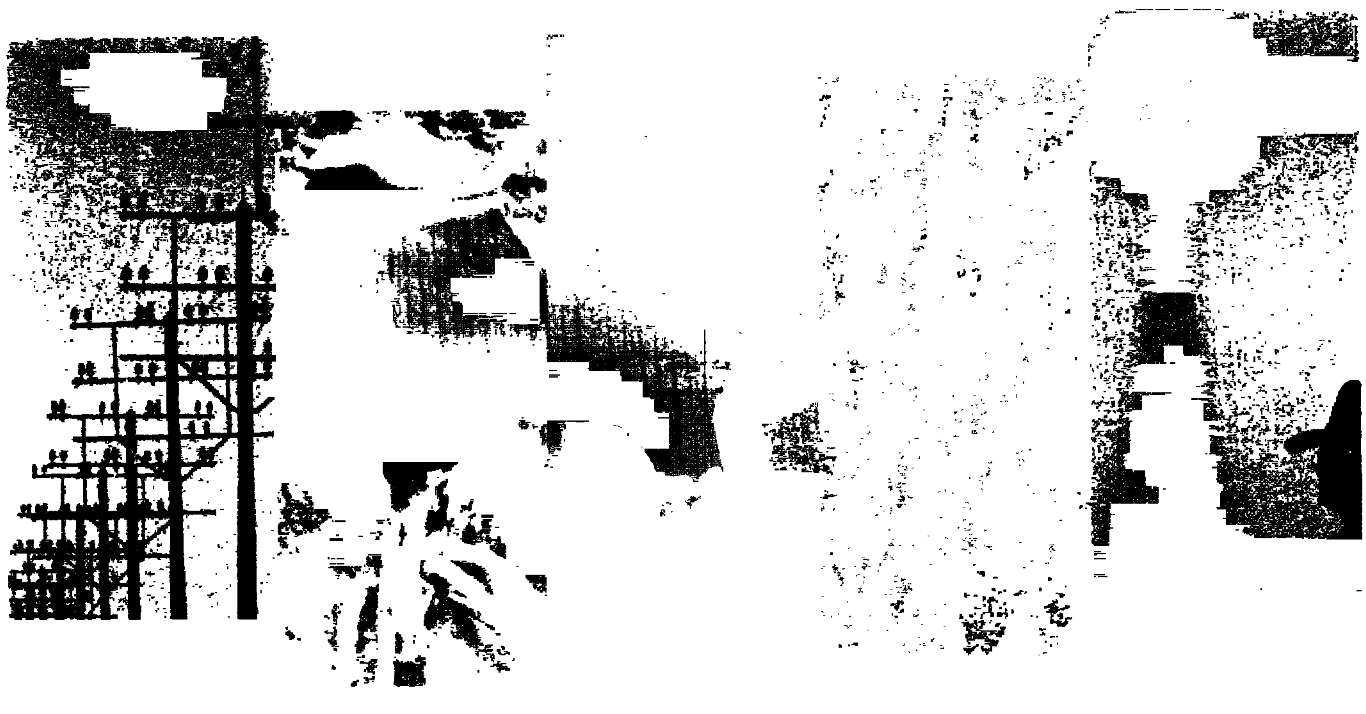
Volume 2



Energy

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May 2001

ESMAP

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JOINT UNDP / WORLD BANK
**ENERGY SECTOR MANAGEMENT ASSISTANCE PROGRAMME (ESMAP)**

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The Joint UNDP/World Bank Energy Sector Management Assistance Programme (ESMAP) is a special global technical assistance program run as part of the World Bank's Energy, Mining and Telecommunications Department. ESMAP provides advice to governments on sustainable energy development. Established with the support of UNDP and bilateral official donors in 1983, it focuses on the role of energy in the development process with the objective of contributing to poverty alleviation, improving living conditions and preserving the environment in developing countries and transition economies. ESMAP centers its interventions on three priority areas: sector reform and restructuring; access to modern energy for the poorest; and promotion of sustainable energy practices.

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# Technology Assessment of Clean Coal Technologies for China:

# Volume 2— Environmental and Energy Efficiency Improvements for Non-power Uses of Coal

May 2001

Joint UNDP/World Bank Energy Sector Management Assistance Programme
(ESMAP)

First printing May 2001

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# Contents

# Foreword

Funding for the studies was provided by a number of sources including Japan Staff and Consultant Trust Fund (JSCTF) large scale study fund, Energy Sector Management Assistance Program (ESMAP), the East Asia and Pacific Region's Energy Sector Unit (EASEG), and the Infrastructure Department's Energy Unit (INFEG). The project was jointly managed by EASEG and INFEG.

This report is based upon a report prepared for the World Bank by the China Coal Processing and Utilization Association with the assistance of Electric Power Research Institute (EPRI), under a contract to The Electric Power Development Corp (EPDC) and Tokyo Electric Power Co (TEPCo) of Japan. World Bank staff[1] led the overall project team supervising this study.

This is the second volume of the Clean Coal Technology Assessment report which focus on the cleaner and more efficiently use of coal in non-power sector. In publishing this report, we hope to provide an insightful analysis of the long-term opportunities CCT presents for the sustainable development of China

Yukon Huang
Director
China Country Unit
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# Preface

This study is one part of the overall project "Clean Coal Technologies for China". The primary objective of the overall project is to assist policy makers, energy and environmental planners in choosing the most appropriate clean coal technologies and environmental control options.

This report focuses on summarizing the development of and technology assessment of clean coal technologies for the non-power sector in China.

# Acknowledgments

The original report was prepared largely by the following persons, working for organizations that are members of the China Coal Processing and Utilization Association (CCPUA).[2] EPRI provided technical review and language editing services to the CCPUA team, and also contributed most of the material for Section 2 on energy and environmental betterment opportunities in the various sectors using coal.

Participating authors includes: Hong Shaohe, Team Leader; Jiang Xianrong, General coal production and use information; Wu Shiyu, Coal preparation; Qin Junjie, Coal briquette; Shi Guochang, Coking; Xu Zhengang, Coal gasification; and Jin Jialu, Direct coal liquefaction.

Technical review was provided by Neville Holt and George Offen from EPRI in California, USA, while Deborah Dunster of Bevilacqua-Knight, Inc., in California edited the document.

This report was prepared by Dean Girdis with editorial assistance by Carl Hammerdorfer. Takahashi Masaki supervised this report preparation.

2 The names of the Chinese and Japanese contributors are presented in conventional Chinese and Japanese fashion (family name, then given name).

# Abbreviations and Acronyms

| | |
|---|---|
| BRICC | Beijing Research Institute of Coal Chemistry |
| BSU – | Bench Scale Unit |
| CCPUA | China Coal Processing and Utilization Association |
| CCRI | China Coal Research Institute |
| COD | Chemical Oxygen Demand |
| DCS | Distributed Control Systems |
| EASEG | East Asia and Pacific Region's Energy Sector Unit |
| EMTEG | Energy, Mining and Telecommunications Department Energy Unit |
| EPRI | Electric Power Research Institute |
| EPDC | Electric Power Development Corporation |
| ESP | High Efficiency Electrostatic Precipitators |
| FCP | New Coke Bricking Technology |
| FGD | Flue Gas Desulfurization |
| IPP | Independent Power Producers |
| IGCC | Integrated Gasification Combined Cycle |
| JCR | Giant Scale Cooking Reactor |
| LPG | Liquefied Petroleum Gas |
| NEDOL | New Energy Power Producers |
| PLC | Programmable Logic Controllers |
| SCR | Selective Catalytic Reduction |
| SEPA | State Environment Protection Agency |
| SETC | State Economic Trade Commission |
| TEPCO | Tokyo Electric Power Company |

# Executive Summary

## Coal Use in China

China is the world's leading producer and consumer of coal, accounting for about three quarters of it's primary energy—in resources, production, and consumption. However, this heavy reliance on coal raises serious sustainability concerns, in terms of both natural resource conservation and environmental impacts.

In particular, these coal resources are not being used as efficiently as possible. More than 80% of the coal consumed in China is combusted directly in equipment that is not designed for high efficiency, such as small kilns and residential stoves. At present, the general energy utilization efficiency of coal in China is about half that of highly industrialized countries.

From an environmental perspective, coal use has had serious impacts on China's land, air, and water. The large amount of coal mining, with associated processing and waste storage, has damaged the ecology of vast tracts of land that could otherwise be used for agriculture. Spontaneous burning of coal refuse piles emit substantial amount of air pollutants, as well as carbon dioxide ($CO_2$), the primary greenhouse gas. Greenhouse gas emissions also come from the estimated 5 $Gm^3$ of coal bed methane vented from underground mines each year. Wastewater is also a problem: every year, large quantities of mine drainage water, slurried fines, effluent from coal cleaning, and other mining-related industrial wastewaters are discharged.

## Clean Coal Technologies for Sustainable Development

China could address concerns over resources and the environment from coal use in the non-power sector by adopting clean coal technologies in a comprehensive "cradle to grave" approach. Coal cleaning should be the starting point and clean, high-efficiency combustion the core in a coordinated program that includes:

- **Coal processing:** Coal preparation and coal briquettes
- **Coal combustion:** Retrofit of industrial boilers and kilns with advanced combustion systems for low nitrogen oxides ($NO_x$) and/or modifications to allow the use of cleaned coal; fluidized-bed boilers; and integrated gasification combined-cycle power generation technology.
- **Coal conversion:** Advanced coke ovens; coal gasification to produce gas for fuel or chemical feedstock; and liquefaction to produce a petroleum substitute from domestic coal.
- **Pollution control/prevention:** Flue gas cleanup of particulate and sulfur dioxide ($SO_2$); comprehensive utilization of fly ash and slag; power generation from coal refuse and fines; utilization of mine water and coal fine slurries; development and utilization of coal bed methane; and environmental treatment of coal mining areas.

## Energy And Environmental Opportunities In Key User Sectors

The coal combustion equipment used in much of the non-power sector in China has not kept pace with advances in the OECD countries. Table 1 compares the typical efficiencies of processes in China with those in OECD countries. In general, the efficiencies in China are about half those in the OECD countries. Correcting this deficiency could reduce coal consumption by 20 to 55%, depending on the sector. Absent any other differences in the processes, most emissions would be reduced proportionally. However, the higher-efficiency technologies are also usually more advanced, lower emitting sources.

**Table 1: Energy and Environmental Benefits from Process Improvements**

| *Sector* | *China Current Coal Usage, Mt/a* | *China Typical Efficiency, %* | *OECD Typical Efficiency, %* | *Potential Coal Reduction with OECD Technology, Mt/a (%)* | *Potential $CO_2$ Reduction, Mt/a* |
|---|---|---|---|---|---|
| Power Generation | 481 | 30 | 36-38* | 80–100 (20) | 47-60 |
| Industrial Boilers | 262 | 60–65 | >80 | 50–60 (20+) | 30–36 |
| Industrial Kilns | 120–140 | 20–25 | 40–60 | 60–70 (50) | 36–42 |
| Metallurgy | 105 | ~1.4 t coal/ t steel | ~0.7 t coal/ t steel | 40–50 (45) | 24–30 |
| Chemicals | 76 | ~2.5 t coal/t ammonia | ~1.5 t coal/ t ammonia | 20 (25) | 12 |
| Residential | 135 | 15% with coal 20–25% with briquette | 50–60% new | 70–80 (55) | 42–56 |

* These efficiencies are averages that include sub- and super-critical, new and old units.

In addition to cleaning coal prior to burning, gasifying, or coking it, the greatest benefits in the non-power sector would be realized by adopting the following strategies for the worst emitters (in terms of number of sources, emissions per unit of product or service, and proximity of the discharges to the population ["nose-level" emitters]).

- Replace the 8,000 indigenous (beehive) coke ovens with larger, advanced coke ovens.
- Accelerate the ongoing switch from raw coal to gas in households and building heating systems. For regions where gas is uneconomical, foster the use of honeycomb briquettes with sulfur capture additives fabricated with modern techniques and burned in new stoves or heaters.
- Upgrade industrial boilers and kilns to cleaner, more-efficient models. Using washed coal could reduce particulate emissions by 25-50% in boilers or kilns without particulate controls, and $SO_2$ emissions by 40-60%. Briquettes would reduce particulate even more, while replacing direct firing of coal with town gas would essentially eliminate particulate and $SO_2$ emissions.

## Metallurgical Industry

The main approach to reducing the coal-based environmental impact of the metallurgical industry is to upgrade coke-making processes. The most significant upgrades are:

- Upgrade to large ovens. Over 75% of the current coke-making capacity is small ovens, especially the indigenous (beehive) ovens mentioned above
- Add particulate controls to existing ovens
- Change from conventional to stamping ovens, which produce a somewhat better coke and are able to use a larger proportion of lower-cost, more abundant high-volatile/weakly caking coals than conventional coke ovens. Alternatively, switch to direct reduction methods using the reducing species in gas derived from coal.

## Chemical Industry

The chemical industry uses about 8% of China's coal consumption to generate synthetic gas (also called 'syngas') as a feedstock for producing ammonia for fertilizer, methanol, and other chemicals. Specifically, two-thirds of the ammonia produced in China comes from syngas, and this conversion takes place in the many small- and medium-sized fertilizer plants, using older, heavily polluting atmospheric fixed-bed water gas producers. Replacing these old units with modern technology could halve the use of coal per ton of ammonia produced and reduce emissions even more. Similarly, because the chemical industry uses 25-30% of the coke manufactured in China, adoption of modern coke-making technologies would have a significant impact on coal conservation and environmental protection. Not only are the modern coke ovens more efficient and lower emitters, but they also produce valuable chemical by-products (e.g., coal gas and benzene).

## Residential Sector

The residential sector has tens of millions of heaters and stoves that use 135 Mt/a of coal, of which 50 Mt/a is in the form of briquettes and most of the rest is raw coal. Raw coal contains a significant percentage of fine coal dust, which is a major source of the particulate emissions from residential stoves and heaters. Many, if not most, households obtain their coal from small mines that typically produce poor quality, untreated coal. Briquettes avoid this problem, as well as capture some $SO_2$, if sulfur capture additives are added to the coal when fabricating the briquettes. In urban areas, approximately 80% of the coal used by residences is in the form of briquettes. Nationally, this number is less than 40%. In addition to their environmental benefits, briquettes can provide efficiency gains if used in newer stoves.

Coal preparation would help as well, but would take a policy or pricing structure that makes it more attractive than unwashed coal. Currently, power plants burn the better quality, cleaner coals and households the dirtier ones, but centralized, large-scale flue gas cleanup at power plants is more cost-effective (and enforceable) than attempts to reduce emissions from each residence and small industrial facility.

Switching to gas would be the cleanest approach, but also the most expensive. Substantial progress is being made in this direction in China, and about two-thirds of the residences in several mid-size and large cities use some form of gas today (natural gas, LPG, or coal-derived gas). However, this number is lower in many other cities and much lower in towns and rural areas. Nationwide, only 10% of the households use gas.

## Coal Preparation

Coal preparation can remove impurities that cause particulate and $SO_2$ emissions. Removing the solid impurities will especially reduce particulate emissions, especially in the many small boilers, furnaces, and kilns with no particulate controls or with low-collection-efficiency devices. In addition, ash removal improves the quality of coke made from coal.

High-sulfur coal (> 2%) currently accounts for 10% of China's coal output. Coal preparation can remove almost half of this sulfur, decreasing $SO_2$ emissions by the same amount. Major reasons for China to significantly increase the use of cleaned coal include:

- China treats only about 26% of its coal, whereas most of the developed world cleans over 60% of its coal.
- It is more important for China to clean its coal than for many other countries because (1) coal provides a greater percent of primary energy than in the other countries (which use more oil and gas), and (2) most of the boilers and kilns that burn this coal have inefficient air pollution controls, if any.
- Coal cleaning is usually the lowest cost method of reducing air pollution and solid combustion by-products, and it is always a cost-effective first step when additional pollution controls are needed to meet an emission limit.
- Coal cleaning reduces the costs and energy consumption of gasifying coal or making coke, and results in better quality coke and briquettes.
- Similarly, coal cleaning reduces operational costs for boilers. For example, at one 300 MW power plant, the station realized the following savings by switching to cleaned coal.

***In financial terms, the net savings were 20 M yuan/year.***

- Cleaned coal avoids the unnecessary transportation of refuse, thereby saving money, reducing the demand on the transportation infrastructure, and decreasing pollution from locomotive exhaust and coal spillage.
- Technology is neither a barrier to widespread use of coal cleaning nor to upgrades to modern equipment. Mature, reliable, and low cost technologies are available from domestic suppliers inside China. In fact, China has demonstrated some advanced systems, notably the integrated Zhongliangshan cleaning plant in Chongqing city, which reduces sulfur content by 63%, sells the cleaned coal, burns the middlings in an on-site fluidized bed combustor, and recovers sulfur from the refuse.

**Key development needs to further the use of coal preparation include:**

- Conversion of existing facilities to state-of-the-art equipment, especially large, centralized plants (to benefit from economies of scale);
- Development of dry processes so that coal cleaning can be used in the arid northwest, where coal mining is being extensively developed;
- More effective coal desulfurization processes;
- High efficiency de-watering equipment for coal fines to improve the product and avoid problems and costs of transporting wet coal fines;
- Automated sensors and data detection instruments to increase product quality and reduce operating costs.

**Obstacles to wider use of coal preparation include:**

- High price differential between cleaned and raw coal, due largely to artificially low prices for raw coal, the absence of widely applied and enforced $SO_2$ emission limits, and low $SO_2$ discharge fees;
- Transportation and coal storage/handling systems that are not organized to handle a variety of coal qualities at the same time -- i.e., keep them separate;
- An investment policy that favors mine expansion at the expense of coal cleaning, especially in locally run state-owned mines and village- and township-run mines.

## Coal Briquetting

Nearly 70% of the coal used in direct combustion devices is fired in small units—about 500,000 industrial boilers, 160,000 industrial kilns, and tens of millions of residential stoves. Many of these combustors require some form of sized, or "pelleted," coal. Yet with the increase in mechanized coal mining, the production of sized coal has dropped significantly and can no longer keep pace with demand. At the same time, there is an over-supply of fine coal.

Briquetting technology offers a solution to this supply/demand dilemma. Briquettes are a form of coal with fixed strength and shape produced from cheap fine and/or low rank coal, held together by a binder. They can answer the need for pelleted or sized coal in residential stoves and in furnaces and kilns used by the metallurgical, chemical manufacturing, machinery, and glass industries. Briquettes also offer significant advantages over traditional sized coal:

- **Energy savings:** Briquettes burn more efficiently than sized coal. For residential ovens and stoves used for heating and cooking, current efficiencies of 15% could be increased up to as much as 60% if briquettes are burned in the newest, high-efficiency stoves. Similarly, industrial boilers, kilns, and steam locomotives burning briquettes can reduce the losses due to entrainment and incomplete combustion, thereby using about 8–20% less coal.

- **Less air pollution:** Compared with bulk coal, honeycomb household briquettes reduce particulate emissions by 40–60%, CO by 80%, $NO_x$ by 55%, and benzo(a)pyrene (BaP) by 90%. Industrial briquettes can reduce particulate emissions by 60% relative to raw coal, $NO_x$ by 25%, and BaP by more than 50%. With desulfurization additives, $SO_2$ emissions can be reduced 40–60% in both sectors.

**Figure 1: Classification of Briquettes by Function**

- Briquette
  - Industrial Briquette
    - Fuel Briquette
      - For industrial boilers
      - For industrial kilns
      - For locomotives
    - Gasification Briquette
      - For gas production in fertilizer industry
      - For industrial fuel gas
    - Briquetting Coke & Briquette for Coking
  - Household Briquette
    - Honeycomb Briquette
      - Upper-ignition honeycomb briquette
      - Common honeycomb briquette
      - Briquette for air hanger heaters
      - Square briquette for roasting
    - Briquette (egg-shaped)
      - For household cooking and heating
      - For chafing dish
      - For heating
      - For roasting

Most of the current production of household briquettes is burned in large and medium-sized cities, where this technology has rapidly gained popularity. As towns continue to strengthen environmental measures and forbid the burning of raw coal, urban demand for household briquettes should increase dramatically. Even greater market growth opportunities for briquette technology lie in the vast countryside, especially in poor and minority nationality areas, which still burn raw coal.

Household briquettes in China are mainly the anthracite honeycomb variety. To make bituminous-based briquettes a viable option for areas where anthracite is not available requires the development of (1) bituminous honeycomb briquettes that cost less than currently available products and (2) dust-free stoves designed to burn these briquettes. Improved sulfur-capture additives are another area requiring development, as people in acid rain and $SO_2$–regulated areas urgently need household briquettes that reduce sulfur emissions.

Briquette technologies also represent an export opportunity. Many countries in Asia and Africa are interested in importing briquette technologies from China to protect their environment, reduce forest lumbering, and encourage the use of bituminous coal.

Industrial briquettes are making slow progress. At present, the total annual output is only about 20 Mt—comprising mainly gasification briquettes, boiler briquettes produced by small-scale stokehold units, and coke briquettes for the metallurgical industry. While the prospects for industrial briquettes are promising, especially as replacement fuels for raw coal in fixed-bed industrial boilers and kilns, technology development should be encouraged for the environmental benefits. For example, stokehold briquetting should be attractive because of its simple process and low capital investment. Alternatively, because blended coals produce better briquettes than single coals, constructing blended-coal briquette plants at existing steam coal blending plants would speed up deployment of this technology and increase its benefits. In addition, research and development is needed on binders and production facilities.

Gasification briquettes require improved waterproof characteristics, which will be developed during the Ninth Five-Year Plan period by tackling the key technology problems of process, facilities, binders, chemical and physical analytical methods, and briquetting theory.

According to international indices comparing prices of commodities, coal prices are unreasonably low relative to the prices of other industrial commodities in China. Therefore, the cost of a briquette (which equals the cost of its fine coal raw material plus the processing costs) is higher than the cost of sized coal, its main competition. In the absence of market forces or restrictions on the use of sized coal (e.g., directly or indirectly through environmental regulations), this price handicap is one of the most important factors restricting coal briquette development.

The Law on the Prevention and Control of Atmospheric Pollution, published in August 1995, expressly provided for vigorous expansion, production, and use of briquette technology. However, the law lacks a complete set of detailed enforcement regulations to restrict various sectors from burning raw coal. Further, the emission fees are so low that enterprises prefer to pay this fee rather than burn a more expensive, environmentally superior coal product (or install pollution controls).

## Coke Manufacture

An important clean coal technology, coking produces both clean secondary energy and feedstock for refined chemical products. The process removes the volatile components in coal to produce coke, a fuel that burns without producing smoke. An important use of coke is to generate the reducing gas needed by the iron and steel industry. Coking already plays a vital role in China's economy, primarily in the metallurgy sector, but also in chemical manufacturing and other sectors. In 1997, coal consumption for coking accounted for more than 13% of China's total coal consumption. In addition, the industry now produces 100,000–200,000 t/a of by-products from the hydrocarbons (especially aromatics) generated when the volatiles are driven out of the coal by the heating process.

Coke is produced in indigenous ovens (also known as 'beehive' ovens), simple mechanical ovens, and the more complex 'regular' ovens. In 1997, indigenous ovens produced nearly 50% of the nation's total coke output, almost equaling the quantities produced by mechanical ovens. Because the indigenous coking process has the lowest capital cost, over 8000 small units are operating now (especially concentrated in Shanxi province). However, coke making by indigenous ovens takes a long time, yields only small amounts of coke per charge and per unit of coal feed, is thermally inefficient (higher heat losses than other processes), and releases substantial amounts of pollutants. In addition, this process discharges the valuable hydrocarbon by-products that are recovered in the other processes. Therefore, the government has established a policy to shut down these ovens, a policy that should be implemented aggressively.

In recent years, metallurgy consumed 50–60% of the coke produced nationwide; the chemical industry used 25–30%; and the machinery industry consumed 5–10% (mainly foundry coke). At present, coke exports are a small percentage of total production, but increasing rapidly. From 1992 to 1998, they increased from about 1% to 8% of the national production.

China's coke oven technology can be as advanced as any in the world, meeting the best technical specifications for coking cabin height and width, oven wall thickness, and heat transfer efficiency. Ninety percent of the design for state-of-the-art ovens can be done in China, and the entire coke oven body can be manufactured domestically. Advanced designs, especially dry coke quenching, are being introduced into China.

Despite the availability of large, modern coke ovens in China, much of the installed capacity is in small units. These small systems inherently emit more pollutants per unit product than large ones. For this reason alone, China should accelerate its policy of shutting down old ovens and replacing them with new, large ones.

Pollutants from the coking industry consist mainly of particulates, harmful gases (leaked raw gas, benzo(a)pyrene, CO, $SO_2$, $NO_x$, and $NH_3$), and wastewater. China has not only developed several gas cleanup processes for coke ovens, but has also mastered a variety of other processes in cooperation with foreign partners and through introduction of key technologies from abroad. These include gas and water cleanup process, such as scrubbing for desulfurization, deoxidization, benzene, and cyanate removal, as well as particulate controls for coal charging and coke pushing operations (75-90% particulate removal is possible). However, these environmental controls are not widely used on coke ovens, particularly on the many small ones.

Computer-automated control systems are widely used in new coking plants and have been retrofit to some old coking facilities. By providing better control of the process, they maximize efficiency and minimize emissions. Increasingly, the primary components and equipment for data processing are produced domestically. The latest automatic control system for oven temperature and pressure, as well as advanced computer management systems for coal charging and coke pushing (discharging), are being developed and deployed.

Much research has been conducted on improving coke quality, with special emphasis on forecasting coke quality based on the coal's petrography and its physical and chemical properties. Because China has so much highly volatile coal, considerable work has been done on the rational utilization of this resource. In addition, laboratory and pilot tests of stamping coking, coal briquette blending, and coal preheating technologies have been carried out. Research has also been conducted on coke properties at both atmospheric and high temperatures, its microscopic structure, and mechanical and other physical properties. Some research results have garnered international interest.

In addition, a process has been developed recently which yields char and a gas that is similar to coke-oven gas using lignite or low-rank coal as feed. Improved upright ovens with continuous distillation capability have been put into operation, and produce a coke with low ash and low sulfur that can be used for the production of ferroalloy.

A relatively new coke making process that merits much wider application is 'stamping coking.' In this process, the coal is compacted by 'stamping' it with hammers before feeding it to the coke oven. The chief benefits of this technology are greater production capacity (due to higher density of the coal feed), lower investment, cheaper feedstock (high-volatile and weakly caking coals can be used instead of strongly caking coals; they cost 10–15 yuan/t less and are much more abundant), and more efficient use of coal. In addition, stamping coking technology can improve coke quality, which improves operation of blast furnaces.

In summary, opportunities for improving the energy, environmental, and/or product yield performance of coke making include:

- Replace the many indigenous and other small coke ovens with large, advanced plants;
- Strengthen environmental protection laws to force the use of the available pollution controls (air and water) and promote the development of improved controls;
- Support the wide deployment of stamping coking technology;
- Develop the emerging processes of: blending briquettes with coal to improve coke strength; dry coke quenching to save energy and reduce pollution; and moisture adjustment to the optimum level to increase coke oven thermal efficiency and output. Moisture adjustment also produces a more uniform, stronger coke block and allows the use of more weakly caking coals;
- Add computerized, automated controls to most coke plants;
- Develop refining techniques that can produce more, higher value products from the off-gases and tars by-products of the coke making process.

## Coal Gasification

Gasification converts coal into coal gas, a convenient form of secondary energy that can be used either as a clean-burning fuel in industry or households, or as a feedstock for chemical synthesis processes. When replacing the use of raw coal in older, inefficient boilers and furnaces, coal gas increases the utilization efficiency of coal, thereby prolonging the life of China's coal resources. Moreover, gasification allows impurities and pollutants such as particulates, $SO_2$, and $NO_x$, to be removed efficiently and economically before combustion.

Coal gasification technology is a prerequisite for clean coal power production by the integrated gasification combined cycle (IGCC) technology, and for large-scale coal chemical manufacture.

Although coal gasification has more than a half-century history in China, its development rate has been comparatively slow. There are 8,000 gasifiers in operation throughout the country, but most are still based on medium- and small-scale atmospheric fixed-bed technologies that are seldom used in most industrialized countries. Advanced, large-scale gasification technologies have rarely been applied in China. However, China has supported significant efforts to develop domestic expertise in gasification technologies, starting in the early 1970s, as well as to import technology from most of the major international suppliers.

One of the biggest applications of coal-derived gas in China is as feed material for synthetic ammonia ($NH_3$) in the many medium- and small-scale nitrogen-based fertilizer plants. Of the total 30 Mt/a output of $NH_3$ in China, about half is produced from coal gas. In addition, coal gas is also used as feed material by some of China's chemical enterprises to produce chemicals such as methanol and as a reducing gas in the metallurgical industry. The CO and $H_2$ in coal gas can directly reduce iron ore into sponge iron, solving the problem of iron smelting in regions lacking coke and coking coal. In the nonferrous metal industry, metallic oxides such as nickel, copper, and tungsten can be melted by using coal gas as the reducing agent.

