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# Applying Environmental Externalities to U.S. Clean Coal Technologies for Taiwan

C.B. Szpunar and J.L. Gillette
International Coal and Technology Studies
Environmental Assessment and Information Sciences Division
Argonne National Laboratory
Argonne, Illinois, USA

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## ABSTRACT

*The United States is well positioned to play an expanding role in meeting the energy technology demands of the Asian Pacific Basin, including the Republic of China (ROC - Taiwan). The U.S. Clean Coal Technology (CCT) Demonstration Program provides a proving ground for innovative coal-related technologies which can be applied domestically and abroad. These innovative U.S. CCTs are expected to satisfy increasingly stringent environmental requirements, while substantially improving power generation efficiencies. They are expected to provide distinct advantages over conventional coal combustors. They are also expected to be competitive with other energy options currently considered in the region. Potential technology scenarios for the ROC - Taiwan are presented, along with consideration of an environmental cost-benefit approach employing a newly developed method of applying environmental externalities.*

## INTRODUCTION

Coal is an abundant resource found in many locations throughout the world. It is, and has been for many years, one of the most widely used energy sources in many parts of everyday life including cooking, heating, transportation, industrial processes, and the production of electricity. Its use in the industrial and electric sectors is expected to grow as these sectors attempt, in general, to reduce their dependence on imported oil. Increased coal utilization is anticipated not only in industrialized countries where demand for electricity and industrial products is growing steadily, but also in developing and newly industrializing countries where attempts to expand industrial production and to provide electricity in a rapidly expanding society abound.

## TAIWAN'S ENERGY AND ENVIRONMENTAL SITUATION

Taiwan is heavily dependent on imported energy with about 90% of its energy consumption derived from foreign sources. It is very dependent on Middle East oil supplies with about 80% of the imported crude coming from this region. Although poor in energy resources, Taiwan's energy demand has grown significantly due to its meteor-like economic rise and its tremendous surge in living standards for its 19 million people [1].

Coal is widely regarded as a reliable, low-cost fuel in the production of large quantities of baseload electricity, available from a diverse group of international suppliers. The demand for coal, especially imported coal, is a direct result of the government's policy dealing with the deregulation of coal importation and its diversification policy on energy [2]. Coal imports have come principally from Australia, with the U.S. and South Africa also supplying significant quantities. Recently however, imports from South Africa have increased at the expense of those from the U.S. and Australia. The expressed policy of the Taiwanese government is that coal imports will continue to be spread among several sources so that Taiwan can take advantage of varying prices while maintaining supply security.

With the rapid increase in coal demand, both in steam coal for power generation and also in coking coal for its developing steel industry, environmental concerns and pollution controls for mitigation have become important considerations. To develop and implement energy and environmental plans for the country, several organizations and institutions -- including the Council for Economic Planning and Development, the Environmental Protection



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## DISCLAIMER

Administration, the National Corporation Commission, the Bureau of Industry, the Energy Commission, Taiwan Power Company (Taipower), the Chinese Petroleum Corporation, and the China Steel Corporation -- have become involved [3].

Domestic coal resources are estimated at 200 million tonnes (Mt), with 120 Mt judged as exploitable reserves. However, increasing operating costs, ever-deepening mines, the decrease of skilled coal miners, keen competition from relatively inexpensive imported coals, and several disasters resulting in the closing of many unsafe mines have all contributed to a reduction in domestic coal production -- from 5 Mt per year in the 1960s, to less than 800,000 t in 1984, and expected to decrease to approximately 100,000 t by the year 2000. Nevertheless, total coal demand is forecast to increase from 19 Mt in 1990, to 35 Mt by the year 2000, and reaching more than 56 Mt by 2010. Steam coal for electricity generation is expected to increase from 9.7 Mt in 1990, doubling to nearly 20 Mt by the year 2000, and doubling again to almost 40 Mt in 2010 [3,4]

Because of limited land areas and dense population, as well as vigorous industrial and commercial activities, environmental quality in Taiwan has seriously deteriorated in recent years. However, environmental quality has become of greater concern to the public at large, with the environment and its protection recognized as prominent and urgent priorities. Hence, pollution control has been foremost in the public focus in recent times [3].

