Proceedings American Meteorological Society 12th Conference on Cloud Physics
10 – 14 July 2006, Madison, WI.

JP1.9

Optimal Air Pollution Control Strategies with Application to the Power Generation Sector

M. Ba-Shammakh, A. Elkamel*, P. Douglas, and E. Croiset
Department of Chemical Engineering
University of Waterloo
Waterloo, Ontario CANADA N2L 3G1
**Corresponding author e-mail*:aelkamel@cape.uwaterloo.ca

ABSTRACT

Economic and industrial developments are expected to be accompanied by an increase in the emissions of air pollutants. These pollutants often have detrimental effects, directly or indirectly, on human health and natural resources. Electricity generation is considered to be one of the main contributing sources to the air pollution problem. It is therefore important to develop and implement effective control strategies to prevent the expected abrupt increase in emissions from this sector. Any control strategy must be suitable for local implementation and must also be economically viable. The main objective of this paper is to present optimization models that can be used to determine the most cost effective strategy or combination of strategies to reduce CO2 emissions to a specific level.

Optimization results for an existing network of power plants show that it may be possible to reduce CO2 emissions by increasing power plant efficiency through a variety of adjustments in the plants. These include fuel balancing, fuel switching, and the implementation of improvement technologies to existing power plants to increase their thermal efficiency.

Introduction

Carbon dioxide (CO_2) is the main greenhouse gas and is suspected to be the principal gas responsible for global warming and climate change. Fossil fuel power generation plants are being challenged to comply with the Kyoto Protocol developed by the United Nations Framework Convention and Climate Change (UNFCCC). Canada actively participated in the UNFCCC and signed the Kyoto Protocol in 1997. In the Protocol, Canada agreed to reduce its net GHG emissions by 6 per cent from 1990 levels by the period 2008-2012. [Canada Energy Outlook, 2002]

In 2002, Canadians contributed about 731 megatonnes of CO_2 equivalent (Mt CO_2 eq) of GHGs to the atmosphere, an increase of 2.1% over the 716 Mt recorded in the year 2001. This increase contrasts with the decrease in emissions that was recorded between 2000 and 2001 (-1.2%). Emissions are now slightly above the year 2000 figure of 725 Mt, an increase of about 1%. Approximately 74% of total GHG emissions in 2002 resulted from the combustion of fossil fuels. [Canada Energy Outlook, 2002]

Ontario Power Generation (OPG) is one of the largest electricity generators in North America. OPG currently operates approximately 74 % of the available generation capacity in Ontario. About 35% of OPG electricity is produced through combustion of fossil fuels, same percentage from nuclear, 29% from hydroelectricity and the remaining 1 % comes from renewable or green energy sources, such as wind turbines. As of December 31, 2003, OPG's electricity generating portfolio had a total in-service capacity of 22,777 megawatts (MW), generated about 109.1 TWh of electricity and emitted approximately 36.5 million tones (Mt) of CO_2, mainly from coal fired power plants. [Canada Energy Outlook, 2002]

CO_2 control strategies for the electric sector may include one or more of the following options: increasing power plant efficiency, fuel balancing, fuel switching, using renewable energy (i.e. solar, wind turbines, fuel cells) and CO_2 capture and sequestration. In this paper, we will focus on three possible options to reduce CO_2 emission by a certain target while maintaining the electricity to the grid at nominal levels. The options being considered are increasing power plant efficiency, fuel balancing and fuel switching. Increasing power plant efficiency is one option to reduce CO_2 emission by implementing improvement technologies to an existing power plant to increase its thermal efficiency. Fuel balancing is the optimal adjustment of the operation of generating stations to reduce CO_2 emission without making structural changes to the fleet. On the other side, fuel switching, which is changing from coal to natural gas, involves structural changes to the fleet.

The basic problem here can be addressed as follows: "having a number of power plants that are emitting CO_2 to the environment, the target is to find the best technologies and alternatives, such as fuel switching or improving power plants efficiency, to meet electricity demand at minimum cost, while reducing CO_2 emissions to a specific target". The objective of this paper is to develop an optimization model that can be employed to find the best strategy or combination of strategies that should be implemented to reduce CO_2 emissions from power generation.

Recently, several papers have been published which addressed the cost effectiveness of CO_2 control strategies. Yamaji et al. [1993] presented a study on the effectiveness of CO_2 emission control strategies in Japan. They considered applying CO_2 tax as one control option. Wu et al. [1994] analyzed the characteristics of China's CO_2 emissions from the energy sector and proposed several options for mitigating the CO_2 emissions on a large scale, such as strengthening energy conservation, introducing energy-efficient technologies into the energy system, speeding up non-fossil fuels development, and importing oil and natural gas to substitute for coal. They evaluated the effectiveness of the different CO_2 mitigation options but they did not employ any optimization techniques. Rovere et al. [1994] summarized a cost benefit analysis based on applying alternative energy strategies, such as increasing amounts of hydropower for abatement of carbon emissions in Brazil. Elmahgary et al [1994] considered a case study on Egypt to mitigate CO_2 emissions from the energy sector. They considered several technologies including energy conservation, fuel switching and use of renewable energy to decrease CO_2 emissions. The impact of energy conservation measures on the economy of the country was found to be positive. Zhou et al. [2004] developed an expert system to assist power plant decision makers in selecting an economical and efficient pollution control system that meets new stringent emission standards. A fuzzy relation model and a Gaussian dispersion model were integrated into the expert system. Genchi et al. [2002] developed a prototype model for designing regional energy supply systems. Their model calculates a regional energy demand and then recommends a most effective combination of eleven different power supply systems to meet required CO_2 emission targets with minimum cost. The new energy system, to be installed, included co-generation systems, garbage incineration and solar energy. Linares and Romero [2000] proposed a methodology that combines several multi-criteria methods to address electricity planning problems within a realistic context. The method was applied to an electricity planning scenario in Spain with a planning horizon set for the year 2030. The model includes the following objectives: (1) total cost; (2) CO_2; (3) SO_2; and (4) NO_x emissions as well as the amount of radioactive waste produced. Mavrotas et al. [1999] developed a mixed integer multiple objective linear programming (MOLP) model and applied it to the Greek electricity generation sector for identifying the number and output of each type of power units needed to satisfy the expected electricity demand in the future. The core of their model is a branch and bound algorithm, which has been properly modified for the multi-objective case and is capable of generating the whole set of efficient solutions. Antunes et al. [2004] presented a multiple objective mixed integer linear programming model for power generation expansion planning that allows the consideration of modular expansion capacity values of supply side options. Climaco et al. [1995] developed new techniques that incorporate multiple objective linear programming and demand-side management (DSM). The techniques are able to determine the minimum expansion cost by changing the levels and forms of the electricity use by the consumers and generating alternatives from the supply side. The model also considered the emissions caused by the electricity production. Noonan et al. [1977] studied and developed an optimization program for planning investments in electricity generating systems. The optimization program determined the mix of plant types, sizes of the individual plants to be installed and the allocation of installed capacity to minimize total discounted cost while meeting the system's forecasted demand for electricity. This problem is referred to as the Generation Planning Problem (GPP). In order to comply with the variation in electricity demand, the electricity demand to be met was described by the Load Duration Curve (LDC). The mathematical model was solved using the Benders' Decomposition Method (BDM) and it was applied to New England Generation Planning Task Force**.** Yokoyama et al. [2002] formulated a mixed integer linear programming model for the structural design problem to determine an optimal structure of energy supply system to match energy demand requirement, by expressing the selection and on/off status of operation of equipment by binary variables and capacities and load allocation of equipment by continuous variables. The dependence of the performance characteristic of the equipment on their capacities as well as capital cost, were incorporated into the optimization model. The objective was to minimize annual capital cost, and is evaluated as the sum of the annual capital cost of the equipment and annual operational cost of energy purchased. Bai and Wei [96] developed a linear programming model to evaluate the effectiveness of possible CO_2 mitigation options for the electric sector. The options considered were fuel alternatives, energy conservation, reduced peak production and improved electric efficiency. The results indicated that energy conservation can significantly reduce CO_2 emissions only when combined with reduced peak production and improved electric efficiency. More recently, Haslenda et al. [2005] considered the problem of reducing CO_2 emissions from a power grid consisting of a variety of power-generating plants: coal, natural gas, nuclear, hydroelectric, and alternative energy. The problem was formulated as a mixed integer linear program (MILP) and implemented in GAMS. Two carbon dioxide mitigation options were considered in their study: fuel balancing and fuel switching. The optimization results showed that fuel balancing can contribute to the reduction of the amount of CO_2 emissions by up to 3%. Beyond 3% reductions, more stringent measures that include fuel switching and plant retrofitting have to be employed. Improving power plant efficiency was not considered in their study. Increasing power plant efficiency can represent an effective option that can lead to less CO_2 emissions. Efficiency improvements techniques in power plants can range from boiler maintenance and cleaning to improved combustion control. These are discussed in more details in the near section.