Coal gas can be used as fuel by a variety of industries—including iron and steel, machinery, building materials, textile, food, and light industries—for heating industrial stoves and kilns, half-made products, and finished products. China currently uses substantial quantities of coal gas with low heating value to heat steel-making furnaces, coke ovens, metal forging heating furnaces, various metal heat-treating furnaces, refractory material kilns, cement kilns, glass kilns, various dryers, and more.

Coal gas is also used as a household fuel, in which case it is usually called town gas. However, because it was introduced for this application only in the last 20–30 years, it now accounts for less than 10% of the total gas consumed by households; the rest is natural gas or liquefied petroleum gas (LPG). Coal gas is used by homes in many large and medium-sized cities, some towns, and several coal mine areas. It is also burned in some larger factories. Due to competition from natural gas and LPG, further development of coal gas for household use is facing a serious challenge. Greater use of coal-based synthetic gas would enhance China's energy security by allowing it to take advantage of its large domestic coal resources and depend less on imports.

Gasification technologies widely used in China or having good prospects for successful application.

- Atmospheric fixed-bed producer gas gasifier—one- and two-stage
- Atmospheric fixed-bed water gas gasifier—one- and two-stage
- Lurgi pressurized fixed-bed gasifier (under dry ash discharge conditions)
- Texaco pressurized entrained-flow gasifier with coal water slurry feed

- Shell pressurized entrained-flow coal gasifier with dry feed of pulverized coal
- GSP pressurized entrained-flow coal gasifier

Although the atmospheric fixed-bed gasifiers are the most widely used in China, the Lurgi, Texaco, Shell, and GSP systems represent large-scale, state-of-the-art technology and should be the preferred systems for all new and upgraded installations.

China's Ninth Five-Year Development Program of CCT and the long-range Objectives of 2010 identify coal gasification as a priority development area. This designation recognizes the benefits that would accrue to the Chinese economy, energy security, and the environment if coal gasification were used more widely and wisely.

For example, because most of the gasifiers used to synthesize ammonia are atmospheric fixed-bed water gas processes with backward technology, out-of-date equipment, and inadequate environmental protections, technology retrofit and renovation are urgently needed to reduce both energy consumption and environmental impacts. In the residential sector, improvement in the standard of living requires replacing bulk coal—and even briquettes—with cleaner, more efficient and convenient fuel sources such as coal gas.

China's coal resources are mainly distributed in the Northwest, while most big coal users are located in the Southeast coastal area. Therefore, a substantial portion of the country's transportation system is dedicated to coal transportation, potentially displacing other goods that could improve the economy or standard of living. In addition, coal is wasted through the energy used to transport the refuse content of unwashed coal and by losses during long-distance transport. This waste could be avoided by mine-mouth conversion of coal to coal gas (as well as electricity), which can be transported (or transmitted) with fewer losses. However, this would require government financing/taxation assistance, in addition to stricter environmental regulations, to offset the costs of the transmission infrastructure.

The market potential for coal gasification is vast; currently less than 8% of China's total coal consumption is used for gasification. Realization of the potential energy and environmental benefits from wider use of this technology requires the following:

- Retrofit of existing gasifiers with newer, more effective technology
- Development of fluidized-bed gasification technology that can use fine coal directly as a feedstock
- Development of larger-scale entrained-flow gasification technology, both by learning from international suppliers (such as the Texaco, Shell, Destec, and GSP) and by conducting independent development efforts
- Development of hot coal-gas cleanup technology to prepare for construction of an IGCC demonstration project

## Direct Coal Liquefaction

Direct coal liquefaction refers to the process by which solid coal is changed into liquefied oil under high pressure at elevated temperature in the presence of a hydrogen donor solvent and catalyst. About 0.5 ton of liquefied oil can be obtained from 1 ton of raw coal (dry ash free basis). The liquefied oil from coal can be processed into high-quality gasoline, diesel, and jet fuel.

Indirect liquefaction is a well-established alternative process for obtaining liquid fuels from coal in which coal is first gasified, and then the resulting synthetic gases are converted to gasoline or other hydrocarbon fuels (typically by the Fischer-Tropsch catalytic conversion process). Currently, China favors direct liquefaction because of its perceived potential for lower costs.

At present, oil accounts for about 18% of China's total primary energy consumption. As the economy continues its rapid growth, the proportion of oil consumption will gradually increase, further widening the gap between domestic petroleum output and consumption. Already, China has switched from an oil-exporter to an oil-importer. Petroleum demand in China is estimated to exceed 200 Mt/a in 2000, but domestic supply will be only 165 Mt/a. Liquefaction processes would allow China to reduce its dependence on oil imports by making use of its extensive coal resources.

The Middle East oil embargo of 1973 led to a resurgence of interest in coal conversion technologies. Some developed countries such as Germany, the United States, Japan, and others researched and developed new processes of direct coal liquefaction, seeking to reduce production costs by extending the range of reaction conditions. Pilot tests (150–600 t/d) were completed for several processes by these countries, all at lower reaction temperatures and/or pressures than the earlier technologies to reduce costs.

Already proven in industrial production, direct coal liquefaction could be a commercially feasible technology in the right economic climate. However, at present there is no commercial plant anywhere in the world because the price of liquefied oil is higher than the price of petroleum. Energy economists estimate that direct coal liquefaction will become economically competitive when the price of petroleum reaches $25/barrel (bbl) and remains at least at that level for an extended period of time. China is in a particularly favorable position to commercialize direct liquefaction because it has ample coal resources, limited oil resources, and lower costs than in other countries. The latter economic factors, in particular, should enable coal-derived oils produced in China to compete more readily with oil at world market prices.

Since the late 1970s, China has been researching direct coal liquefaction technology with the aim of producing transportation fuels and chemical feedstock. The considerable basic R&D on direct coal liquefaction processes has identified 15 types of domestic coals that work well for liquefaction, achieving oil yields of more than 50%. At the same time, high-reactivity catalysts for direct coal liquefaction have been developed. Therefore, China now has completed sufficient basic research on direct coal liquefaction to lay the technical foundation for pilot testing and building a commercial plant. At present, the China Coal Research

Institute has signed cooperation agreements with the related government departments and corporations from Germany, Japan, and the United States for technical and economic feasibility studies of potential direct coal liquefaction demonstration plants in China. Pilot tests with Chinese coals have been completed in these three countries, producing substantial design information. The need remains for one or more larger scale development and demonstration projects in China.

## Policy Recommendations

The following policy changes should be considered to promote quicker, wider adoption of clean coal technologies throughout the nation.

**Increase awareness.** Unless people understand the quality-of-life and economic consequences of the status quo, they have no incentive to support programs that switch to clean coal technologies—and certainly no sense of urgency. Therefore, the authors urge the government to promote education in the following specific areas:

- Environmental impacts;
- Conservation -- explain the need for wise use of coal and the opportunities available from efficient combustion, full use of by-products, and processes that consume the most available coals types;
- Energy security -- a better understanding of why China is a "coal nation" would build support for the expansion of town gas production and development of coal liquefaction technologies;
- Clean coal technologies -- Advise potential end users of the availability and benefits of these processes.

**Strengthen environmental laws.** The key to improving the environment in China's coal economy is to strengthen emission limits and other environmental laws in ways that offer clear preference to clean coal technologies. This requires (1) setting the fines or penalties high enough to provide economic incentive for facilities and individuals to install cleaner technologies, and (2) consistently enforcing the law. To date, lack of enforcement and low discharge fees have impeded the deployment of cleaner, coal-based technologies, as many facilities consider it less expensive to pay penalties than to install the clean equipment.

**Implement clean coal technologies.** Achieving the goal of cleaner, more efficient use of coal will require more intensive processing and conversion of coal at mines, including the construction of large-scale chemical manufacturing facilities and integrated gasification combined cycle (IGCC) power plants directly at these fuel sources.

In its own construction projects, and through mandates and other means, government should ensure that new construction meets stricter standards for emissions and efficiency. Possible measures include the following:

- Require new power plants and industrial kilns to be designed to burn cleaned coal;
- Require new coal mines to build associated cleaning plants;
- Increase investment in cleaning plants for existing mines and foster centralized plants for their economies of scale;
- Construct large coal cleaning plants near power and building material plants, since they can use the by-products (middlings, fines, and refuse);
- Build briquette plants at steam coal blending facilities to take advantage of equipment that is common to both.

More extensive use of washed coal will require development of systems for loading, transporting, unloading, and storing coal that separate it by classification. Government should help the mining and railway sectors coordinate overall planning and construction.

Policies regarding gasification must recognize that different coal gas users have quite different demands, and different grades of coal are distributed unevenly across China's vast territory. Therefore, no single gasification technology is best for all situations. It is necessary to encourage a variety of technologies, based on the type of feed coal, production scale, and specific usage requirements.

Government at both the national and provincial level can also accelerate the transition to a cleaner, more efficient energy economy by encouraging or requiring existing coal-using facilities to upgrade their current equipment with new technology. The highest priorities are:

- Upgrade existing power plants and industrial kilns to burn cleaned steam coal;
- Replace indigenous coke ovens, as well as small- and medium-sized mechanical ovens, with advanced units equipped with environmental and automated process controls;
- Retrofit existing gasifiers with newer technology.

**Intensify R&D.** China should intensify its research and development efforts in clean coal technologies to: (1) develop better technologies than exist in the world today, and (2) raise China's capabilities, so as to reduce the need for imported equipment and expertise. Specific recommendations have been identified previously for each technology.

**Establish preferential tax and funding policies.** Clean coal technologies are generally more expensive than their lower-technology counterparts—sometimes only in the initial investment but not in the life-cycle costs. Because environmental impacts and other negative externalities, such as accelerated depletion of high-value resources, are not incorporated into the price of the equipment that causes these impacts, the private sector has no incentive to pay the premium for the cleaner technologies. To hasten widespread deployment of beneficial clean coal technologies, it is therefore necessary to establish preferential financial policies, such as tax breaks, easy-to-obtain loans with favorable interest rates, or even direct subsidies. Financial assistance should be given to both new installations and environmentally beneficial upgrades to existing facilities. Beyond equipment installation, long-term favorable treatment could also be extended to industries that contribute significantly to better coal use. For example, briquette production companies could be eligible for lower taxes.

**Integrate programs, policies, and regulations.** Central to the success of all the above recommendations is their effective integration. As soon as possible, China should establish a mid- and long-term coal industry development program. The program should promote development and deployment of clean coal technologies and promote improvement of coal quality and environmental protection. The program's goals and assignment of responsibility should be clear and practicable.

A dedicated clean coal program at the level of the central government will allow rational implementation of measures with broad impacts, such as adjustments to the price of coal. Avoiding overproduction—by closing small, inefficient, polluting mines—will improve the cost-competitiveness of both washed coal and briquettes, and, indeed, all technologies offering higher efficiency.

# 1

# Introduction

China is the world's leading producer and consumer of coal, which is by far its dominant energy source. Coal accounts for about three quarters of China's primary energy—in resources, production, and consumption. Given the nation's energy resource reserves, advanced capabilities in the science and technology of coal use, and demand for rapid economic development, China will continue to rely on coal as its dominant fuel for a long time to come.

However, this heavy reliance on coal raises serious sustainability concerns, in terms of both natural resource conservation and environmental impacts.

## Sustainability Issues

Natural resource depletion is a concern with high coal use in the face of rapid economic expansion. Although China's proven recoverable reserves of coal are extensive—accounting for 11% of the world's reserves—on a per capita basis they are less than half the world average. And these reserves are being mined at a very fast pace, with current mining accounting for more than a quarter of total world coal output. This pace of consumption threatens sustainable development of the national economy.

Moreover, these coal resources are not being used as efficiently as possible. More than 80% of the coal consumed in China is combusted directly in equipment that is not designed for high efficiency, such as small kilns and residential stoves; consequently, the utilization efficiency of coal is much less than it could be. At present, the general energy utilization efficiency of coal in China is only about 9%—about half that of highly industrialized countries.[3]

From an environmental perspective, coal use has had serious impacts on China's land, air, and water. The large amount of coal mining, with associated processing and waste storage, has damaged the ecology of vast tracts of land that could otherwise be used for agriculture. The quantity of coal refuse (mine tailings plus cleaning plant discharge solids) amounts to 3 Gt, with an additional 140 Mt being added each year at today's production rates. This coal waste

[3] The 9% figure is based on a mining efficiency of 32%; a combined processing, conversion, storage and transportation efficiency of 70%; and an end use efficiency of 41%.

is distributed in 1200 piles, of which more than 120 have caught fire spontaneously, emitting substantial amounts of sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$) , carbon monoxide (CO), hydrogen sulfide ($H_2S$), and particulate matter, as well as carbon dioxide ($CO_2$), the primary greenhouse gas. Greenhouse gas emissions also come from the estimated 5 $Gm^3$ of coal bed methane vented from underground mines each year. Wastewater is also a problem: every year, 2.2 Gt of mine drainage water, 10 Mt of slurried fines, about 28 Mt of effluent from coal cleaning, and 30 Mt of other mining-related industrial wastewaters are discharged.

In addition to production impacts, coal consumption—especially direct combustion—is causing serious air quality problems in most of China's cities. About 74% of the $SO_2$ emitted in China, 85% of the CO, 60% of the $NO_x$, and 70% of the particulate emissions come from coal combustion. Coal combustion is also the chief cause of the country's growing acid rain problems; acid rain areas now exceed 40% of China's territory.

All told, excessively fast consumption of coal resources and serious environmental deterioration have become keyfactors limiting the pace of China's economic development. Accepting that future development must follow a sustainable path, it is inevitable that China pursue vigorous development of clean coal technology. This strategy is the only feasible way to resolve the competing demands of economic development on the one hand, and resource conservation and environmental concerns on the other.

## Clean Coal Technologies

China should approach clean coal technologies as a comprehensive "cradle to grave" system, with coal cleaning as the starting point; clean, high-efficiency combustion as the core; gasification and coke making to improve metallurgical processing, obtain chemicals from coal (especially ammonia for fertilizer and aromatic hydrocarbons), and provide an indigenous source of gas for residential, institutional, and small industrial boilers and effective pollution control and reclamation of mining areas to protect the environment. Specifically, the following clean coal technologies should be used:

- **Coal processing:** Coal preparation and coal briquettes
- **Coal combustion:** Retrofit of industrial boilers and kilns with advanced combustion systems for low $NO_x$ and/or modifications to allow the use of cleaned coal, fluidized-bed boilers, integrated gasification combined-cycle power generation technology, etc.
- **Coal conversion:** (1) advanced coke ovens; (2) coal gasification to produce gas for other uses, including fuel cells, or as part of an integrated gasification combined-cycle system; and (3) liquefaction to produce a petroleum substitute from domestic coal.
- **Pollution control:** Flue gas cleanup, comprehensive utilization of fly ash and slag, power generation from coal refuse and fines, utilization of mine water and coal fine slurries, development and utilization of coal bed methane, and environmental treatment of coal mining areas.

This report focuses on the key technologies that merit priority development:

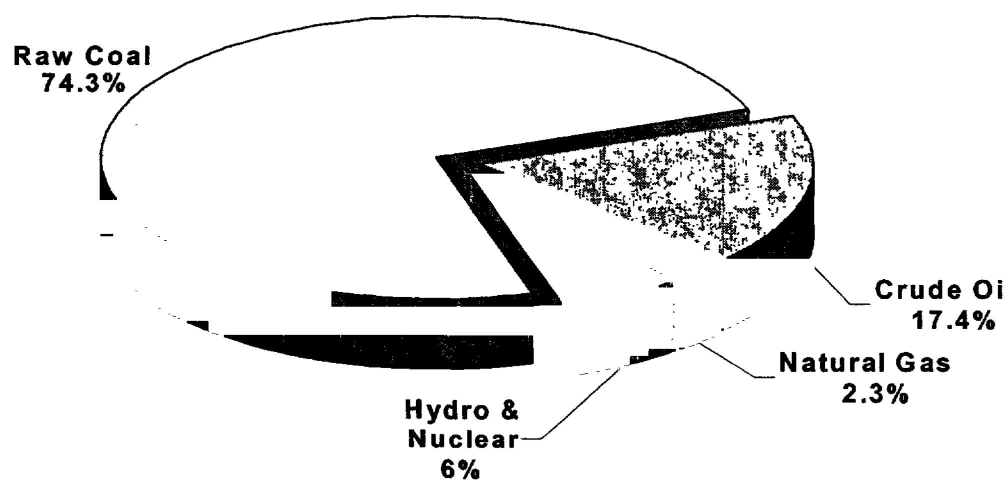
- Coal preparation
- Coal-based briquettes
- Coke making
- Coal gasification
- Direct coal liquefaction (primarily to produce transportation fuels)

Each technology is discussed in a separate section of the report, following a summary in Section 2 of the opportunities for each of the major non-power-sector coal consumers to improve their energy utilization and environmental performance when using coal.

## Coal Production

Over the last two decades, coal has accounted for 70–75% of China's primary energy production.[4] In 1997, China produced 1325 Mt of coal (1026 Mt bituminous, 241 Mt anthracite, and 57 Mt lignite), which accounted for 74.3% of its primary energy production as shown in Figure 1.1. In contrast, China's 1997 crude oil production was 160 Mt, (17.4% of the total energy mix); natural gas production was 22,800 $Mm^3$ (2.3%); and hydropower and nuclear generation combined were 196 TWh (6.0%).

**Figure 1.1: Primary Energy Production n China, 1997**

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[4] Primary energy refers to energy obtained directly from natural resources—fossil fuels, hydropower, and nuclear; coal-derived gas, coke, etc., are called secondary energy sources.

Table 1.1 indicates coal's share in China's total primary energy mix for selected years from 1980 to 1997. The proportion of coal increased each year through 1995, when it began to decrease slightly. Levels of coal production, classified by rank of coal, are shown in Table 1.2.

**Table 1.1: Coal Output and Primary Energy Output and Mix (1980–1997)**

| *Year* | *Total Output, Mtce/a** | *Raw Coal, Mt/a* | *Primary Energy Mix, %* | | | |
|---|---|---|---|---|---|---|
| | | | *Raw Coal* | *Crude Oil* | *Natural Gas* | *Hydropower and Nuclear* |
| 1980 | 637 | 620 | 69.4 | 23.8 | 3.0 | 3.8 |
| 1985 | 855 | 872 | 72.8 | 20.9 | 2.0 | 4.3 |
| 1990 | 1039 | 1080 | 74.2 | 19.0 | 2.0 | 4.8 |
| 1995 | 1290 | 1361 | 75.3 | 16.6 | 1.9 | 6.2 |
| 1997 | 1320 | 1374 | 74.3 | 17.4 | 2.3 | 6.0 |

* Mtce/a means "million tonnes of coal equivalent per annum" based on a coal with heating value of 7000 kcal/kg.

**Table 1.2: China's Coal Output in 1997, Mt/a**

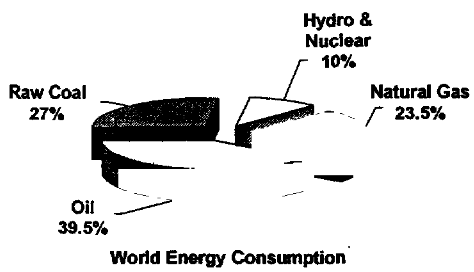
<table>
<tr><td colspan="3">Total</td><td>1325</td></tr>
<tr><td colspan="3">Anthracite Coal</td><td>242</td></tr>
<tr><td rowspan="17">Bituminous Coal</td><td colspan="2">Total Bituminous Coal</td><td>1026</td></tr>
<tr><td rowspan="9">Coking bituminous</td><td>Subtotal</td><td>637</td></tr>
<tr><td>Meager lean coal</td><td>29</td></tr>
<tr><td>Lean coal</td><td>51</td></tr>
<tr><td>Coking coal</td><td>109</td></tr>
<tr><td>Fat coal</td><td>84</td></tr>
<tr><td>1/3 Coking coal</td><td>102</td></tr>
<tr><td>Gas-fat coal</td><td>69</td></tr>
<tr><td>Gas coal</td><td>112</td></tr>
<tr><td>Other</td><td>81</td></tr>
<tr><td rowspan="7">Other bituminous</td><td>Subtotal</td><td>389</td></tr>
<tr><td>Meager coal</td><td>59</td></tr>
<tr><td>½ Medium caking coal</td><td>0*</td></tr>
<tr><td>Weakly caking coal</td><td>81</td></tr>
<tr><td>Non-caking coal</td><td>20</td></tr>
<tr><td>Long flame coal</td><td>117</td></tr>
<tr><td>Other</td><td>112</td></tr>
<tr><td colspan="3">Lignite</td><td>57</td></tr>
</table>

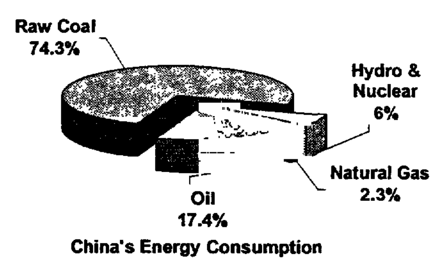
* Actually 0.24 Mt/a

## Coal Consumption

In 1996, total primary energy consumption in the world was 11.97 Gtce, of which petroleum accounted for 39.5%, coal 26.9%, natural gas 23.5%, and hydropower and nuclear energy, 10%. As shown in Figure 1.2, energy consumption patterns in China do not mirror this world average. In China, coal is far and away the dominant energy source, accounting for over 70% of the country's primary energy use. Coal's share of the primary energy consumption mix consistently increased from 1980 to 1987, when it peaked at 76.2% (see Appendix A for details). Throughout the 1990s, coal's percentage contribution to total energy use has decreased, while petroleum, hydropower, and nuclear energy use have increased. Despite this slight downward trend, coal will continue to dominate China's energy consumption mix for the foreseeable future.

**Figure 1.2: Primary Energy Use, World Average and China**




Coal consumption in China is dominated by five main sectors: power generation and heating (combined heat and power, district heating, and "central" heating, i.e., boilers in large residential or commercial buildings), metallurgy, building materials, chemical manufacturing, and residential use. The industrial sectors use coal for furnaces, boilers to produce steam for industrial processes and space heating, and coke making, as well as a raw material (e.g., in a gasifier at a fertilizer plant that produces ammonia from the gasifier's output). As shown in Table 1.3, these five sectors' share of the total coal consumption increased 10 percentage points from 1990 to 1997. Significantly, the increases were in the power generation and heating sector, while residential use decreased, being replaced by gas (natural or liquefied petroleum) or centrally supplied heating boilers. This change is good news, indicating progressive improvement in overall energy use efficiency, environmental quality, and public awareness of the importance of energy conservation.

**Table 1.3: Coal Consumption by Main Sectors in China (Mt/a)**

| | *1990* | *1995* | *1996* | *1997* |
|---|---|---|---|---|
| Total Coal Consumption | 1055.23 | 1307.39 | 1356.19 | 1310.70 |
| 1. Power generation and heating | 290.82 | 476.61 | 522.08 | 538.43 |
| power generation portion | 264.97 | 430.01 | 470.46 | 481.23 |
| heating portion | 25.85 | 46.60 | 51.62 | 52.20 |
| 2. Metallurgy | 80.87 | 101.47 | 107.80 | 104.32 |
| 3. Chemicals | 59.72 | 81.68 | 82.32 | 76.22 |
| 4. Building materials | 106.86 | 154.52 | 154.98 | 152.07 |
| 5. Residential use | 167.00 | 135.30 | 143.99 | 135.00 |
| Subtotal of these 5 sectors | 715.18 | 949.57 | 1011.17 | 1001.04 |
| Five-sector share of total coal use | 66.83% | 72.63% | 74.56% | 76.37% |

## Energy Consumption Forecasts

The demand for energy is closely related to such factors as population growth, rising living standards, economic development and restructuring, energy mix, energy conservation efforts, and technological innovation. At present, China is vigorously pushing fundamental economic system reform and growth, and seeking to adjust industrial and energy structures accordingly.

Analysts suggest that China will be able to sustain an average annual economic growth rate of 7.2% during the ninth and tenth Five-Year periods, with little or no increase in energy consumption. Such an accomplishment will require major efficiency improvements in energy production, conversion, and use, as well as the introduction of new, more efficient industrial processes.

The five main coal-consuming sectors have increased their share of China's coal consumption from 66.8% in 1990 to 76.4% in 1997, with 1.4% average annual growth. Preliminary estimates indicate that these five sectors accounted for 80% of total national coal consumption in 1998. If their percentage of coal consumption is 81% in 1999 and 82% in 2000, China's total coal consumption will be about 1.2 Gt in these years. If the share is still 82% in 2005, total coal consumption will reach 1.3 Gt of coal—which just matches China's mining production capacity. By 2010, analysts predict annual coal usage of 1.5 Gt, which will be achieved by opening new, large mines using advanced technologies, while at the same time shutting down older, smaller, less-efficient, and more-polluting mines. Predictions of the distribution of this coal usage by energy sector are presented in Table 1.4.

**Table 1.4: Predicted Coal Consumption of Main Sectors in China (Mt/a)**

| | *1998* | *1999* | *2000* | *2005* |
|---|---|---|---|---|
| Total Coal Consumption | 1200 | 1182 | 1200 | 1300 |
| 1. Power generation and heating | 517 | 534 | 552.5 | 615 |
| power generation portion | 462 | 478 | 495 | 550 |
| heating portion | 55 | 56 | 57.5 | 65 |
| 2. Metallurgy | 100 | 100 | 100 | 100 |
| 3. Chemicals | 73 | 74.5 | 76 | 78.5 |
| 4. Building materials | 138 | 135 | 135 | 140 |
| 5. Residential use | 130 | 125 | 120 | 130 |
| Subtotal of these 5 sectors | 958 | 968.5 | 983.5 | 1063.5 |
| Five-sector share of total coal use | 80% | 82% | 82% | 82% |
| Consumption by other sectors | 242 | 213.5 | 216.5 | 236.5 |
| Share consumed by other sectors | 20% | 19% | 18% | 18% |

## Substituting Gas for Coal

Natural gas is the cleanest of fossil fuels, with only 1/200 the sulfur emissions and half the $CO_2$ emissions of coal—and no particulate emissions (compared to 21.9 kg of particulate for each tonne of coal burned). Moreover, natural gas can be burned efficiently in small combustors. Therefore, it is easy to see why, around the world, natural gas is being rapidly substituted for other fossil fuels. Increasing the share of natural gas in China's energy mix can alleviate the country's air pollution. However, this is a limited solution.

As of 1997, natural gas comprised only 2.2% of China's energy consumption mix, compared with a world average of 23.5%. Natural gas output in 1996 was 20.1 $Gm^3$. The country's reserves are not extensive; as of 1996, proven natural gas reserves were 1170 $Gm^3$, with a reserve-to-mining ratio of 58.8, ranking 20th in the world. Although several new, large gas fields have been found recently in the northwest and south of China, to date they have not been explored sufficiently to estimate their reserves. Moreover, natural gas requires a more complex transmission and distribution infrastructure than coal, with pipelines and underground storage reservoirs.

Analysts project that natural gas production and use will grow to 7–8% of China's primary energy resources by 2010, and to 9–10% by 2020. Yet even with this approximate quadrupling in use over the next two decades (as a percent of overall energy consumption; the actual use in absolute quantities [i.e., in $Gm^3/y$] will increase faster), the role of natural gas in China's overall energy consumption will remain relatively small. Natural gas will chiefly be used in areas where transmission and distribution piping systems can be installed economically, such as newly developed areas of major cities, industrial centers, and regions close to gas fields.

Nonetheless, natural gas can make an important contribution to environmental improvement, particularly in cities afflicted with poor air quality. Government policy should promote expanded natural gas exploration and industry development.

# 2

# Energy And Environmental Opportunities In Key User Sectors

The major part of this report (Sections 3 through 7) presents the energy and environmental status and opportunities for betterment of coal processing technologies. These technologies produce fuels and feedstocks for household, commercial, and industrial users, and the discussion focuses mainly on approaches to improving the overall performance of these conversion processes. However, the real purpose of these processes is to produce fuels and feedstocks that lead to better energy efficiency, lower pollution, and conservation of natural resources when used by end users. This section summarizes the opportunities for achieving these objectives in the principal non-power end user sectors.