Since 1985, the government has required that all major engineering projects, including coal-fired power plants, must undergo environmental impact assessments in the planning stage prior to government review. In addition and simultaneously, two major regulations must be satisfied -- the Air Emission Standards for Stationary Sources (1986) and the Wastewater Effluent Standards (1987). $SO_2$ emissions from combustion must be less than 750 ppm (1990), decreasing to less than 500 ppm in 1993. Hence, high-efficiency combustion and pollution control equipment must be the focus [3]. And clean coal technologies may be beneficial to Taiwan in fulfilling its requirements.

## U.S. CCT DEMONSTRATION PROGRAM

Extensive research and development (R&D) is underway to improve coal-based technologies so that the use of this vast energy resource can be expanded while maintaining strict environmental standards. Through the development of a slate of technological options, decision makers are provided a greater latitude in balancing the needs of a growing population, desired economic expansion, environmental concerns, and costs. The scope of ongoing R&D includes improved coal cleaning processes, more efficient combustion technologies, and improved flue gas cleanup systems that provide for higher levels of $SO_2$, $NO_x$, and particulate control without the production of large quantities of solid waste. The technologies under development are applicable to a wide range of conditions including refurbishments and new facilities, industrial and electric plants, and a wide range of coals.

In the United States, R&D on clean coal technologies (CCTs), a new generation of advanced, coal-based technologies, continues with numerous jointly funded demonstration projects. The U.S. CCT Demonstration Program is designed to take some of the most promising of the advanced coal-based technologies and, over the next decade, move them into the commercial marketplace. These advanced technologies are expected to be environmentally cleaner and, in many cases, more efficient and less costly than conventional coal processes. The widespread interest in coal technologies and utilization is evidenced by the fact that many foreign countries and companies also have large coal R&D programs [5].

## APPLICABLE CLEAN COAL TECHNOLOGIES FOR THE ROC - TAIWAN

Economy in the republic is trade-oriented, with the United States being the leading trading partner, followed by Japan, and the former West Germany. The industrial sector is undergoing a change from labor and energy intensiveness to more capital intensiveness. The service sector is also becoming increasingly important. As these changes occur, economic expansion and increased demand for electricity are rapidly occurring. With improvements in the overall standard of living comes an increase in the demand for electricity - with the difference between base and peak demands becoming ever larger.

During the period 1971 to 1980, electricity consumption increased remarkably at an average rate of 12.2% per year. Despite experiencing a record low in 1982 and 1983, electricity demand returned to double digit growth, reaching 11.6% and 10.2% in 1987 and 1988, respectively, due to a strong economic recovery. In 1988, 71.6 TWh of electricity was produced, 21.1 TWh of which was from coal-fired units (29%).

The electricity demand for Taiwan is expected to continue to grow at a very rapid rate during the 1990-2006 time frame. The average load is expected to grow at an annual rate of 5.6% while the peak load is projected to increase at an annual rate of 6.0% [4]. To meet this demand, the installed electric-generation capacity is expected to increase from its 1990 level of about 17,000 MW to more than 36,000 MW. Of this new capacity, current plans call for 13 units of coal-fired generation totaling 8,150 MW to be added to the existing 10 coal-fired units with 3,675 MW of total capacity. Each new unit will have electrical-generation capacities of 550 MW or 750 MW. Coal consumption by Taipower is estimated to exceed 20 Mt per year. Reports indicate that terminals, ship-unloading facilities, and coal yards are also planned and/or under construction to allow for the importing of this quantity of coal.

All new coal-fired power plants are expected to comply with government regulations on $SO_2$, $NO_x$, and particulate emissions. Taipower reports that all of its proposed coal-fired units will be equipped with modern flue gas emission reduction devices, such as electrostatic precipitators or baghouse filters, flue gas desulfurization and de$NO_x$ devices, to reduce the pollutants to their minimum practical levels [6].

New coal-based generation requirements in the sizes needed in Taiwan create an opportunity for several of the CCTs currently under demonstration in the United States. Options to be considered include:

- A pulverized-coal (PC) fired plant with no $SO_2$-emission controls and moderate particulate control. (This option is not under consideration for use in Taiwan but can serve as a reference case to demonstrate the effectiveness of emission control capabilities available in CCTs);

- A PC-fired plant with $SO_2$-emission control (flue gas desulfurization or FGD) and a higher level of particulate control --PC/FGD;

- An atmospheric fluidized-bed combustion plant -- AFBC;

- A pressurized fluidized-bed combustion plant -- PFBC; and

- An integrated coal gasification combined-cycle plant --IGCC.

