Integrating LCA and LCC study of FGD system at a thermal power plant in China

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Abstract—**This paper presents the integrating Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) study of the Flue Gas Desulphurization (FGD) system in Fengcheng thermal power plant in China. The FGD systems have been installed in a power generation plant to reduce the large amount of SO_2 emission. Studies to appraise FGD system in power plant have mainly focused on economic analysis. This paper gives a way of combing LCA and LCC analysis, which can be used to evaluate ecological and economic benefits both before and after the installation of the FGD system. The focus of this study is to consider not only the LCA outcome but also the LCC factors. LCA provides a broad view by generating a model which links the industry to be assessed through all its material and energy resource flows to other environmentally significant processes in the wider industrial network. The Life Cycle Costing was used to provide a comparison between alternative before and after installation of the FGD system. LCC, as a powerful analytical tool, examines the total cost, in net present value terms, of a FGD system over its entire service lifetime. Comparative models of the power plant, before and after the installation of the FGD system, are evaluated using the LCA model. The results indicate that the installation of the FGD system can reduce the acidification problem associated with combustible fossil fuel plants by approximately 97%. The LCC estimation shows the major costs of the FGD system: capital investment, operating and maintenance, and miscellaneous costs. The modeling and model analysis of LCA and LCC for FGD system provide the foundation for assessing the selection of desulphurization technology for large thermal power plant in China; it is also helpful to optimize construction, operation and maintenance of FGD installation.**

Index Terms—**life cycle assessment, life cycle costing, flue gas desulphurization, power plant**

I. INTRODUCTION

Electricity is one of the most important contributors to a nation's economy. The electric industry, and in particular its coal-fired power plants, has been affected greatly by the increasing public attention being paid to the environment. There are mass emissions of solid particles and gases into the atmosphere, the discharge of contaminated waters, chemicals, ash and slag, as well as the heat and materials from the processes. In China, about 90% electricity is produced using fossil fuels, and of coal are the dominant contributors [1]. The environmental impact of electricity from these fuels is highly significant. FGD is the most commonly used processes in large-capacity power plant to reduce atmospheric pollution from combustion fumes, but the process involve the generation of great amounts of variable composition by-product (hydrated sulfates and sulfites) with solid or sludge appearance. The final consequence of the use of the processes is the transformation of the physical state of the waste from gaseous to solid or sludge [2].

In China, a series of strict emission standards for coal combustion have been established. With the requirement of stringent environmental requirements, large amounts of FGD engineering have been constructed in fossil fuel power plant for the recent decades. Some problems are observed in the course of large-scale construction, operation and management of FGD system. To evaluate the ecological and economical efficacy of the FGD system, in terms of its contribution to protecting the environment, the LCA model estimates the environmental impact of the power plant over its entire life cycle, and the LCC model estimates the costs of the FGD system in terms of installation, operating and maintenance, and ongoing miscellaneous costs, at all stages in the operational life of the system [3,4]. The objective of this study is to evaluate the LCA and LCC of the FGD system in terms of its impact on the environment. The private sector decision making situations which LCA addresses must also eventually take the economic consequences of alternative products or product designs into account. However, neither the internal nor external economic aspects of the decisions are within the scope of developed LCA methodology, nor are they properly addressed by existing LCA tools. This traditional separation of life cycle environmental assessment from economic analysis has limited the influence and relevance of LCA for decision-making, and left uncharacterized the important relationships and trade-offs between the economic and lifecycle environmental performance of alternative product design decision scenarios [5,6]. Still standard methods of LCA can and have been tightly, logically, and practically integrated with standard methods for cost accounting, life cycle cost analysis, and scenario-based economic risk modeling [7]. The result is an ability to

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take both economic and environmental performance into account in product/process design decision making [8].

In this study, the differences between LCA and LCC analysis are discussed, and the approach for linking LCA and LCC are also presented. Life Cycle Assessment - Numerical eco-load total standardization (LCA- NETS) system was used to evaluate the environmental impact by identifying and quantifying the energy and materials used and the waste released into the environment, and also to identify and determine opportunities for the adoption of environmental improvement methods [9,10,11].