## Overview

Table 2.1 identifies the main users of coal in China and shows which coal processing technologies can improve the energy and environmental performance of these end users. This is the same list of end users that was presented in Tables 1.3 and 1.4, but with the industrial boilers that provide heating and process steam listed separately and the building sector included in industrial kilns. The earlier tables included these boilers in the industrial sector that used them (e.g., heating, chemical, etc.). The table shows that gasification can reduce emissions and/or improve thermal efficiency for all end users; this includes replacement of older gasifiers with more advanced ones where they are currently already being used—to produce feedstock primarily for making ammonia in fertilizer plants and secondarily for other chemicals—as well as substitution of coal, briquettes, or coke with a fuel gas. Industrial boilers and residences, especially those burning raw coal, could also benefit from switching to briquettes, while the metallurgy and chemical industry would benefit indirectly by obtaining coke that is produced with less environmental impact or use of scarce coking coals. All users of coal, including the gasification and coke making sectors, could benefit from cleaning of a greater amount of coal.

**Table 2.1: Opportunities for Environmental Betterment from Fuel or Feedstock Changes**

| *Fuel Sector* | *Gasification* | *Briquette* | *Coke* | *Coal Preparation* |
|---|---|---|---|---|
| Power Generation | X | | | X |
| Industrial Boilers | X | X | | X |
| Industrial Kilns | X | | | X |
| Metallurgy | X | | X | X |
| Chemicals | X | | X | X |
| Residential | X | X | | X |

The equipment used in many of these sectors has not kept pace with advances in the OECD countries. Table 2.2 compares the typical efficiencies of processes in China with those in OECD countries. In general, the efficiencies in China are about half those in the OECD countries, and correcting this deficiency could reduce coal consumption by 20 to 55%, depending on the sector. Absent any other differences in the processes, most emissions would be reduced proportionally; however, the higher-efficiency technologies are also usually more advanced, lower-emitting sources. Of course, upgrading the combustion systems in all these industries would require an extensive investment and, therefore, time to accomplish.

**Table 2.2: Energy and Environmental Benefits from Process Improvements**

| *Sector* | *China Current Coal Usage, Mt/a* | *China Typical Efficiency, %* | *OECD Typical Efficiency, %* | *Potential Coal Reduction with OECD Technology, Mt/a (%)* | *Potential $CO_2$ Reduction, Mt/a* |
|---|---|---|---|---|---|
| Power Generation | 481 | 30* | 36-38* | 80-100 (20) | 47-60 |
| Industrial Boilers | 262 | 60–65 | >80 | 50–60 (20+) | 30–36 |
| Industrial Kilns | 120–140 | 20–25 | 40–60 | 60–70 (50) | 36–42 |
| Metallurgy | 105 | ~1.4 t coal/ t steel | ~0.7 t coal/ t steel | 40–50 (45) | 24–30 |
| Chemicals | 76 | ~2.5 t coal/t ammonia | ~1.5 t coal/ t ammonia | 20 (25) | 12 |
| Residential | 135 | 15% with coal 20–25% with briquette | 50–60% new | 70–80 (55) | 42–56 |

* These efficiencies are average that include sub- and super-critical, new and old units

## Environmental Improvements by Sector

Section 3 presents information on the benefits of cleaning coal prior to burning it in power plants, and that discussion will not be repeated here. The balance of this section discusses the other opportunities available to the main end-use sectors. Overall, the biggest benefits would be realized by adopting the following strategies, which focus on the biggest and worst emitters in terms of emissions per unit of economic productivity or personal service, and proximity of the discharge to the population ("nose-level" emitters).

Replace the 8000 indigenous (beehive) coke ovens with larger, advanced coke ovens using designs, such as stamping coking ovens, that maximize the use of China's abundant resources of high volatile, weakly caking coals (and minimize the need for the less abundant, higher value fat and primary coking coals). This is already government policy, to be implemented as quickly as social conditions allow.

- Accelerate the ongoing switch from raw coal to gas in households and building heating systems. For energy security reasons, consider policies that favor coal-derived gas (from gasification) over natural gas or liquefied petroleum gas. Foster the use of honeycomb briquettes with sulfur capture additives fabricated with modern techniques and burned in new stoves or heaters where any kind of gas is uneconomical (e.g., in rural areas or towns too small to justify a centralized gasifier plant).

- Upgrade industrial boilers and kilns to cleaner, more-efficient models.

### *Industrial Boilers*

China has about 500,000 industrial boilers, and they consume over 260 Mt/a coal (another source reports 400 Mt/a for "fixed-bed" industrial boilers and kilns, as reported in Section 4.4.2; this includes the coal fired by the 160,000 industrial kilns in China). In addition to the boiler upgrades for improved efficiency and lower inherent emissions mentioned above, this sector could benefit from using washed coal or briquettes instead of raw coal, or from switching to gas. The emission benefits and costs of each of these options are summarized in Table 2.3.

**Table 2.3: Benefits of Switching Industrial Boilers to Cleaner Fuels**

| *Fuel* | *Particulate Reduction, %* | *$\Delta SO_2$, %* | *$\Delta NO_x$, %* | *Cost** |
|---|---|---|---|---|
| Washed Coal | 25–50% ash reduction; also 25–50% particulate reduction if the boiler is uncontrolled** | 45 | -- | • ~15% (45 yuan/t) for conventional cleaning at 20% ash removal (24 kJ/kg)<br>• ~23% (70 yuan/t) at 37% ash removal (27 kJ/kg) |
| Briquettes with Sulfur-Capture Additives | 60 | 40–60 | 25 | ~ 50 yuan/t |
| Town Gas† | 100 | 100 | ~50 (estimate) | • 1–1.2 yuan/$m^3$ @ 3500 kcal/$m^3$<br>• 0.6–0.8 yuan/$m^3$ @ 2500 kcal/$m^3$ |

* All costs exclude the savings from having a higher heat content and/or more efficient burning fuel.

** The percent reductions may be less if the boiler has particulate controls, depending on the type of control, firing type (pulverized or grate), and coal grinding system used.

† Costs are for town gas delivered to the burner tip in a residence, and include the gasifier plant, distribution net, and stove/heater upgrade in the home; in an industrial application the user would be expected to incur the combustor upgrade.

Natural gas and liquefied petroleum gas (LPG) are options that are receiving increasing favor by certain government agencies, but they are not clean coal technologies, and their availability and price are expected to be very site-specific.

### *Building Materials*

Most of the coal used by this industry sector is burned in industrial kilns, and the environmental betterment options for these units are essentially the same as those discussed in the prior Section on industrial boilers; hence it will not be repeated here. The opportunities for energy efficiency were presented in Table 2.2 under the category of industrial kilns. One difference between the OECD and Chinese kilns is capacity; for example, most cement plants in OECD countries produce 300–400 kt/a, whereas the average for China is 40 kt/a.

In a different vein, this industry could *contribute* to energy savings in residential, commercial, and industrial buildings by producing hollow building blocks for walls. These blocks reduce energy consumption for heating by about 20%. China uses solid clay bricks for most walls, whereas these account for only 22% of the wall materials produced in OECD countries; the rest is hollow blocks.

### *Metallurgical Industry*

Coke production is the main consumer of coal by the metallurgical industry; therefore, this process is the main source of coal-derived pollution and a key contributor to both below-standard thermal efficiencies and the depletion of more high-value (high-caking) coals than necessary. Therefore, the methods for improving the efficiency and decreasing the emissions of the coke-making processes discussed in Chapter 5 are the means of achieving these goals for the metallurgical industry. These options are summarized here.

- **Upgrade to large ovens.** Only 12.7% of the total coke produced in China comes from large ovens, and 9.7% comes from small-size units.[5] Therefore, over 75% of the capacity comes from small units. The biggest improvement would come from replacing the many indigenous coke ovens with large, advanced-technology ovens. This would greatly reduce the emissions from these sources—the indigenous units typically emit 20 kg of particulate, 6.1 kg of $SO_2$, and 3.9 of kg benzene compounds per tonne of coke produced, not to mention large quantities of volatile phenol, cyanide, and wastewater contaminated with organics. Additional benefits would accrue from the recovery of chemicals, improved efficiency of the metallurgical and chemical processes that use the coke (due to a higher quality, lower ash coke), and lower coal consumption to produce the coke.

  For the mechanical units, increasing cabin size reduces the length of the seals through which pollutants escape from the cabin and, therefore, the emission rates (because the surface to volume ratio decreases as cabin volume increases). For example, increasing the cabin height from 4.5 m to 7.6 m or 10.0 m reduces the seal length by 62% and 83%, respectively, and the emissions would be expected to decrease proportionally. A state-of-the-art plant that produces 900,000 t/a in two ovens would cost approximately 1.3 billion yuan (including modern environmental controls), while current technology costs 0.5–0.7 billion yuan.

- **Add particulate controls to existing ovens.** Approximately 90% of the mechanical ovens have particulate controls for coal charging, and these controls typically capture 80–90% of the particulate emissions. However, only about 15% have controls for coke pushing, the other major emission source. The cost and benefits of adding particulate controls for coke pushing are:

| Cabin Height/ Capacity | Investment, $10^4$ yuan | Power Demand, kW | Particulate Removal, % |
|---|---|---|---|
| 6 m, 900,000 t/a | 1700 | 300 | 90 |
| 4.3 m, 280,000 t/a | 1000 | 180 | 85 |

If a plant needs controls for both coke pushing and coal charging, the costs would be:

5 "Large" is considered to be cabin heights ≥ 4.3 m with cabin volumes up to 38.5 $m^3$; even this size is only half the size of the biggest units built in OECD countries. "Small" typically is a unit with ≤ 6-$m^3$ cabin volume.

| Cabin Height/ Capacity | Investment, $10^4$ yuan | Power Demand, kW | Particulate Removal, % |
|---|---|---|---|
| 6 m, 900,000 t/a | 3450 | 680–980 | 90 pushing<br>80 charging |
| 4.3 m, 280,000 t/a | 2250 | < 580 | 85 pushing<br>90 charging |
| Coal feed "truck" (roof-top rail car) for charging | 250 | 180 | 85 |

- **Change to stamping coke ovens.** These ovens produce a somewhat better coke and are able to use a higher proportion of the lower-cost high-volatile/weakly-caking coals than conventional coke ovens. In addition, they have a greater production capacity (for a given size) and require a lower investment than conventional ovens. Just using a higher fraction of the lower cost coal in the blend that feeds the coke oven would reduce the cost of coke by 3.3 yuan/t. From the use perspective, a 2000 $m^3$ blast furnace could save 17,500 t/a of coke feed and produce 73,000 t/a more iron if it switched from conventional to stamping coke.

An alternative approach to reducing emissions from metallurgical operations is to switch from coke to direct reduction methods, thereby avoiding the emissions from the coke making process. The CO and $H_2$ in the coal gas are strong reducing agents, and can be used to directly reduce iron ore into sponge iron. In the nonferrous metal industry, metallic oxides such as nickel, copper, and tungsten can be melted by using coal gas as the reducing agent.

### *Chemical Industry*

In addition to using coal to fire process heaters and furnaces, this industry consumes much of the synthetic gas produced from coal as a feedstock to produce ammonia for fertilizer, methanol, and other chemicals. About 8% of China's coal consumption is used to produce synthetic gas. Two-thirds of the 30 Mt/a ammonia produced in China is manufactured and in small- and medium-sized fertilizer plants, and 75–90% of these plants use synthetic gas as a feedstock, versus only 12% of the large plants. Importantly, the gasifiers at these smaller plants are the older, heavily polluting, atmospheric fixed-bed water gas producers. The industry also uses 25–30% of the total national coke production as a fuel for its furnaces or as feedstock for various chemicals. Therefore, coal-based environmental gains in this sector could come mainly from the replacement of existing gasification and coke making technologies with advanced processes. For the gasification sector, such a replacement strategy could halve the use of coal per tonne ammonia produced and reduce emissions by an order of magnitude (i.e., approximately 90%). The opportunities for improvement in coke making were summarized in the discussion of the metallurgical industry (previous subsection).

Other opportunities for improved productivity in this industry that are related to coal could come from changing how it is used. Replacing the indigenous coke ovens with advanced coke-making technology would provide the industry with 352 $m^3$ of coal gas, 54 kg tar, and 15.4 kg of crude benzene per tonne of coke produced that is now lost (not recovered from the exhaust gas) in this archaic process. Using coke produced from partly or even fully weakly caking, high volatile coal instead of metallurgical-grade coke to produce gas, calcium carbide, and iron alloy would save the less abundant, higher cost coals needed to make metallurgical-grade coke for applications that need this quality. And, finally, building large coke plants and concentrating them in areas where there are many chemical plants would increase the diversity of chemicals that could be produced from the tar by-products of the coke making process.

### *Households (Residential Uses)*

Currently, the tens of millions of heaters and stoves in the residential sector use 135 Mt/a of coal, of which 50 Mt/a is in the form of briquettes and most of the rest is raw coal. Individual households use about 1 t/a in the north and 0.6–0.7 t/a in the south. Raw coal contains a significant percentage of fine coal dust, which is a major source of the particulate emissions from residential stoves and heaters. Virtually no sized coal is used by households because it costs more and is not needed by their stoves and heaters (unlike gasifiers, and some industrial kilns and boilers, which do need a sized, or pelleted, feedstock). Many, if not most, households obtain their coals from small mines that typically produce a poor quality, untreated coal.

Briquettes avoid this problem, as well as capture some $SO_2$, if sulfur capture additives are added to the coal when fabricating the briquettes. In urban areas, approximately 80% of the coal used by residences is in the form of briquettes. Nationally, this number is less than 40%. In addition to their environmental benefits, briquettes can provide the following efficiency gains if used in newer stoves.

| Fuel | Stove | Efficiency | Added Fuel Cost (yuan/t) | Stove Upgrade Cost (yuan) |
|---|---|---|---|---|
| Raw Coal | Old | 15 | -- | -- |
| Briquette | Old | 15 | 30 | -- |
| Briquette | New | 20–25 | 30 | 100 |
| Briquette | Advanced | 40–50 | 30 | 400–500 |

Of course, coal preparation would help as well, but would take a policy or pricing structure that makes it more attractive than unwashed coal. Currently, power plants burn the better quality, cleaner coals and households the dirtier ones, but centralized, large-scale flue gas cleanup at power plants is more cost-effective (and enforceable) than attempts to reduce emissions from each residence and small industrial facility.

Switching to gas would be the cleanest approach, but also the most expensive. Substantial progress is being made in this direction in China, and about two-thirds of the residences in several mid-size and large cities use some form of gas today (natural, LPG, or coal-derived). However, this number is lower in many other cities and much lower in towns and rural areas; nationwide, only 10% of the households use gas.

The environmental benefits and associated costs of all three options are presented in Table 2.4.

**Table 2.4: Benefits of Switching Household Heaters and Stoves to Cleaner Fuels**

| *Fuel* | *Particulate Reduction, %* | *$\Delta SO_2$, %* | *$\Delta NO_x$, %* | *Cost* |
|---|---|---|---|---|
| Briquettes with Sulfur Capture Additives | 55 (from 17.6 to 7.9 g/kg) | 55 (from 14 to 6.3 g/kg) | — | 30 yuan/t, including sulfur capture additive. Typical raw coal price to households in Hunan is 100–200 yuan/t. |
| Washed Coal | 25–50% ash reduction; particulate reduction would depend on the stove (air flow rates) and proportion of fine particles | 45 | — | Similar to industrial boilers (see Table 7.3) |
| Town Gas* | 100 | 100 | ~50 (estimate) | • 1–1.2 yuan/$m^3$ @ 3500 kcal/$m^3$<br>• 0.6–0.8 yuan/$m^3$ @ 2500 kcal/$m^3$ |

* Costs are for town gas delivered to the burner tip in a residence, and include the gasifier plant, distribution net, and stove/heater upgrade in the home; in an industrial application the user would be expected to incur the combustor upgrade.

# 3

## Coal Preparation

### Role of Coal Preparation as a Clean Coal Technology

Coal preparation can remove impurities that cause particulate and $SO_2$ emissions. Removing the solid impurities will reduce particulate emissions, especially in the many small boilers, furnaces, and kilns with no particulate controls or with low-collection-efficiency devices. In addition, ash removal improves the quality of coke made from coal.

High-sulfur coal (St > 2%)[6] currently accounts for 10% of China's coal output, and coal preparation can remove 50–70% of the sulfur contained in this type of coal as pyrite. Since two-thirds of the sulfur in high-sulfur coal is in the pyrite form, almost half the sulfur in this coal can be removed by coal preparation, decreasing $SO_2$ emissions by the same amount.

For China, expanded coal preparation technology should be considered the foundation, or initial step, of a clean coal technology system designed to improve the environment while still fostering economic growth. This approach follows that used in the past by developed countries such as Europe, USA, and Japan; these countries now stress the highly efficient combustion of coal and back-end cleanup to obtain further emission reductions (e.g., flue gas desulfurization [FGD] for $SO_2$, high-efficiency electrostatic precipitators [ESP] or baghouses for particulate, and, in some countries, selective catalytic reduction [SCR] for ultra-high $NO_x$ reductions). China has numerous reasons to emphasize a significant increase in the use of coal preparation in the immediate near term:

1. **Coal preparation especially benefits China's energy mix and consumption patterns.** As shown in Table 3.1, most highly developed countries use petroleum and natural gas as their main primary energy sources; coal is used mainly for electricity generation, and so clean coal technologies are primarily aimed at the electric power industry. In China, coal accounts for more than 75% of primary energy consumption and is widely used in many fields; power generation accounts for only about a third of China's total coal consumption (see Table 1.3). Thus, China requires clean coal technologies that address far more combustion situations than power generation. For example, coal cleaning provides the least

[6] The Chinese convention is to use 'St' to denote total sulfur, including sulfur in the pyrites, that which is organically bound, and that which appears as sulfates.

expensive and least disruptive environmental improvement for the remaining coal-burning residential stoves and heaters (although switching to briquettes or even gas would be still better solutions).

**Table 3.1: Primary Energy Consumption Mix of Key Countries**

| *Country* | *Oil, %* | *Natural Gas, %* | *Coal, %* | *Nuclear, %* | *Hydro-power, %* | *Total, Mt/a oil equivalent* |
|---|---|---|---|---|---|---|
| USA | 39.8 | 26.3 | 24.3 | 8.5 | 2.1 | 2028.6 |
| Canada | 35.7 | 28.5 | 11.2 | 12.5 | 12.1 | 222.5 |
| Denmark | 49.0 | 12.1 | 38.9 | | | 20.6 |
| France | 39.0 | 11.9 | 6.0 | 40.0 | 3.1 | 232.0 |
| Germany | 40.5 | 18.3 | 28.9 | 11.7 | 0.6 | 333.2 |
| U.K. | 38.1 | 28.0 | 23.0 | 10.5 | 0.4 | 217.8 |
| Former Soviet | 23.1 | 49.3 | 21.0 | 4.5 | 2.1 | 1001.3 |
| Union | 24.5 | 50.4 | 19.0 | 3.9 | 2.2 | 644.6 |
| Japan | 56.1 | 11.4 | 17.1 | 14.0 | 1.4 | 478.5 |
| **China** | **19.2** | **2.0** | **76.4** | **0.5** | **1.9** | **748.7** |
| Total in the world | 40.0 | 23.0 | 27.2 | 7.2 | 2.6 | 7923.8 |

2. **There are many opportunities to increase the proportion of raw coal treated.** In more developed industrial countries, most coal is washed, resulting in a good-quality commercial coal. In China, only 25.6% of raw coal is treated (Table 3.2), and the quality of the resulting commercial coal is poor (Table 3.3). The positive experience of the developed countries with extensive use of coal cleaning and the low current washing rate in China means that this country has a significant opportunity to improve its coal utilization and environmental performance simply by increasing the use of available, cost-effective coal preparation processes.

**Table 3.2: Proportion of Raw Coal Treated by the World's MainCoal-Producing Countries**

| Country | Proportion of Raw Coal Treated, % |
|---|---|
| China | 25.6 |
| USA | 55 |
| Former Soviet Union | 60 |
| Germany | 95 |
| Poland | 40 |
| Australia | 75 |
| South Africa | 60 |
| U.K. | 75 |
| Canada | 95 |
| Japan | 100 |

**Table 3.3: Quality of Coal Sold by China's State-Owned Coal Mines in 1997**

| *Quality Indices (averages)* | *Ash, %* | *Moisture, %* | *Sulfur, %* |
|---|---|---|---|
| Raw coal | 25.4 | 6–7 | 1.0 |
| Coal sold | 20.5 | 9.2 | 0.8 |

3. **Coal preparation technology is mature, reliable, and low cost.** As the most mature clean coal technology, coal preparation has a long, widespread history of use with demonstrated reliability. Further, as a first step to reducing $SO_2$ emissions, coal preparation costs significantly less than flue gas desulfurization. The unit costs for a typical coal preparation plant (costs per tonne of coal processed) are only 10% those of a power plant desulfurization unit, and the operating costs are also much lower. For example, according to the Luohuang power station in Chongqing, the cost of reducing $SO_2$ by coal preparation is 500–700 yuan/t (expressed as yuan per tonne of $SO_2$ removed), whereas the cost of owning and operating their FGD unit is 1,400–1,600 yuan/t (including amortization of the investment). Further, they are unable to sell their $CaSO_4$ by-product (due to discoloration from the fly ash not captured by their ESP and the local availability of lower-cost gypsum from natural sources); this introduces a secondary pollution problem Of course, coal cleaning can reduce $SO_2$ emissions by only 40–50%, whereas an FGD system can achieve > 95% $SO_2$ control.

4. **Poor coal quality results in serious air pollution.** According to the State Environment Protection Agency (SEPA), China's air quality problems are caused primarily by coal combustion; the main pollutants are particulate and $SO_2$ from coal, both of which can be reduced by coal preparation. The damage caused by these pollutants (to health, agriculture, etc.) hurt the national economy.

5. **Coal preparation lowers the cost of intensive coal processing.** Coal preparation is an inexpensive way to raise coal quality and reduce the cost of coal processing. On average in China, coal preparation costs only 5–7 yuan for 1 tonne of steam coal and 10–14 yuan for 1 tonne of coking coal.[7] It benefits briquetting, coal-water slurries for use as a boiler fuel, coking, gasification, and coal liquefaction. As such, coal preparation should be considered the foundation of more advanced clean coal technologies.

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7 These unit *costs* are referenced to the weight of the incoming raw coal—i.e., the actual *cost* is divided, or normalized, by the weight of the feed coal. When stated in terms of the *price* of washed coal, the *price* at the mine/coal preparation plant (process costs + loss of about 20% of the coal as refuse by the cleaning process + taxes + profits) of cleaned coal, normalized by the weight of the *washed* coal, can be as much as 50% higher than that of unwashed coal. This larger number is found elsewhere in this report. This 50% figure equates approximately to 50 yuan/t, on top of a typical price of 100 yuan/t of unwashed coal at the mine. Delivered coal is, of course, more expensive, but the cost differential in yuan per tonne remains approximately the same. For example, the price of unwashed Shanxi coal delivered to Hunan province (the case study province for this project) can be about 280 yuan/tce, while the corresponding figure for washed coal is 333 yuan/tce, which is just a 15% difference (based on the more meaningful 'tce' or standard heating value basis, rather than a pure weight basis).

6. **Coal preparation is an important method of energy conservation.** Coal preparation offers energy conservation benefits. For example, if the ash content of coking feed coal is reduced by 1%, coking ash decreases 1.3%, coke consumption for iron-smelting decreases 2.7%, and the efficiency of puddling furnaces increases 4%. Similarly, using washed instead of raw anthracite in the production of synthetic ammonia decreases coal consumption by 20–25%.

For the metallurgy industry, the average ash of washed coal in China is 9.9%, compared to only 7% in Japan and the United States. This difference is due to both the high ash content of the raw coal and the absence of many state-of-the-art coal preparation plants in China. This lower-quality coal partially contributes to the higher consumption of coal per tonne of steel in China—twice the amount of Japan or the USA.

Washed high-quality steam coal consumes less in-house electricity than raw coal when burned in boilers, leading to potential energy savings of 10% (see the example in Section 3.3.2). In 1997, the average ash content of coal used in power plants was as high as 28–30%, partially contributing to the high average coal consumption for power generation—430 gce/kWh. In contrast, in the United States, the average ash of coal for power generation is only 8.8% and average coal consumption is much lower, only 330 gce/kWh. Each year, China consumes 50 Mtce more coal for power generation than it would if all its boilers operated at the world average efficiency (see Section 3.3.2 for an explanation of the coal quality impacts on efficiency).

To a certain extent, these benefits of using washed coal offset the loss of carbon in the cleaning process. Burning the high ash, high-sulfur residue from coal cleaning in fluidized-bed combustors at the cleaning plant to generate electricity and/or process steam would recover this loss.

7. **Coal preparation increases transportation efficiency.** Coal mines are primarily located in the north and northwest of China; there are very few coal resources in the economically developed coastal areas of the east and southeast. This necessitates a high volume of transport from north to south and west to east. An average of 650 Mt of coal is transported every year over an average distance of 620 km. This transportation accounts for 40% of the volume of rail freight, 25% of the volume of road haulage, and 20% of the volume of water transportation in China. Of the total coal shipped, 500 Mt is not washed and contains about 80 Mt of refuse, wasting approximately 48 Gt-km of transport capacity. In addition, transport of this residue results in unnecessary pollution and energy consumption for transportation (plus actual coal losses of about 5% through spillage, etc.).

It is important to emphasize that the environmental and energy consumption consequences of using uncleaned coal have corresponding impacts on China's economic development. The environmental damages are identified in item 4, above, and the economic impacts of the efficiency losses described in items 5–7 are self-evident.

## Current Production and Utilization of Washed Coal

### *Coal Cleaning Capacity*

Coal preparation technology has developed rapidly since China opened to the outside world. In 1980 there were 110 cleaning plants with a total design capacity of 116 Mt/a. By 1997, this number had increased dramatically to 1571 cleaning plants, each with a design capacity of over 30,000 t/a, for a total national coal cleaning capacity of 483 Mt/a (see Table 3.4). Of these, 223 were stated-owned cleaning plants with a design capacity of 335 Mt/a. They included 139 coking coal cleaning plants with a design capacity of 186 Mt/a and 84 steam coal cleaning plants with a combined design capacity of 149 Mt/a (see Appendix B for the distribution of these capacities by size). Locally run and village- and township-run cleaning plants are mostly cleaning plants for coking coal.

**Table 3.4: Number and Capacity of Cleaning Plants in China at the End of 1997**

| *Type of Coal Mine* | *Number of Cleaning Plants* | *Capacity, Mt/a* |
|---|---|---|
| Key stated-owned coal mines | 223 | 335 |
| Locally run stated-owned coal mines | 469 | 84 |
| Village- and township-run coal mines | 879 | 63 |
| Total | 1571 | 482 |

The average design capacity of the key state-owned cleaning plants is 1.5 Mt/a; 1.34 Mt/a for coking coal cleaning plants and 1.77 Mt/a for steam coal cleaning plants. The largest coking coal cleaning plants are Fangezhuang cleaning plant and Qianjiaying cleaning plant at Kailuan coal mine, and Baodian cleaning plant in Yanzhou. Their design capacities are all 4 Mt/a. The largest steam coal cleaning plant is Antaibao cleaning plant at Pingshuo coal mine, which has a design capacity of 19 Mt/a.

### *Quantity of Raw Coal Cleaned*

In 1997, the amount of washed coal was 338 Mt, accounting for 25.6% of total raw coal production. Table 3.5 summarizes statistics for the different categories of coal mines. As shown, the percentage of coal washed was significantly higher for the larger mines than the smaller, locally operated ones. Thus, 46.8% of the coal produced by the state-owned coal mines was washed, while only 23.0% of the coal produced by the locally run state-owned coal mines and an even smaller 7.0% of the production by the village- and township-run mines was washed.

**Table 3.5: Proportion of Raw Coal Washed in China in 1997**

| *Type of Coal Mine* | *Raw Coal Output, Mt* | *Raw Coal Washed, Mt* | *Proportion of Raw Coal Washed, %* |
|---|---|---|---|
| Key state-owned coal mines | 526 | 246 | 46.8 |
| Locally run state-owned coal mines | 226 | 52 | 23.0 |
| Village- and township-run coal mines | 573 | 40 | 7.0 |
| Total | 1325 | 338 | 25.6 |

In 1997, 100 Mt of steam coal was washed nationwide, mainly for use in the fertilizer, town gas, blast furnace, and power industries, as well as for export. At the same time, the production of washed coking coal was 110 Mt nationwide, with state-owned cleaning plants accounting for 72 Mt of this amount. The yield of washed coal for coke making is 53.8%, with an average ash content of 9.8% and moisture content of 10.4%. This is the percentage of the raw coal that can be used for coke making; the balance is middlings (~30%), which could be used for power generation, and refuse (~20%). Table 3.6 indicates the main uses of washed coking coal.

**Table 3.6: Consumption of Washed Coking Coal by Industry Sector**

| *User* | *Metallurgy* | *Chemistry* | *Town Gas* | *Foundry* | *Export* | *Other* | *Total* |
|---|---|---|---|---|---|---|---|
| Amount, Mt/a | 85 | 5.8 | 5.6 | 5.4 | 7.2 | 1 | 110 |

## Methods of Coal Preparation

China's cleaning plants use all the coal preparation methods available worldwide. As shown in Table 3.7, the jigging process is the most common; it was first introduced into China in 1938. The heavy-medium separation process has a shorter history, only 40 years in China.