Estimates of the reduction levels and emission rates for air pollutants from these generic coal technologies are presented in Table 1. These values are considered representative of those for a family of variations within each technology and serve as the base case estimates in this analysis. The values for $SO_2$ and particulate control given in this table do not necessarily represent the full capabilities of the advanced technologies. Instead, they are intended to represent improvements over the reference-case PC-fired plant under conditions believed representative of Taiwan. Values for $CO_2$ emissions are based on a release rate of 205 pounds per million British thermal unit (Btu) of heat input (369 kg/million kilocalorie) adjusted by the efficiency of the technology and an assumed amount of limestone required for $SO_2$ control.

Of the 19 Mt of total coal used in Taiwan in 1990, only about 3% was from indigenous sources. The remaining 97% was imported from Australia, the United States, Canada, South Africa, and Indonesia. Approximately half of this imported coal was from Australia with the other half predominately from the United States and South Africa. Thus, for purposes of the analyses presented here, it is assumed that the new coal-based plants will be fueled with imported coals from Australia, the United States, or South Africa.

Table 2 presents selected characteristics of coals that could be imported from these countries. These characteristics represent raw coal and are not necessarily the precise characteristics that would be expected to be received at the plant site. These coals include both a high-sulfur and a high-ash coal from the United States which are not necessarily the most commonly exported U.S. coals. Although both U.S. coals could also be beneficiated easily to remove substantial fractions of sulfur and ash, they are presented here to serve as illustration of the increased environmental qualities of CCTs. Of course, other coals could also be imported to Taiwan but these coals were selected to illustrate the points of these analyses.

The large expansion program undertaken by Taipower provides the opportunity to implement several CCTs. The AFBC, PFBC, and the IGCC all can be built in the sizes needed, can use a variety of coals that might be expected from a diversified supply system, and can meet the emission standards put forth by the government. Additional CCT opportunities may exist in the retrofitting of some of the approximately 4900 MW of oil-fired capacity currently owned by Taipower. Conversion of some of these units to slagging combustors or to coal-water mixtures could help to reduce operating costs, along with allowing for a more diversified fuel supply than is currently achieved with imported oil. Such retrofit applications were not considered in the analyses described herein.

## AMBIENT ATMOSPHERIC CONDITIONS -- ROC - TAIWAN

Taiwan's considerable efforts in industrialization and economic development have caused the air pollution concentrations to increase dramatically during the 1960s and 1970s [7], principally due to:

- a substantial increase in the number of industries,
- the continued combustion of fuel oil, coal, and wood,
- an increase in automobile exhaust emissions, and
- a high population density.

Preliminary measurements of pollution in the heavily industrialized city of Kaohsiung appear comparable to other Asian industrial centers, as indicated in Table 3 illustrating ambient air conditions for $SO_2$ and particulates (ug/m$^3$). Although these data are somewhat dated, they illustrate the fact that the ambient air quality in Taiwan generally exceeds World Health Organization (WHO) guidelines for both $SO_2$ and particulates. Chow et al. [7] have called for long-term monitoring at more sites using standardized procedures.

In 1984, there were 170 monitoring stations reported for Taiwan, but most of these were identified as consisting of manual particulate measuring devices only; a monitoring center, 19 automatic, all-criteria stations, and one mobile van were said to have been planned [8]. At that time, particulates from stationary sources were reported to show a decreasing trend, while pollutants from mobile sources were reportedly on the rise. Taiwan has been characterized as moderately polluted, about 15 years behind Japan in its environmental protection efforts. Moreover, Tsai and Jenq [9] reported that candidate locations for air quality monitoring sites are still under study (perhaps as refinements) for Taipei [10]. Recently, calculations for an East Asian (Japan, mainland China, Taiwan, South Korea, and North Korea) emissions inventory indicated that $SO_2$ emissions from Taiwan are similar to those of Japan and South Korea, with the principle emission sources concentrated in the Taipei, Jilong, and Gaoxiong areas [1].

