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Evaluation of Natural Gas Combined Cycle Plants in China through Environomic Modeling and Multi-objective Optimization

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Due to the requirements of lower capital investment, higher operational flexibility, and the pressures from environmental legislations on local pollutants and global greenhouse gases (GHGs) emissions, power generation market is in favour of natural gas based electricity production in many regions, which is expected to be tripled between now and 2030. This trend will be particularly marked in developing countries such as China, where electricity demand is expected to rise most rapidly, while their local environment has been or is being severely damaged by heavily using low efficiency high polluted pulverized coal plants. Such a fuel switching can both enhance the local environment protection, and reduce the CO_2 emissions, however, at a higher and more dynamic power generation cost.
In this paper, the Pareto Optimal solutions regarding to two objectives of levelized cost of electricity and the associated CO_2 emissions in relation to the design configurations and technical process parameters are obtained and presented for a natural gas combined cycle project in China, based on the developed 'environomic' models and a multi-objective optimizer. The obtained Pareto Optimal Frontiers tend to supply a flexible tool for handling the dynamics of important economic/market and environmental factors, so that the most proper design under a given circumstance can be easily identified through post-optimization simulation. Based upon which, the Clean Development Mechanism potentials of NGCC project in China are also discussed.

1. Introduction

In China, the use of gas will grow by more than 5% a year, where gas will win market share from coal in the power sector and in industry (IEA, 2004). Although natural gas is a much cleaner fossil fuel compared with coal, due to its higher price and significant price fluctuation in the energy market, the use of natural gas for power generation will be still limited to some of the well developed urban areas for a certain period, where very strict local pollutant standard has been or is being established. The wide and rapid market penetration of natural gas combined cycle (NGCC) plants is still facing great challenges such as the expected even higher natural gas prices, limited resources, and the undergoing energy market liberalization. Possible financial supports from

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international cooperation such as Clean Development Mechanism (CDM) may help NGCC get a better position in competing with the conventional pulverized coal plants.

To investigate the impacts of important factors associated to the highly dynamic market and environmental legislation background on NGCC plants is therefore essential for power generation technology suppliers to identify their market potential, for power generation utilities and investors to evaluate profitability of such projects, and for policy makers to adopt proper political measures to promote the clean and affordable power generation technologies to address the environmental protection issue. An implementation of a multi-criteria evaluation approach based on 'environomic' modelling of NGCC plants and multi-objective optimization techniques are presented in this paper, for addressing this requirement.

2. Superstructure based environomic modelling and multi-objective optimization evaluation approach

With the increased attention given to not only the thermodynamic performances of power generation technologies, but also to their emission and financial performances, the terminology of 'Environomic' is proposed to denote the combination of 'Thermodynamic, Economic and Emission' (Frangopoulos, 1991). The superstructure based 'environomic' modelling approach has been developed and implemented to simulate not only the thermodynamic, but also the economic and emission performances of an energy conversion system as the function of the configurations and decision thermodynamic parameters, and to deal with the increased complexity of the energy conversion system as well as to maximize the reusability of developed models. The developed environomic models for different subsystems/components can be flexibly coupled according to the superstructure of the studied power generation technology to simulate the environomic performance of the overall plant, as shown in Fig. 1.

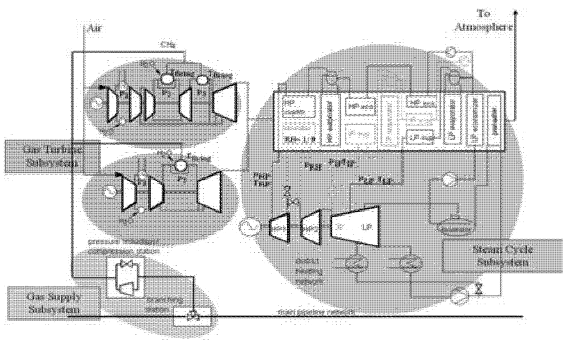

Fig. 1. Superstructure of advanced NGCC plant

Based on developed environomic models, the design evaluation of an energy conversion system, such as a NGCC plant can be performed through *single objective 'Environomic Optimization'*. 'Environomic Optimization' approach is trying to interpret the emissions from the power generation system into monetary terms through weighting factors for these criteria with respect to the decisive criterion of the project - the *total* cost of electricity with internalized emission costs (Curti 1998, Pelster 1998), before optimization starts. However, there are unavoidable difficulties for single objective optimization because the weighting factors such as the emission tax rates are highly dynamic. Pareto optimal frontiers derived from direct multi-objective optimization respect to the two objectives of the *cost of electricity* (COE, without emission cost internalization) and the *CO_2 emission rate (RCO_2)* of the analyzed power plant, will supply a more flexible tool for such an evaluation. Along the POFs, each solution corresponds to the minimum CO_2 emission rate under a given COE, or, in other words, the minimum COE under a given CO_2 emission rate level. The influence of the CO_2 tax value can then easily be evaluated through post-optimization analysis.