**Table 3.7: Proportion of Various Coal Preparation Methods in China**

| *Coal Washing Methods* | *Proportion, %* |
|---|---|
| Jigging | 59 |
| Heavy-medium separation | 23 |
| Flotation | 14 |
| Other | 4 |

Steam coal cleaning plants use the simpler preparation processes, i.e., heavy-medium separation or jigging for refuse discharge processes. The raw coal ranges from an upper size bound of 100 mm to a lower bound of 25 mm. A closed water circuit process is used in 80% of the state-owned cleaning plants, while the other plants mostly meet the emission standards for discharged wastewater.

Coking coal requires a more complicated cleaning process than steam coal. Raw coking coal is generally 50–0 mm (i.e., < 50 mm).[8] For easy- and moderately easy-to-wash coal, the cleaning plants use the jigging-flotation process. For the hard- and hardest-to-wash coals, they use the combination of (1) heavy-medium separation with flotation or (2) heavy-medium separation with jigging and flotation, plus jigging with middlings heavy-medium separation and flotation.

[8] When discussing coke and coking coals, this report follows the international practice for these materials by showing size ranges with the larger number first and the smaller number second.

### Coal Preparation Equipment

China manufactures its own coal preparation equipment, including equipment for high-capacity (4 Mt/a) coking coal cleaning plants. The equipment used in large-scale coal preparation plants is identified in Appendix B.

## Typical Coal Preparation Applications

This section gives examples of how coal preparation is used, with several cases drawn from Hunan province, the location studied in the energy/economic/environment assessment under Task B of this project. Hunan province is relatively poor in coal resources: reserves are few, coal seams are thin, and the inherent ash and sulfur contents are high. The production of coal is too low to support the needs of the province, so coal is transported from Shanxi and Henan provinces.

### Coal Preparation for Coking

Although generally poor in coal resources, Hunan province has some high-quality coking coal resources, such as the coking coal of Niumasi mine. The raw coal is relatively low in ash (14–15%) and sulfur (< 0.8%), with good washability. But the mine's reserves are low, with raw coal output only 500,000 t/a—not enough to meet the needs of Hunan province for high-quality raw coal. Therefore, 1 Mt of primary coking coal is transported from Lu'an Coal Bureau of Shanxi province and Pingdingshan Coal Bureau of Henan province to the Zhuzhou cleaning plant of Hunan province for washing. The Zhuzhou cleaning plant uses jigging-flotation process, which reduces the ash content from 15–18% (in raw coal) to 8.8% (washed), with an 81% yield of washed coal. Washed coal from this coal cleaning plant meets the quality specifications of Hunan, Guangdong, and Fujian provinces for coking coal.[9]

### Coal Preparation for Power Plants

The bituminous coal used in large power plants in Hunan province is mostly transported from Shanxi and Henan provinces. The Taiyuan cleaning plant, for example, can provide a washed steam coal whose ash has been reduced from 30% down to 14.3% (52% reduction), and sulfur from an uncleaned level of 2.1% to a cleaned level of 1.15% (45% reduction).

The Huangtai power plant in Shandong province, which burns cleaned coal from Taiyuan, offers an example of the benefits of using washed high-quality steam coal instead of raw coal. Unit 7 is a 300 $MW_{gross}$ ABB-CE radiant reheating boiler with a forced-circulation steam circuit boiler. When using raw coal from Xishan Coal Bureau, the fuel heating value $Q_{net.ar}$ was 21.087 MJ/kg, and the plant burned 980,000 t/a of coal. After changing to washed coal, the fuel's $Q_{net.ar}$ improved to 26.96 MJ/kg, and the plant reduced its coal consumption to 790,000 t/a. The use of washed coal produced many other savings for this power plant:

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9 These quality specifications are different in different provinces.

- The decrease in coal consumption meant that 190,000 t/a of raw coal did not need to be transported from other regions, saving 74 trains of transport capacity (assuming 50 rail cars per train and 50 tonnes of coal per car).
- The decrease in coal consumption also decreased in-house electricity consumption—e.g., for the fan and coal pulverizer—saving 3.52 GWh/a.
- With raw coal, 5 mills were needed; with washed coal, only 4 mills are needed, leaving 1 mill as a spare.
- Equipment maintenance costs have dropped from 920,000 yuan/a to 300,000 yuan/a.
- The improvement in coal quality has helped stabilize boiler combustion, obviating the need for an oil support—and thus saving 5073 t/a of fuel oil.
- Ash discharges have decreased by 180,000 t/a.
- $SO_2$ emissions have decreased by 23,000 t/a.

The power plant and coal cleaning facility produced a joint study of the savings realized by using washed coal, and concluded that this power plant could reduce its costs by more than 20 M yuan/year as a result of the above savings. These are net savings, after deducting the investment needed to allow combustion of this higher-grade coal (changes to the heat transfer sections—especially the waterwall refractory—to maintain the design steam conditions). Coal washing also saved the plant nearly 50 M yuan/year in lower $SO_2$ emission fees and avoided installation of an FGD system (based on a levelized cost for the installation and operation of the FGD of 2000 yuan/tonne $SO_2$ removed). At the same time, the cleaning plant increased its profits by more than 10 Myuan/year by utilizing its capacity more fully.

### *Coal Preparation Technology for Industrial Boilers and Domestic Coal*

Coal for small boilers would typically come from small, local mines. This is true nationally as well as for Hunan province, but the refuse[10] content of Hunan's coal is high (> 20%) and its quality is poor (ash > 25%). Therefore, a cleaning plant would use a moving-bed jig to reduce the refuse content. This technology is a simple process, requiring only a low investment and little space; it also saves water and does not produce much noise.

An alternative currently under development is an air separator with the following characteristics (see Appendix B for technical specifications):

Air-coal fines, not water, are used as the medium, so the products need not undergo dehydration. The cleaning plant does not need a wastewater treatment system.

The size range of separation is large (6–50 mm).

The air quantity is two-thirds less than with traditional pneumatic cleaning.

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[10] Refuse is stone mixed with the coal, while ash is mineral matter contained in the coal

Separation efficiency is higher; treatment capacity of per square meter is 10 $t/m^2h$.

The plant does not require much space, and it can be constructed quickly for low investment. Moreover, operating costs are also low (2–3 yuan/t).

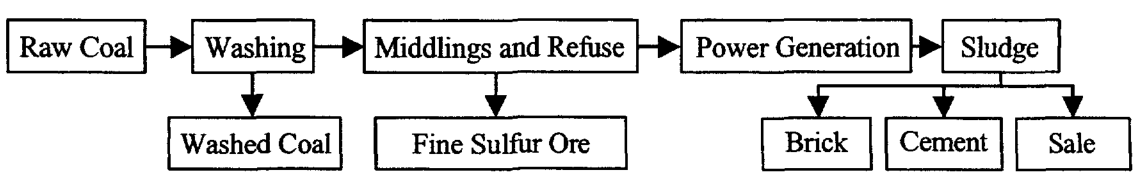
With this process, when the ash content of the raw coal is 25%, the ash in the cleaned coal is 13% at a yield of 78%; ash in the remaining refuse is 67.5%.[11] A two-stage particulate removal system is used to meet emission standards: the first stage uses a cyclone, while the second stage uses a baghouse.

### *High-Sulfur-Coal Preparation Technology*

Coal washing can remove 50–70% of the sulfur in the pyrites. Current coal separation and desulfurization processes for high-sulfur coal, when using a heavy-medium cyclone, have a size range of separation of 50–0.5 mm; when using a columned pneumatic flotation machine, the size range of separation is 0.5–0 mm.

The Zhongliangshan cleaning plant in Chongqing city is an example of a modern, integrated facility. It uses a new process that combines both cyclone and flotation to reduce the sulfur content from 3.5% down to 1.3%, a 63% reduction. The middlings can be used in a power plant fluidized-bed boiler, and the refuse, which has a sulfur content of 11–14%, can be re-separated to recover pyrite, which can then be sold to a sulfuric acid plant as raw material. This integrated process provides a comprehensive utilization of a high-sulfur coal and is illustrated in Figure 3.1.

**Figure 3.1: Comprehensive Utilization of High-Sulfur Coal**




## Development Prospects and Barriers for Coal Preparation

### *Development Prospects*

In general, coal preparation technology is relatively backward in China. It is not used extensively, and much of the equipment that is used is older and less effective. However, coal preparation technology is mature and stable, requires less investment than other clean coal technologies, and produces immediate results. Therefore, it is a logical foundation for China's clean coal technology system, and its wider use would yield the energy and environmental conservation benefits presented earlier. Because of its relative economic

[11] Since this process is still under development, sulfur removal rates and heat content of the clean fuel are not yet available.

advantage, coal preparation is expected to see increased use once China establishes and enforces strict emission limits and increases emission fees to levels that motivate users to take positive actions. Other factors that provide an impetus for the introduction and widespread use of state-of-the-art coal preparation facilities are as follows:

- **Need by modern mines**. With increased mechanization and the mining of low-grade and high-sulfur coal seams, the quality of coal is declining. Thus, coal preparation is increasingly important.
- **Economic boost for mines**. For every tonne of raw coal that is washed, coal mine profits increase 5–10 yuan. Coal preparation can help mines retain their profitability.
- **Increased export competitiveness of China's coal**. The word market prices coal based on its quality, so better coal quality means higher prices and a bigger market.

According to the coal industry's development plan, coal washing capacity in 2000 will be 500–550 Mt. The proportion of washed coal (vs. raw coal) will rise from 30% in 2000 to 40% in 2005 and 50% in 2010.

China needs to focus its coal preparation development on washing steam coal. The output of coking coal for metallurgy exceeds 100 Mt and currently meets market demand. However, 90% of China's coal is used as steam coal, and only 9% of it (about 100 Mt) is washed.

### *Development Needs*

The following technology developments and improvements would greatly increase the efficiency and cost-effectiveness of coal preparation systems that could be used in China, thereby increasing their attractiveness:

- **More effective separation processes and equipment**. These include a new heavy-medium separation process and a high-efficiency jig to raise the quality and yield of washed coal.
- **Dry coal preparation processes.** The development of coal will concentrate on mining areas in northwest China. In these regions, coal resources are abundant and the quality of coal is good, but the climate is dry. Dry coal preparation has promising development prospects.
- **Effective desulfurization processes for high-sulfur coal.** High-sulfur coal is located mainly in southwest and central-south China; deep seams in northern China also have high sulfur content. More effective desulfurization techniques should be researched to reduce this pollutant.
- **Highly effective de-watering equipment for coal fines**. Presently, vacuum filtration is used to de-water washed coal from a flotation process. The moisture content of the filtered coal cake is about 30%, which increases the moisture of the overall washed coal product, making transport more difficult. Therefore, more effective de-watering equipment needs to be developed.

- **More reliable and efficient large-scale equipment.** In the future, large, high-efficiency equipment for coal preparation will be installed in big cleaning plants. The reliability of this larger-scale equipment must be monitored and improved, as necessary; reliability has been a problem with large equipment in the past.
- **Automated sensors and data detection instruments.** China should make use of online detecting instruments and equipment for ash content, moisture, solids concentration in slurries, flow rate, material level, etc. Raising the level of automation will increase product quality while reducing operating costs

### *Obstacles to the Wider Application of Coal Preparation Technology*

The following technical and economic factors are currently hindering the wider acceptance of coal preparation:

- **High price differential.** The cost of cleaning coal (including taxes and profits) naturally increases its price. With the current coal economics in China, the price of washed steam coal is about 50% above the price of raw steam coal at the mine (50 yuan/t typical differential), when normalized on the basis of a tonne of washed coal as described in footnote 2. The corresponding delivered price differential is still about 50 yuan/t, or about 15% of the price to the user. This relative price disadvantage of washed versus raw coal is largely due to the low price of raw coal; the absence of strict, widely applied and enforced $SO_2$ emission limits; and low fees for pollutant emissions.
- **Upgrade requirements needed to burn clean coal.** Most power plant boilers, industrial boilers, and kilns are designed to accommodate low-grade, high-ash coal (with a calorific value of about 21 MJ/kg and an ash content of 25–30%). Therefore, they need to modify their heat transfer surfaces to match the heat release characteristics of the cleaned coal, which entails a cost. Once this modification has been made, these boilers can accommodate the high-quality steam coal and, in fact, should be able to quickly recapture the cost of the modification from the use of washed coal.
- **Transportation/storage management limitations.** Washing increases the variety of different coal classifications, which complicates transport and storage by requiring careful sorting and separation. The transportation system—as well as many coal users—is not currently set up to accommodate separate handling of different specifications.
- **Investment focus on production growth.** China's limited investment in the coal industry gives priority to construction of mines, while insufficient funding is allocated to building cleaning plants. Lack of funding is especially a problem for locally run state-owned mines and village- and township-run mines.
- **Inadequate R&D.** State funding for coal preparation R&D is too low to yield technical innovations.

### Suggested Technical Countermeasures

The following list presents technical measures that could promote the use of cleaned coal in order to realize its environmental and economic benefits. Policy recommendations prepared by the CCPUA authors for all clean coal technologies discussed in this report are consolidated in Section 8.

- **Improved advanced and high-efficiency coal preparation technologies, especially:**
  - Processes and equipment for high-ash and hard-to-wash coals; the key technologies are heavy-medium separation and jigging processes and equipment;
  - High-efficiency and dry processes and equipment for the arid northwest regions;
  - High-efficiency processes and equipment for sulfur removal; this work should focus on heavy-medium cyclones and columned pneumatic flotation machines;
  - High-efficiency centrifuges, filters, and pressure filters for de-watering fine coal;
  - Enhanced reliability and service life of large-scale and high-efficiency equipment;
  - Automatic inspection instruments and process control equipment to improve efficiency and cleaned coal quality;
- **Expansion priorities.** When making investment decisions on the construction of coal preparation plants at mines, priority should be given to mines that produce export products, have poor coal quality (ash > 25%, sulfur > 2%), and long transport distances to the main coal consuming areas.
- **Centralized cleaning plants**. As with any capital-intensive technology, coal preparation plants exhibit economies of scale. Therefore, government at all levels should support the construction of central cleaning plants. This would be particularly applicable at the county level, where government could bring together locally run state-owned mines and village- and township-run mines to build central cleaning plants.
- **Designing for washed coal**. Requiring that new power plants and industrial kilns be designed for washed steam coal as a fuel would remove one impediment to the use of this environmentally preferred fuel.
- **Compatible transportation systems**. Facilities for loading, transportation, unloading, and storage of coal that separate it by classification need to be introduced to meet the needs of washed coal and supply patterns. The government should help the mining and railway sectors coordinate overall planning and construction to provide these facilities.
- **Coordinated production**. If large cleaning plants (over 1.5 Mt/a) are constructed adjacent to power plants and building material plants, the net costs of coal preparation can be reduced because the power and material plants can utilize the by-products of coal washing (middlings, fines, and refuse).
- **Polices to encourage other uses**. Many industries could benefit from the use of cleaned coal, thereby producing both environmental and economic benefits. These

industries include the iron and steel, chemical fertilizer, electric power, cement, and railway industries. Policies that encourage large plants in these industries to sign mid- and long-term contracts with coal preparation facilities for direct supply of coal that meets their specifications would encourage investors to expand existing coal preparation plants and build new ones.

- **Correcting price disparities**. Currently, the price ratio of washed steam coal to raw steam coal is too low to permit the mines and their cleaning plants to survive in a market economy. Currently, the *price* ratio is 1.2:1, but the *production cost* ratio is 1.5:1 (at today's very low coal prices). Second, the sulfur increments (measured as % sulfur) at which prices change are currently 0.5% increments. Reducing these increments to 0.2% would promote coal preparation and desulfurization.

# 4

# Coal Briquetting

## Role of Coal Briquetting in China as a Clean Coal Technology

Direct combustion processes account for over 80% of total national coal consumption, with nearly 70% of this amount fired in a large number of small units—about 500,000 industrial boilers, 160,000 industrial kilns, and tens of millions of residential stoves. Many of these combustors require some form of "pelleted" coal, traditionally sized coal. Yet with the increase in mechanized coal mining, the production of sized coal has dropped significantly and can no longer keep pace with demand. At the same time, there is an over-supply of fine coal.

Briquetting technology offers a solution to this supply/demand dilemma. Briquettes produced from cheap fine coal answer the need for pelleted feed coal. Briquettes can replace sized coal in residential stoves and in coal gas furnaces used by the metallurgical, chemical manufacturing, machinery, and glass industries. Briquettes can also replace bulk coal in layer-combustion industrial boilers, kilns, and steam locomotives.

Moreover, briquettes offer significant advantages over traditional sized coal:

- **Energy savings.** Briquettes burn more efficiently than sized coal. For residential ovens and stoves used for heating and cooking, where thermal efficiency averages just 15% when burning coal in existing equipment, a switch to solid (egg-shaped) coal briquettes and a low-cost (100 yuan) new stove can increase thermal efficiency to 20–25%. Honeycomb briquettes—the most common household briquette in China—offer even higher thermal efficiency, up to 30–50% in a similar type of new stove. And if briquettes are burned in still newer, high-efficiency stoves (400–500 yuan), the thermal efficiency can reach 60%.

Briquettes also offer significant energy savings in the industrial sector. Industrial boilers, kilns, and steam locomotives burning briquettes can reduce the losses due to entrainment and incomplete combustion, thereby using about 8–20% less coal.

- **Less air pollution.** Compared with bulk coal, honeycomb household briquettes reduce particulate emissions by 40–60%, CO by 80%, $NO_x$ by 55%, and benzo(a)pyrene (BaP) by 90%. With desulfurization additives, $SO_2$ emissions can be reduced 40–60%. Opacity can be as low as a Ringelmann reading of ½. Industrial briquettes can reduce particulate emissions by 60% relative to raw coal, $NO_x$ by 25%, BaP by more than 50%, and $SO_2$ by 40–60%.

And these energy-saving and air quality benefits come fairly inexpensively: compared with other clean coal technologies, briquetting features lower capital investment and production costs. Given China's high demand for pelleted coal, briquette technology is an economical, practical clean coal technology that merits priority attention by the government to expand its use, improve its effectiveness, increase its applicability, and reduce its cost.

## Current Production and Application Status

### *Varieties of Briquettes and Binders*

A briquette is a coal product with fixed strength and shape produced from fine coal and low-rank coal by mechanical methods. Briquettes can be classified by their function (household or industrial) or production method (roller press or impact, cold or hot, high-pressure or low-pressure, and with or without binder). A classification scheme by function is shown on the next page.

The more than 100 kinds of binders that have been used to date can be divided into four categories according to their properties:

- Organic binders, including tar, pitch, starch, humic acid, lignin, sulphonate, polyvinyl alcohol, polyvinyl acetate, polyurethane, etc.
- Inorganic binders, including clay, bentonite, kaolin, lime, water glass, gypsum, cement, sodium chloride, etc.
- Industrial-waste binders, including paper pulp waste water, sugar industry waste water, leather production waste liquor, brewing waste liquor, carbide slag, animal blood, ecological chemical sludge, etc.
- Compound binders, including clay–pulp waste, starch-bentonite, wheat straw–lime, etc.

The caking property of the binder determines the cold (mechanical) strength of the briquette, while the thermal performance of the binder influences the hot strength, ash fusibility, and ash strength of the briquette (the ash properties affect the handling of the spent briquette after it has burned out). Organic binders, with strong caking strength and measurable heating value in their own right, can raise the cold mechanical strength without affecting the thermal performance of the briquette (i.e., without increasing the briquette's ash content). Inorganic binders have poorer caking properties than organic binders and no heating value. The advantage of inorganic binders is their wider availability, low cost, and high thermal strength.

**Figure 4.1: Classification of Briquettes by Function**

- Briquette
  - Industrial Briquette
    - Fuel Briquette
      - For industrial boilers
      - For industrial kilns
      - For locomotives
    - Gasification Briquette
      - For gas production in fertilizer industry
      - For industrial fuel gas
    - Briquetting Coke & Briquette for Coking
  - Household Briquette
    - Honeycomb Briquette
      - Upper-ignition honeycomb briquette
      - Common honeycomb briquette
      - Briquette for air hanger heaters
      - Square briquette for roasting
    - Briquette (egg-shaped)
      - For household cooking and heating
      - For chafing dish
      - For heating
      - For roasting

### *Household Briquettes*

Most household briquettes are made by compression of coal with binders such as clay, lime, and slurried coal fines. Household briquettes do not need to be dried by fire, but are cold-formed and dried in the sun until reaching the appropriate moisture level. The shape, size, and weight of the briquette can be adjusted to fit different applications, stove types, utilization habits, and coal quality in different regions. Household briquettes are mainly sold for residential cooking and heating, with lesser amounts used in restaurants.

Beijing and other cities use anthracite coal as the main feedstock, blended with charcoal, oxidant, and binder to produce hot-box briquettes, roasting briquettes, and briquettes for chafing dishes. These briquettes can be used for hand warming in the winter and roasting or cooking of meat, since they can burn for over four hours. Drying requirements for this kind of briquette are strict; to avoid the need for fire, the briquette must be dried at low temperature.

The most common household briquette in China, with the highest production rate, is the honeycomb briquette. China has developed the whole-piece honeycomb, such as two-in-one, three-in-one, embedded type, etc., and the separated honeycomb, in which the ignition layer, lighting fire layer, and basic briquette are separated. Many kinds of ignition layers have been developed, such as the paraffin type, rosin type, and oxidant type. Indeed honeycomb briquettes are available in diverse forms; shape ranges from the basic cylinder ($\phi$102 mm, $\phi$ 120 mm) to the square, polygon, and concave varieties, with various dimensions between 100 and 250 mm and 12, 16, 19, or 21 holes per briquette.

Honeycomb briquettes increase thermal efficiency by changing the heat convection properties and burnout degree of raw coal during the combustion process. When used in furnaces designed for honeycomb briquettes, briquettes made from bituminous coal can achieve smokeless combustion.

Binders for household briquettes have evolved from traditional clay into myriad materials such as coal fines, fly ash, carbide slag, lime, starch, etc. Some binders provide a degree of desulfurization.

More than 60 types of advanced stoves have been designed and applied for burning various briquettes. Besides residential cooking and heating, honeycomb briquettes have found wide application in collective canteens and mess halls, tea water furnaces, and heated greenhouse brick beds.

Household briquette plants are located in every town, and are supplied with equipment from the more than 200 honeycomb machinery plants in China. In general, briquette machines could stand improvement; they still have low production efficiency, and are very noisy, creating a bad working environment. Some new, prototype honeycomb production lines have been designed and built, such as the demonstration production lines in Shenyang, Hanzhong, Nanyang, Jiangmen, Huzhou, Kunming, and Hangzhou. These new plants use advanced technologies and a complete set of energy-saving features, such as stereoscopic processing, electronic blending of raw materials, and computer controls. In big cities, honeycomb briquettes are usually produced by centralized facilities for blending the raw materials and separate, localized briquetting plants. This division of functions enhances production efficiency and decreases costs.

Because the production process for household briquettes is quite mature in China, some briquetting machines and coal briquette products, such as roasting briquettes, have been exported to international markets. These include machines that produce honeycomb briquettes as well as other types of briquettes used in residences. The Philippines, Singapore, Thailand, Mongolia, and Indonesia, among other countries, have adopted China's briquette technologies and equipment to produce their own household briquettes.

## Industrial Briquettes

Coal briquettes are used in industrial boilers and gasifiers, while coke briquettes are used as a feedstock for blast furnaces. Each of these applications is discussed below.

### *Boiler Briquettes*

Boiler briquettes are categorized as either centralized or stokehold. Centralized systems are the traditional approach and used for all applications that are not candidates for stokehold units. Stokehold briquetting is the presumed name in English of a simple briquetting process that is directly coupled with a combustion source; i.e., the briquettes are fed directly to the boiler as they are produced. Because a stokehold briquetting system is close-coupled with the combustor it is fueling, the process can be simple, usually without binder and drying. This greatly decreases the production cost, and, therefore, contributes to the high sales levels that this process now enjoys.

Stokehold briquetting has been successfully applied in textile plants in Zhejiang and Xiaoshan, a Xinye plastic factory, and more than 100 companies in the Lanzhou district of Ganshu province. It has also been applied successfully at chain-grate boilers smaller than 4 t/h in Xinxiang and Kaifeng of Henan province, Shijiazhuang of Hebei, Liuzhou of Guangxi, and Guizhou province.

From 1980–1990, China significantly improved its briquetting technologies and equipment for use with lignite, bituminous coal, and anthracite. Fifteen series of binders, six kinds of waterproof agents, and four sets of sulfur-capture additives were developed, and three binder pilot production lines were constructed. Two briquette pilot production lines, three stokehold briquetting test sites, and three briquette demonstration factories (in Handan, Luoyang, and Lishuwan in Chongqing) were built with a total production capacity of 0.55 Mt/a. However, because the production cost of boiler briquettes is higher than the price difference between sized coal (the alternative to briquettes) and raw coal, and there was no policy support for this energy-saving and environmentally cleaner technology, the demonstration plants stopped production.

A 10,000 t/a high-pressure biomass briquette project supported by Japan's Green Aid Plan was built and operated for a period of time at the Tangzhuang coal mine of Linyi Coal Mining Administration in Shandong province. Japan provided a complete set of equipment for the production line and built the plant. The products supplied small industrial boilers, but the biomass plant ceased operation because its production cost was too high and the briquettes did not combust completely (the inside remained unburned).

Stokehold briquetting represents the near-term future of industrial briquettes in China, and is a key technology supported by the government. Plans call for stokehold technology to be implemented in industrial boilers smaller than 4 t/h in selected cities across the whole country. In each city, 100 boilers are expected to switch to these briquettes.

The growing use of industrial briquettes owes much to environmental regulations and the drive to conserve energy as coal prices increase. After the United Nations Environment and Development Conference of 1995, local governments all over the country established pollution control measures, many of which promoted coal briquetting technology. For example:

- The Beijing Municipal Government prohibited burning raw coal within the third ring road. They also invested 6.8 million yuan to build an industrial briquette demonstration production line with an annual output of 50,000 tonnes at the Beijing Coal Utilization Research Institute, and a briquette production line with an annual output of 25,000 tonnes at the Fengtai Coal Machinery Factory. In addition, they demonstrated and popularized stokehold briquetting technology in tens of organizations in Chongwen district.

- Shanghai invested 13 million yuan to build an industrial briquette production line with an annual output of 120,000 tonnes at the Shanghai Fuel Company, and plans to build two production lines of the same scale during the Ninth Five-Year Plan period, which will bring briquette production capacity to 360,000 tonnes per year. All coal-fired stoves within the inner ring road will convert to briquette.
- During the Ninth Five-Year Plan period, the Environmental Protection Department of Chongqing city plans to build a briquette production line with an annual output of 0.9 Mt of industrial briquette and 0.3 Mt of household briquette with sulfur-capture additives. This project depends on foreign funds and government support; the total investment is estimated at 140 million yuan. As the first step in this project, a briquette demonstration plant with the annual output of 30,000 tonnes is being built in the Nantong coal mining area, and is scheduled to be completed within two years.
- The Environmental Protection Department of Guiyang city is building a pilot industrial briquette production line with an annual output of 20,000 tonnes, and further improving an existing briquette plant with an annual output of 100,000 tonnes. The plan is to forbid combustion of raw coal in a central 36 $km^2$ area.
- Hangyang (Hubei province), Nanchang (Jiangxi), Qingdao (Shandong), and Shijiazhuang (Hebei) are all planing to build briquetting plants. The goal is to control air emissions and save coal resources by using industrial briquettes as a boiler fuel and forbidding the combustion of raw coal.

### *Gasification Briquettes*

Briquettes used for gasification are more generally classified according to the binders used. The most common types are described below.

**Lime-carbonated briquettes.** Lime-carbonated briquettes are the most mature gasification briquette technology and the most widely used. In 1988, 800 out of 1057 small nitrogen-based fertilizer plants across the country used lime-carbonated technology. Now, due to the closure of many small plants and a switch to different briquettes by other plants, only 900 nitrogen-based fertilizer plants remain in China; more than 600 of these use lime-carbonated briquette production facilities, with an annual briquette output of about 20 Mt. The disadvantage of the lime-carbonated production process is that it requires 20–30% lime as a binder, resulting in a complicated carbonation process, and it produces a briquette with low fixed carbon and high ash content (thereby reducing the efficiency of the gasifier that burns the briquette).

**Clay briquettes.** The binder adopted by clay briquetting is yellow and white clay, which is not only widely available and low-cost, but also emits fewer pollutants during briquetting. The amount of clay in the briquette is about 10%, only half the amount of lime used in the lime-carbonated briquette. Production costs for clay briquettes are low, but their resistance to dampness and rain is poor and they lose strength when wet.