Power Plant Efficiency Improvement

Several studies have been conducted in order to increase power plant efficiency and as a consequence decrease CO_2 emissions. One of the driving forces which are currently encouraging the use of more efficient power plant is the environmental concern in many countries, and the declared goal of most governments to reduce CO_2 emissions to 1990 levels. This is a goal which leaves power generators with many unsolved problems, but increasing thermal efficiency of converting coal to power is one of the less expensive ways of reducing CO_2 emissions.

The thermal efficiency of a plant can be defined as a percentage determined by the ratio of electrical energy output to the fuel energy input. Increased plant efficiency means that less coal is burned (producing less CO_2) for the same power output [Audus, 1993]. Improved efficiency in any power plant can produce significant reductions in CO_2 emissions- typically, a 1% point gain in efficiency reduces CO_2 output by 2% [Torrens and Stenzel, 2001].

Boiler efficiency in any power plant is a function of size, capacity factor, the fuel fired, operating and ambient conditions and unit design. Existing coal boilers use subcritical or supercritical steam cycles. A supercritical steam cycle normally operates above the water critical temperature (705 ^{0}F) and critical pressure (3210 psia) where water can exist only in the gaseous phase. Subcritical systems historically have achieved thermal efficiencies of 34 to 36 %. Supercritical systems can achieve thermal efficiencies 3 to 5 % higher than subcritical systems [US department of Energy, 2001].

There are various measures that can be used to increase power plant efficiency relative to current design. Increasing the steam pressure and temperature from 25 MPa/540 ^{0}C to 30 MPa/600 ^{0}C can increase efficiency by nearly 2%. Controlling the excess air is an important function in boiler operation and reducing the excess air ratio from 25% to 15% can bring a small increase of about 1% in efficiency. Controlling the excess air is an important issue since too much air will cool the furnace and carry away useful heat and too little air will lead to incomplete combustion. Using a second reheat stage can add another 1 % and decreasing the condenser pressure from 0.0065 MPa to 0.003 MPa can further increase efficiency. Table (1) shows some actions that can be employed to improve the efficiency of coal power plants [Audus, 1993].

For the initiatives listed in Table (1), the gain in efficiency stated would appear to be optimistic. For example, low excess air operation might bring slightly more than 1 % gain in efficiency. One other efficiency improvement measure where the nominated gain would appear to be optimistic is for the improvement of the cooling tower performance by the inclusion of a film pack. A potential improvement of 1.97% has been stated. In order to achieve this improvement, a reduction in condenser pressure of 3.5 kPa would be required which in turn would necessitate an 8 ^{0}C reduction in cooling water temperature. A film pack is capable of reducing the water temperature by only some 3 ^{o}C. In order to advance the practical options for efficiency improvement, a soundly based engineering study with costing would need to be undertaken for each station [US department of energy, 2001].

Wisconsin Electric Power Company (WEPCO) in US has implemented a number of actions to improve the efficiency at five coal power plants [US department of energy, 2001]. Some of which are already included in Table (1) below. These plants are namely Oak Creek, Pleasant Prairie, Port Washingto, Presque Isle and Valley. At Oak Creek power plant, the efficiency for instance improved by 3.9%. Projects that contributed to efficiency improvements include variable pressure operation, variable speed drives on the forced and induced draft fans, reduced air in-leakage and feed water heater replacements. Additional projects to improve unit efficiency may include transformer replacement. At Pleasant Prairie power plant, the efficiency improved by 3.2%. This improvement came from variable pressure operation, unit and equipment performance monitoring, reduced air in-leakage and installation of variable speed drives. Additional projects may include operation at lower cooling water tower temperatures to improve condenser vacuum and variable speed drives on boiler fans and other large motors. At Port Washington power plant, the efficiency improved by 11 %. This improvement was the result of a major plant renovation project, which included the refurbishment or replacement of most major plant equipment. The result of the project was a restoration of the units to their original capacity and improved efficiency. At Presque Isle power plant, the efficiency improved by 4 %. Some actions that contributed to improvements include reduced air in-leakage, reduced excess boiler O_2, boiler chemical cleaning, CO_2 monitors on the boiler, improved turbine pressure and updated or additional instrumentation. At Valley power plant, the efficiency improved by 2.3% due to last row turbine blade replacement, variable speed drives for the forced and induced draft fans and reduced air in-leakage.