3. Design evaluation of a NGCC project in China

3.1 Case description

The design evaluation of a *400 MW* advanced NGCC plant under the market and environmental legislation background in China based on proposed methodology is given here. The plant's superstructure is given in Fig.1. It has three subsystems: gas turbine subsystem with either simple or advanced sequential combustion turbine, dual or triple pressure steam cycle with option of reheat, and gas supply subsystem. A bank loan associated with an 8% interest rate and a 15 years amortization period is contracted for the NGCC unit investment. The natural gas price is of 1.45 UScents/kWh (Li, 2001).

3.2 Objective functions and independent variables

The generic environomic models for this NGCC plants was originally developed by Pelester (1997) and adapted by Li (2006) in this study. A fast evolutionary based multi-objective optimizer featuring queuing and clustering techniques developed in LENI (Lyland 2003) is used to directly optimize the objective couple of COE and RCO_2. Besides CO_2 emissions from fuel combustion, the indirect CO_2 emissions due to exploration, production, preparation and the transportation of natural gas and due to gas leakage have also been taken into account. The optimization problem is therefore defined as follows:

$$Min(COE, RCO_2) = f(\vec{x}, \vec{y}) \tag{1}$$

subject to

$$\begin{cases} h_j(\vec{x},\vec{y}) = 0 & j = 1,......,J \text{ (equality constraints)} \\ g_k(\vec{x},\vec{y}) \geq 0 & k = 1,......,K \text{ (inequality constraints)} \end{cases}$$

where, $\vec{x}$ and $\vec{y}$ are sets of independent and dependent variables, respectively.

Table 1. Some of the independent variables and their boundary conditions

	Lower Bound	Higher Bound
GT Pressure Ratio (for SC or low pressure part of SQC) [-]	10.0	25.0
GT Pressure Ratio for high pressure part of SQC [-]	1.5	3.0
GT Turbine firing temperature (°C)	1000.0	1450.0
GT Excess air ratio [-]	1.5	2.5
STC Live steam pressure (bar)	50.0	150.0
Temperature difference between GT exhaust gas and STC live and reheat steam (°C)	50.0	90.0
HRSG pinch (°C)	8.0	20.0
Condenser Pressure (bar)	0.05	0.06

The independent variables include integer variables for system configuration design selection, and continuous variables such as gas turbine pressure ratio. Some of the independent variables and their boundary conditions are given in Table 1.

3.3 Analysis of Pareto Optimal Frontiers

The obtained Pareto Optimal Frontiers (POFs) are shown in Fig. 2. The values of some of the independent variables and the thermodynamic, financial and emission performances of selected solutions are given in Table 2. Two clusters of Pareto Optimal solutions are identified: 1) From solution A1 to A2, simple combustion gas turbines are selected. RCO_2 is gradually reduced along with the electrical efficiency improvement when the COE and the specific investment cost increasing, as a result of the evolution of the following decision variables: increased gas turbine pressure ratio and firing temperature, improved steam cycle live steam pressure and live/reheat steam temperature, lower condenser pressure and HRSG pinch. 2) From solution B1 to B3, advanced sequential combustion turbines are utilized, resulted in a higher electrical efficiency and lower RCO_2 compared with solutions within cluster A1-A2, at a higher COE. From B1 to B2, the electrical efficiency improvements are due to the similar reasons. When the highest commercial available gas turbine firing temperature (1427 ˚C) is reached by solution B2, further increase turbine firing temperature will be very costly and the electrical efficiency improvement will mainly reply on the increase of the steam cycle live steam pressure and live/reheat steam temperature, as seen in Table 2 (Solution B2 and Solution B3). These derived POFs allow user to choose the best solution, for example, under a given CO_2 tax rate, or to identify the CDM potential as illustrated below, through post-optimization simulations.

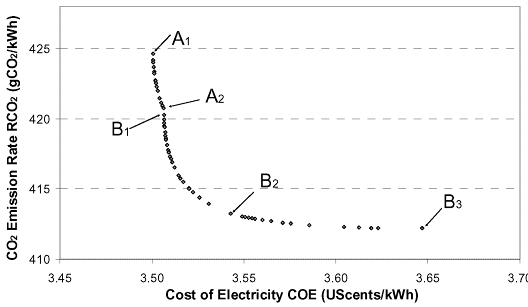

Fig. 2. Pareto Optimal Frontiers (POFs) of a 400 MW NGCC plant in China

3.4 CDM potential evaluation

Kyoto Protocol instituted the Clean Development Mechanism to grasp Greenhouse Gases reduction opportunities in developing countries: investing countries get credit for certified emission reductions (CERs) from CDM projects, provided ‘benefits’ accrue to the host country. CERs are tradable on the international market. This provides a possible opportunity to enhance the NGCC plant’s competitiveness over pulverized coal plant if investing in such a plant is eligible to be a CDM project. A concise impact analysis is given here for 10 years crediting period (with no renewal), under three possible emission baselines options: 1) *Build Margin (BM)*, which is the strictest baseline option among the three options. The emission level of the 600MW supercritical

Table 2. Values of some of the independent variables and the thermodynamic, financial and emission performances of selected solutions along the POFs