In 1980, the Tongxiang fertilizer plant of Zhejiang province developed pottery clay briquettes as a feed fuel for gasification. Since 1986, the Shanghai Qingpu chemical factory has used white mud (clay) as a binder with Jincheng anthracite to make a white mud briquette fuel used to produce synthetic ammonia. Up to the 1990s, more than 40 small nitrogen-based fertilizer plants in Zhejiang, Jiangshu, Shanghai, Fujiang, and other provinces and cities adopted clay briquettes to produce gas for ammonia manufacture.

**Water coal bars.** Certain anthracites contain 25–30% ash, which is mainly clay with strong caking properties. Those in Hunan province are an example. By adding some water, the coal can be formed into a bar in a screw extruder. This coal bar can be fed directly into a gasifier without drying. In 1972, Yueyang Nitrogenous Fertilizer Plant of Hunan province first succeeded in producing water coal bars. Up to 1989, about 60 small nitrogen-based fertilizer plants adopted water coal bar technology to produce feedstock for their gasifiers. Note that this technology only works with anthracite that has a high clay content; anthracite with a low clay content is not suitable for making water coal bars.

The principal advantage of water coal bar is its simple, low-cost production, with no need for binders. However, it is low in strength (soft and, therefore, readily loses its shape), cracks easily when fed into the furnace, and gasifies slowly (thereby reducing the gasifier production rate).

**Briquettes using clay with pulp waste liquor or humate.** Different binder materials can be mixed to create a compound binder that is superior to either constituent binder used alone. In this case, clay can be mixed with either pulp waste liquor (the discharge from a paper mill) or humate. An alkali solution of humate was developed as a briquette binder by the Beijing Research Institute of Coal Chemistry (BRICC), a part of the China Coal Research Institute (CCRI), in 1974. Humate binder made of peat, lignite, weathered coal, and alkali solution is used mainly in small synthetic ammonia plants that lack lime or pulp waste liquor. As binding agents, humate and pulp waste complement clay, producing a briquette with both good cold and hot strengths. The chief disadvantages of clay–pulp waste liquor and clay-humate briquettes is that the binder sources are limited and the resulting briquettes absorb moisture easily. The technology has been applied in more than ten fertilizer plants in Guangxi, Jiangxi, Fengrun of Hebei, Liuyang of Hunan, and elsewhere.

**Anthracite briquettes.** Since the 1980s, research and development of anthracite gasification briquettes has focused on building a large-scale central briquetting base in an anthracite mining area that will produce briquettes with enhanced cold and hot strength and higher fixed-carbon content. The briquettes must be waterproof to withstand transportation. It is hoped that the improved briquettes can replace 600 existing lime-carbonated and other briquette production lines to reduce production costs at small nitrogen-based fertilizer plants and increase their productivity.

China's gasification briquette technologies can only be advanced by improvements in binding agents. Currently, encouraging progress is being made in the development of both different binders and different combinations of binders. Notably, some success has been achieved in producing binders that are waterproof and do not need drying. Gasification experiments with briquettes using different binders developed by BRICC and others were carried out in a $\phi$

2.26-m fixed-bed water gas furnace with good results. The specifications of the various briquettes tested in this furnace are presented in Appendix C.

### *Coke Briquettes for Blast Furnaces*

The use of coke briquettes as a feedstock for blast furnaces in the metallurgical industry reaches back to initial research in the 1950s. As of 1987, 35 enterprises in 14 provinces used coke briquettes, supplied by more than ten plants producing 10,000–20,000 tonnes per year. The best examples of these briquette users are a 30-$m^3$ blast furnace of the Longbei Steelworks of Guangdong and a 73-$m^3$ blast furnace of the Wanfu Steelworks of Sichuan, which are both using coke briquettes to smelt iron. The Lancangjiang Smeltery in Yunnan province has been using lignite coke briquettes to smelt aluminum. These coke briquettes are all produced by a cold briquetting process, which is quite mature in China. Most use tar and pitch as the binder and make full use of local weakly caking and non-caking coal.

In 1972, the New Coking Plant of Xiamen built a coke briquette plant with a capacity of 2.5 t/h, using a hot pressure process. The product was used in a 13-$m^3$ blast furnace and a coal gas furnace. Jinzhou Steelworks of Hubei and Maanshan Iron & Steel Company built the hot coke briquetting equipment. In 1994, Shizhuishan Coke Plant of Ningxia built a coke briquetting plant with an annual output of 40,000 tonnes, which now is under test. However, because of its high capital cost, complicated process, and difficulty of operation and adjustment, the hot briquetting process has not been expanded or widely applied.

Shanghai Baoshan Iron & Steel Company built a coke briquetting plant in the mid-1980s with 0.80 Mt of annual output capacity, using equipment imported from Japan. The plant, which was designed in China, blends a raw low-sulfur, low-ash anthracite with briquettes in a 70:30 mixture to produce the feedstock for the coke-making process. Organic binders are use to keep the ash content low. Using this process improves the quality of the coke.

## Technical Summary of a Typical Briquetting Process

This section illustrates the briquetting process, using as an example the process for blending fat coal with coal refuse and sodium humate to produce coke briquettes.

## Process Overview

A typical briquetting plant could have an annual output of 20,000 tonnes of coke briquettes produced by a cold process. The process consists mainly of sodium humate production, briquetting, and baking and distillation. This example plant could use weathered coal as feedstock to produce a sodium humate binder (for low-temperature performance). Coal refuse and fat coal could be blended to make the briquette, and some fat coal could also be used as a binder due to its strong caking ability at high temperature. The blending ratio of raw materials and parameters of the briquetting process are as follows:

- Solid constituents: 65% refuse and 35% fat coal (both sized at 80 mesh)
- Sodium humate: 15% of the solids (added as an aqueous solution with 10% concentration of sodium humate)

- Briquetting pressure: 17.6–19.6 Pa
- Agitating time: 12 minutes
- Moisture of briquette: 15–18%

The physical properties of the feed coal and briquette product are shown in Appendix C.

In such a plant, refuse coal fines and fat coal are uniformly mixed with the binder under atmospheric temperature, according to the ratios presented above, and the mixture is fed to roller briquetting machines. The final product is obtained by low-temperature pyrolysis.

The raw briquette produced by the foregoing process is then dried (40–140□C) and roasted (850□C). During this process, coal particles in the raw briquette undergo decomposition, softening, curing, and shrinking—at last forming the char. The final step is cooling in a cold water pool. Such coke briquette products have higher cold and hot strength and are more waterproof than coal briquettes.

## Process Costs

The total investment (capital) cost of the plant described above is 1.72 million yuan (see Appendix C for costing details). Assuming a sale price of 140 yuan/t, the annual product value is 2.8 million yuan—yielding a profit of 0.6 million yuan after deducting 2.04 million yuan for production costs and 0.16 million yuan for the annual product tax. Thus, the briquetting plant is quite profitable, and the profits are realized quickly, as the investment is relatively low. Moreover, this particular briquette process—which uses refuse or weathered coal as the raw material—transforms waste into a valuable product that is environmentally superior to the sized coal or coke feedstocks it replaces.

## Development Prospects and Barriers for Briquette Technology

## Household Briquettes

Most urban and many rural residents in China use coal as their main household fuel, annually consuming more than 200 Mt nationwide (including use in central and district heating boilers). The current annual production of household briquettes is only 50 Mt, most of which is burned in large and medium-sized cities, where this technology has rapidly gained popularity. As towns continue to strengthen environmental measures and forbid the burning of raw coal, urban demand for household briquettes should increase dramatically. Even greater market growth opportunities for briquette technology lie in the vast countryside, especially in poor and minority nationality areas, which still burn raw coal.

Household briquettes in China are mainly the anthracite honeycomb variety. To make bituminous-based briquettes a viable option for areas where anthracite is not available requires the development of (1) bituminous honeycomb briquettes that cost less than currently available products and (2) dust-free stoves designed to burn these briquettes. Improved sulfur-capture additives are another area requiring development, as people in acid rain and $SO_2$–regulated areas urgently need household briquettes that reduce sulfur emissions.

Briquette technologies also represent an export opportunity. Many countries in Asia and Africa are interested in importing briquette technologies and facilities from China in order to protect their environment, reduce forest lumbering, and encourage the use of bituminous coal. Mongolia, Indonesia, South Africa, and Nigeria have come to China many times to negotiate the construction of briquette plants

## Industrial Briquettes

Compared with household briquettes, industrial briquettes are making slow progress. At present, the total annual output is only about 20 Mt—comprising mainly gasification briquettes, boiler briquettes produced by small-scale stokehold units, and coke briquettes for the metallurgical industry. However, the prospects for industrial briquettes are promising, especially as replacement fuels for raw coal in fixed-bed industrial boilers and kilns and in water gas furnaces used in the chemical and metallurgical industry.

The annual coal consumption of existing fixed-bed industrial boilers and kilns in China amounts to 400 Mt, and this amount of fuel should be provided as sized coal, specifically in the 13–25 mm or 25–50 mm size range. Yet due to mechanized mining, the output of sized coal has declined so that supply falls short of demand—creating a perfect opening for briquette technology. Further, briquettes avoid the large losses when the fine coal fraction of the raw coal drops out of the furnace through small openings and cracks or is entrained with the flue gas; these losses cause low thermal efficiency and air pollution.

Briquette technology has already begun to penetrate the water gas furnace market. About 40 Mt of anthracite are required each year by some 900 small nitrogen-based fertilizer plants that employ water gas furnaces to produce raw materials for synthetic ammonia. An additional 9 Mt of sized anthracite or bituminous coal are consumed by furnaces producing fuel gases for the metallurgical and machinery industries. There is only enough sized coal to supply half this demand; the shortfall is supplied mainly by low-quality briquettes such as carbonated briquettes. However, water gas furnaces are old technology with high emissions and low efficiency. Therefore, this report recommends that these furnaces be replaced by modern, large, well-controlled gasifiers, and these new gasifiers do not need pelleted fuel.

Industrial boiler briquettes are currently at an initial stage of development, and this development should be encouraged because the use of briquettes reduces particulate emissions, and sulfur-capture additives can be included to reduce $SO_2$ emissions. Stokehold briquetting should be attractive because of its simple process and low capital investment. Alternatively, because blended coals produce better briquettes than single coals, constructing blended-coal briquette plants at existing steam coal blending plants would speed up deployment of this technology and increase its benefits. To increase the use and effectiveness of boiler briquettes, further research and development is needed on binders and production facilities.

Gasification briquettes require improved waterproof characteristics, which will be developed during the Ninth Five-Year Plan period by tackling the key technology problems of process, facilities, binders, chemical and physical analytical methods, and briquetting theory.

## Barriers to Development

### *Effect of Coal Price*

According to international indices comparing prices of commodities, coal prices are unreasonably low relative to the prices of other industrial commodities in China. In part this is due to overproduction of coal, which is being addressed by new policies that seek to reduce production by closing the small, inefficient, polluting mines. Because the price of raw coal is so low, the price difference between sized and fine coal is also low, and less than the processing cost to make briquettes. Therefore, the cost of a briquette (which equals the cost of its fine coal raw material plus the processing costs) is higher than the cost of sized coal, its main competition. Obviously, in the absence of other market forces or restrictions on the use of sized coal (e.g., directly or indirectly through environmental regulations), this price handicap is one of the most important factors restricting coal briquette development.

### *Environmental Protection Policies*

The Law on the Prevention and Control of Atmospheric Pollution, published in August 1995, expressly provided for vigorous expansion, production, and use of briquette technology. However, the law lacks a complete set of detailed enforcement regulations to restrict various sectors from burning raw coal. The emission fees are so low that enterprises prefer to pay this fee rather than burn a more expensive, environmentally superior coal product (or install pollution controls).

### *Technical Issues*

The lack of binders that are widely available, low-cost, and suitable for many uses is one of the key factors restricting development of industrial coal briquettes. And once new binders are developed, production processes using these binders will also need to be engineered and refined. Production equipment must also be improved; household briquette equipment has been used for industrial briquette production, but it consumes too much energy, among other problems. There are also challenges to overcome in developing industrial briquettes that are suitable for long-distance transport (i.e., waterproof with high strength). Production processes using new types of binder need to be improved. Quality standards and measurement methods for industrial briquettes need to be developed and applied.

## Suggested Countermeasures

The following list summarizes the technical measures mentioned in the previous discussion that could promote the use of briquettes as a means of improving the environmental and economic performance of various processes. Policy recommendations prepared by the CCPUA authors for all clean coal technologies discussed in this report are consolidated in Chapter 8.

- Build briquette plants at steam coal blending facilities to take advantage of equipment that is common to both processes. Add sulfur-capture additives to all briquettes—but especially those used in industrial processes—to provide an additional motivation for using them (presuming $SO_2$ standards will be expanded to more sources, the standards will be enforced, and $SO_2$ emissions fees will be increased).

- In allocating R&D resources, give priority to the development of gasification briquettes, because they are urgently needed and have good economic benefits.
- Continually research cheap binders that would be easy to popularize, develop cement-type waterproof binders that do not require a drying process, and improve processing equipment such as briquetting machines and mixers.
- Develop boiler briquette technologies—based on processes for making household briquettes—that are simpler and lower cost than current technologies and can produce a quick return on investment.
- Develop high-temperature desulfurization additives, which are particularly urgent for areas with high-sulfur coal, such as Sichuan, Guizhou, and Hubei provinces.
- Obtain access to foreign high-pressure briquetting technology information and improve the equipment for application in China.
- Develop biomass briquette technology to make fuller use of this environmentally friendly, renewable energy source.

# 5

# Coke Manufacture

An important clean coal technology, coking produces clean secondary energy as well as clean chemical materials or refined chemical products by further processing of the hydrocarbon by-products. The process removes the volatile components in coal to produce coke, a fuel that burns without producing smoke and that can be used to generate the reducing gas needed by the iron and steel industry. Besides providing a variety of clean fuels and chemicals, coking can make effective use of China's coal resources, raise the value of coal use, and reduce pollution. Coking already plays a vital role in China's economy, primarily in the metallurgy sector, but also in chemical manufacturing and other sectors; in 1997, coal consumption for coking accounted for more than 13% of China's total coal consumption.

To enhance the benefits available from the use of coke, new processes and facilities should be developed to raise coking production efficiency and the quality of its products. New techniques such as dust-proof ovens and particulate controls, wastewater treatment, and gaseous emissions controls should be developed to improve environmental quality.

## Current Production and Utilization Status

Coke is produced in indigenous ovens (also known as 'beehive' ovens), simple mechanical ovens, and the more complex 'regular' ovens. In 1997, indigenous ovens produced about 67.3 Mt (48.4%) of the nation's total coke output, almost equaling the 71.7 Mt produced by mechanical ovens. China has approximately 741 enterprises with mechanical ovens. Because the indigenous coking process has the lowest capital cost, over 8000 small units are operating now (especially concentrated in Shanxi province). However, coke making by indigenous ovens takes a long time, yields only small amounts of coke per charge and per unit of coal feed, is thermally inefficient (higher heat losses than other processes), releases substantial amounts of pollutants, and wastes the valuable hydrocarbon by-products that are recovered in the other processes. Therefore, the government has established a policy to shut down these ovens.

The height of the coking cabin is a key indicator of its age and thermal and environmental performance (a larger cabin is cleaner and more efficient); therefore, Table 5.1 on the next page presents a summary of mechanical coke oven capacity in China according to this parameter.

Shanxi province has the most abundant coal resources in China, with its coking coal reserves accounting for 53% of the total amount of coking coal in the nation (see Appendix D for production rates of the various coking coals). The province produced the most indigenous coke in the nation—more than 40 Mt in 1997 from 3000 coking enterprises—accounting for about 60% of the national total. The mid-sized and large coking ovens supply only 8–10% of the total coke production from this province, while the small 'regular' ovens produce about 15%, and the indigenous and simple mechanical ('improved') ovens account for the majority of the production, at about 75%.

At present, coke exports are a small percentage of total production, but increasing rapidly. From 1992 to 1997, they increased about seven-fold, from 1.35 Mt to 10.58 Mt, rising further to 11.46 Mt in 1998.

In recent years, metallurgy consumed 50–60% of the coke produced nationwide (producing 76% of its need itself and buying the remaining 24% from other coke ovens); the chemical industry used 25–30%; and the machinery industry consumed 5–10% (mainly foundry coke).

**Table 5.1: Distribution of Mechanical Coking Ovens in China by Cabin Height and Capacity**

| *Height of Coking Cabin, m* | *Number of coking ovens* | *Capacity of coking ovens, Mt/a* | *Application* |
|---|---|---|---|
| 6 | 22 | 9.6 | Capital Iron & Steel Co., Xuanhua, Baoshan, Maanshan, Wuhan, Panzhihua, Kunming Iron & Steel Co., Beijing Coking Plant, Shijiazhuang Coking Plant |
| 5.5 | 8 | 3 | Panzhihua, Shuicheng and Tangshan Iron & Steel Co. |
| 4–5 | 138 | 43 | Metallurgical sector: 101 coking ovens, 32.3 Mt/a |
| | | | Other sectors: 37 coking ovens, 10.7 Mt/a |
| 2.5–3.8 | 193 | 13 | Including 17 stamping ovens, 1.57 Mt/a |
| <2 | 380 | 7.4 | Simple ovens |
| Total | 741 | 76 | |

## Status of Coking Technology

### *Coke Ovens*

China's coke oven technology—taking the 6-m coke oven of Shanghai Baoshan Iron & Steel Company as an example—can be as advanced as any in the world. This oven meets the best technical specifications for coking cabin height and width, oven wall thickness, and heat transfer efficiency. Ninety percent of the design for a 6-m state-of-the-art oven can be done in China, and the entire coke oven body can be manufactured domestically. Commercial tests for a more advanced oven with an 8-m coking cabin were completed in the 1980s, and China can now design this kind of oven internally. Another advanced design incorporated in Chinese coke-making plants is dry coke quenching, which is used by the Baoshan Coking

Plant, Pudong Gas Plant, and Jinan Iron & Steel Co. In addition, a dry coke quenching unit provided by Japan's Green Aid Plan is under construction by Beijing Iron & Steel Co. Reliable and stable automatic coal blending systems have been installed at several large coke plants, as has high-performance pulverizing equipment (sometimes separately, other times together with automatic controls).

## Coke Oven Gas Cleanup

China has not only developed several gas cleanup processes—ammonia removal and recovery, sulfur/ammonia removal and recovery as ammonium sulfate, ADA desulfurization, ammonia incineration, and single-tower benzene removal—but has also mastered a variety of other processes in cooperation with foreign partners and through introduction of key technologies from abroad. These include a gas cleanup process with full negative pressure; AS scrubbing for desulfurization, deoxidization, and benzene removal; the T-H process for sulfur and cyanate removal; and the Fusamu cooling and heating process that produces anhydrous ammonia as a by-product.[12]

Other environmental protection technologies that have been developed and applied include smokeless coal charging by high-pressure ammonia spraying, thermal floatation shade systems (gas driven by buoyancy flows into a scrubber-type device in the gas discharge flue on top of the oven) to collect dust from coal charging and coke pushing, large coke ovens with flue gas particulate removal, dry coke quenching, biological removal of phenols in wastewater, wastewater processing with activated carbon, etc. Cost and collection efficiency data for the most common particulate controls for coal charging and coke pushing are presented in Section 5.5.5. Much used in China is a process developed locally for the biological removal of nitrogen from coking wastewater. Its use in the second phase of the coking plant at Baoshan Iron & Steel Company was an early successful application.

### *Automatic Control*

Programmable logic controllers (PLC) and distributed control systems (DCS) are computer-automated control systems that have been widely used in new coking plants and as retrofits to old coking facilities. Increasingly, the primary components and equipment for data processing are produced domestically. The latest automatic control system for oven temperature and pressure, as well as advanced computer management systems for coking plants, are being developed and deployed. A reliable and stable automatic control system for coal blending has also been developed and implemented.

### *Refining of Chemical Products*

A by-product of coke making is the generation of hydrocarbons, especially aromatics, when the volatiles are driven out of the coal by the heating process. The industry now processes 100,000–200,000 t/a of tar by-products, yielding phenol, pyridine, coumarone, refined naphthalene, delayed coke, etc. The production of hydrogenated benzene and distilled

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[12] ADA, AS, and T-H are all suppliers' names or acronyms for their processes.

benzene is 50,000 t/a, while that of refined naphthalene by step-distillation is 20,000 t/a. Techniques to produce modified pitch and hard pitch (pitch with higher softening temperatures) have been developed and applied.

Intensive processing of tar in large-scale and coal-based needle coke processes has been mastered and applied. The varieties of naphthalene, anthracene, pyridine, and benzene compounds and their refined products are proliferating, and the production of these products is rising steadily.

### *New Developments*

**Fundamental research.** Research has been conducted on improving coke quality, with special emphasis on forecasting coke quality based on the coal's petrography and its physical and chemical properties. Because China has so much highly volatile coal, much work has been done on the rational utilization of this resource. In addition, laboratory and pilot tests of stamping coking, coal briquette blending, and coal preheating technologies have been carried out. Research has also been conducted on coke properties at both atmospheric and high temperatures, its microscopic structure, and mechanical and other physical properties. Some research results have garnered international interest.

**Formed coke.** A set of commercial briquetting units that use the flue gas and hot solids (e.g., anthracite coal) from the coal furnace to heat the briquettes directly has been placed into operation in the northwest of China. After several years of experience have been gained with this process, another formed coke briquette plant will be constructed in a different region based on the lessons learned from this first plant.

**Coal pyrolysis.** A process has been developed recently which yields char and a gas that is similar to coke-oven gas. This process offers a new way to utilize lignite or low-rank coal. Improved upright ovens with continuous distillation capability have been put into operation, and produce a coke with low ash and low sulfur that can be used for the production of ferroalloy.

## Technical, Economic, and Environmental Evaluation of Main Coking Technologies

Given the nature of China's coking coal reserves and their distribution, the following discussion will concentrate on stamping coking. This technique suits the characteristics of Chinese coking coal resources and can improve coke quality; moreover, it is mature and ranks as the country's second most common practical coking production technique. Technical, economic, and environmental characteristics of several other common coking ovens are also presented.

### *Stamping Coking*

In stamping coking, the coal is compacted by 'stamping' it with hammers before feeding it to the coke oven. The chief benefits of this technology are:

- **Greater production capacity.** Because the bulk density of the charged coal is greatly increased but the coking period is only slightly longer, a stamping oven exceeds conventional oven production capacity by more than 15%.
- **Lower investment.** A stamped coke oven body costs less than a conventional oven because it has fewer cabins.
- **Cheaper feedstock.** Stamping technology can use high-volatile and weakly caking coals, which cost less than strongly caking coals. Because the price of coal accounts for 75–80% of coke production costs, use of a cheaper feedstock can significantly reduce the price of coke.
- **More efficient use of coke.** Stamping coking technology plays an important role in improving the coke quality and, therefore, the operation of the blast furnace; it reduces the amount of coke needed and increases the production capacity of the blast furnace.

The price of high-volatile and weakly caking coal is 10–15 yuan/t lower than that of strongly caking coal. While small amounts of this lower-cost coal is already used as part of a feedstock blend in coke making, its use could increase by 15–20% if the coke is produced by stamping coking. At 15%, the production cost would drop about 3.3 yuan per tonne of coke (including typical benefits from shorter transportation distances for this widely available resource).

Stamping coking technology can improve coke quality and yield high profits for a blast furnace plant. For example, in a 2000 $m^3$ blast furnace, if its utilization efficiency increases by 0.1 $t/m^3$, the output of iron will increase by 73,000 tonnes; the coke-to-iron ratio will drop by 10 kg/t; and 17,500 tonnes of coke will be saved. Based on current prices, these operational improvements will reduce annual costs for the blast furnace plant by over 10 Myuan.

Appendix D contains a table that compares stamping ovens and conventional ovens operating with the same type of coal and blending ratio

### *Environmental Impacts*

Pollutants from the coking industry consist mainly of particulates, harmful gases (leaked raw gas, waste gas, etc., including benzo(a)pyrene, CO, $SO_2$, $NO_x$, and $NH_3$), and wastewater; most of the pollution comes from the coking oven. The pollution sources can be classified as continuous, intermittent, or occasional, depending on the duration of discharge. For example, the cover of the coal charging hole, cover of the coal gas discharge duct, furnace door, and chimney are all continuous discharge sources, whereas the processes for coal charging, coke pushing, and coke quenching are intermittent polluters.

### *Controls for Mechanical Ovens*

At present, the following pollution control measures are used for the different emission sources:

- **Coal charging.** Although pressurized aqueous ammonia spraying units are installed in large coking ovens, most are not very effective. The other options are a hood and duct arrangement that carries the discharge to a pollution control (e.g., scrubber) on the plant floor—called 'ground station' control—and the 'thermal floatation shade' system mentioned in Section 5.2.2. At present, only Baoshan Iron & Steel Company uses a ground station control for coal charging; the other plants use the thermal flotation shade or ammonia processes.
- **Coke pushing.** Baoshan Iron & Steel Company and the Coking Plant of Capital Iron & Steel Company use ground station controls, while the Wuhan Coking Plant uses the thermal flotation shade.
- **Gas cleanup.** Sulfur and cyanide removal units are used by the Baoshan Iron & Steel Plant, Panzhihua Iron & Steel Plant, coking plants in Shijiazhuang City and Xuanhua City, Tianjin Second Gas Plant, Beijing Coking Plant, and Shanghai Coking Plant.
- **Wastewater treatment.** Since the 1980s, wastewater treatment units have been installed in new and expanded mid- and large-scale coking plants. Generally speaking, phenol removal has reached the state standard, but removal of dicyan and chemical oxygen demand (COD) has not reached the state standard in many coking plants, and removal of ammonia and nitrogen is just beginning.

In summary, pollution due to particulates, harmful gases, and wastewater is very serious, and cleanup processes need to be improved, especially in the numerous small coking plants.

### *Controls for Indigenous Ovens*

The production of indigenous coke releases extremely serious pollutants, including benzo(a)pyrene and other benzene compounds, which are particularly harmful to people, animals, and plants. Production of 1 tonne of indigenous coke results in the discharge of 20 kg of particulate matter, 6.1 kg of $SO_2$, 3.9 kg of benzene compounds, and large quantities of volatile phenol, cyanide, and wastewater with phenol, etc. The environmental damage is particularly serious in Shanxi, where much of the indigenous coke production is concentrated.

Furthermore, indigenous coke consumes much more coal than mechanical coke, resulting in proportionally higher residual ash and particulate emissions. In Shanxi province alone, indigenous coke production produces 1.8 Mt/a of particulate emissions (based on an estimate of 0.015 tonnes of particulate per tonne of coal).

Therefore, effective environmental protection measures should be taken to strengthen the control of both continuous and intermittent particulate and gaseous emissions, as well as wastewater discharges, to reduce the resulting environmental degradation.

### *Oven Capacity*

Many coking ovens in China are small, and these units emit more pollutants than larger plants. In addition, different kinds of coking ovens result in different levels of pollution, approximately proportional to the seal lengths. Differences in seal lengths for several ovens are shown below; further details on the design of these ovens are presented in Appendix D.

- Mid-sized coking oven (4.5-m cabin) 14.0 m
- Mid-sized coking oven (6-m cabin) 9.5 m
- Mansmen plant (7.85-m cabin) 5.6 m
- Kaizest No. 3 plant (7.63-m cabin) 5.3 m
- Large reactor (10-m cabin) 2.4 m

By increasing the effective volume of the coking oven—using a higher and wider coking cabin—the number of charges per tonne of product and the number of leakage points in the oven are reduced sharply (see Appendix D), enabling emissions to be controlled more effectively. If a coking oven with a 4.3-m high cabin is remodeled into an oven 5 m high, 0.5 m wide, and 15.98 m long—taking a coking plant with 450,000–500,000 t/a as an example—emissions will be reduced by a third.

### Main Problems in Current Coking Technologies

Although China produces more coke than any other nation, the overall technology level of its coking equipment is comparatively low. The ratio of large coking ovens and units with advanced dry coke quenching, gas cleanup, and wastewater treatment systems to the overall coking equipment is quite low. There are many small and mid-sized 'regular' coking ovens as well as 'simple' coking ovens in China, and even more indigenous coke ovens, with their low efficiencies and high emissions. These issues are explained further below.

### Indigenous Coke Production Is Wasteful and Polluting

As noted earlier, nearly half the coke produced in China comes from indigenous coke ovens. Therefore, their poor environmental and energy performance is a serious problem, and the elimination or improvement of these processes would make a significant impact on the environment and on conservation of high-value coal resources.