Several power plants in different countries have implemented improvement technologies for increasing power plant efficiency. For example, Ontario Power Generation (OPG) was involved in a project to help Jordan to improve the efficiency of its oil fuelled electricity generating units [Jordan central electricity, 2000]. In 2000, the project was completed and the total emissions savings resulting from the project estimated over a three year period was 141,983 Mg of carbon dioxide.

Among the different options, greater reduction of CO_2 from power plant flue gas is expected to be technically possible using CO_2 capture and sequestration. The goal of CO_2 capture technology is to separate the CO_2 from its sources in appropriate forms for transportation or sequestration. Some types of CO_2 capture technologies (based on both chemical and physical absorption) are well established and have been in use for several decades. The majority of chemical-based methods rely on scrubbing systems that utilize amine solutions to remove CO_2 from exhaust gases. Amine scrubbers have already been applied to different types of coal-fired industrial process and power stations. In most cases, the systems used are similar in concept and configuration and usually employ a regenerable amine, such as monoethanolamine (MEA) as the working solvent. Depending on the particular application and type of flue gas being treated, such systems can recover up to 98% of the CO_2 present and produce a CO_2 stream of up to 99% purity. Recently, however, more advanced amines have been developed, for instance by Mitsubishi Heavy Industries (MHI), and are now being applied commercially. Such new amines are claimed to suffer less degradation and to have lower consumption rates and energy requirements than conventional MEA-based solvents [International Energy Agency, 2003]

A number of commercial scale physical absorption technologies are also in use, generally applied to systems operating at higher pressures. These rely on a range of solvents that include methanol and propylene carbonate. Alternative capture technologies that may also be applicable to coal-fired power plants in the longer term include systems based on the application of specialized separation membranes and cryogenic technologies. However, the major shortcomings for the application of CO_2 capture process in fossil fuel power plants are that it is very energy intensive and necessitates high capital and operating costs [International Energy Agency, 2003].

The main objective of this paper is to present a mathematical programming model for the reduction of CO_2 emissions from a network of power plants. The various CO_2 emission reduction strategies discussed thus far will be considered in the model. These include efficiency improvement actions, the fuel balancing, and fuel switching. As mentioned before, CO_2 capture processes are energy intensive and are out of the scope of this study. The remainder of this paper is organized as follows: first, the superstructure representation of the different CO_2 reduction strategies considered in this study will be illustrated. A mathematical programming model will then be introduced. The model is a mixed integer nonlinear program (MINLP) and an exact linearization strategy will be employed. Finally, a case study based on Ontario Power Generation (OPG) will be illustrated and the results for reducing CO_2 emission to meet electricity demand will be given.

Methodological Approach

Superstructure representation

The superstructure representing a power generation energy supply system from different types of power plants is shown in Figure 1. Different types of power plants generate electricity and inject it into the grid directly. It is assumed that there is no CO_2 capture at any existing power plant. Figure 2 shows the fuel balancing which means that CO_2 emissions are decreased by increasing the load on existing non-fossil fuel power plants and decreasing the load on existing fossil fuel power plants. The target of this is to determine the optimal load from each power plant in order to maintain electricity to the grid and reduce the CO_2 emissions at the same time; since non-fossil fuel power plants emit no CO_2. Figure 3 illustrates the fuel switching which involves switching for fossil fuel power plants from coal to natural gas. Figure 4 shows the possible improved technologies that can be implemented in coal power plants to increase the thermal efficiency and hence decrease the CO_2 emissions generated from coal power plants while maintaining the same electricity to the grid.

Mathematical Model

A mathematical model will be formulated for this purpose for energy sectors. The mathematical model consists of an objective function to be minimized and equality and inequality constraints. The objective function is written as:

$$MinZ = \underbrace{\sum_{i \in F} \sum_{j} C_{ij} E_{ij}}_{\substack{\text{Cost of electricity generation} \\ \text{from fossil fuel power plant}}} + \underbrace{\sum_{i \in NF} C_i E_i}_{\substack{\text{Cost of electricity generation} \\ \text{from non-fossil fuel power plant}}} + \underbrace{\sum_{i \in F} \sum_{j} R_{ij} X_{ij}}_{\substack{\text{Retrofit cost for switching} \\ \text{from coal to natural gas}}} + \underbrace{\sum_{i} \sum_{k} C_{ik} Y_{ik}}_{\substack{\text{Cost of applying technology} \\ \text{for effeciency improvement}}} \quad ----- (1)$$

Where:

F = Fossil power stations including coal and natural gas.

NF = Non-fossil power stations including nuclear, hydroelectric and wind turbines.

i = Power plant.

j = Type of fuel (coal or natural gas).

k = Technology applied to increase power plant efficiency.

C_{ij} = Cost of electricity generation if j fuel is used on fossil power plant i ($/MWh).

C_i = Cost of electricity generation for non fossil fuel power plants i ($/MWh).

C_{ik} = Cost of applying improvement technology k in plant i ($/yr).

E_{ij} = Electricity generated from i^{th} power plant if fuel j is used (MWh/yr).

E_i = Electricity generated from i^{th} non fossil power plants (MWh/yr).

R_{ij} = Retrofit cost to switch from coal to natural gas generating stations ($/yr).

X_{ij} =Binary variable either to choose coal or natural gas.

Y_{ik} = Binary variable either to implement improvement technology k in plant i or not.

The first term in equation (1) above represents the cost associated with electricity generated from fossil power plants whereas the second term shows the cost for electricity generated from non-fossil power plants. The third represents the retrofit cost if the fuel is to be switched from coal to natural gas. There is no retrofit cost for non fossil power plants. The last term is the cost associated with applying technologies for efficiency improvements.

Constraints:

a) Power demand satisfaction:

The electricity generated from all power plants must be equal to or greater than the demand (D).

$$\sum_{i \in F} \sum_{j} E_{ij} + \sum_{i \in NF} E_i \geq D \qquad (2)$$

b) Fuel selection or plant shut down:

For each fossil fuel power plant i, the plant either operates at another fuel or is shut down. For this reason, a binary variable is introduced to represent the type of fuel used in a given fossil fuel plant. It is one if fuel j is used in plant i or zero otherwise.

$$\sum_{j} X_{ij} \leq 1 \qquad \forall i \in F \qquad (3)$$

c) Upper bound on operational changes:

The adjusted electricity generated from each power plant should be less than or equal to a certain percentage higher than current production.

$$E_{ij} \leq (1 + r_i) E_i^{current} X_{ij} \qquad \forall i \in F \qquad (4)$$

$$E_i \leq (1 + r_i) E_i^{current} \qquad \forall i \in NF \qquad (5)$$

This constraint set requires that the electricity produced from any plant i should not exceed the current electricity produced from the same plant by r_i which is the maximum increase in the base load due to operational constraints.

d) Lower bound on operational changes:

These constraints introduce a lower bound for each power plant and the plant production must be at least equal to this lower limit or otherwise the plant should be shut down.