II. BACKGROUND

Fengcheng thermal power plant has been in operation since 1996 and consists of six units with power of 2520 MW, which consists of 4×300MW and 2×660MW. Each unit of 2×660MW is equipped with one set of wet flue gas desulfurization installation. These FGD installations have been installed with the construction of the generating units simultaneously. In 2006, over 5×10^6 tons soft coal has been burned in the power plant to generate electricity. At the same time, about 1.5×10^6 tons of ash (slag), 6×10^4 tons of FGD gypsum and 2×10^6 m^3 of used water are produce during the process [12]. These substances may cause serious environmental problem if without sound disposition and management.

A. Flue Gas Desulphurization (FGD) System

The sulphur content of soft coal for the units of 2×660MW in the power station is around 2.0%. SO_2 emission from the plant spreads to villages in the surrounding areas and is considered to have contributed to the increase in health complaints, most commonly respiratory, especially in winter. The operation of the FGD system at power generation units has now reduced SO_2 emission to what is considered to be a satisfactory level. Studies on the flue gas desulfurization (FGD) process for the gas emitted from power plants have attracted considerable attention since the sulfur compound in the gas has been known to bring about serious environmental problems [13]. Many FGD facilities for eliminating SO_2 are currently operating and some of them are under construction now in China. In most of these power plants, limestone is used as an absorbent; a forced oxidation method is also applied to produce gypsum as a byproduct. The chemical reactions--absorption, oxidation, neutralization, and crystallization--occurring in the FGD facilities are shown in Scheme 1.

Absorption $SO_2 + H_2O \rightarrow H_2SO_3$

Oxidation $H_2SO_3 + \frac{1}{2}O_2 \rightarrow H_2SO_4$

Neutralization $H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + CO_2 + H_2O$

Crystallization $CaSO_4 + 2H_2O \rightarrow CaSO_4 \bullet 2H_2O$

Scheme 1: Chemical reactions of the FGD process

Gypsum is a by-product of the wet FGD systems. In the counter-flow of flue gases and the atomized suspension of calcium carbonate, the sulphur dioxide bonds to the calcium sulphite which is collected. In absorption and aeration tanks it reacts with oxygen from the air and the result is calcium sulphate. The FGD system is located after the electrostatic precipitator. Although the gypsum obtained in the desulfurization process has been reclaimed as raw material in the commercial gypsum industry in China, but the application often demand additional processes and high quality control. In 2006, only 40% gypsum was used in commercial gypsum industry as raw material, while most of the by-product in the FGD process has not been reused, the residual FGD gypsum grout mixed with coal ash/slag is transported to ash field by pipeline. The compositions of FGD gypsum are practically indicated in Table Ⅰ. The gypsum samples are collected and examined monthly in 2006.

TABLE Ⅰ
COMPOSITIONS OF FGD GYPSUM

Component	Max value	Min value
$CaSO_4 \cdot 2H_2O$ (%)	95.68	75.35
$CaSO_3 \cdot 1/2H_2O$ (%)	1.53	0.06
Cl^- (mg/L)	2876.9	345.3
$CaCO_3$ (%)	65.81	2.65
Solid content (g/L)	690.6	211.3

B. Disposition and stabilization of solid waste

During the process of coal combustion in power plants most of the organic coal components are oxidized, while the inorganic components mostly remain in the coal ash. A large number of elements present in coal are found in combustion by-products, regardless of whether these elements were associated with the mineral and/or the organic coal fraction. The ways in which trace elements appear in coal ash is influenced by different factors, most important of which are coal characteristics and combustion conditions [14]. Various methods have been applied to determine the origin of trace elements in coal. Coal combustion often causes changes in solubility of different elements, so the portions of trace and major elements may become mobilized when coal ash is introduced into terrestrial, aquatic and/or atmospheric environments [15,16]. The dry ash is one kind of coal combustion by-product removed with electrostatic precipitators and the slag collected in the boiler. The compositions and characteristic of coal fly ash are practically indicated in Table Ⅱ, it is fit for cement industry.

Most of the fly ash generated in the power station is reused as architectural material, and the rest are transport to ash field as FGD gypsum stabilization additive. The bottom ash/slag mixed with fly ash and gypsum slurry is transported to landfill filed. The compositions and characteristic of slag are practically indicated in Table Ⅲ.