Indigenous coking takes a long time (8–10 days), yields only a small amount of coke per charge and per tonne of coal feed, and suffers from large thermal losses. Compared to coke produced by mechanical ovens (assuming the same raw materials), indigenous coke will have 2–3% more ash and consume 200–400 kg more coking coal to produce 1 tonne of coke. And because the indigenous coking process cannot retrieve the chemical by-products from coking, producing 1 tonne of indigenous coke loses the opportunity to provide 352 $m^3$ of coal gas with a heating value of 17.9 MJ/$m^3$ (after deducting 137.6 $m^3$ of gas consumed to heat the coke oven), 54 kg of tar, and 15.4 kg of crude benzene. Assuming average market prices for these commodities, producing 1 tonne of indigenous coke will bring the oven operator 300 yuan less than an operator of an advanced mechanical oven (because of lost revenues from chemical sales and increased operating costs due to thermal inefficiencies). In 1997, the output of indigenous coke was 67.28 Mt, representing a lost opportunity cost (or direct economic damage) of approximately 20 billion yuan.

Moreover, indigenous coking wastes precious coking coal resources. First, it requires primary coking coal and fat coal with good caking and coking properties as raw materials. Mechanical ovens, on the other hand, can use a blend of 40–50% primary coking coal and fat coal, with a less valuable coal for the balance, thereby saving these limited coking coal resources. Second, for the same amount of high-quality coking coal feed, indigenous coking produces only 100 Mt of coke while mechanical coking produces 150 Mt.

For many years, the Chinese government has worked to establish policies to improve and limit indigenous processes for coking. For example, Shanxi province established a policy to close these small, old ovens by the end of 2000, but recently extended the deadline due to social concerns. Nevertheless, the policy still stipulates that these ovens should be replaced with larger, advanced technologies as soon as possible. The State Economic and Trade Commission (SETC) recently approved a similar policy. To support this policy, SETC publishes lists of the facilities that should be shut down in newspapers and other public media in an attempt to achieve its goals through public pressure.

### Excessive Use of Inefficient, Polluting, Low-Technology Coking Cabins

Since the 1960s, the height and width of coking cabins in the international market have been increased to boost production capacity and resulting profits. Coking cabin height has increased to 7 m, 8 m, and even 10 m, while the width has increased from 407 mm to 450 mm to 610 mm and 850 mm. The effective volume of a coking cabin is now over 70 $m^3$. Yet these improved technologies have not been applied in China, where the largest effective volume is only 38.5 $m^3$, and even these cabins account for only 12.7% of total coking capacity. More prevalent are the 380 small coking ovens with an effective cabin volume of 6 $m^3$/cabin; while accounting for 51% of the nation's coking ovens, they supply only 9.7% of its total coking capacity. The rest of the capacity is supplied by indigenous and other smaller units. Production capacity, profits, and environmental control are all impaired by reliance on low-technology ovens with small coking cabins.

### Existing Coking Technologies Do Not Match Coal Resources

Conventional coking ovens, which require feed coal with good caking properties, account for 98% of China's coking ovens; whereas stamping ovens, which can use weakly caking coal with high volatility, account for less than 2%. Yet China has far greater reserves of feed coal appropriate for stamping ovens than conventional ovens.

When a conventional oven is used to produce high-quality metallurgical coke, the feed coal must be highly caking. In a typical coal feed blend, at least 50% of the coal must be primary coking coal and/or fat coal to produce metallurgical grade coke. However, only about a quarter of China's total proved coal reserves are primary coking and fat coal, and a third of this coal resource cannot be used to produce coke because of its high ash and sulfur content. Relative to the national reserves of just coking coals, fat and primary coking coals with moderate volatility and better caking and coking properties together account for less than 36% of these reserves; again, not all can be used for coke due to its high ash and sulfur content. On the other hand, China has a far greater supply of weakly caking coal with high volatility—as much as 50% of the proved reserves of coking coals—and these lower-quality coals can be used in stamping ovens. Thus, because China relies on conventional ovens instead of stamping ovens (which are also less expensive and more efficient), the demand for strongly caking coal exceeds the supply. This problem is exacerbated by the fact that 40% of the coal mined is such high quality coal, exceeding the need for this coal for coke making; therefore, valuable resources are wasted by burning this special coal in boilers.

### Coke for Chemical Production Could Use Lower-Value Coals

Today there is a coke shortage of over 1 M t/a for producing gas, calcium carbide, and iron alloy. The coke needed for these products could be produced from partly or even fully weakly caking coal with high volatility. But currently, metallurgical-grade coke is used as the raw material, which not only wastes China's strongly caking coking coal resources, but also increases production costs.

### Scattered Sitting of Chemical Plants Limits the Variety of Chemical Products

To date, China has 31 tar distillation plants of varying capacities, providing a collective processing capacity of 2.3 M t/a. The maximum capacity of an individual unit is 0.1 M t/a. In addition, 28 crude benzene refining units can supply a total of 0.4 M t/a. However, the units are quite scattered, making it difficult to extensively process these products—a situation that limits the variety of chemical products produced in China. In general, tar can be processed into more than 70 kinds of products—of which more than 20 can be made in a single, large coking plant. Concentration of large coking plants in areas where there are many chemical processing facilities could increase China's chemical processing capacity and also bridge the gap between the quality of the main chemical products produced domestically and those produced abroad (see Appendix D).

### Development Prospects for Coking Technology

With the expansion of the Chinese iron and steel industries, there is increasing demand for high-quality coal as a feedstock for making coke with the currently available equipment. Given the quality of Chinese coal resources, development of the coking industry in China should emphasize stamping coking, briquette blending for coking, dry coke quenching, and coal humidity adjustment. The nation also needs to reduce the environmental releases from coke making through the application of existing environmental control technologies and the development of improved technologies suitable for China's situation. In addition, China should continue to conduct research and development on larger coking ovens. The giant-scale coking reactor (JCR) technology from Germany and new coke briquetting (FCP) technology from Japan should be investigated.

#### *Stamping Coking Technology*

In the northeast and east of China, where the supply of high volatile, weakly caking gas coal is abundant, there are 329 coking batteries in seven coking plants with stamping coking technology. While these facilities are good examples of how the lower cost, abundant gas coal can be used for making coke, the production by these plants is only about 1.6 M t/a, or just 2% of the country's total mechanical coke production (i.e., excluding indigenous coke).

Presently, the largest stamping oven in China is only 3.8 m high (ovens overseas reach 6 m). Although China has not replaced its ovens with larger ones, it has adopted continuous coal feed and multiple-hammer stamping techniques in its existing units, which has greatly raised operating efficiency. For example, operation time has decreased from 12 minutes to 3 minutes; production capacity per unit is 120 charges per day; coal cake density has increased from 0.95 $t/m^3$ to 1.1 $t/m^3$; and particulate emissions from coal charging are adequately controlled.

By increasing bulk density, stamping coking can raise coke quality. Given the same coke quality, stamping coking can increase the percent of gas coal used in the feedstock blend by 20%. Or, for the same coal blend (using a coal with volatile matter of 30%), the strength of the coke as measured by the $M_{40}$ index will increase by 2–4%, and its $M_{10}$ strength measure will also be improved.[13] Therefore, stamping techniques are mature and beneficial, and they should be used more widely.

### *Briquette Blending for Coking Technology*

Technology to blend briquettes with coal as feedstock for making coke was imported from Japan for the first installation at the Baoshan Iron & Steel Company. The use of blended briquette is 30% in the line installed during the first phase and about 15% in the line installed during the second phase of construction. Another set of briquetting units will be built in the third phase. Besides Baoshan Iron & Steel Company, Baotou Iron & Steel Company and Maanshan Iron & Steel Company may adopt briquette blending technology when they rebuild and expand their plants.

Generally speaking, briquette blending coking can improve coke quality, especially its strength.[14] In recent years, coal briquetting units have moved towards higher production capacity and a simpler process, whereby the mixing and blending processes are combined into one operation (hence, one machine); this also eliminates the need for a large cooling system.

### *Dry Coke Quenching Technology*

Dry coke quenching is an energy-saving technology that can reduce the pollution caused by quenching red-hot coke while also improving coke quality. Dry coke quenching makes use of the cool inert gases (e.g., nitrogen or $CO_2$) to cool the red-hot coke slowly, thereby increasing the coke's strength. It is estimated that dry coke quenching will increase the $M_{40}$ index of the coke by 3–8%, decrease its $M_{10}$ by 0.3–0.8%, and produce a more uniform coke block.

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[13] $M_{40}$ and $M_{10}$ are measures of coke strength used in China and refer to the percent of material that is above 40 mm or below 10 mm, respectively, after the test. $D^{150}{}_{50}$, which is mentioned several paragraphs later, is a similar measure of coke strength developed by Japan; it is based on the percent of material > 150 mm and < 50 mm after the test.

[14] For example, one index of coke strength, $DI^{150}{}_{50}$, typically increases by 0.7–1.1% when the proportion of blended briquette increases by 10%, and by 2–3% when the proportion increases by 30%. Industrial tests of the coke produced at Baoshan Iron Steel Company using briquette blending showed that, compared to a 100% conventional coal feed material, a 30% briquette blend resulted in an $M_{40}$ increase from 76% to 82%, an $M_{10}$ drop from 7.4% to 6.1%, and greatly increased cold strength.

Four sets of dry coke quenching units with a capacity of 75 t/h were imported from Japan with the first-phase installation at Baoshan Iron & Steel Company. Four more sets of dry coke quenching units were designed and built in China in the second phase; some of these components came from abroad. Two sets of dry coke quenching units (capacity of 56 t/h) were imported from Russia by the Shanghai Pudong Gas Plant.

### *Coal Moisture Adjustment Technology*

Adjusting the coal's moisture to the optimum level (usually increased, but sometimes decreased) has many advantages, such as raising the output and strength of the coke, making a more uniform block of coke, reducing the thermal consumption of coking, and enabling the use of more weakly caking coal through blending.

The Coking Plant of Chongqing Iron & Steel Plant is preparing to construct a coal humidity adjustment unit using a 140 t/h drying machine imported from Japan. These facilities can drop the moisture of the feed coal from 10.5% to 6%. It is estimated that the production capacity of the coking ovens will increase by 7.7%. Thermal consumption for coking will decrease by 301 kJ/kg or 263 kJ/kg, depending on whether blast furnace or coking oven gas is used. The amount of weakly caking coal will increase by 8%. The coke strength will increase by 1%, equivalent to blending 10% briquettes into the feed coal.

## Particulate Controls for Coking Ovens

Environmental protection calls for widespread use of particulate controls. Table 5.2 compares various particulate control technologies. Where two approaches are indicated for a given source, either control technology can be used. New technologies should be developed for particulate removal from coking ovens, especially stamping ovens, and existing technologies should be improved to increase their collection efficiency and decrease their investment and operating costs.

**Table 5.2: Comparison of Particulate Control Technologies for Coking Ovens**

| | *Items* | *Methods for Removing Dust** | *Investment, $10^4$ yuan* | *Power Demand, kW* | *Particulate Collection, %* |
|---|---|---|---|---|---|
| | 6-m coke oven | Ground station | 3000 | 1000 | 75 |
| Coke Pushing | (2 ovens) | Thermal flotation shade | 1600–1700 | 300 | 90 |
| | 4.3-m coke oven | Ground station | 2000 | < 600 | 70 |
| | (2 ovens) | Thermal flotation shade | 1000 | 180 | 85 |
| | 6-m coke oven 2 ovens) | Ground station | 1500 | 200–500 | 80 |
| Coal Charging | 4.3-m coke oven | Ground station | 1000 | < 220 | 90 |
| | (2 ovens) | Capture of dust from coal truck | 250 | 180 | 85 |

* Ground station and thermal flotation shade are explained in Sections 5.3.2.1 and 5.2.2. Dust from the coal 'truck,' or small rail car on top of the oven that carries coal to the charging door and dumps it in, is captured via an enclosure over the truck and an exhaust system that draws the particles to a scrubber.

### *Refining of Chemical Products*

Advances in chemical product refining should mainly address crude benzene hydrogenation technology, with a focus on developing a hydrogenation process with solvent extraction distillation, to reduce energy consumption and increase capacity. The capacity of each tar distillation unit should be raised to 150,000 t/a using ordinary pressure or vacuum distillation, and plants should add intensive processing of pitch, anthracene oil, and wash oil to produce high-value coal chemical products such as needle coke, refined anthracene, carbazole, methyl naphthalene, etc.

## Recommendations for Improved Coking Performance

1. Strengthen environmental protection regulations—and their enforcement—to rapidly limit indigenous coking and hasten the conversion of the many (8000) small ovens to mechanical coking in large, advanced plants.

2. Speed the upgrade or replacement of small- and middle-size mechanical coking ovens with large, advanced plants.

3. Apply computerized, automated operation and control of coking processes.

4. Actively develop stamping coking, briquette blending for coking, and coal moisture adjustment technologies.

5. Develop refining technologies, such as crude benzene hydrogenation and intensive processing of tar, to increase the variety and value of chemical products that can be manufactured from coking by-products.

# 6

# Coal Gasification

Gasification converts coal into coal gas, a convenient form of secondary energy that can be used either as a clean-burning fuel in industry or households or as a feedstock for chemical synthesis processes. When replacing the use of raw coal in older, inefficient boilers and furnaces, coal gas increases the utilization efficiency of coal, thereby prolonging the life of China's coal resources. Moreover, gasification allows impurities and pollutants such as particulates, $SO_x$, and $NO_x$, to be removed efficiently and economically before combustion. Coal gasification technology is a prerequisite for clean coal power production by the integrated gasification combined cycle (IGCC) technology, and for large-scale coal chemical manufacture. As such, coal gasification is a critical route to rational, high-efficiency, clean use of coal, and therefore should be a key component of China's clean coal technology system, warranting priority development.

## Current Development and Application Status

Although coal gasification has more than a half-century history in China, its development rate has been comparatively slow. There are 8,000 gasifiers in operation throughout the country—about 4,000 coal gasifiers and 3,000–4,000 water gas gasifiers—but most are still based on medium- and small-scale atmospheric fixed-bed technologies that are seldom used in most industrialized countries. Advanced gasification technologies, especially large-scale technologies, have been applied only rarely in China.

The atmospheric fixed-bed gasifiers in China used coke initially as their feedstock. Later, sized anthracite was substituted for coke, followed by non-caking and weakly caking meager coal and subbituminous coal, as well as briquettes made of fine anthracite.

China has supported significant efforts to develop domestic expertise in atmospheric fluidized-bed and entrained-flow gasification technologies. Starting in the early 1970s, China began trying to use the fixed-bed Lurgi pressurized gasification (dry ash removal) by the aid of technology imported from abroad. Now, more than 20 sets of Lurgi gasifiers have been installed throughout the country.

Then, during the 1980s, China began to develop pressurized fluidized-bed and atmospheric fixed-bed two-stage gas producers, atmospheric fixed-bed two-stage water gas producers, and 'back-fire-type' coal gasifiers (i.e., with air entering from the top instead of the bottom of the gasifier). Dozens of the two-stage gas producers, water gas producers, and back-fire-type gasifiers are now in operation.

In the 1990s, China developed new underground (i.e., in situ) coal gasification processes. The country also imported Texaco's pressurized entrained-flow, water-coal mixture gasification technology, and it developed a variant of the U-gas ash-agglomerating pressurized fluidized-bed gasifier through a combination of technology transfer and domestic development. One plant with nine U-gas gasifiers and three plants with Texaco gasifiers are now operating in China.

Despite these efforts, the overall technology level of China's gasification installations is low, with few installations featuring the more advanced fluidized-bed and entrained-flow designs.

## Coal Gas Applications

As noted earlier, coal-derived gas is a clean energy source or feedstock with many potential uses. One of its biggest applications in China is as feed gas for synthetic ammonia ($NH_3$) in the many medium- and small-scale nitrogen-based fertilizer plants. China has 852 small-scale nitrogen-based fertilizer plants ($NH_3$ output of 15,000–60,000 t/a), 55 medium-scale plants ($NH_3$ output of 100,0000–150,000 t/a), and 28 large-scale plants ($NH_3$ output of 0.3 M t/a). The total output of $NH_3$ is about 30 M t/a, two-thirds of which is produced by the medium- and small-sized fertilizer plants. Use of coal gas predominates in these small and medium plants: 92% of smaller plants and 70% of medium plants use coal gas as a feedstock, whereas only 12% of the large plants use it. In addition, coal gas is also used as feed material by some of China's chemical enterprises to produce chemicals such as methanol.

Another application of coal gas is as a reducing gas in the metallurgical industry. The CO and $H_2$ in coal gas are strong reducing agents, which can be used to directly reduce iron ore into sponge iron; this solves the problem of iron smelting in regions lacking coke and coking coal. In the nonferrous metal industry, metallic oxides such as nickel, copper, and tungsten can be melted by using coal gas as the reducing agent.

Coal gas can be used as fuel by a variety of industries—including iron and steel, machinery, building materials, textile, food, and light industries—for heating industrial stoves and kilns, half-made products, and finished products. China currently uses substantial quantities of coal gas with low heating value to heat steel-making furnaces, coke ovens, metal forging heating furnaces, various metal heat-treating furnaces, refractory material kilns, cement kilns, glass kilns, various dryers, and more.

Coal gas is also used as a household fuel, in which case it is usually called town gas. However, because it was introduced for this application only in the last 20–30 years, it now accounts for less than 10% of the total gas consumed by households; the rest is natural gas or liquefied petroleum gas (LPG).[15] Coal gas is used by homes in many large and medium-sized

[15] Overall, more than two-thirds of the families in many large and mid-sized cities use some form of gas, but this number is only 10% for the whole country.

cities, some towns, and several coal mine areas. It is also burned in some larger factories. Due to competition from natural gas and LPG, further development of coal gas for household use is facing a serious challenge. Greater use of coal-based synthetic gas would enhance China's energy security by allowing it to take advantage of its large domestic coal resources and depend less on imports.

Integrated gasification combined cycle (IGCC) technology using coal gas as the fuel is a promising new electricity generation technology that offers higher energy conversion efficiency and reduced emissions. Accordingly, it is receiving serious attention worldwide. China has launched a feasibility study for an IGCC demonstration project and plans to build a larger-scale IGCC demonstration project in the early 2000's, to be followed by widespread application of this clean coal technology.

## Evaluation of China's Principal Coal Gasification Technologies

This section describes the key gasification technologies that are widely used in China or have good prospects for successful application. These include mature and reliable traditional technologies—e.g., atmospheric fixed-bed gasifiers for coal gas and water gas—as well as some large-scale advanced technologies:

- Atmospheric fixed-bed producer gas gasifier—one- and two-stage
- Atmospheric fixed-bed water gas gasifier—one- and two-stage
- Lurgi pressurized fixed-bed gasifier (under dry ash discharge conditions)
- Texaco pressurized entrained-flow gasifier with coal water slurry feed
- Shell pressurized entrained-flow coal gasifier with dry feed of pulverized coal
- GSP pressurized entrained-flow coal gasifier

Table 6.1 summarizes the main characteristics of these technologies. The atmospheric fixed-bed producer gas gasifiers and water gas furnaces are the most widely used in China; accordingly, these two technologies are discussed in greater detail below. However, the last four processes in the table—Lurgi, Texaco, Shell, and GSP—represent state-of-the-art technology and should be the preferred systems for all new and upgraded installations.

### *Atmospheric Fixed-Bed Gasifiers*

This basic gasification technology uses various sized fuels—coke, anthracite, and non-caking or weakly caking coal—as the raw feed, and air plus steam as the gasification agents. The oxidation of carbon (to produce $CO_2$ and CO) is a strong exothermic reaction, while steam gasification of carbon is an endothermic reaction; therefore, because the two reactions occur in the gasifier at the same time, the heat released from carbon oxidation can be used for the steam gasification of carbon; thus the coal gasification process can be continuous and steady.

**Table 6.1: Comparison of Typical Coal Gasification Technologies**

| | *Producer Gas One-Stage* | *Water Gas One-Stage* | *Producer Gas Two-Stage* | *Water Gas Two-Stage* | *Lurgi* | *Texaco* | *Shell* | *GSP* |
|---|---|---|---|---|---|---|---|---|
| **Bed Type** | Fixed | Fixed | Fixed | Fixed | Fixed | Entrained-flow | Entrained-flow | Entrained-flow |
| **Suitable Feed Coals** | Coke, Anthracite | Coke, Anthracite | Long-flame coal, Non-caking coal | Long-flame coal, Non-caking coal | Lignite, Long-flame coal | Various | Various | Various |
| **Shape of Feed Coal** | Sized coal | Sized coal | Sized coal | Sized coal | Sized coal | Coal slurry | Dry fine coal | Dry fine coal |
| **Coal Feeding Position** | Furnace top | Furnace top | Furnace top | Furnace top | Furnace top | Furnace top | Furnace bottom | Furnace top |
| **Gasification Agent** | Air plus steam | Air plus steam | Air plus steam | Air plus steam | Oxygen plus steam | Oxygen plus steam | Oxygen plus steam | Oxygen plus steam |
| **Agent Feeding Location** | Furnace bottom | Furnace top/bottom | Furnace bottom | Furnace top/bottom | Furnace bottom | Furnace top | Furnace bottom | Furnace top |
| **Ash Form** | Solid | Solid | Solid | Solid | Solid | Liquid | Liquid | Liquid |
| **Pressure** | Atmospheric | Atmospheric | Atmospheric | Atmospheric | Pressurized | Pressurized | Pressurized | Pressurized |
| **Gasification Temp., °C** | 1100 | 900–1100 | 1100 | 900–1100 | 1050 | 1400 | 1600 | 1500 |
| **Capacity** | Small | Small | Small | Small | Small | Large | Large | Large |
| **Gas Yield, $Nm^3/kg$** | 3 | 1.2 | 2.6 | 1.1 | 1.0 | 1.6 | 1.6 | 1.6 |
| **Gas Heating Value, $MJ/Nm^3$** | 4.6 | 10 | 5.4 | 10.8 | 14.6 | 9.5 | 10 | 10 |
| **Gasification Efficiency, %** | 70 | 60 | 70 | 60 | 75 | 75 | 80 | 78 |
| **Unit Investment, yuan/MJ-day** | 20 | 25 | 25 | 30 | 60 | 90 | — | — |
| **Cost of Gas, yuan/GJ** | 40 | 60 | 50 | 70 | 80 | 100 | — | — |
| **Particulate Emissions** | Low | Low | Low | Low | Low | Very low | Very low | Very low |
| **$SO_2$ Emissions** | Low | More | Low | More | Low | Very low | Very low | Very low |
| **$NO_x$ Emissions** | Low | More | Low | More | Low | Very low | Very low | Very low |

### *Feed Coal Requirements*

The properties of the feed coal have a decisive effect on the gasifier structure (e.g., 1- versus 2-stage), the technology, gasification ate, and operation. It is necessary to select a feed coal that is non-caking or only weakly caking, with good thermal stability, high strength, and high ash fusibility. Further the coal should have less than 25% ash and 2% sulfur if it is anthracite or meager coal, and less than 20% ash and 1.2% sulfur if it is subbituminous coal or lignite. Further feed coal quality requirements for gasifiers are presented in Appendix E.

### Gasifier Structure

The most common types of atmospheric fixed-bed coal gasifiers used in China are identified in Table 6.2 along with the coals for which they are each best suited. Additional design details are provided in Appendix E.

**Table 6.2: Main Atmospheric Fixed-Bed Gasifiers in China**

| *Gasifier Designation* | *Best Coal* | *Key Features* |
|---|---|---|
| 3M21 | Non-caking coals: meager coal, anthracite, coke | Large capacity, reliable |
| 3M13 | Weakly caking bituminous | |
| Wellman-Galusha (W-G) | Non-caking coal: anthracite, coke | Longer residence time for low-reactivity coals, large capacity, reliable |
| TG-3MI (W-G derivative) | Coke, anthracite, weakly caking bituminous | Design improvement with large capacity and high efficiency; can gasify fines (6-13 mm) |
| TG-3MII (W-G derivative) | Caking bituminous | Same |

### Process Differences for Hot and Cold Raw Gas

Atmospheric fixed-bed gasifiers can operate using one of two processes:

**Hot gas process,** in which the raw gas is supplied directly to users without cooling after exiting the furnace. Particulate in the gas (coke fines, fine dust, etc.) is removed by cyclone(s).

1. **Cold gas process,** in which the raw gas must undergo a series of cooling and cleanup processes, including scrubbing, removing the tar fog, etc., before it is supplied to users. The gas cooling step uses one of two approaches, depending on the feed coal, as described in Appendix E.

### Main Equipment

Besides the gasifier itself, coal gasification requires the following additional equipment: an air blower, cyclone, double stand pipe, scrubber (the latter two serving mainly to cool the gas), ESP for tar collection, and gas delivery equipment.

### Main Technical and Economical Indices

Table 6.3 shows the main technical and economical parameters for two different coal gas plants, each with three sets of gasifiers (two for operation, one for standby). One plant uses the 3M13 type gasifier while the other uses Wellman-Galusha technology.

**Table 6.3: Main Technical and Economic Parameters of Coal Gasifiers**

| *Type of Gasifiers* | *3M13* | | *W-G* | |
|---|---|---|---|---|
| Number of Gasifiers | 3 | | 3 | |
| Type of Feed Coal | Weakly caking bituminous | | Coke, anthracite | |
| Size of Feed Coal, mm | 25–50 | | 13–25, 25–50 | |
| Coal Consumption, t/h | 3.0 | | 3.2 | |
| Gas Yield, $Nm^3/h$ | 9500 | | 10,000 | |
| Fresh Water Consumption, t/h | 9 | | 9 | |
| Soft Water Consumption, t/h | 3.6 | | 2.0 | |
| *Process* | *Hot gas* | *Cold gas* | *Hot gas* | *Cold gas* |
| Gas Heating Value, $MJ/Nm^3$ | 5.86 | 5.44 | 5.36 | 5.23 |
| Steam Consumption, t/h | 3.0 | 3.5 | 1.5 | 2.0 |
| Power Requirement, kW | 160 | 320 | 160 | 320 |
| Operating Personnel | 41 | 48 | 48 | 41 |
| Land, $m^2$ | 7200 | 8200 | 7200 | 8000 |
| Construction Investment, $10^4$ yuan, of which: | 700 | 1000 | 700 | 1000 |
| gasifier, % | 50 | 40 | 50 | 40 |
| coal preparation, % | 10 | 7 | 10 | 8 |
| cleanup, % | 11 | 19 | 11 | 19 |
| other, % | 29 | 34 | 29 | 33 |

### *Water Gas Gasifiers*

Water gas is produced by a multi-step batch process. Air is blown into the gasifier to cause a combustion reaction between the carbon in the coal and oxygen in the air. The resulting heat accumulates in the bed material until it reaches the temperature required by the gasification reaction, at which time the air flow is shut off, and steam is fed into the gasifier to initiate the water-gas reaction. When the temperature of the material in furnace decreases to the lower limit for the water gas reaction, the feed system switches back from steam to air, starting the next gasification cycle. To ensure the quality of the water gas, the particulate-laden gas produced during air blowing should be vented to the atmosphere after suitable processing.

### *Feed Coal Requirements*

A water gas gasifier usually takes coke or anthracite as its feed coal. Coal quality requirements are listed in Appendix E.

### *Gasifier Type*

The most commonly used water gas gasifiers have diameters of $\phi$1.6 m, $\phi$1.98 m, $\phi$2.26 m, $\phi$3.0 m, $\phi$3.3 m, or $\phi$3.6 m. Coal is usually fed by hand into furnaces with diameters < $\phi$2.26 m, and by automated mechanical systems to larger furnaces. With manual batch feeding, the temperature at the top of the gasifier fluctuates greatly, from 400–430°C at the top of the furnace before coal is fed to 200–250°C after coal is fed. This temperature fluctuation makes the coal gas quality fluctuate, as do the relatively large feed amount for one batch and the long intervals between batches. This varying operation mode also produces ash agglomerates, slagging, and blowing upsets, which in turn lead to a decrease in gas output and an increase in the oxygen content of the coal gas. Therefore, most $\phi$2.26 m water gas gasifiers have converted to automated mechanical feeding of coal. The circulation cycle and time distribution of water gas production are presented in Appendix E.

### *Technological Process*

Batch technological processes for water gas production are divided into three types based on their size and degree of waste heat utilization:

- **No waste heat recovery.** This simple process uses the least auxiliary equipment and thus occupies the smallest amount of land as well as requiring a lower initial investment. It is generally arranged as a single set, i.e., a furnace equipped with a coal gas scrubber unit. The disadvantage is that the lack of waste heat recovery results in lower thermal efficiency. This process is suitable for water gas gasifiers < $\phi$1.6 m.
- **Sensible heat recovery.** This process is equipped with a waste heat boiler for recovering the sensible heat in the water gas and flue gas (combustion gas products from the heating stage) to produce steam, which enhances overall thermal efficiency. When the temperature of water gas in the furnace outlet is about 500°C, its temperature at the exit of the waste heat boiler will be 200°C. The process is suitable for water gas furnaces sized $\phi$1.98 m and $\phi$2.26 m.
- **Recovery of sensible heat and heat content of combustion gas.** Besides a waste heat boiler, this process is equipped with a combustor for recovering the latent heat of the combustibles in the flue gas (CO, $H_2$, and $CH_4$). Fresh air is used to burn these combustibles and the resulting heat accumulates in the combustor grid brick for superheating the steam entering the gasifier. The process is suitable for water gas furnaces > $\phi$2.74 m and has found wide application in large-scale water gas plants.