## ENVIRONMENTAL EXTERNALITIES - AN APPLICATION

Historically, decisions in electric power generation planning are usually made on the basis of a consideration of traditional costs such as capital, operating and maintenance, fuel costs, and fixed charges. Social costs, which could be significant, are not incorporated explicitly into such decisions. These social costs could result in a net reduction in the welfare of individuals, and of society as a whole. Because these social costs and their effects are not represented in the price of energy, individuals have no way to explicitly value them. Hence, they remain unaccounted for in market decisions [11]. By accounting for external costs, the selection of energy sources and production of energy products can lead to an equilibrium, where the total cost of energy and energy products, together with the resulting social costs, can be brought to an economic minimum.

All energy conversion technologies pose some risk to society. Economists and social scientists continue to develop monetary values to represent loss of life, illness, global warming, decreased visibility, acid rain, and other consequences of electricity production. These monetary values, referred to as *environmental externality values*, have been translated to emissions through consideration of dose-response relationships and similar cause-and-effect principles. The term may be defined as those external or social costs related to any unpriced impacts created in the process of energy production and use, typically in the form of environmental damage, adverse health effects, and materials damage [11].

In considering and applying externality costs rigorously, first, the necessary dose-response and physical damage functions involved need to be identified and quantified. Second, the validity of the economic value of statistical lives, a very controversial concept, needs to be considered and accepted. Third, the appropriate economic data need to be applied in deliberations, even though in general, these data are costly and difficult to gather. And, fourth, even with the appropriate data, the fact that significant uncertainty and imprecision in the estimates will continue to exist needs to be recognized [12].

The authors have developed a simplified two-step approach for the valuation of environmental externalities [13,14]. First, power-plant-generated emissions are calculated from various electric power generation options. These calculated emissions are dependent on plant type, plant age, fuel type, fuel grade, sulfur content, installed/operating emissions technology, and plant operating parameters such as heat rate, combustion temperature, and injection options. Second, the value for monetary damage to the environment is assessed, assuming conservative estimates for point source emissions.

The ambient air quality data for Taiwan has been shown to be similar to that of other countries in the region (Table 3). Hence, the same externality values can be applied. These values, the conservative, damage-based Lave values which consider health impacts, one set of many such externality values, include: $1090 per tonne $SO_2$ emitted; $495 for $NO_x$; $1650 for particulates; and $11 for $CO_2$. Szpunar and Gillette [13,14] have demonstrated previously how the costs and benefits of controlling emissions -- specifically those from new, advanced-technology, coal-based, electric-power plants to be sited in Indonesia and Thailand -- might be considered. The reader is directed to the referenced works for additional details.

## METHODOLOGY

Traditional methods for determining the costs of electricity production involve techniques for annualizing capital costs, incorporating operating and maintenance costs, and calculating fuel costs. These costs form the basis for establishing the price of electricity that consumers must pay. Utilities have acknowledged concerns related to environmental issues by ensuring compliance, by incorporating the additional costs of compliance into the cost of electricity, and by conducting some evaluation of the impacts or consequences of the emissions or residuals.

By combining the economic value of environmental impacts with the quantity of the electricity produced per unit of emission, an *environmental cost* of electricity production can be determined. This cost can be expressed in the same terms as are the more traditional costs (e.g., U.S. cents per kilowatt hour) and can thus be combined with the traditional costs. It can also be directly compared with the traditional costs to illustrate the relative magnitudes of each cost.

For these analyses, a model was developed to estimate the traditional cost of electricity production for conditions representative of those in Taiwan. Externality costs were also estimated through the use of the emission rates (or control levels) for the individual technologies and the externality values. These costs were added to yield a total cost for each option.

A *figure of merit* was developed to illustrate the benefit-to-cost ratio for each advanced option relative to the reference case. This figure of merit is equal to the benefit of reduced atmospheric emissions divided by the increase in traditional cost of electricity production. A benefit-to-cost ratio of less than 1.0 means that the benefits are less than the additional production costs, while a ratio greater than 1.0 means that the benefits exceed the additional costs. A value of 1.0 means that the benefits of reduced atmospheric emissions exactly offset the additional cost of electricity production.

Several economic and technical assumptions were made to allow quantitative assessments of the emission control costs and the benefits of the advanced technologies. All technologies were considered to operate as baseload plants, with annual capacity factors of 70%. As noted earlier, several 550-MW coal-fired units are anticipated for Taiwan in the near future. Therefore, a plant of this capacity was used in these analyses. The analyses were performed in terms of constant U.S. dollars. Fuel costs ranging from U.S. $6.30 to $8.30 per million kilocalories ($1.6 to $2.1/million Btu) were used.