The electricity generated from each power plant must be greater than some minimum (E_i^{min}), otherwise the plant will be shut down.

$$E_{ij} \geq E_i^{\min} X_{ij} \qquad \forall i \in F \qquad (6)$$

$$E_i \geq E_i^{\min} \qquad \forall i \in NF \qquad (7)$$

e) Emission constraints:

The CO_2 emission from electricity generation must satisfy a CO_2 reduction target. Different technologies k to increase the power plant efficiency are implemented in the mathematical model. It is assumed that the effects of these technologies is additive. If this is not the case, then different sets of technologies can be defined as a single composite technology with a proper corresponding overall efficiency.

$$\sum_{i\in F}\sum_{j} CO_{2ij}\left(1-\sum_{k}\varepsilon_{ik}Y_{ik}\right)E_{ij} \leq (1-\%CO_2)CO_2 \quad (8)$$

$$CO_{2ij} = \frac{0.03667(\%C/HHV)}{\eta_{ik}}$$

$(CO_2)_{ij}$ = CO_2 emission from coal plant i (million tones per year).

$\%CO_2$ = reduction target.

CO_2 =CO_2 emission (million tonne per year).

% C = Carbon percentage for a given fuel.

HHV = Higher heating value for the fuel (MJ/tonne).

η_{ik} = Efficiency of power plant i if technology k is implemented.

ε_{ik} = Gain in efficiency associated with applying technology k in coal power plant i.

Y_{ik} = Binary variable defined earlier.

The CO_2 emission from each power plant, if technology k is chosen, must be within certain reduction target.

f) Technology selection:

A binary variable (Y_{ik}) is introduced in the model to represent whether technology k for efficiency improvement should be implemented in power plant i or not.

$$\sum_{k} Y_{ik} + Card(K) * X_{ij\varnothing ng} \leq Card(K) \quad \forall i \in F \qquad (9)$$

Where *Card(K)* is cardinality of the set of technologies k.

This constraint imposes the fact that no improvement technology should be implemented in a plant that is to be switched from coal to natural gas.

g) Non-negativity constraints:

The electricity produced from all power plants must be greater than zero.

$$E_{ij} \geq 0 \quad and \quad E_i \geq 0 \qquad (10)$$

The previous mathematical model was developed based on the following assumptions:

1. The process units are modeled at a low level of detail and treated as black boxes to simplify the large scale problem of power plants
2. The nominal electricity generated is fixed
3. The electricity price is constant
4. All coal fired power plants use Canadian Eastern Bituminous coal with 78 % of carbon and high heating value is 6000 MJ per tonne.
5. No technology for efficiency improvement is currently being implemented.

The resulted model is a mixed integer non linear (MINLP) because of constraint set where there is a multiplication of a decision variable (E_{ij}) and a binary variable (Y_{ik}) in the CO_2 emission term. The model is linearized and proved to have the same optimum as the original one. The linearization and the proof are given in the Appendix.

Case Study:

The model was applied to the existing OPG fleet of power plants to determine the best strategy for OPG to reduce the amount of CO_2 at a minimum cost. The options being considered are fuel balancing, fuel switching and improving power plants efficiently through different strategies.

OPG operates 6 coal fuel power plants ($C_{i=1-6}$) in which one is running by natural gas, 69 hydroelectric ($H_{i=1-69}$), 3 nuclear ($N_{i=1-3}$) and one wind turbine ($A_{i=1}$). In total, OPG generates 13765 MW of electricity emitting about 36.5 Mt of CO_2 as of 2003, mainly from fossil fuel power plants. There are 27 fossil fuel boilers at the 6 fossil-fuel stations: 4 boilers at Lambton (L1-L4), 8 boilers at Nanticoke (N1-N8), 1 boiler at Atikokan (A1), 8 boilers at Lakeview(LV1-LV8), 4 boilers at Lennox (L1-L4), and 2 boilers at Thunder Bay (TB1-TB2). Currently, 4 boilers operated by Lennox are running on natural gas. Table 2 shows a general view of OPG fossil fuel generating stations. Since non fossil fuel power plants do not emit CO_2, the main focus is on electricity generated from the fossil fuel power plants. The operational costs for nuclear, hydroelectric, and wind turbine were estimated to be \$32, \$5, and \$4/MWh, respectively. The nominal conditions for OPG's existing fleet of power plants are [Hashim et al. 2005]:

Total electricity generation: 13,765 MWe

Total CO_2 emissions : 36.57×10^6 tonne/yr

Total operational cost : 2.808×10^9 \$ / yr

Figure 5 shows the existing OPG fossil fuel power plants (27 boilers) and their associated electricity generation. As was mentioned earlier, three different options to reduce CO_2 emission are considered and these are fuel balancing, fuel switching and improving efficiency for coal power plants. The technologies being considered in this study for efficiency improvement are shown in Table 3. Since non fossil fuel power plants do not emit CO_2, the main focus is on electricity generated from the fossil fuel power plants. There are 27 fossil fuel units working on coal but only four of them are working on natural gas as shown in Figure 5.

Figure 6 shows the optimization results for the case of 1% CO_2 reduction target. For this case, no fuel switching is needed. In other words, the objective can be obtained by only adjusting the operation of current boilers e.g. increasing load from existing non fossil power plants and decreasing load from some existing fossil power plants (fuel balancing). The results show that electricity generation from all four natural gas boilers has been reduced. The electricity generation from other fossil fuel boilers and non fossil fuel power plants were increased at 1% higher than the nominal operational level to maintain the electricity to the grid. No technology for efficiency improvement is applied.

In order to achieve more than 1% CO_2 reduction, it was found that fuel switching must be implemented. This involves fleet changes from coal to natural gas. The optimization results show, for instance, that in order to achieve 5% CO_2 reduction while maintaining the electricity to the grid at a minimum cost, non-fossil fuel power plants increase the electricity generation by 1% higher than the nominal operational level. Only one boiler (L2) needed to be switched to natural gas and the model showed also that technology (K5) (Table 3) should be implemented on the (A1) boiler.

Higher CO_2 reduction targets required more coal boilers to switch to natural gas. For 10% reduction (Figure 8), for example, the results show that the electricity generation should be increased from all non fossil fuel power plants. The optimizer considered to switch four boilers (L2, N2, TB1 and TB2) and apply technology (K5) for efficiency improvement on the boiler (A1).

Figure 9 shows that for 20% CO_2 reduction many boilers are chosen to operate with natural gas and only ten boilers out of 27 are still operating with coal. The electricity generated from the non fossil fuel power plants are still increased to a maximum allowable level which is 1% higher than normal production. It is suggested not to apply any technology for efficiency improvement on any boilers.