Overall Average and NGCC

	COE (UScents/ kWh)	RCO_2 (gCO_2/ kWh)	Electrical efficiency (%)	Fuel Mass Flow Rate (kg/s)	Specific investment cost (US$/kW)
A1	3.500	424.6	58.48	15.2	411.2
A2	3.506	420.8	59.02	15.03	422.6
B1	3.507	420.0	59.03	15.0	422.9
B2	3.543	413.2	59.98	14.77	453.37
B3	3.647	412.2	60.13	14.73	498.07

Gas Turbine Cycle

	Capacity (MW)	Electrical efficiency (%)	Type	Pres-sure Ratio [-]	Turbine firing tempera-ture (°C)	Exhaust gas temperature (°C)	Exhaust gas mass flow rate (kg/s)	Excess air ratio [-]
A1	267.27	39.08	SC	19.5	1389	611.7	586.95	1.65
A2	266.34	39.29	SC	20.1	1404	614.8	575.21	1.67
B1	270.0	39.84	SQC	30.3	1381.4	636.4	537.14	1.88
B2	268.09	40.20	SQC	31.9	1427.0	654.0	507.30	1.91
B3	266.16	40.01	SQC	31.1	1427.0	659.6	503.59	2.06

Steam Cycle

	Capacity (MW)	Electrical efficiency (%)	Type	Live steam pressure (bar)	Live/reheat steam temperature (°C)	Condenser Pressure (bar)	HRSG pinch (°C)
A1	132.73	31.85	3Pressure +RH	102	540.9	0.054	11.2
A2	133.66	32.49	3Pressure +RH	109	550.2	0.050	8.2
B1	130.0	31.89	3Pressure +RH	104.6	547.4	0.054	11.9
B2	131.91	33.07	3Pressure +RH	139.2	566.0	0.050	8.0
B3	133.84	33.54	3Pressure +RH	145.3	592.2	0.050	8.0

pulverized coal plants with an average electrical efficiency of 40% is chosen as the BM here, corresponding to a CO_2 emission rate of 761 gCO_2/kWh (Li, 2006). 2) Another extreme is the *Simple Operating Margin (SOM)* baseline option. It is the generation-weighted average emissions rate of all generating sources serving the system, not including low-operating cost and must-run power plants such as nuclear and large hydro. Because of the dominated position of pulverized coal plant in China and the fact that even large capacity coal plant are also sometime operating under partial load due to the load variation, the average emission rate of coal plant is taken as the SOM, with a much higher CO_2 emission rate of 968 g/kWh (Li, 2006). 3) The modest baseline option is the *Combined Margin* – the average of build margin and the operating margin, with a value of 865 g/kWh for the case of China in this study. Compared with these possible CO_2 emission baselines, and the average COE of 3.0 UScents/kWh of newly built pulverized coal plants (Li, 2006), the optimized 400MW NGCC plants along the POFs (see Fig. 1) are all eligible to be CDM project due to their higher COE and lower RCO_2, and their CO_2 abatement percentage and the abatement cost during the CDM crediting period (10 years in this case) are computed and shown in Fig. 3. However, under an expected CER market price of 5US$/ton$CO_2$, even the most 'dirty' baseline (SOM) would be chosen, the cheapest NGCC plants that has a CO_2 abatement cost of 9.21 US$/ton still needs additional financial support. Given the fact that the CER price may increase due to more and more stringent legislation on CO_2 emissions, and the high abatement potential (ranging from 44 to 57% according to different baseline options), investing in NGCC CDM project in China may be still attractive, especially when further considering the possible help from legations on local pollutant emissions.

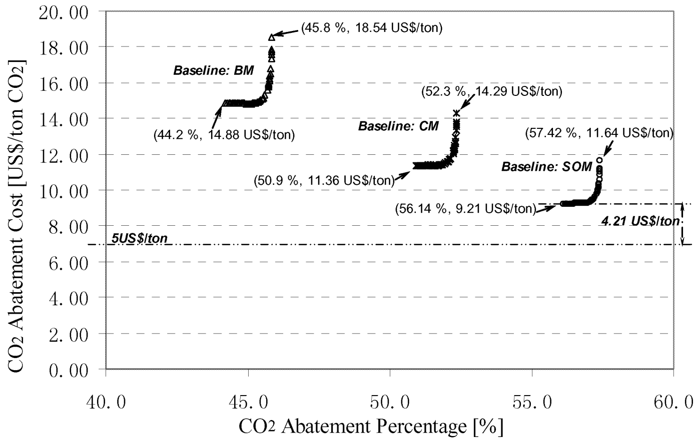

Fig. 3. CDM potential of NGCC plants under different CDM baseline options

4. Conclusions

The COE versus RCO_2 POFs of a 400 MW NGCC plant in China has been presented and analyzed. It seems that the current costs of electricity of such a NGCC plant in China is still high in contrast to that of the conventional pulverized coal plant, due to the relatively high fuel price, and a new NGCC plant to be built may be eligible to be a CDM project. The financial support from CDM may reduce its cost of electricity to a level that depends on the Certified Emission Reductions (CERs) market price.

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