For purposes of these analyses, it is assumed that all of the additional costs of the advanced technologies, as compared to the reference PC plant, are attributable to environmental controls. In reality, some of these additional costs could result from the desire to make the advanced technologies more reliable and more fuel flexible. By assigning all additional costs to environmental control, the results of the analyses will conservatively (i.e., under) estimate the ratio of benefits to costs. Thus, the advanced technologies should provide, in practice, an environmental benefit to environmental control-cost ratio at least as high as the values presented in this paper.

The environmental externality values selected for these analyses are the higher of Lave's conservative externality values, which are neither the highest nor the lowest values that have been presented in the literature. These values, however, do represent the lowest estimated environmental externality values that do include health effects. Thus, the use of these values also tends to result in a benefit-to-cost ratio that is conservative (lower) than those that would result from the use of other externality values that incorporate health effects.

## RESULTS

The numerical results of these analyses include values for the traditional cost of electricity production (capital, operating and maintenance, and fuel) and for the cost of environmental externalities. As noted earlier, a ratio of the incremental benefits due to the reduction in emissions divided by the incremental cost in the traditional cost of electricity production is used as a figure of merit for these technologies.

Results from these analyses are shown in Table 4. In every case, the results demonstrate a benefit-to-cost ratio greater than 1.0. In other words, over the variety of technology applications and coals considered, the value of the reduction in atmospheric emissions is estimated to be far greater, in many cases, than the additional cost that may be incurred in attaining the higher levels of emission control.

The benefit-to-cost ratios in Table 4 range between 1.6 and 7.2. The highest ratios are shown for the IGCC with its high levels of particulate and sulfur control, but with costs comparable to the other technologies. The reader should recall that the performance parameters used in these analyses do not necessarily represent the full capabilities of the technologies. Higher benefit-to-cost ratios are exhibited for the higher ash and sulfur content coals, due to the greater reductions in the quantities of atmospheric pollutants that can be attained.

## OBSERVATIONS/OTHER CONSIDERATIONS

A more detailed examination of these options provides some additional insight into their significance. The traditional cost of electricity production with an IGCC in Taiwan burning U.S. Upper Freeport coal is estimated at approximately 4.4 cents (U.S.)/kWh. The corresponding cost for the reference case PC-fired unit is approximately 3.8 cents/kWh. However, the cost of the environmental externalities due to air emissions from the IGCC is approximately 5.5 cents/kWh while the emissions from the reference plant have a cost of about 9.6 cents/kWh. Thus, when the 550-MW plant operates for a year at a capacity factor of 70%, the additional cost of electricity production from the IGCC as compared to the reference technology is about $22.5 million (U.S.). However, the reduction in atmospheric emissions realized by using the IGCC rather than the reference technology reduces environmental externality costs by $162 million (U.S.).

As indicated in Table 4, the estimated figure of merit for the other cases considered are lower than this example -but all ratios were greater than 1.0 thus showing that an investment in the U.S. CCTs would be more than repaid by reductions in costs from air pollution from the reference plant burning the same coal.

The environmental externality values involve considerable uncertainty with respect to state of the science (e.g., atmospheric dispersion and health effects) and the selected economic values (e.g., the dollar value of a health impact or of visibility impairment). Sensitivity analyses were therefore performed on several parameters, including capital and operating costs, values of environmental externalities, and emission rates and emission control levels. Although the individual costs and benefits change, the basic conclusions remain the same. These are that: 1) significant environmental benefits are likely to accrue when using U.S. CCTs and 2) the value of these benefits will generally be much greater than the incremental cost resulting from reducing emissions.

Therefore, environmental externality values can be used as demonstrated here to make a quantitative estimate of the benefits to be derived, so that they can be compared with the traditional cost of electricity production.