As more reduction is required, the optimizer will go for fuel switching since natural gas emits less CO_2 and technologies for efficiency improvement will no longer be sufficient. For 30 % reduction, the results show that only seven boilers should continue to operate with coal and the remaining boilers should be switched to natural gas (Figure 10).

Conclusion

The optimization of CO_2 emissions from the Ontario power grid was studied. The reduction options being considered are fuel switching, fuel balancing, and technologies for power plant efficiency improvement. The results indicate that applying several strategies for increasing the power plant efficiency is an effective way for reducing CO_2 emissions. Fuel balancing has also proved to be a promising option for reducing CO_2 emissions. Optimization results show that overall CO_2 emissions can be reduced by reducing capacity factor of large coal boilers such as the boilers at Nanticoke and increasing all power plants capacity factor by 1%. Fuel switching involving structural changes to the fleet has been considered as the best option for CO_2 reduction especially if the reduction target is 10% or above.

References:

Antunes, C., Martins, A., and Brito, I., "A Multiple Objective Mixed Integer Linear Programming Model for Power Generation Expansion Planning", Energy, Vol. 29, pp. 613-627, 2004.

Audus, H., "Greenhouse Gas Releases from Fossil Fuel Power Stations", IEA Greenhouse Gas R& D Program, UK, 1993.

Bai, H. and Wei, J., "The CO_2 Mitigation Options for the Electric Sector", Energy Policy, Vol. 24, pp. 221-118, 1996.

Canada Energy Outlook, http://www.nrcan.gc.ca/es/ener2002/online/html, 2002.

Climaco J. et al. "A Multiple Objective Linear Programming Model for Power Generation Expansion Planning", International Journal of Energy Research,Vol. 19, pp. 419-432, 1995.

Elmahgary, Y., Ibrahim, A., Shama, A., Hassan, A., Rifai, M., Selim, M., Higazi, A., Amin, A., Bedewi, F., and Korkor, H., "Costs of CO_2 Abatement in Egypt Using Both Bottom-up and Top-down Approaches", Energy Policy, Vol. 22 (11), pp. 935-946, 1994.

Genchi, Y., Saitoh, K., Arashi, N., and Inaba, A., "Assessment of CO_2 Emissions Reduction Potential by Using an Optimization Model for Regional Energy Supply Systems", Paper B5-6 presented at the Sixth International Conference on Greenhouse Gas Control Technologies, Kyoto International Conference Hall, Japan, October 1-4, 2002.

Hashim H., Douglas P.L., Elkamel A., Croiset E., Optimization Model for Energy Planning with CO_2 Emission Considerations, Industrial & Engineering Chemistry Research, Vol.44 (4), pp. 879-890, 2005.

International Energy Agency, Technical reports "Control and Minimization of Coal-fired Power Plant Emissions", France, 2003.

Jordan Central Electricity, "Efficiency Improvements in Power Plants", project 82, 2000.

Linares, P., and Romero, C., "A Multiple Criteria Decision Making Approach for Electricity Planning in Spain: Economic versus Environmental Objectives", J. Operational Research Society, Vol. 51, pp. 736-743, 2000.

Mavrotas,G., et. al., "An energy Planning Approach Based on Mixed 0-1 Multiple Objective Linear Programming. International Transactions in Operational Research. Vol. 6, pp. 231-244, 1999.

Noonan F., et al. "Planning Electric Power Generation: A Linear Mixed Integer Model Employing Benders Decomposition", Management Science, Vol. 23, pp. 946-956, 1977.

Rovere, L., Leget, L., and Miguez, J., "Alternatives Energy Strategies for Abatement of Carbon Emissions in Brazil", Energy Policy, Vol. 22 (11), pp. 914-924, 1994.

Torrens, I., and Stenzel, W., "Industry Perspectives on Increasing the efficiency of Coal Fired Power Generation", International Energy Agency, http://www.iea.org , 2001.

US Department of Energy, "Review of Potential Efficiency Improvements at Coal Fired Power Plants", http://www.energy.gov/engine/content.do, 2001.

Wisconsin Electric Power Company (WEPCO), Wisconsin, USA, personal communication, 2005.

Wu, Z., Jiankun, H., Zhang, A., Xu, Q., Zhang, S., and Jayant, S., "A Macro-assessment of Technoloy options for CO_2 Mitigation in China's Energy System", Energy Policy, Vol. 22 (11), pp. 907-913, 1994.

Yamaji, K., Matsuhashi, R., Nagata, Y., and Kaya, Y., "A Study on Economic Measures for CO_2 Reduction in Japan", Energy Policy, Vol. 21 (2), pp. 123-132, 1993.

Yokoyama, R., Hasegawa, Y. and Ito, K., "A MILP Decomposition Approach to Large Scale Optimization in Structural Design of Energy Supply Systems", Energy Conversion and Management, Vol. 43, pp. 771-790, 2002.

Zhou, Q., Huang, G., and Chan, C., "Development of an Intelligent Decision Support System for Air Pollution Control at Coal Fired Power Plants", Expert Systems with Applications, Vol. 26, pp. 335-356, 2004.

Appendix:

The emission constraint (8) is the one that causes non-linearity to the model. The nonlinear term is:

$$\sum_{i\in F}\sum_{j} CO_{2ij}\left(1-\sum_{k}\varepsilon_{ik}Y_{ik}\right)E_{ij} \qquad (1A)$$

Non-linearity is due to the product ($Y_{ik}E_{ij}$)

Let $\gamma_{ijk} = Y_{ik}E_{ij}$ (non-linear term) (2A)

The term can be linearized by adding these constraints to the model:

$$0 \le \gamma_{ijk} \le E_{ij} \qquad (3A)$$

$$E_{ij} - E_{ij}^{\max}(1-Y_{ik}) \le \gamma_{ijk} \le E_{ij}^{\max}Y_{ik} \qquad (4A)$$

Where $E_{ij}^{\max}$ is a maximum upper bound on E_{ij}.

Table 1. Some Actions for efficiency improvement.