In order to reduce the environmental influence of coal combustion by-product, an integrated system for solid-residue disposal and contaminated waters is employed in Fengcheng power plant. The integrated system is based on the following principles. As much as possible of the waste should be reused. The deposition of waste should be ecologically harmless and environmentally acceptable, as little as possible of the waste water be discharged.

TABLE Ⅱ
COMPOSITION AND CHARACTERISTIC OF COAL FLY ASH

	Determination		Value
1	Size distribution (wt. %)	0.315–0.2 mm	2.7
		<0.2 mm	97.3
2	Bulk density (kg· m^{-3})		540
3	Content of combustible part (wt. %)		10.1
4	Moisture content (wt. %)		0.47
5	Content of metals oxide (wt. %)	SiO_2	47
		Al_2O_3	24
		Fe_2O_3	14
		CaO	2.5
		MgO	3
6	Content of heavy metals (mg· kg−1)	Lead	137
		Cadmium	5
		Chromium	82
		Copper	66
		Nickel	78
		Zinc	133
		Manganese	939

TABLE Ⅲ
THE COMPOSITIONS AND CHARACTERISTIC OF SLAG

The unit in the table is weigh percent (%)

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O
47.25	21.89	21.75	5.7	1.03	1.34
MnO_2	P_2O_5	SO_3	Moisture	Combustible Part	
0.05	0.53	0.21	21.5	1.25	

The process of disposition of solid waste is described in the figure 1. In the power plant, most of the fly ash is reused in cement industry; some of the FGD gypsum is used as commercial gypsum after additional processes. The residual FGD gypsum grout, fly ash and bottom slag are mixed with waste water in the mixed pond in the plant site. The mixture of these by-products is transported to ash field by pipeline. During the mix, transportation and deposition, a series of physical and chemical reactions happened, such as the reactions of the FGD gypsum slurry with the fly/bottom ash. As a result of these reactions, the fresh, dispersed by-product in the dam binds into a more solid, undispersed structure after some time. Pure gypsum has no binding properties and as such needs to be stabilized by adding ash. The presence of gypsum in the ash enables better thickening. The environmental influence from the by-produce is reduced by the function of stabilization to these poisonous materials and heavy metal ions. The fresh, dispersed ash in the dam binds into a more solid, undispersed structure; the mixture is called the stabilizer. Pure gypsum has no binding properties and as such needs to be stabilized by adding ash. The presence of gypsum in the ash enables better thickening. Table Ⅳ presents the mechanical properties of the ash, the gypsum sludge and the stabilized mixture, which are important for the deposition of materials in the ash field. The results in Table Ⅳ show that the stabilized mixture has up to 15% more density and compression strength than the pure ash. Since the impermeability of the layer of the hardened, strengthened stabilizer is a desired property, so some of the mixture is used for the construction of the ash dam, the mixed disposition of solid waste from the power plant is useful to prevent the penetration of contaminated water from ash field to the surrounding environment.

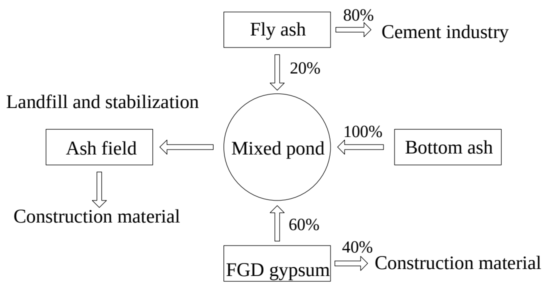

FIG.1. Disposition of Solid Waste

TABLE Ⅳ
SOME PROPERTIES OF ASH, GYPSUM SLUDGE, AND STABILIZED MIXTURE

	Ash	Gypsum sludge	Stabilized mixture
Humidity (%)	Dry	40	16-22
Optimal humidity (%)	17-51	18-21	12-16
Compression strength after 30 days (MPa)	≥1	Not solid	≥2
Max density (Kg/m^3)	900-1300	1400-1460	1430-1620
Permeability to water (cm/s)	10^{-6}-10^{-7}	10^{-5}	10^{-6}-10^{-7}