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TABLE 1 EMISSION RATES AND REDUCTION LEVELS BY TECHNOLOGY

| Emission | Uncontrolled Pulverized Coal | Controlled Pulverized Coal | AFBC | PFBC | IGCC |
|---|---|---|---|---|---|
| $SO_2$ (%) | no controls | 80 | 80 | 90 | 95 |
| $NO_x$ (ppm) | 800 | 400 | 150 | 150 | 150 |
| TSP (%) | 80 | 90 | 90 | 95 | 99.99 |
| $CO_2$ (lb/kWh) | 2.0 | 2.1 | 2.2 | 1.9 | 1.9 |
| $N_2O$ (ppm) | 1 | 1 | 1 | 1 | 1 |
| CO (ppm) | 120 | 120 | 200 | 170 | 5 |

TSP = total suspended particulates ppm = parts per million kWh = kilowatt hour

TABLE 2 REPRESENTATIVE COAL QUALITY CHARACTERISTICS

| Coal | Calorific Value (Btu/lb) | Calorific Value (kcal/kg) | Moisture (%) | Ash (%) | Sulfur (%) |
|---|---|---|---|---|---|
| Australia Hunter Valley | 11,510 | 6390 | 9.0 | 12.7 | 0.5 |
| Australia Ulan | 10,880 | 6050 | -- | 16.3 | 0.7 |
| South African Ermelo | 11,240 | 6240 | -- | 12.6 | 1.0 |
| South African Witbank | 10,880 | 6050 | -- | 15.1 | 1.0 |
| United States Upper Freeport | 9750 | 5420 | 4.8 | 30.2 | 1.8 |
| United States Illinois No. 6 | 10270 | 5710 | 9.5 | 16.8 | 4.2 |

| TABLE 3 ANNUAL AVERAGE AMBIENT AIR QUALITY | | | | | |
|---|---|---|---|---|---|
| Country | City | Area Type | 1978[a] | 1979[a] | 1980[a] |
| $SO_2$ (ug/m$^3$) | U.S. NAAQS = 80[b] -- WHO Guideline = 40 - 60[c] | | | | |
| ROC - Taiwan | Kaohsiung | urban industrial | 54-3780[d] | na | na |
| Thailand | Bangkok | suburban residential | na | 10 | na |
| | | suburban industrial | 15 | 9 | na |
| Indonesia | Jakarta | city center residential | na | na | na |
| | | suburban industrial | na | na | na |
| Malaysia | Kuala Lumpur | suburban residential | 5 | 3 | 3* |
| | | suburban industrial | 43 | 15 | 22 |
| Philippines | Manila | city center commercial | 66 | 91* | 75* |
| | | suburban residential | 46 | 58 | 62 |
| | | suburban industrial | 91* | 100* | 79 |
| | | | | | |
| PARTICULATES (ug/m$^3$) | U.S. NAAQS = 50[b] -- WHO Guideline = 60 - 90[c] | | | | |
| ROC - Taiwan | Kaohsiung | urban industrial | 200-300, 260 typical[d] | | |
| | | pristine mountain | 150 typical[d] | | |
| Thailand | Bangkok | suburban residential | 137* | 170 | 232* |
| | | suburban industrial | 162 | 167 | 170 |
| Indonesia | Jakarta | city center residential | 210* | 255 | 275 |
| | | suburban industrial | 129* | 138 | 167 |
| Malaysia | Kuala Lumpur | suburban residential | 90 | 79 | 98 |
| | | suburban industrial | 153 | 158 | 182 |
| Philippines | Manila | city center commercial | 87 | 73 | 79 |
| | | suburban residential | 87 | 101 | 99 |
| | | suburban industrial | 76* | 82* | 92* |

a. Ref. 17
b. Ref. 15, $SO_2$ converted from ppm to ug/m$^3$ -- ppm $SO_2$ x $2.7x10^3$
c. Ref. 16
d. Ref. 7
* = Insufficient data for reliable statistics; na = not available

| TABLE 4 RATIO OF REDUCED COST OF ENVIRONMENTAL EXTERNALITIES TO INCREASED COST OF ELECTRICITY PRODUCTION | | | | | | |
|---|---|---|---|---|---|---|
| Technology | Australia Hunter Valley | Australia Ulan | S. A. Ermelo | S. A. Witbank | U. S. Upper Freeport | U.S. Illinois No. 6 |
| PC/FGD | 1.6 | 2.1 | 1.9 | 2.1 | 4.4 | 4.4 |
| AFBC | 1.6 | 2.1 | 1.9 | 2.2 | 4.2 | 4.7 |
| PFBC | 1.8 | 2.4 | 2.1 | 2.4 | 5.0 | 4.7 |
| IGCC | 2.6 | 3.4 | 2.9 | 3.4 | 7.2 | 6.1 |