Action	Efficiency Improvement (%)
Restore Plant to Design Conditions	
Boiler chemical cleaning	0.84
Reinstate any feedheaters out of service	0.46
Refurbish feedheaters	0.84
Reduce steam leaks	1.0
Reduce turbine gland leakage	0.84
Change to Operational Settings	
Low excess air operation	1.22
Improved combustion control	0.84
Retrofit Improvements	
Extra airheater surface in the boiler	2.1
Install new high efficiency turbine blades	0.98
Install variable speed drives	1.97
Install on-line condenser cleaning system	0.84
Install new cooling tower film back	1.97

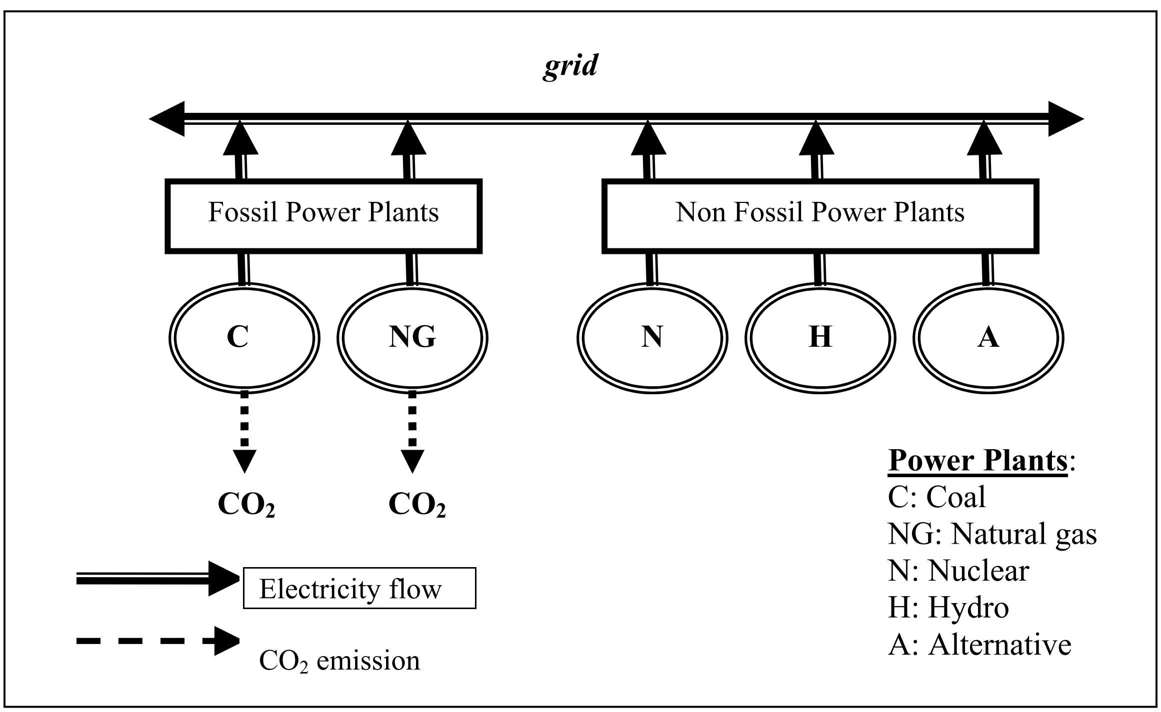

Figure 1. Superstructure for power plants.

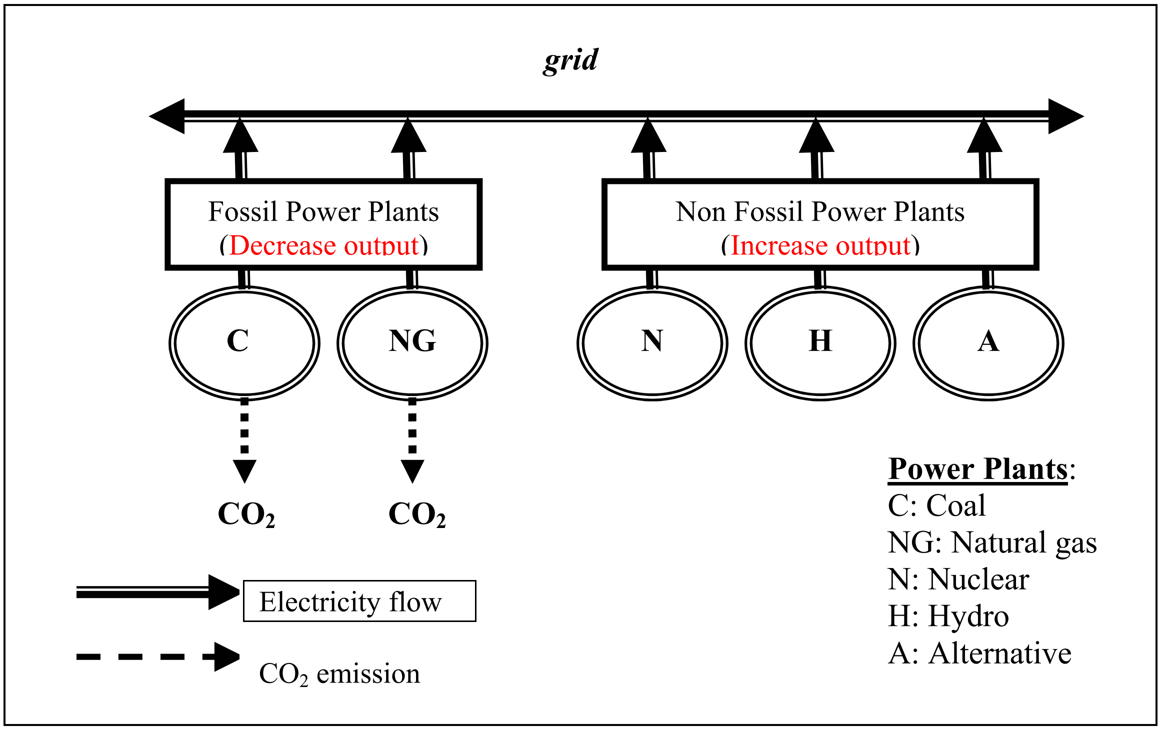

Figure 2. Superstructure for fuel balancing.