C. Disposition and reuse of waste water

In the thermal power plant, the waste waters mainly result from the demineralization (DM) plant and partially from the continuous blow down from steam boilers, from the liquid ash removal/slag removal, FGD waste water, the boiler chemical cleaning, and the gravitational separators of oil [17]. Water supplied to the boiler is to be demineralized to prevent the boiler from scaling. The DM plant involves pressurized filtration (using pumps) and removal of ions through a series of cation and anion exchanger beds. During the process of demineralization of water, plenty of hydrochloric acid and sodium hydroxide are used to keep these exchanger beds working. The waste water generated in the process includes high salinity and demands some form of treatment prior to drainage. It is a kind of waste of water resource and not economic for power plant, if the water is discharged. In the plant, the waste water is collected to remove the fly ash and slag. The quality of waste water from the FGD system is very poor; it is discharged into the mixed pond and transported to ash field by pipeline. A closed cycling system of waste water between mixed pond and ash field has been constructed to pump the solid waste slurry from the power plant to the ash dump. The advantage of the system is the repeated use of technological water for the ash pumping. The water and elutes are collected on the deposit of ash and pumped back to the system.

The process of the waste water disposition in Fengcheng power plant is described in figure 2. Most of industry contaminated water is collected in two waste water ponds, the water in the ponds after been defecated are used to remove the fly ash and slag. Then the solid waste slurry flow into the mixed pond, where the fly/bottom ash, FGD slurry mixed with cycling water from ash field and fresh water for complementarities are transported to ash field by pump. In the ash field, about 30% of the quantity of the contaminated water is vaporized, 60% of the water is recycled, and about 10% of the water is discharged after decontaminated in a waste water treatment plant.

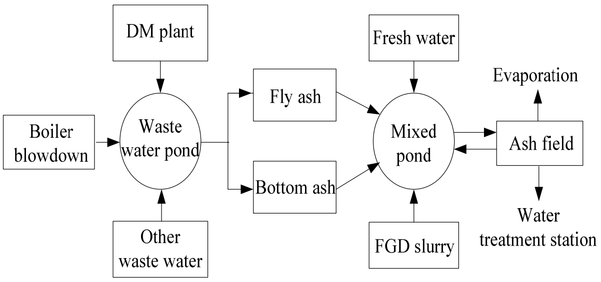

FIG. 2. Disposition and Reuse of Waste Water

III. METHODOLOGY

A. Differences between LCA and LCC Analysis

LCA is a useful and effective tool to address the environmental performances and potential impacts of a product throughout its life cycle from raw material acquisition through production, use and disposal. At the same time, a well-defined process life cycle model retains the power to relate potential environmental liability directly to specific unit operation in the industry which is being assessed. The private sector decision making contexts addressed by LCA must also eventually take the economic consequences of alternative products or product designs into account. However, neither the internal nor external economic aspects of the decisions are within the scope of developed LCA methodology, nor are they properly addressed by traditional LCA tools. Neither has the ISO 14040 series of standards for LCA methodology addressed the integration of economic analysis with LCA [18, 19].

TABLE V
THE DIFFERENCES OF BETWEEN LCA AND LCC ANALYSIS IN PURPOSE AND APPROACH

Method	LCC Analysis	LCA
Purpose	Determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision maker such as a manufacturing firm or a consumer	Compare relative environmental performance of alternative product systems for meeting the same end-use function, from a broad, societal perspective
Flows considered	Cost and benefit monetary flows directly impacting decision maker	Pollutants, resources, and inter-process flows of materials and energy
Activities which are considered part of the "Life Cycle"	Activities causing direct costs or benefits to the decision maker during the economic life of the investment, as a result of the investment	All processes causally connected to the physical life cycle of the product; including the entire pre-usage supply chain; use and the processes supplying use; end-of-life and the processes supplying and-of-life steps
Units for tracking flows	Monetary units	Primarily mass and energy; occasionally volume, other physical units
Time treatment and scope	Timing is critical. Present valuing of costs and benefits. Specific time horizon scope is adopted, and any costs or benefits occurring outside that scope are ignored.	The timing of processes and their release or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impacts, but future impacts are generally not discounted

Despite the similarity of their names, Life Cycle Cost analysis (LCC) and LCA have major methodological differences as summarized in Table 1. These differences stem from the fact that LCC and LCA are each designed to provide answers to very different questions. Life Cycle Assessment evaluates the relative environmental performance of alternative product systems for providing the same function. This environmental performance is assessed as holistically as possible, aiming to consider all important causally-connected processes, all important resource and consumption flows, regardless of whether or not they eventually impact anyone. Life Cycle Cost compares the cost-effectiveness of alternative investments or business decisions from the perspective of an economic decision maker such as a manufacturing firm or a consumer. These differences in their purpose have properly resulted in differences in their scope and method. How LCA and LCC differ in purpose and approach is presented in Table Ⅴ.