### *Main Equipment*

Besides the furnace, the main facilities for water gas production include an air blower, cyclone, waster heat boiler, combustor, scrubber box, scrubber tower, steam accumulator, and coal gas buffer.

### *Key Technical and Economic Indices*

Table 6.4 presents the main technical and economical parameters for three coal gasification plants, each with two sets of water gas producers of $\phi$1.6 m, $\phi$2.26 m, and $\phi$3.0 m (one set in operation, the other on stand-by).

**Table 6.4: Key Technical and Economic Indices of Water Gas Gasifier Technology**

| *Type of Gasifier* | *ϕ1.6 m* | *ϕ2.26 m* | *ϕ3.0 m* |
|---|---|---|---|
| Number of Gasifiers | 2 | 2 | 2 |
| Type of Feed Coal | Coke, Anthracite | Anthracite, Carbonizing briquette | Gasification coke, Anthracite |
| Size of Feed Coal, mm | 20–80 | 20–80 | 25–100 |
| Feed Coal Consumption, t/h | 0.4–0.5 | 1.0–1.2 | 3.8–4.2 |
| Gas Yield, $Nm^3/h$ | 500 | 1200–1500 | 4500–5000 |
| Gas Heating Value, $MJ/Nm^3$ | 10.05–10.47 | 10.05–10.89 | 10.05–10.89 |
| Fresh Water Consumption, t/h | 2–2.5 | 4–6 | 16–20 |
| Soft Water Consumption, t/h | 0.8 | 1.5–2.5 | 5–7 |
| Steam (0.4-0.8 MPa) Consumption, t/h | 0.5–1 | 3–4.5 | 4–5 |
| Electricity Consumption, kW | 120 | 350 | 1180 |
| Operation Personnel | 36 | 50 | 64 |
| Land Area, $m^2$ | 5000–7000 | ~10,000 | 16,000–20,000 |
| Construction Investment, $10^4$yuan, of which: | 600 | 900 | 1200 |
| gasifier, % | 45 | 48 | 50 |
| coal preparation, % | 3 | 4 | 5 |
| gas cleanup, % | 10 | 9 | 8 |
| other, % | 42 | 39 | 37 |

### *Cost Comparison of Gas Furnace and Water Gas Gasifier*

Table 6.5 (next page) compares the capital and operating costs of gasifiers for producing coal gas and water gas.

**Table 6.5: Cost Comparison: Coal Gas Gasifiers and Water Gas Gasifiers**

| *Gasification Technology* | *Coal Gas Gasifier* | *Water Gas Gasifier* |
|---|---|---|
| Construction investment, yuan/MJ(gas)-day, | 25–15 | 30–20 |
| of which: equipment and install, % | 45 | 45 |
| civil engineering, % | 25 | 25 |
| other, % | 30 | 30 |
| Cost of gas production, yuan/GJ (gas), | 30–50 | 50–70 |
| of which: feed coal, % | 50 | 50 |
| depreciation, % | 20 | 20 |
| other, % | 30 | 30 |

## Development Prospects for Coal Gasification

Because coal gasification is a key technology for converting coal into clean secondary energy resources, China's Ninth Five-Year Development Program of CCT and the Long-Range Objectives of 2010 identify it as a priority development area. This designation recognizes the benefits that would accrue to the Chinese economy, energy security, and the environment if coal gasification were used more widely and wisely.

For example, almost all of the gasifiers used in the many medium- and small-scale nitrogen-based fertilizer plants in China to synthesize ammonia are atmospheric fixed-bed water gas processes with backward technology, out-of-date equipment, and inadequate environmental protection facilities. This has not only resulted in higher energy consumption and cost per tonne of ammonia produced, but also in large quantities of pollutants with serious environmental impacts. Technology retrofit and renovation are urgently needed.

China's residential energy mix also points to opportunities for cleaner processes while still taking advantage of the large domestic coal resources. In this sector, the share of fuel gas from all sources is quite low because a great number of heating boilers and household stoves still burn bulk coal directly, which wastes coal resources, produces high quantities of air pollution, and is inconvenient. Improvement in the standard of living requires replacing bulk coal—and even briquettes—with cleaner, more efficient and convenient fuel sources such as coal gas.

China's coal resources are mainly distributed in northwest, but most of the big coal users are located in the southeast coastal area. Therefore, a substantial portion of the country's transportation system is dedicated to coal transportation (see Section 3 for quantitative details), potentially displacing other goods that could improve the economy or standard of living. In addition, coal is wasted through the energy used to transport the refuse content of unwashed coal and by losses during long-distance transport (coal dust flying off trucks, spills, etc.). This waste could be avoided by minemouth conversion of coal to coal gas (as well as electricity), which can be transported (or transmitted) with fewer losses.

## Measures to Realize Development Prospects

The market potential for coal gasification is vast: currently less than 8% of China's total coal consumption is used for gasification. Realization of the potential energy and environmental benefits from wider use of this technology requires the following:

- Retrofit of existing gasifiers with newer, more effective technology; for example, retrofitting atmospheric fixed-bed coal gas furnaces and water gas gasifiers with oxygen-enriched technology would enhance the gasification efficiency of these many sites and reduce their air emissions
- Development of fluidized-bed gasification technology that can use fine coal directly as a feedstock
- Development of larger-scale entrained-flow gasification technology, both by learning from imported suppliers (such as the Texaco, Shell, Destec, and GSP processes) and by conducting independent development efforts
- Development of hot coal-gas cleanup technology to prepare for construction of an IGCC demonstration project

# 7

# Direct Coal Liquefaction

Direct coal liquefaction refers to the process by which solid coal is changed into liquefied oil under high hydrogen pressure at elevated temperature in the presence of a hydrogen donor solvent and catalyst. About 0.5 tonne of liquefied oil can be obtained from 1 tonne of raw coal (dry ash free [daf] basis). The liquefied oil from coal can be processed into high-quality gasoline, diesel, and jet fuel.

Indirect liquefaction is a well-established alternative process for obtaining liquid fuels from coal, but it has higher capital costs than those *projected* for direct liquefaction systems. In the indirect process, coal is first gasified, and then the resulting synthetic gases are converted to gasoline or other hydrocarbon fuels by the Fischer-Tropsch catalytic conversion process. The Sasol plants that produced gasoline from domestic coal in South Africa during the many embargo years were indirect liquefaction systems. Currently, China favors the development and demonstration of direct liquefaction technologies because of their perceived potential for lower costs, recognizing that they are not yet as mature as indirect technologies, and thus are likely to achieve greater cost reductions with further development. Therefore, this section will discuss only the direct liquefaction process.

## Role of Direct Coal Liquefaction in China as a Clean Coal Technology

In China, coal resources are abundant, but oil resources are deficient. By the end of 1996, recoverable oil reserves were estimated at 3.3 Gt. In that year, crude oil production was 157 Mt, yielding a reserve-to-output ratio of less than 22—i.e., at that rate of production, reserves will be depleted in 22 years. Coal resources, however, are far more plentiful. As of the end of 1996, proven coal reserves were more than 1000 Gt; recoverable reserves were 114.5 Gt, of which half can be used for direct coal liquefaction.

Currently, oil accounts for about 18% of China's total primary energy consumption. As the economy continues its rapid growth, the proportion of oil consumption will gradually increase, further widening the gap between petroleum output and consumption. Already, China has switched from an oil-exporter to an oil-importer—importing 13.9 Mt in 1996 alone. Petroleum demand in China is estimated to exceed 200 Mt/a in 2000, but domestic supply will be only 165 Mt/a, requiring the importation of over 30 Mt/a.

Through the application of liquefaction processes, China can reduce its dependence on oil imports by making use of its extensive coal resources. Direct coal liquefaction technology, as a substitute for petroleum, cannot be replaced by nuclear energy, solar energy, or any other electricity-generating technologies. For this reason, direct coal liquefaction has received much attention from government leaders. President Jiang Zemin inspected the direct coal liquefaction units at Beijing Research Institute of Coal Chemistry (BRICC) on January 19, 1996, and pointed out that the development of direct coal liquefaction technology should be considered from the perspective of energy strategy. Former Premier Li Peng also pointed out, in a 1997 article entitled "Chinese Energy Policies," that coal should be converted into oil and liquid fuels to provide clean energy. The Ninth Five-Year Plan (1996–2000) and tentative plan for 2010 indicate that China will strive to complete construction of a commercial demonstration plant for direct coal liquefaction by 2010.

## Historical Perspective

Direct coal liquefaction technology originated in Germany in the early 1900s. In 1913, Bergius, a German, studied hydrogenation of coal with high pressure, thereby laying the foundation for direct coal liquefaction technology, and obtained the first patent on coal liquefaction. In 1927, the first direct coal liquefaction plant, with a capacity of 100,000 t/a, was built in Leuna, Germany. From 1936 to 1943, 11 direct coal liquefaction plants were put into operation. By 1944, German production of oil products from direct coal liquefaction plants reached 4.23 Mt/a, providing two-thirds of the jet fuel and 50% of the fuel for cars and tanks in the Second World War. At that time, the reaction temperature of coal liquefaction was 470°C, and the reaction pressure was 70 MPa. Around the Second World War, the United States, Japan, France, Italy, the former Soviet Union, and others also conducted research on direct coal liquefaction technology.

Because of the destruction of the German plants during the Second World War—as well as the availability of cheap petroleum, especially after the 1950s—direct coal liquefaction lost its competitive position. Nevertheless, the United States carried out basic research on the technology during this period, using German research material, scientists, and facilities.

## Current Technology Status

The Middle East oil embargo of 1973 led to a resurgence of interest in coal conversion technologies. Some developed countries such as Germany, the United States, Japan, and others researched and developed new processes of direct coal liquefaction, seeking to reduce production costs by extending the range of reaction conditions. Pilot tests were completed for such processes as the IGOR process by Germany, the H-Coal process by the United States, and the NEDOL process by Japan. The characteristics of these processes are summarized below. Note that all the new processes use lower reaction temperatures and/or pressures than the earlier technologies to bring down production costs.

## IGOR process (200 t/d):

(a) Reaction temperature remains at 470°C, but pressure is relaxed to 30 MPa.

(b) The processes for coal liquefaction and upgrading of the resulting oil are integrated in a high-pressure system, yielding a purified oil with only a few heteroatoms. This lowers the facility investment and operational costs.

(c) Hydrogenated oil with good hydrogen-donor ability is used as the recycle solvent to obtain higher conversion of coal to oil.

**H-Coal process (600 t/d):**

(a) The reaction temperature is 440–450□C and the pressure is reduced further to 17 MPa.

(b) The reactor uses an ebullated (gently fluidized) bed.

(c) A highly active Co-Mo catalyst is used for high conversion of coal to oil.

(d) A pump circulates the heavy oil through the ebullated reactor, slowing the reaction time in order to obtain a high yield of light oil.

**NEDOL process (150 t/d):**

(a) Reaction conditions are relaxed to a temperature of 430–460°C and a pressure of 17–20 MPa.

(b) Pre-hydrotreatment of the circulating solvent is used.

(c) Synthetic iron monosulfide is used as the catalyst.

(d) The process can deliver a high yield of light oil.

Already proven in industrial production, direct coal liquefaction could be a commercially feasible technology in the right economic climate. However, at present there is no commercial plant anywhere in the world because the price of liquefied oil is higher than the price of petroleum. Energy economists estimate that direct coal liquefaction will become economically competitive when the price of petroleum reaches $25/barrel (bbl) and remains at least at that level for an extended period of time. According to a United States Department of Energy engineering economic analysis, if a direct coal liquefaction plant and a conventional oil refining plant are constructed adjacent to each other, the investment cost will be less than if they are built independently; the savings come from avoiding duplicate installation of some equipment used by both processes. These savings would reduce the cost of the liquefied oil to $19–23/bbl. Specialists believe that production costs can be reduced further through additional process R&D.

Since the late 1970s, China has been researching direct coal liquefaction technology with the aim of producing fuels, such as gasoline and diesel that are convenient for transportation, and chemical feedstocks, especially for the production of aromatics. Through key research projects in the Sixth and Seventh Five-Year Plans, as well as international cooperation projects, China has set up advanced units for coal hydrogenation and upgrading of coal-derived oils, as well as analysis instruments, at BRICC. The considerable basic R&D on direct coal liquefaction processes conducted by BRICC has yielded valuable results as well as many specially trained personnel. In the last 20 years, BRICC has screened more than 100 kinds of Chinese coals by autoclave tests to evaluate their liquefaction behaviors; 27 of these coals have been tested in a 0.1 t/d bench scale unit (BSU). Results indicate that 15 types of coals work well for liquefaction, achieving oil yields of more than 50%. Tests for ideal process conditions have been completed for four of the most promising of these coals. At the same time, high-reactivity catalysts for direct coal liquefaction have been developed. Using a domestically produced hydrogenation catalyst, research has been conducted on upgrading coal-derived oils into gasoline, diesel, and jet fuels. The upgrading processes tested are hydrorefining, hydrocracking, and hydroreform.

China has completed sufficient basic research on direct coal liquefaction to lay the technical foundation for pilot testing and building a commercial plant. At present, the China Coal Research Institute (CCRI) has signed cooperation agreements with the related government departments and corporations from Germany, Japan, and the United States for technical and economic feasibility studies of potential direct coal liquefaction demonstration plants in China for a technology from each country. Pilot tests with Chinese coals have been completed in these three countries, producing substantial design information.

## Development Prospects and Barriers for Direct Coal Liquefaction

Direct coal liquefaction technology has excellent development prospects for the following reasons:

- **China has abundant coal resources suitable for direct coal liquefaction.** China's proven coal resources are more than 1000 Gt and recoverable reserves are 114.5 Gt. Nearly half of these reserves can be used for direct coal liquefaction with an oil yield equal to 30 Gt of oil resources.
- **China has limited oil resources.** With rapid economic growth, China has shifted from an oil-exporting country to an oil-importing country. Although oil exploration has been expanded, no large oil fields have been discovered so far. Thus, the search for a petroleum substitute is a strategic, long-term energy policy issue, and direct coal liquefaction technology can be a promising solution.
- **The basic research has already been completed and domestic expertise is available.** Based on this basic R&D, China has participated in pilot tests on three Chinese coals, one each in Germany, Japan, and the United States. Some technological design data have been obtained to lay the foundation for developing direct coal liquefaction technology in China.
- **Enthusiasm for direct coal liquefaction is high in some coal-rich/oil-poor regions.** These regions hope to soon realize the commercialization of direct coal liquefaction to simultaneously solve their petroleum shortage and promote local economic growth.
- **Commodity prices are low.** Because the prices of coal, labor, and facilities are lower in China than in other countries—especially at some coal mines—the capital and operating costs of a direct coal liquefaction plant would also be lower than elsewhere. Therefore, coal-derived oils produced in China should be better able to compete with oil at world market prices.

# 8

## Policy Recommendations

This section presents policy recommendations that the authors believe are needed to promote quicker, wider adoption of clean coal technologies throughout the nation. They are based on the overarching goal of a cleaner, more efficient, and self-reliant energy future for China. These recommendations range from infrastructure changes and technology changes to supportive tax and funding policies, the establishment and enforcement of strict environmental limits, and increased research and development. To build support for many of these changes, the government should undertake education programs to increase public awareness of the issues and needs.

### Increase Awareness

Unless people understand the quality-of-life and economic consequences of the status quo, they have no incentive to support programs that switch to clean coal technologies—and certainly no sense of urgency. Therefore, the authors urge the government to promote education in the following specific areas:

**Environmental impacts.** Air pollution including acid rain, damage to land and water systems, health effects, agricultural effects, and economic impacts are all topics for general public education, targeting children as well as adults. While particular emphasis should be placed on the need to reduce particulate and sulfur emissions nationwide, toxic organics and metals can be serious problems near certain factories.

- **Conservation issues.** The general public should understand why coal is China's energy mainstay and that coal reserves (and particular grades of coal) are limited in supply and should thus be used as wisely as possible—i.e., combusted efficiently, making full use of by-products, and using the right grade of coal for a given function. (See, for example, the discussion on coke making [Section 5] that explains how conversion to stamping coke ovens and the elimination of indigenous coke ovens would reduce the consumption of China's limited resources of very high-grade coking coals.)
- **Energy security issues.** Again, a basic understanding of why China is a "coal nation" is necessary to build support for technologies that make better use of China's domestic resources and reduce reliance on imported petroleum products. For example, strategic

understanding of energy security issues is fundamental to garnering support for expanded use of town gas and the introduction of direct coal liquefaction.

- **Additional uses for coal.** People should understand that coal is not only an important primary energy source, but a versatile resource with other useful applications. For example, when gasified, coal is a valuable feedstock for industrial chemical production (e.g., aromatic hydrocarbons or synthetic ammonia ) and a reducing gas in the metallurgical industry.
- **Specific clean coal technologies.** End users must be made aware of the availability and benefits of clean coal technologies. For example, mines and industries that purchase raw coal will need to learn about the importance of coal preparation, while all households, urban and rural, should learn about the benefits of honeycomb briquettes and more-efficient ovens to burn them in.
- **Available assistance programs.** Information must be disseminated regarding the availability of any special funds, loans, or information programs.

## Strengthen Environmental Laws

- The key to improving the environment in China's coal economy is to strengthen emission limits and other environmental laws in ways that offer clear preference to clean coal technologies. This requires (1) setting the fines or penalties high enough to provide economic incentive for facilities and individuals to install cleaner technologies, and (2) consistently enforcing the law. To date, lack of enforcement has impeded the deployment of clean coal technologies, as many facilities consider it less expensive to pay penalties than to install the clean equipment. Such enforcement is crucial to the cost-competitiveness of clean coal technologies. Fines and penalties for pollution are the easiest way to convert the environmental benefits of clean technologies into economic benefits, thereby promoting their use.

Specifically, policy makers and government agencies should consider the following actions:

- Revise standards governing coal use, with initial attention to standards for coking, fertilizer, cement, locomotive, power plant, and blast furnace applications. As an interim step, the standards could be set at a level that promotes the use of washed coal, taking account of the characteristics of the coal resources and the current condition of the coal-using and coal preparation equipment. However, the standards should move quickly to the ultimate goal of significant emission reductions below today's levels.
- Set a date by which household stoves must burn briquettes with sulfur capture additives.
- Set a date by which industrial kilns can no longer burn bulk coal (without advanced pollution controls).
- Formulate detailed environmental-based directives for the manufacture and use of briquettes to supplement the statement of principle favoring briquettes as a policy in the current Law on the Prevention and Control of Atmospheric Pollution.

## Implement Clean Coal Technologies

Achieving the goal of cleaner, more efficient use of coal will require more intensive processing and conversion of coal at mines, including the construction of large-scale chemical manufacturing facilities and integrated gasification combined cycle (IGCC) power plants directly at these fuel sources. Greater processing at the mines provides benefits in two ways—it is an administratively more effective way of reducing pollution than setting and enforcing emission limits on thousands of users; and it can avoid the emissions and energy costs of coal transportation by shifting this transport to the transmission of secondary energy sources, such as clean electricity and coal gas, or chemicals, such as methanol and fertilizer.

Certainly in its own construction projects, and through mandates and other means, government can ensure that new construction meets stricter standards for emissions and efficiency. Possible measures include the following:

- Require new power plants and industrial kilns to be designed based on washed steam coal as a fuel.
- Require all new mines to build associated cleaning plants. The cleaning plants at new and existing mines can be built in stages to match the capacity of the mines.
- Increase investment in cleaning plants concomitant with investment in the coal industry as a whole. Cleaning plants should account for more than 10% of the overall construction investment in the coal industry. In the Ninth and Tenth Five-Year Plan period, allocate 200 Myuan per year for coal mines in high-sulfur districts to build cleaning plants.
- Build centralized cleaning plants, to take advantage of economies of scale. Have county government work out a uniform plan for locally run state-owned mines and village- and township-run mines to build central cleaning plants, starting with the 100 counties that produce the most coal. Give highest priority to mines that produce export products, have poor coal quality (ash > 25%, sulfur > 2%), and have long transport distances to the end users.
- Construct large (> 1.5 Mt/a) cleaning plants adjacent to power plants and building material plants, since they can utilize the by-products of coal washing (middlings, fines, and refuse).
- Build briquette plants at steam coal blending facilities to take advantage of equipment that is common to both processes.

A barrier to the expansion of coal cleaning at mines is the inability of the current transport and storage systems to accommodate different sizes of coal. More extensive use of washed coal will require development of systems for loading, transporting, unloading, and storing coal that separate it by classification. Government should help the mining and railway sectors coordinate overall planning and construction.

Policies regarding gasification must recognize that different coal gas users have quite different demands, and different grades of coal are distributed unevenly across China's vast territory. Therefore, no single gasification technology is best for all situations, and it is necessary to encourage a variety of technologies, based on the type of feed coal, production scale, and specific usage requirements. Key technologies include fluidized-bed gasifiers that can use fine coal directly, larger-scale entrained-flow technologies (using imported designs as a starting point), and hot coal-gas cleanup techniques. Technology development should combine importation with technology transfer and gradual development of internal capabilities.

Government at both the national and provincial level can also accelerate the transition to a cleaner, more efficient energy economy by encouraging or requiring existing coal-using facilities to upgrade their current equipment with new technology. Possible approaches include regulations, financial incentives, low/zero interest rate loans, tax preferences, or a combination of these measures. For example, government could increase discount loans from 300 Myuan to 800 Myuan for upgrading existing coal cleaning plants. The following improvements are the highest priorities:

- Upgrade existing power plants and industrial kilns to burn washed steam coal.
- Upgrade or replace small- and mid-sized mechanical coking ovens, and all indigenous coke ovens, with large, advanced units and automated controls.
- Retrofit existing gasifiers with newer technology, e.g., oxygen-enriched technology.

## Intensify Research and Development

The purpose here is two-fold: (1) to develop better technologies than exist in the world today, and (2) to raise China's capabilities, so as to reduce the need for imported equipment and expertise.

Technology-specific research needs have been identified separately for each coal processing technology in the report section that discusses that technology. The key recommendations for all the technologies are consolidated here for easy reference.

- **Coal preparation.** R&D should focus on improved heavy-medium separation and jigging processes and equipment; dry preparation processes; heavy-medium cyclones and columned pneumatic flotation machines for desulfurization of high-sulfur coal; high-efficiency centrifuges, filters, and pressure filters for de-watering coal fines; enhanced reliability for large-scale equipment; and automated inspection and process control equipment.
- **Briquettes.** Industrial briquettes especially need development: better, cheaper binders, improved waterproofing, and improved transport characteristics, along with better production equipment. High-temperature desulfurization additives and biomass briquette technology are other areas for development.
- **Coking.** Priorities include further development of stamping coking (and appropriate particulate controls), briquette blending for coking, and coal moisture adjustment technologies. R&D is also needed on refining technologies, such as crude benzene

hydrogenation and intensive processing of tar, to increase the variety and value of chemical products that can be manufactured from coking by-products.

- **Direct coal liquefaction.** Greater attention should be paid to direct coal liquefaction because it is an important way to deal simultaneously with the petroleum shortage and a desire for economic growth in the coal mining regions, and to do so in an environmentally prudent fashion. China is now in a position to conduct larger-scale pilot tests, so the government should resume support of this work. New R&D results since the early 1990s have shown that China has developed the knowledge to scale up the laboratory data obtained earlier on liquefaction processes and liquefaction behavior of coals. Therefore, funding should be increased for research on new liquefaction processes—at lower temperature and pressure—that can reduce both capital and operating costs. Research should focus on new processes that can increase oil yield and decrease gas yield; methods to increase catalyst activity and reduce the amount of catalyst used; and chemical pre-treatment approaches that remove ash, inactive components, and oxygen from the coal in order to reduce hydrogen consumption and increase production capacity.

### Establish Preferential Tax and Funding Policies

Clean coal technologies are generally more expensive than their lower-technology counterparts—sometimes only in the initial investment but not in the life-cycle costs. For example, washed coal is more expensive than raw coal; oil derived from direct coal liquefaction costs more than petroleum if the price of crude oil on the international market is depressed due to overproduction; and even large gasifiers, which are not only cleaner but also cost less to build and operate per unit of capacity, require a larger capital outlay than small gasifiers, thus deterring investors who cannot raise the required capital. Because environmental impacts and other negative externalities, such as accelerated depletion of high-value resources, are not incorporated into the price of the equipment that causes these impacts, the private sector has no incentive to pay the premium for the cleaner technologies.

To hasten widespread deployment of beneficial clean coal technologies, it is therefore necessary to establish preferential financial policies, such as tax breaks, easy-to-obtain loans with favorable interest rates, or even direct subsidies. Financial assistance should be given to both new installations and environmentally beneficial upgrades to existing facilities. Beyond equipment installation, long-term favorable treatment could also be extended to industries that contribute significantly to better coal use; for example, briquette production companies could be eligible for lower taxes.

An important factor in setting subsidy rates or tax preferences is recognition of the payback period required to recover the cost of an upgrade or the cost difference between a new, clean technology and the old, polluting process. Financial policies should be designed to significantly reduce the payback period and thus make clean coal technologies more economically competitive. Of course, financial assistance is not the only way of reducing payback: raising the fees for emission violations can also reduce the payback period by increasing the cost of using outdated, polluting technologies. In addition to providing direct assistance, government can help plant owners obtain funding by helping to form joint investment consortia or by attracting attract foreign investment.

## Integrate Programs, Policies, and Regulations

Central to the success of all the above recommendations is their effective integration. As soon as possible, China should establish a mid- and long-term coal industry development program. The program should promote development and deployment of clean coal technologies and promote improvement of coal quality and environmental protection. The program's goals and assignment of responsibility should be clear and practicable. For example, in coal production, the goal should be for the proportion of washed coal to reach 30% in 2000, 40% in 2005, and 50% in 2010.

A dedicated clean coal program at the level of the central government will allow rational implementation of measures with broad impacts, such as adjustments to the price of coal. According to international indices comparing commodity prices, coal prices are unreasonably low relative to the prices of other industrial commodities in China. Avoiding overproduction—by closing small, inefficient, polluting mines—will improve the cost-competitiveness of both washed coal and briquettes (which are made with fines), and, indeed, all technologies offering higher efficiency.

Only a national-level program can properly coordinate issues such as price and taxes. Nonetheless, there should be flexibility to involve local governments. This will build widespread support as well as ensure that policy measures and regulations are appropriately adapted to local conditions.

In addition to establishing an organizational structure to promote clean coal technologies, government can also speed their deployment by developing a national energy plan that integrates economic development with resource conservation, energy security, and environmental protection. Such a plan is vital to the introduction of advanced technologies that can meet these diverse goals, but are more expensive than existing technologies, which satisfy lesser objectives.

Clean coal technologies call for a significant, coordinated commitment of governmental resources. Yet they are fundamental to China's economic future. The sooner these advanced technologies are deployed, the sooner China can reap their environmental and societal benefits.

# Appendix A
## Energy Production Data

Tables A-1 and A-2 (on the next page) provide detailed statistics on China's energy output and consumption that expand on the summary information presented in Section 1.

**Table A.1: Coal Output and Primary Energy Output and Mix (1980–1997)**

| *Year* | *Total Output, Mtce/a** | *Raw Coal, Mt/a* | *Primary Energy Mix (%)* | | | |
|---|---|---|---|---|---|---|
| | | | *Raw Coal* | *Crude Oil* | *Natural Gas* | *Hydropower and Nuclear* |
| 1980 | 637.35 | 620.0 | 69.4 | 23.8 | 3.0 | 3.8 |
| 1981 | 632.27 | 622.0 | 70.2 | 22.9 | 2.7 | 4.2 |
| 1982 | 667.82 | 666.3 | 71.2 | 21.9 | 2.4 | 4.5 |
| 1983 | 712.70 | 714.5 | 71.6 | 21.3 | 2.3 | 4.8 |
| 1984 | 778.55 | 789.2 | 72.4 | 21.1 | 2.1 | 4.4 |
| 1985 | 855.46 | 872.3 | 72.8 | 20.9 | 2.0 | 4.3 |
| 1986 | 881.24 | 894.0 | 72.4 | 21.2 | 2.1 | 4.3 |
| 1987 | 912.66 | 928.1 | 72.6 | 21.0 | 2.0 | 4.4 |
| 1988 | 958.01 | 979.7 | 73.1 | 20.4 | 2.0 | 4.5 |
| 1989 | 1016.38 | 1054.2 | 74.1 | 19.3 | 2.0 | 4.6 |
| 1990 | 1039.22 | 1079.9 | 74.2 | 19.0 | 2.0 | 4.8 |
| 1991 | 1048.44 | 1087.4 | 74.2 | 19.1 | 2.0 | 4.7 |
| 1992 | 1072.56 | 1116.4 | 74.3 | 18.9 | 2.0 | 4.8 |
| 1993 | 1110.59 | 1149.7 | 74.0 | 18.7 | 2.0 | 5.3 |
| 1994 | 1187.29 | 1239.9 | 74.6 | 17.6 | 1.9 | 5.9 |
| 1995 | 1290.34 | 1360.7 | 75.3 | 16.6 | 1.9 | 6.2 |
| 1996 | 1326.16 | 1397.0 | 75.2 | 17.0 | 2.0 | 5.8 |
| 1997 | 1319.89 | 1373.5 | 74.3 | 17.4 | 2.3 | 6.0 |

* Mtce means "million tonnes coal equivalent" based on a coal with heating value of 7000 kcal/kg.