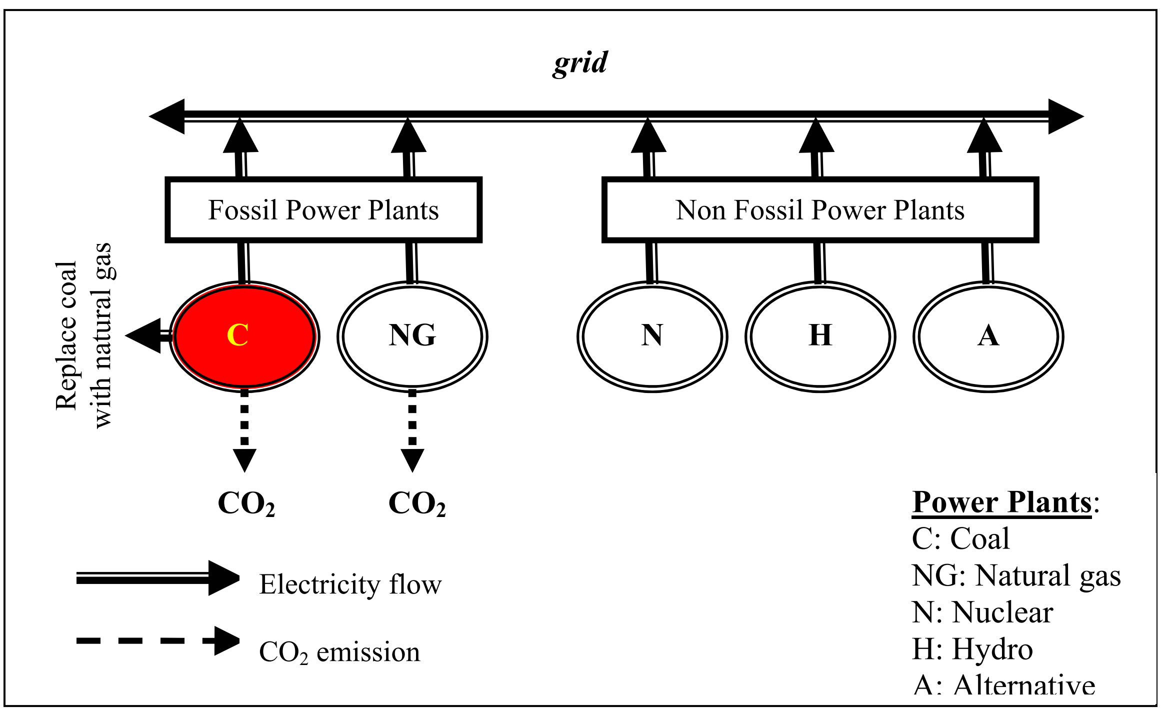

Figure 3. Superstructure for fuel switching.

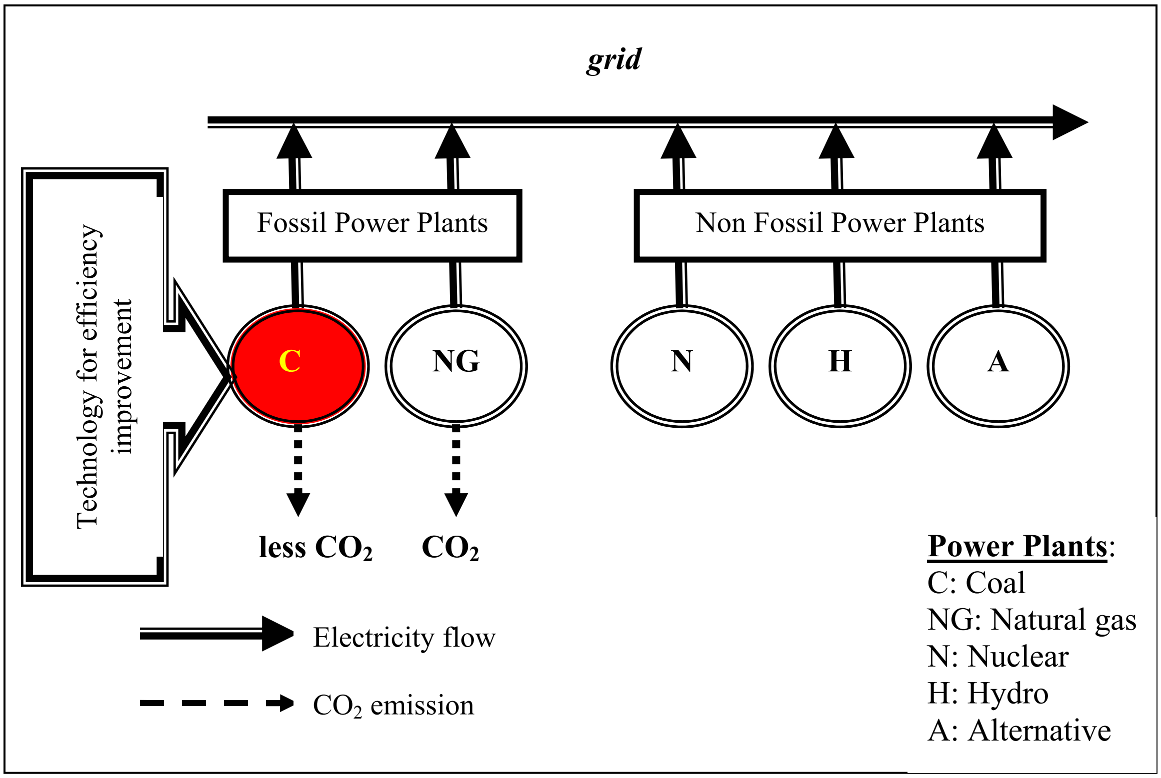

Figure 4. Superstructure for efficiency improvement.

Table 2. Ontario Power Generation fossil fuel generating stations.

Station	Fuel	Installed Capacity (MW)	Number of units	Annual capacity factor	Operational cost ($/MWh)	CO_2 emission rate (tonne/MWh)
Lambton1 (L1)	Coal	500	2	0.75	25	0.9384
Lambton2 (L2)	Coal	500	2	0.5	34	0.9386
Nanticoke 1 (N1)	Coal	500	2	0.75	30	0.9300
Nanticoke2 (N2)	Coal	500	6	0.61	30	0.9300
Atitokan (A)	Coal	215	1	0.44	30	1.0230
Lakeview (LV)	Coal	142	8	0.25	35	0.9765
Lennox (LN)	Natural gas	535	4	0.15	50-70	0.6510
Thunder Bay (TB)	Coal	155	2	0.55	30	1.0230