The main consequences of leaving LCC out of LCA are: Limited influence and relevance of LCA for decision making; Inability to capture relationships among environmental and cost consequences, which also inhibits the search for the most cost-effective means to environmental improvements; Potential to miss economically important or in some cases even economically pivotal environment-related consequences to the company of alternative decisions.

B. Integrating Life Cycle Cost Analysis and LCA

This section outlines an approach to fully integrating LCA with LCC. First it should be stressed that both approaches represent integrations of full LCA with full LCC. In the past proposals have been made which link either full LCA with partial LCC, or vice versa. The first class of partial solutions simply added cost flows into the traditional LCA framework, treating cost flows just like physical flows ［7］. This approach does not augment LCA with capabilities which are useful in an LCC sense, since it treats costs in ways which conflict with the key aspects of LCC listed in Table Ⅴ.

A first combined solution, called “PT Laser”, begins with a capability for process modeling which satisfies and then goes beyond the required LCA attributes listed in Table 5. Non-traditional LCA process modeling capabilities present in PT Laser include the ability to define non-linear relationships anywhere in the system, to include non-flow-based causal influences among processes, to introduce scenarios and conduct multivariate sensitivity analysis, and to define any parameter in the system as uncertain [20].

To this suite of capabilities it adds the required LCC capabilities listed in Table 5. First, the dimension of time is present, which also enables dynamic LCA, time-varying input/output coefficients or emissions coefficients. Also provided the ability to assign to any physical flow an unlimited number of different fixed and/or variable cost functions. Third, users can define investment costs and their timing for each alternative, and then employ flexible depreciation and tax accounting, as well as discounting (present valuing) of all costs and benefits. The analysis satisfies the activity- scope requirements of LCC within an LCA-scoped model by allowing users to add only the costs borne by the decision-making firm.

PT Laser is also designed to provide robust treatment of two additional aspects which are central to many LCC models of environmental investments: uncertainty and risk. Economic as well as physical parameters in the models can be defined as uncertain, even dynamically uncertain. The influence of all input uncertainties upon each alternative's results is then taken into account using Monte Carlo simulation, and uncertainties' influence can be compared as well. A scenario-building capability allows inclusion of occurrences which may take place with specified probability (allowed to be dynamic), and whose cost consequences can also be specified as dynamic and uncertain. Based on the models user inputs, the program calculates life cycle inventories for the modeled system alternatives (LCA results) and provides financial evaluations of all alternatives (LCC results), present valuing costs and benefits.

C. System descriptions

The LCA of the study was carried out according to the framework and procedures of ISO 14040 and ISO 14041. Figure 3 is a process tree of the system. Systems consist of mining, processing, and transport of coal, and electricity generation and transmission. Data for each unit process were collected for the input/output parameters determined by the cut-of criteria in the scope definition. Fig.3 shows the evolution of the power plant from the opening of the mine to the construction of the power plant and the installation of the FGD system. Inputs are the materials and energy consumed at each stage. Outputs are the electricity produced and the impact on the environment.

Inventory data was obtained from both confidential and public sources [21]. There are two major areas for data collection; upstream processes and power generation processes. Required data on environmental loads occurring in the upstream processes include data from the extraction of raw materials, transport, and processing to usable fuels. This is because resource consumption as well as environmental emissions occurs in these upstream processes. Public database or literature information such as report of the environmental loads of extraction of raw energy materials was used to obtain data for extraction. The original input/output data of this study, including material use, energy consumption, product and waste emissions, were collected from the tables of mass and energy balance, the annual report of environmental monitoring and the informative tables of waste emissions and treatment of corresponding enterprises. All these data are true and believable. Other necessary data were gathered and calculated according to the daily statistics of the actual production [22].