**Table A.2: Total Energy Consumption and Mix in China (1980–1997)**

| Year | Total Consumption, Mtce/a | Coal Consumption, Mt/a | Primary Energy Consumption Mix, % | | | |
|---|---|---|---|---|---|---|
| | | | Raw Coal | Crude Oil | Natural Gas | Hydropower & Nuclear |
| 1980 | 602.75 | 610.10 | 72.15 | 20.76 | 3.10 | 3.99 |
| 1981 | 594.47 | 605.84 | 72.74 | 19.65 | 2.79 | 4.51 |
| 1982 | 620.67 | 641.26 | 73.67 | 18.91 | 2.56 | 4.86 |
| 1983 | 660.40 | 689.13 | 74.16 | 18.14 | 2.44 | 5.26 |
| 1984 | 709.04 | 749.68 | 75.27 | 17.45 | 2.37 | 4.91 |
| 1985 | 766.82 | 816.03 | 75.18 | 17.10 | 2.24 | 4.85 |
| 1986 | 808.50 | 860.15 | 75.83 | 17.20 | 2.26 | 4.71 |
| 1987 | 866.32 | 927.99 | 76.21 | 17.02 | 2.13 | 4.64 |
| 1988 | 929.97 | 993.54 | 76.17 | 17.05 | 2.06 | 4.72 |
| 1989 | 969.34 | 1034.27 | 75.80 | 17.20 | 2.10 | 4.90 |
| 1990 | 987.03 | 1055.23 | 76.20 | 16.60 | 2.10 | 5.10 |
| 1991 | 1037.83 | 1104.32 | 76.10 | 17.10 | 2.00 | 4.80 |
| 1992 | 1091.70 | 1140.32 | 75.70 | 17.50 | 1.90 | 4.90 |
| 1993 | 1159.93 | 1204.02 | 74.70 | 18.20 | 1.90 | 5.20 |
| 1994 | 1227.37 | 1285.32 | 75.00 | 17.40 | 1.90 | 5.70 |
| 1995 | 1311.76 | 1307.39 | 74.60 | 17.50 | 1.80 | 6.10 |
| 1996 | 1389.48 | 1356.19 | 74.70 | 18.00 | 1.80 | 5.50 |
| 1997 | 1420.00 | 1310.70 | 73.50 | 18.60 | 2.20 | 5.70 |

# Appendix B
## Technical Specifications For Coal Preparation Equipment and Cleaned Coal

This appendix provides some detailed data that supports or expands on the discussion of coal preparation in Section 3.

The use of coal preparation by the key state-owned coal mines is presented in Section 3.2.1. Table B-1 presents the capacity distribution of these plants.

**Table B.1: Capacities of Key Stated-Owned Cleaning Plants**

| *Unit capacity, $10^4$ t/a* | *Total* | | *Coking Coal* | | *Steam Coal* | |
|---|---|---|---|---|---|---|
| | *Number* | *Capacity, Mt/a* | *Number* | *Capacity, Mt/a* | *Number* | *Capacity, Mt/a* |
| <60 | 46 | 15.8 | 27 | 10.3 | 19 | 5.5 |
| 60–120 | 70 | 54.8 | 43 | 33.9 | 27 | 20.9 |
| 120–180 | 40 | 52.3 | 28 | 36.5 | 12 | 15.8 |
| 180–300 | 35 | 74.0 | 28 | 59.3 | 7 | 14.7 |
| >300 | 32 | 138.6 | 13 | 46.5 | 19 | 92.1 |
| Total | 223 | 335.4 | 139 | 185.5 | 84 | 148.9 |

As mentioned in Section 3.2.4, China manufactures all the equipment needed for coal cleaning plants. For a large plant, this equipment includes:

**Analysis screen:** maximum screening area, 24 $m^2$
**Jig:** maximum jigging area, 40 $m^2$ and 35 $m^2$
**Heavy-medium separator:** maximum trough width, 2.5 m; hoisting wheel diameter, 4.5 m
**Heavy-medium cyclone:** maximum diameter, 1200 mm
**Flotation machine:** maximum volume of flotation trough, 16 $m^3$
**Columned pneumatic flotation machine:** maximum diameter, 3 m
**Disc-type filter:** maximum filtration area, 200 $m^2$
**Pressure filter:** filtration area, 60 $m^2$
**Chamber pressure filter:** maximum pressure filtration area, 1050 $m^2$
**Horizontal centrifuge:** maximum screen basket diameter, 1300 mm
**Vertical centrifuge:** maximum screen basket diameter, 1100 mm
**Thickening machine:** maximum diameter, 45 m

The technical specifications for a typical dry air separator, as might be used by a small mine to prepare coal for industrial boilers and kilns, is presented in Table B-2.

**Table B.2: Technical Characteristics of an FGX-3 Dry Air Separator**

| *Items* | *Units* | *Indices* |
|---|---|---|
| Separating area | $m^2$ | 3 |
| Feed coal size | mm | 50–6 |
| Surface moisture of feed coal | % | < 9 |
| Capacity | t/h | 30 |
| Probable standard deviation in coal feed size (50–6 fraction) | mm | 0.230 |
| Air flow rate | $m^3/h$ | 17,172 |
| Air pressure | Pa | 6143 |
| Power | kW | 58 |
| Equipment weight | Kg | 3,450 |
| Equipment dimensions | mm | 3950 x 2550 x 4140 |

# Appendix C
## Detailed Technical Information On Coal Briquettes

The technical specifications of coal briquettes made by the Beijing Research Institute of Coal Chemistry (BRICC) with improved, waterproof binders are presented in Tables C-1 and C-2.

**Table C.1: Analytical Results of Jincheng Fine Anthracite Coal and Gasification Briquette***

| *Items Sample*** | $M_{ad}$ (%) | $A_{ad}$ (%) | $V_{daf}$ (%) | $Q_{gr,ad}$ (MJ/kg) | $S_{t,d}$ (%) | $FC_d$ (%) | ST (°C) | Ultimate Analysis (%) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $C_{ad}$ | $H_{ad}$ | $O_{ad}$ | $N_{ad}$ |
| Jincheng fine coal | 0.79 | 23.1 | 6.00 | 25.43 | 0.58 | 70.11 | 1500 | 66.89 | 2.48 | 3.21 | 0.83 |
| MJ briquette | 2.07 | 26.68 | 7.54 | 22.57 | 0.61 | 63.71 | 1450 | 65.69 | 2.63 | | 0.63 |
| HM briquette | 3.86 | 29.21 | 7.30 | 22.28 | 0.54 | 59.63 | 1300 | | | | |
| MS briquette | 3.64 | 30.68 | 8.24 | 21.82 | 0.66 | 57.62 | 1430 | 59.72 | 2.39 | 2.51 | 0.58 |
| Fengtai briquette | 1.52 | 20.18 | 7.89 | 25.86 | 0.36 | 70.41 | 1500 | | | | |

* M is moisture, A is ash, V is volatile content, Q is heating value, $S_t$ is total sulfur, FC is fixed carbon, and ST is softening temperature of the ash. The subscripts 'ad' mean air dried, 'd' is dried to remove all moisture (e.g., per ASTM methods), 'daf' is dry ash free, and 'gr' is gross (or higher) heating value.

** The various briquette names refer to different binders.

**Table C.2: Quality Indices of Jincheng Gasification Briquette***

| Briquette | Compressive Strength (N/piece) | Thermal Strength (N/piece) | Dropping Strength (%) | Waterproof Strength (N/piece) | Thermal Stability ($TS_{+6}$) |
|---|---|---|---|---|---|
| MJ briquette | 1120 | 230 | 89.06 | 190 | 72.10 |
| HM briquette | 330 | 75 | 93.55 | 540 | 51.50 |
| MS briquette | 610 | 50 | 81.89 | 190 | 37.50 |
| Fengtai briquette | 280 | 150 | 72.32 | bad | 76.6 |

* 'N' is the force in Newtons applied to the piece at failure; $TS_{+6}$ is a measure of the briquette's ability to keep its shape at high temperatures.

The properties of the feed coal and briquette products produced by the plant discussed in Section 4.3 are presented in Table C-3.

**Table C.3: Analytical Results of Feed Coal and Briquette**

| Items | $M_{ad}$, % | $A_{ad}$, % | $V_{ad}$, % | $C_{ad}$, % | $S_{t,ad}$, % | Coking Index of Coal* |
|---|---|---|---|---|---|---|
| Feed coal | 2.06 | 15.34 | 17.11 | 64.14 | 1.35 | 6 |
| Coal refuse | 1.83 | 59.61 | 10.30 | 26.46 | 1.80 | 1 |
| Briquette | 1.02 | 28.94 | 7.60 | 61.28 | 1.16 | 1 |

* This is a characteristic of the char residue according to international standards, with 1 = the lowest rating and 8 = the highest rating.

Costing details for the 20,000 t/a coke briquette plant discussed in Section 4.3 are presented in Tables C-4 and C-5.

**Table C.4: Budgetary Investment Cost Estimate for a 20,000 t/a Briquetting Plant ($10^4$ yuan)**

| *Items* | *Material* | *Civil Engineering* | *Equipment and Apparatus* | *Installation* | *Other* | *Total* |
|---|---|---|---|---|---|---|
| Power supply system | 1.62 | 0.17 | 9.03 | 0.31 | | 11.13 |
| Ground engineering | | 4.06 | | | | 4.06 |
| Water supply and discharge and heating | 2.67 | 5.03 | 10.15 | 0.72 | | 18.57 |
| Administration and welfare facilities | 0.89 | 6.44 | 21.13 | 0.24 | | 28.70 |
| Accessory buildings and materials | | 11.82 | | | | 11.82 |
| Facilities in the space | | 3.38 | | | | 3.38 |
| Production facilities and factory building | 4.03 | 30.27 | 39.60 | 5.44 | | 79.34 |
| Other capital construction cost | | | | | 15.20 | 15.20 |
| Total | 9.21 | 61.17 | 79.91 | 6.71 | 15.20 | 172.20 |

**Table C.5: Budgetary Production Cost Estimate for a 20,000 t/a Briquetting Plant**

| *Items* | *Unit Price* | *Unit Consumption* | | *Annual Consumption Amount (kt)* | *Total Cost of Annual Consumption( $10^4$ yuan)* | *Remarks* |
|---|---|---|---|---|---|---|
| | | *Amount (t)* | *Cost (yuan)* | | | |
| Refuse | 30 yuan/t | 0.70 | 21.00 | 14 | 42.00 | |
| Fat coal | 90 yuan/t | 0.40 | 36.00 | 8 | 72.00 | |
| Weathered coal | 30 yuan/t | 0.04 | 1.20 | 0.8 | 2.40 | |
| Chemical raw materials | 2000 yuan/t | 0.005 | 10.0 | 0.1 | 20.00 | |
| Power | 0.3 yuan/kWh | 50 | 15.00 | 1000 | 30.00 | |
| Water | 0.3 yuan/t | 0.40 | 0.12 | 8 | 0.24 | |
| Worker salary | 3000 yuan/ person-year | | 7.50 | | 15.00 | 50 persons |
| Administration expenses | | | 5.00 | | 10.00 | 5% of total sale price |
| Depreciation & maintenance cost | | | 4.00 | | 8.00 | 8% of fixed assets |
| Other expenses | | | 2.00 | | 4.00 | 2% of total sale price |
| Factory cost | | | 101.82 | | 203.64 | Sum of above items |
| Product tax | | | 8.00 | | 16.00 | |
| Total | | | 109.82 | | 219.64 | |

# Appendix D
## Technical Information On Coke Ovens

This appendix provides some detailed technical data and specifications on coke making that supplement the information presented in Section 5.

The extensive coking coal reserves in Shanxi province are distributed among the coking coal types as follows:

| *Coal Type* | *Shanxi's Percent of National Total of That Coal Type* |
|---|---|
| Fat | 44 |
| Caking | 45 |
| Lean | > 70 |
| Gas Coal | 59 |

Table D-1 on the next page compares the design and performance of stamping and conventional coke ovens. As indicated in Section 5, stamping ovens have higher output than conventional ovens (the data in Table D-1 are consistent with this difference). Therefore, the total investment cost shown in Table D-1 is higher for stamping ovens than conventional ovens, even though the cost of the coke oven bodies is lower than for conventional ovens of the same capacity. Not shown in this table is the coke quality difference; stamping ovens produce a higher-quality coke than conventional units.

Table D-2 on the next page provides technical and economic data on eight typical small coking ovens, ranging from 2 x $10^4$ to nearly 11 x $10^4$ t/a of coke output. Clearly, the costs vary considerably, even on a yuan/tonne output basis, as do many of the other parameters.

**Table D.1: Comparison of Technical and Economic Indices Between a Stamping and Conventional Oven with 6-m Coking Cabin**

| | | | *Stamping Oven* | | *Conventional Oven* | |
|---|---|---|---|---|---|---|
| | Height | Length | 6,250 | | 6,000 | |
| Coking Cabin | Width (average) | Taper | 17,250 | | 15,980 | |
| Sizes | Central distance | | 490 | | 450 | |
| (mm) | | | 20 | | 60 | |
| | | | 1,350 | | 1,300 | |
| Parameters | Dry coal weight, t/cabin | | 47.2 | | 28.5 | |
| | Coking period, h | | 22 | | 18 | |
| | Total bricks, t | | 19,540 | | 16,350 | |
| | Cabin number | Coke | 50 | | 50 | |
| Technical and | output, $10^4$ t/a | | 60.05 | | 48.7 | |
| Economic | Investment cost, $10^4$ yuan | | 72,000 | | 48,000 | |
| Indices | Energy consumption per tonne coke, Mtce | | 0.258 | | 0.27 | |
| | Number of employees | | 683 | | 648 | |
| | Total weight of power | | 18,158 | | 14,292 | |
| Main Technical | equipment, kg | | | 14,104 | | 11,093 |
| and Economic | Total weight of work | | | 8684 | | 7214 |
| Indices for | equipment, kg | | 4206 | | 3494 | |
| Electrical | Available load, kVAR | | 9649 | | 8016 | |
| Equipment | Idle load, kVAR | | $60.8 \times 10^6$ | | $50.6 \times 10^6$ | |
| | Apparent power load, kVA | | | | | |
| | Annual consumption of electricity, kWh | | | | | |

**Table D.2: Technical and Economic Indices for Common Small Coking Ovens**

| | *66-Coking Oven*$^{\equiv}$ | *70-Coking Oven* | *No.3 Hongqi Coking Oven* | *TJ-75 Coking Oven* | *XY-Coking Oven* | *KM-Coking Oven* | *Luliang Coking Oven* | *Pingxiang Coking Oven* |
|---|---|---|---|---|---|---|---|---|
| Total Coke Output ($10^4$ t/a) | 10.93 | 4.25 | 2.18 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Coke Output with Particle Size > 25 mm ($10^4$ t/a) | 9.65 | 4.00 >10 mm | 2.00 | | | | | |
| Washed Coal Consumption* ($10^4$ t/a) | 14.38 | 5.65 | 2.91 | 3.0 | 3.0 | 2.9 | 3.6 | 3.0–3.6 |
| Number of Cabins | 2 x 25 | 2 x 18 | 2 x 12 | 4 x 2 | 2 x 6 | 10 x 1 | 1 x 20 | 1 x7 |
| Total Estimated Investment ($10^4$ yuan) | 10000 | 3400 | 1000 | 150 | 200 | 180–200 | 60 | 50 |
| Investment Cost Per Tonne Coke (yuan/t) | 1000 | 800 | 500 | 75 | 100 | 90–100 | 30 | 25 |
| Land Used (ha) | 3.84 (14) | 2.5 | 0.7 | 1 | 0.7 | 0.8 | 1.2 | 1 |

| | *66-Coking Oven*≅ | *70-Coking Oven* | *No.3 Hongqi Coking Oven* | *TJ-75 Coking Oven* | *XY-Coking Oven* | *KM-Coking Oven* | *Luliang Coking Oven* | *Pingxiang Coking Oven* |
|---|---|---|---|---|---|---|---|---|
| Total Number of Employees | 328 (620) | 230 | 175 | 30 | 30 | 70 | 90 | 70 |
| Laborers | 312 (550) | 218 | 163 | | | | | |
| Total Productivity (tonne/person-year) | 333 | 185 | 125 | 667 | 667 | 286 | 222 | 286 |
| Laborer productivity (tonne/person-year) | 350 | 195 | 134 | | | | | |
| Total Iron Steel (tonne) | 1497 (4610) | 505 | 117 | 4.2 | 6 | | 50 | 40 |
| Circulating Water Rate | 134 $m^3/h$ (310) | 81 $m^3/h$ | 18.5 $m^3/h$ | 25,000 t/t coke | 25,000 t/ t coke | 1.88 t/ t coke | 42,000 t/ t coke | 62,000 t/ t coke |
| Fresh Water Consumption ($m^3/h$) | 389 (180) | 230 | 41.0 | N/A | N/A | 6.5t/ t coke | N/A | N/A |
| Electricity (kWh/a) | 3.25 x $10^6$ (6.4 x $10^6$) | 1.6 x $10^6$ | 0.43 x $10^6$ | 0.11 x $10^6$ | 0.11 x $10^6$ | 0.53 x $10^6$ | 0.69 x $10^6$ | 0.86 x $10^6$ |
| Steam (t/h) | 6.42 (14) | 3.1 | 1.0 | | | | | |
| Compressed air ($m^3/min$) | 9 | 6 | | | | | | |
| Coke-oven gas ($Nm^3/h$) | 5300 | 2370 | 1000 | | | | | |
| Gas for Heating ($Nm^3/h$) | 3000 | 1670 | 800 | | | | | |
| Surplus Gas ($Nm^3/h$) | 1810 | 700 | 200 | | | | | |
| Coke Oven Life (years) | 15 | 12,5 | 12.5 | | | | 3–5 | |
| Output of Crude Tar (t/a) | 5030 | 1978 | 1000 | | | | 90–120 | 90–120 |
| Thick Ammonia Water (20%) (t/a) | 1726 | 620 | | | | | | |
| Crude Benzene (t/a) | 1582 | 509 | | | | | | |

N/A = Not available

* Raw coal can be used.

≅ Numbers in parentheses include auxiliary equipment such as waste water treatment, coal gas producer, storage and distribution of coke oven gas, etc.

Table D-3 compares the emissions potential of a number of plants with 2 Mt/a production capacity. The main conclusion is that the emission sources and opportunities increase as the cabin size decreases. Key indicators of emission potential are number of charges per tonne of coke, number of leakage points in the oven, and length of the sealed surfaces.

**Table D.3: Emission Potential of Five Coking Plants with 2 Mt/aCoke Production Capacity**

| *Plant Parameters* | *Middle Coking Oven* | | *Mansmen Plant* | *Kaizest Number 3 Plant* | *Large Reactor* |
|---|---|---|---|---|---|
| Effective size of coking cabin, m — Height | 4.5 | 6.0 | 7.85 | 7.63 | 10.0 |
| Length | 11.70 | 14.20 | 17.20 | 18.00 | 19.0 |
| Width | 0.45 | 0.45 | 0.55 | 0.61 | 0.85 |
| Effective volume of coking cabin, $m^3$/cabin | 22.1 | 36.4 | 70.0 | 78.9 | 150.0 |
| Coke output per cabin, t/cabin | 12.7 | 21.3 | 43.0 | 48.7 | 100.0 |
| Number of cabins | | | | | |
| Total number of leakage | 322 | 187 | 120 | 120 | 55 |
| mouths | 2898 | 1469 | 1080 | 1080 | 165 |
| Length of seal surface, km | | | | | |
| Number of charges | 10.5 | 6.9 | 6.0 | 5.5 | 2.4 |
| Total time of opening leakage | 430 | 252 | 128 | 115 | 55 |
| mouths per day | 3870 | 2016 | 1152 | 1035 | 110 |
| Cleaned length of seal surface, km/d | 14.0 | 9.5 | 5.6 | 5.3 | 2.4 |

A specific example of how these potential emissions sources would be reduced by a remodel of the oven is given in Table D-4. This table shows that the key emission sources decrease by one third if a 4.3-m high cabin is converted into a 5-m high cabin.

**Table D.4: Environmental Design Improvements from Upgrading aCoking Oven from 4.3 m to 5 m High**

| | | |
|---|---|---|
| Effective size of coking cabin, m | | |
| height | 4.3 | 5.0 |
| Length | 14.08 | 15.98 |
| width | 0.45 | 0.5 |
| Effective volume, $m^3$/cabin | 23.9 | 35.6 |
| Revolving time, h | | |
| Number of cabins in oven | 18 | 21 |
| Number of coal charging doors | 70 | 54 |
| Total number of leakage points | 3 | 4 |
| Length of seal surface, km | | |
| Number of charges | 560 | 486 |
| Cleaned length of seal surface, km/d | | |
| | 1.5 | 1.34 |
| | 94 | 62 |
| | 2.0 | 1.5 |

As discussed in Section 5, having a greater number of large coke ovens and concentrating them near chemical plants would help China produce a greater variety of chemicals. Table D-5 compares the quality specifications of such chemicals in China with those produced outside China.

**Table D.5: Quality Comparisons of Chemical Products from Domestic and Foreign Plants**

| | *Quality Indices of Products from Abroad* | *Quality Indices of Products Made in China* |
|---|---|---|
| Phenol | Crystallization point:<br>≥ 40.6°C (ASTMD2439-86 by USA)<br>39.5–41°C (BS•523-1964 by U.K.)<br>40.7 (products from imported technologies) | Crystallization point:<br>39.7–40°C (GB6705-89)<br>39.7–40°C (products from China)<br>40.55°C (products from imported technologies) |
| Refined Naphthalene | Crystallization point:<br>≥ 80°C (ГОСТ 16106-82 by Russia)<br>≥ 80°C (products from imported technologies)<br>Sulfur: ≤ 0.4%<br>Heteroindene: ≤ 0.1% | Crystallization point:<br>≥ 79.6°C (GB6699-86)<br>79.8°C (products from China)<br>≥ 80°C (products from imported technologies) |
| Pure Benzene | Crystallization point:<br>5.4°C (DIN51633-86 by Germany)<br>5.5°C (products from imported technologies) | Crystallization point:<br>5.0°C (GB/T2283-86)<br>5–5.2°C (products from China)<br>5.5°C (products from imported technologies) |
| Refined Anthracene | Purity: 95% (products from German units)<br>96% (products from French units)<br>Content of carbazole: < 3% | Purity: 91–93% (products from China)<br>Content of carbazole: < 5% |

# Appendix E
## Technical Information On Coal Gasifiers

This appendix provides some detailed technical data and specifications on gasifier technologies that supplement the information presented in Section 6.

### E.1 Coal Gasifiers

The feed coal requirements for atmospheric fixed-bed gasifiers generating producer gas are presented in Table E-1.

**Table E.1: Quality Requirements of Feed Coal for Coal Gas Producers**

| *Types of Feed Coal* | *Anthracite* | *Meager Coal* | *Subbituminous* | *Lignite* |
|---|---|---|---|---|
| Size, mm | 6–13<br>13–25<br>25–50 | 6–13<br>13–25<br>25–50 | 13–25<br>25–50<br>50–100 | 25–50<br>50–100 |
| Ash, % | < 25 | < 25 | < 20 | < 20 |
| Sulfur, % | < 2 | < 2 | < 1.2 | < 1.2 |
| Refuse content, % coal > 50 mm | < 2 | < 4 | < 3 | < 2.5 |
| Thickness of plastic layer, mm (measure of caking ability) | | | < 16 | |
| Mechanical strength, % (weight % of > 25 mm fragments after drop test) | > 65 | > 65 | > 60 | |
| Thermal stability, % | > 65 | > 65 | > 60 | > 75 |
| Ash fusibility (ST), °C | > 1250 | > 1250 | > 1250 | > 1250 |
| Clinkering property (coal adhesivity) | Below medium | Below medium | Below medium | Below medium |

The most common types of coal gasifiers in China are the 3M21, 3M13, Wellman-Galusha (W-G), TG-3MI, and TG-3MII.

The **3M21** type of gasifier is equipped with a mechanical coal feeder, mechanical ash removal, and a rotating grate, which features high strength, large capacity, and reliability. This model is mainly used for gasification of non-caking feed coal such as meager coal, anthracite, and coke.

The **3M13** gasifier is mechanized with an agitator, and used mainly for gasification of weakly caking bituminous coal. The upper and lower structures of the gasifier are basically the same as the 3M21, except that the upper coal feeder is a double cylinder to accommodate the agitator.

The **Wellman-Galusha (W-G)** process is used for gasification of non-caking feed coal such as anthracite and coke. The furnace body is taller than other gasifiers, as high as 17 m, to provide longer residence time for low-reactivity coals. The coal feeding part is divided two sections; the coal in the upper section passes through four diplegs in the gasifier. Owing to operation with the reactor volume fully loaded, the residence time of the feed coal in the furnace is long, about 4 hours. Because of the considerable depth of the bed material in the furnace and the high outlet pressure of the coal gas (usually about 1500 Pa), dry ash removal is employed. This kind of furnace is commonly used in China due to its large production capacity, reliable operation, and high gasification efficiency.

The **TG-3MI** and **TG-3MII** are new types of gasifiers based on the W-G process but incorporating design improvements used in advanced foreign models. Type I is used for gasification of coke, anthracite, and some weakly caking bituminous coal, while Type II can handle some caking bituminous coals because it is equipped with an agitator to break up caking materials. Higher quantities of coal in the furnace are beneficial to drying and pyrogenic distillation of the feed coal. Fine coal (6–13 mm) can be gasified in large-capacity units of this type, with the gasifier in stable operation and at high gasification efficiency.

As discussed in Section 6.3.1.3, atmospheric fixed-bed gasifiers can use either a hot gas process, in which raw gas is supplied to users without cooling, or a cold gas process, which raw gas is cooled and cleaned before delivery to users. The cold gas process uses the following unit operations to cool the gas, depending on the feed coal:

- When using coke or anthracite as the feed coal, the raw gas flows into the bottom of double stand pipes and then into the scrubber tower. After the water is separated out by a drop collector, the coal gas is pressurized and supplied to users.

- When using weakly caking bituminous coal as the feed coal, the raw gas is contacted by recycle cooling water in the bottom of double stand pipes. The entrained impurities and tar in the raw gas are discharged from the bottom of the double stand pipe while the gas is flowed through a series of gas cleanup and cooling devices—an isolated water seal, an electrostatic tar collector (ESP), where over 95% of the tar is removed, and a second scrubber. At this point, the coal gas is cooled to about 35°C through heat exchange with recycle cooling water in the scrubber. The water is then removed by a drop collector, and the coal gas is pressurized for supply to users.

## E.2 Water Gas Gasifiers

Feed coal requirements for water gas gasifiers are presented in Table E-2.

**Table E.2: Feed Coal Quality Requirements of Water Gas Gasifiers**

| *Quality Index** | *Quality Requirement* |
|---|---|
| Size, mm | 25–75 |
| $A_{ad}$, % | <20 |
| $V_{ad}$, % | <8 |
| $S_{t,ad}$, % | ≤1 |
| $M_{ar}$, % | <10 |
| Shatter strength, % passing drop test | ≥70 |
| Thermal stability, % passing criteria | ≥60 |
| Ash fusibility (ST), °C | 1250 |

* See Table C-1 for definitions of symbols. The subscript 'ar' means as received.

The circulation cycle and time distribution of water gas production are shown in Table E-3.

**Table E.3: Circulation Cycle and Time Distribution of Water Gas Production**

| *Control Style* | *Circulation Cycle, seconds* | *Time Distribution, %* | | | | | |
|---|---|---|---|---|---|---|---|
| | | Air blowing | Steam blowing off | Steam blowing up | Steam blowing down | Second steam blowing up | Air blowing off |
| Automatic | 150–180 | 22–28 | 2 | 24–30 | 34–40 | 7–9 | 3–5 |
| Manual | 240–270 | 25–30 | 2 | 25–32 | 34–38 | 8–9 | 2–4 |

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