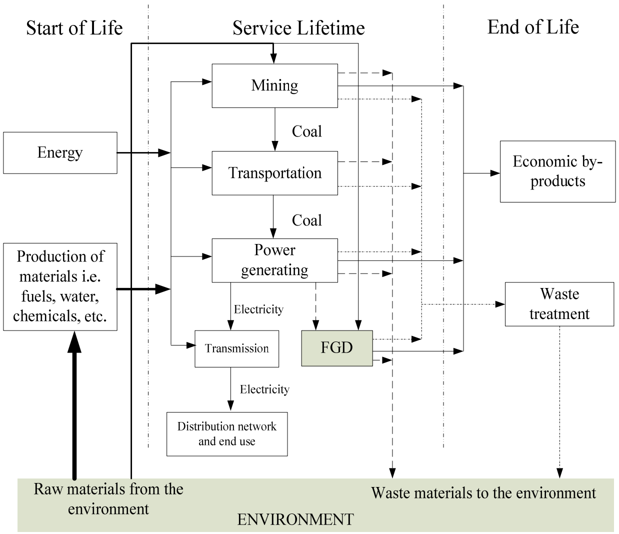

FIG. 3. System boundaries for the LCA case study

D. LCA evaluation model

In order to compare the environmental advantages and disadvantages of the FGD system installed at power plants, LCA-NETS calculation models were developed as decision-making tools when selecting pollution control equipment for a power plant [23].

$$\sum EcL_{pp\cdot without\cdot FGD} = \frac{EcL_{pp}^{in} + 30 years \times EcL_{pp}^{op}}{\sum E_g}$$

$$\sum EcL_{FGD} = \frac{EcL_{FGD}^{in} + 30 years \times EcL_{FGD}^{op}}{\sum E_g}$$

$$\sum EcL_{pp\cdot with\cdot FGD} = \frac{EcL_{pp}^{in} + EcL_{FGD}^{in} + 30 years \times (EcL_{pp}^{op} + EcL_{FGD}^{op} - E_{reduction})}{\sum E_g}$$

In these formulas:

$EcL_{pp\cdot without\cdot FGD}$ — Eco-load of the power plant without FGD installation (NETS/kWh)

$EcL_{pp\cdot with\cdot FGD}$ — Eco-load of the power plant with FGD installation (NETS/kWh)

EcL_{FGD} — Eco-load of the FGD installation (NETS/kWh)

EcL_{pp}^{in} — Initial eco-load of the power plant

EcL_{FGD}^{in} — Initial eco-load of the FGD system

EcL_{pp}^{op} — Operating eco-load of the power plant

EcL_{FGD}^{op} — Operating eco-load of the FGD system

$E_{reduction}$ — The reduction of Eco-load after the FGD system installed

$\sum E_g$ — Total electricity generation in life cycle

The subscript 'in' indicated the state of power generation plant and the FGD system at the construction stage. The subscript 'op' is meant operation and maintenance of power generation plant and the FGD system at the operation stage. These formulas are used to calculate the life cycle environmental impact of the power plant before and after the installation of the FGD system. The initial stage is included the mining and construction stages and to operation stage is also included the maintenance stage.

E. LCC evaluation model

LCC was used to calculate the total cost of the FGD system during its entire life cycle — from the mining of limestone, its transportation, operation of the system, to disposal of waste, per unit of electricity generated. The following equation is the life cycle costing model for determining the total life cycle cost of the FGD system where all costs or benefits were expressed as net present values at the base point [24, 25].

$$LCC_{FGD} = \frac{\sum_{i=1}^{n} NPV_i^{FGD}}{\sum E_{SO_2}}$$

$$NPV_i^{FGD} = \sum_{m=1}^{30} \frac{TC_m}{(1+\alpha)^m}$$

In the formulas:

LCC_{FGD} —— The average LCC for all the FGD installation per unit SO_2 emission

NPV_i^{FGD} — Net present value of FGD at unit 'i'

E_{SO_2} — The amount of SO_2 equivalent emission

TC_m — Total cost at year 'm' (i.e. Investment cost, annual cost, savage cost and other costs)

n — The amount of FGD units in the power plant

m — Life span of the FGD system is 30 years

α — Interest rate %

TABLE Ⅵ
ECONOMICAL DESCRIPTION OF THE FGD SYSTEM AT THE POWER PLANT

Item	Value
Power capacity	2×660MW; 4×300MW
Unit of FGD	2 (Each unit of 2×660MW with one set)
Unit lifetime	30 years
Investment cost of FGD (2 units)	50×10^6 [$ US]
Maintenance cost	400×10^3 [$ US/year]
Operating cost	2×10^6 [$ US/year]
Others cost	700×10^3 [$ US/year]
Interest rate	4.5%

Table Ⅵ shows the economic information for the FGD system installed at the Fengcheng thermal power plant. The life span of the FGD system is assumed as 30 years, equal to life span of the power plant generating units. The LCC cash flow started at year with the investment cost at each unit. The total investment cost of two FGD units equal 50×10^6 dollars [$ US], while there were the annual costs, for instance, maintenance cost, operating cost, limestone cost and other costs. According to the economical data, the total cost in life cycle was calculated into net present value. The net present value was able to indicate the cost and benefit of the FGD system from the economical point of view.

Ⅳ. METHODOLOGY RESULTS AND DISCUSSION

In order to analyze and estimate the total environmental impact of the lignite-fired power plant before and after the installation of the FGD system, the LCA-NETS system evaluated the five main categories of environmental impact.

A. Eco-load of the power plant before installation of the FGD system

The LCA for total environmental impact is analyzed in Table Ⅶ, which shows that most environmental damage occurs at the direct fuel consumption stage in the process. The direct fuel consumption stage is when the power plant is consuming fossil fuel (soft-coal) for electricity generation. Power plants consume fossil fuel during their entire life span, assumed to be 30 years. Because fossil fuel is a non-renewable energy resource, the potential damage to the environment is serious.

TABLE Ⅶ
ECO-LOAD OF POWER PLANT BEFORE INSTALLATION OF THE FGD SYSTEM IN EACH LCA STAGE

Eco-load of power plant		Value (NETS/kWh)
LCA stage	Fuel Consumption	2.24×10^{-2}
	Transportation	5.26×10^{-4}
	Coal Extraction	8.32×10^{-4}
	Power Plant Construction	1.33×10^{-4}

The transportation, construction and coal extraction stages have a lower level of impact on the environment. Details of the environmental impact categories are illustrated in Table Ⅷ. As shown in Table 8, the greatest damage to the environment is caused by acidification. The acidification problem occurs at the direct fuel consumption stage as a direct result of the low quality of the coal. This graph clearly shows that the installation of the FGD system can significantly reduce the impact of acidification on the environment. With the development of industrial economy, the environmental impact resulting from the depletion of fossil fuels cannot be ignored.

TABLE Ⅷ
ECO-LOAD OF POWER PLANT BEFORE INSTALLATION OF THE FGD SYSTEM IN EACH IMPACT CATEGORY

Eco-load of power plant		Value (NETS/kWh)
Environmental impact category	Acidification	2.23×10^{-2}
	Air Pollution	1.35×10^{-5}
	Global Warming	4.67×10^{-5}
	Natural Resources Depletion	8.56×10^{-5}
	Fossil Fuel Depletion	1.02×10^{-4}

B. Eco-load of the FGD system

The FGD system will reduce the impact of acidification; however, the operation process of the system itself has an impact on the environment. The LCA-NETS model of the FGD system evaluates the impact. Table Ⅸ clearly shows that the operational stage of the FGD system has a higher ongoing environmental impact than any of the other stages. The main environmental problems are the acidification, fossil fuel depletion and global warming, respectively. Although, the FGD system is able to reduce SO_2 emission from the combustion of the power plant but the FGD system consumed also the electricity for operating. Therefore, the electricity that is consumed by the FGD system contributed to the acidification problem as well.

C. Comparison of the environmental impact of the power plant before and after installation of the FGD system

After the installation of the FGD system, the SO_2 emission was reduced to a level below the regulation standard. Table 10 shows the comparison of SO_2 emission levels before and after installation of the FGD system. The greatest reduction of environmental impact, 97%, was achieved at the direct fuel consumption stage in the power plant process. The installation of the FGD system reduces greatly the power plants negative impact on the environment, in terms of sulphur emission. The comparison of eco-load values is shown in Table Ⅹ.

TABLE Ⅸ
ECO-LOAD OF THE FGD SYSTEM IN EACH LCA STAGE

Eco-load of the FGD system		Value (NETS/kWh)
Operation of the FGD installations	Acidification	2.5×10^{-5}
	Air Pollution	8.01×10^{-7}
	Global Warming	4.21×10^{-6}
	Natural Resources Depletion	1.05×10^{-5}
	Fossil Fuel Depletion	5.4×10^{-6}
Construction	Acidification	2.31×10^{-7}
	Air Pollution	1.26×10^{-7}
	Global Warming	3.61×10^{-6}
	Natural Resources Depletion	8.17×10^{-6}
	Fossil Fuel Depletion	1.06×10^{-8}
Transportation	Acidification	0.51×10^{-7}
	Air Pollution	3.98×10^{-6}
	Global Warming	5.01×10^{-7}
	Natural Resources Depletion	6.32×10^{-6}
	Fossil Fuel Depletion	2.51×10^{-8}
Extraction	Acidification	3.95×10^{-7}
	Air Pollution	2.87×10^{-7}
	Global Warming	9.51×10^{-6}
	Natural Resources Depletion	9.05×10^{-6}
	Fossil Fuel Depletion	4.26×10^{-7}

TABLE X
ECO-LOAD OF POWER PLANT BEFORE AND AFTER THE INSTALLATION OF THE FGD SYSTEM

Impact Categories	Before (NETS/kWh)	After (NETS/kWh)	Percentage of Reduction (%)
Acidification	2.23×10^{-2}	6.24×10^{-4}	97.2
Air Pollution	1.35×10^{-5}	1.42×10^{-5}	-5.19
Global Warming	4.67×10^{-5}	4.82×10^{-5}	-3.21
Natural Resources Depletion	8.56×10^{-5}	8.5×10^{-5}	0.7
Fossil Fuel Depletion	1.02×10^{-4}	1.06×10^{-4}	-3.92
Total	2.25×10^{-2}	8.77×10^{-4}	96.1

D. LCC calculation results of the FGD system

The LCC system was used to estimate the economic aspects of the FGD system. The 2×660MW units at the power plant are based-load generators, the generating rate is assumed at 65% of full capacity. The serviceable life of a power plant is assumed to be 30 years. Table Ⅺ shows the main costs of the FGD system: investment, operation and maintenance, limestone, and other miscellaneous costs. It will be seen that the highest cost associated with the FGD system is the investment cost.

TABLE Ⅺ
LIFE CYCLE COSTING OF THE FGD SYSTEM

Cost Categories of FGD	LCC ($ US/kg SO_2—equivalent)
Investment Cost	5.69×10^{-3}
Maintenance Cost	2.01×10^{-4}
Operating Cost	4.57×10^{-4}
Others Cost	1.01×10^{-4}

Ⅴ. CONCLUSION

The modeling and model analysis of Life Cycle Assessment and Life Cycle Costing for FGD system in thermal power plant have not been reported in China. The result of research in Fengcheng power plant's FGD installations provides a very good reference to the selection of desulphurization technology, to optimization of construction, operation and maintenance of FGD system. The development of LCC and LCA analysis models allows government and investor to judge the comparative values, both in ecological and economic terms, of new technology designed to reduce environmental impact. In particular, LCA-NETS is a valuable tool when assessing the environmental impact of any type of power plant, and to indicate future trends of potentially harmful environmental degradation. Reducing the environmental impact and the cost of producing power are essential for the sustainable growth of power generation facilities necessary to meet the ever increasing demand.

The results of this study demonstrate conclusively that the negative impact that power plants have on the environment can be significantly reduced by the installation of the FGD system. The benefits, both ecological and economic, to be derived from the use of the FGD system far outweigh the systems inherent negative environmental impact. Given the adverse characteristics of the soft-coal in the plant, high sulphur content and low calorific value, it is essential that all lignite-fired power plants should have the FGD system installed to ensure the continuing sustainable development of the power generation industry in China. As an incentive to electricity producers, the Polluter Pays Principle, the environmental tax system, has being introduced in China to encourage producers to rapidly improve their environmental policies. Furthermore, the development of more effective SO_2 control equipment and new technology for coal-fired power plants should be emphasized in order to minimize environmental impact and maximize the efficient consumption of non-renewable fossil fuels.

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