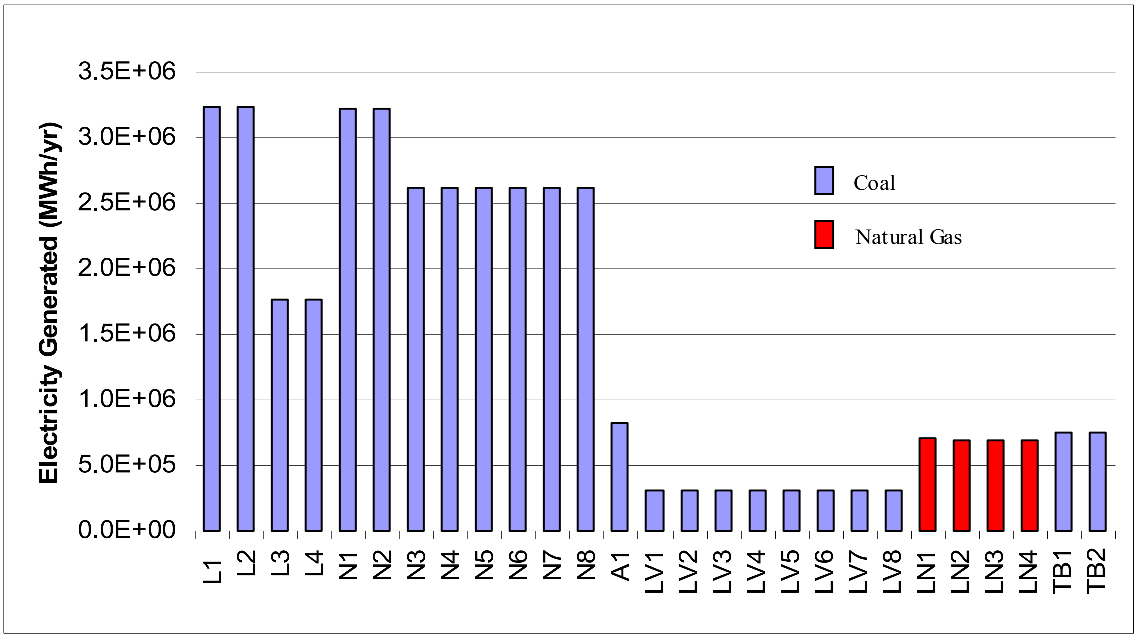

Figure 5. Electricity generated from OPG power plants (27 boilers).

Table 3. Technologies considered for efficiency improvement [29].

Technology	Action	Efficiency Improvement (% point)
K1	Chemical cleaning for boiler	0.84
K2	Install new turbine blades	0.98
K3	Low excess air operation	1.22
K4	Install variable speed drives	1.97
K5	High Temperature & Pressure	4

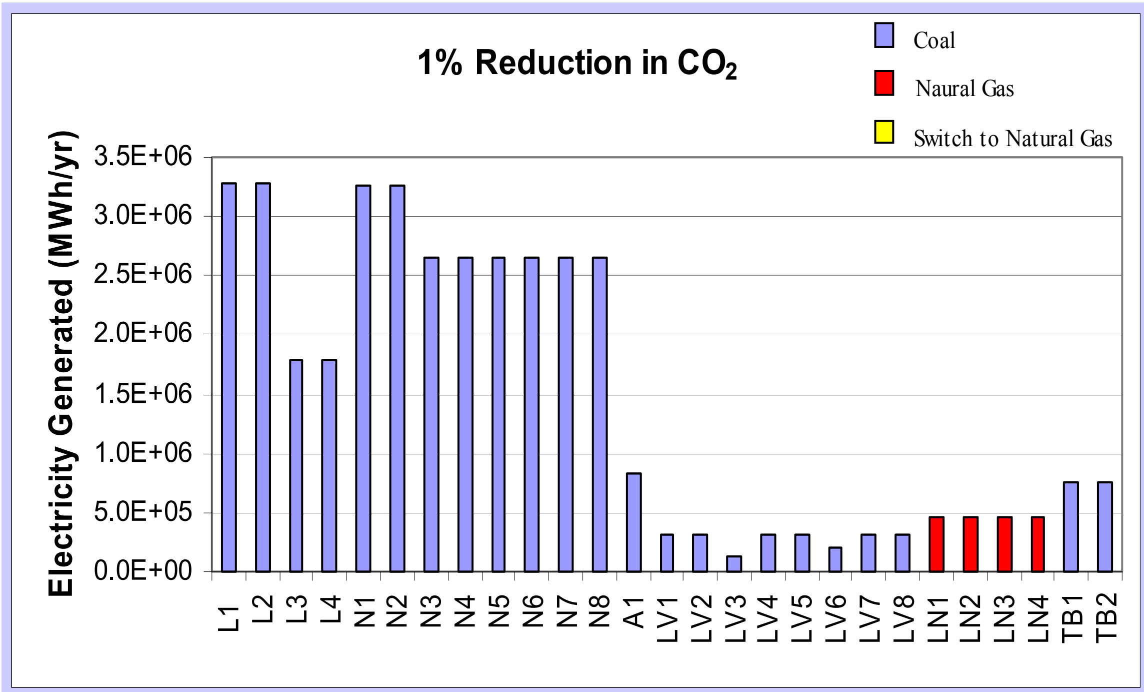

Figure 6. Electricity generation strategy for 1% CO_2 reduction.

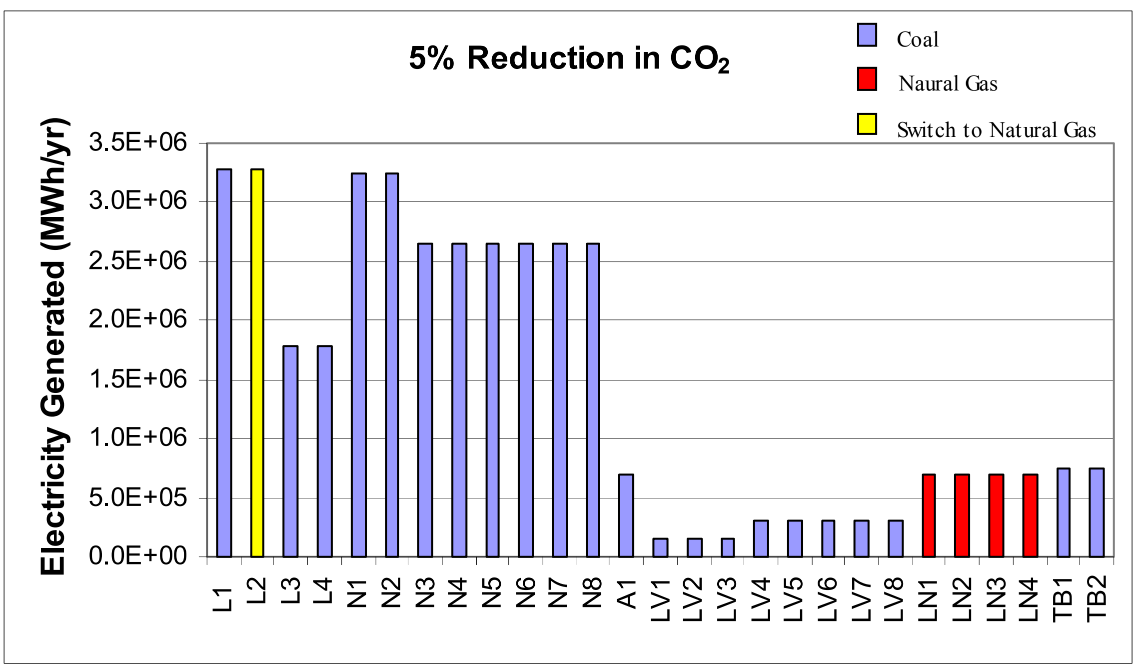

Figure 7. Electricity generation strategy for 5% CO_2 reduction.

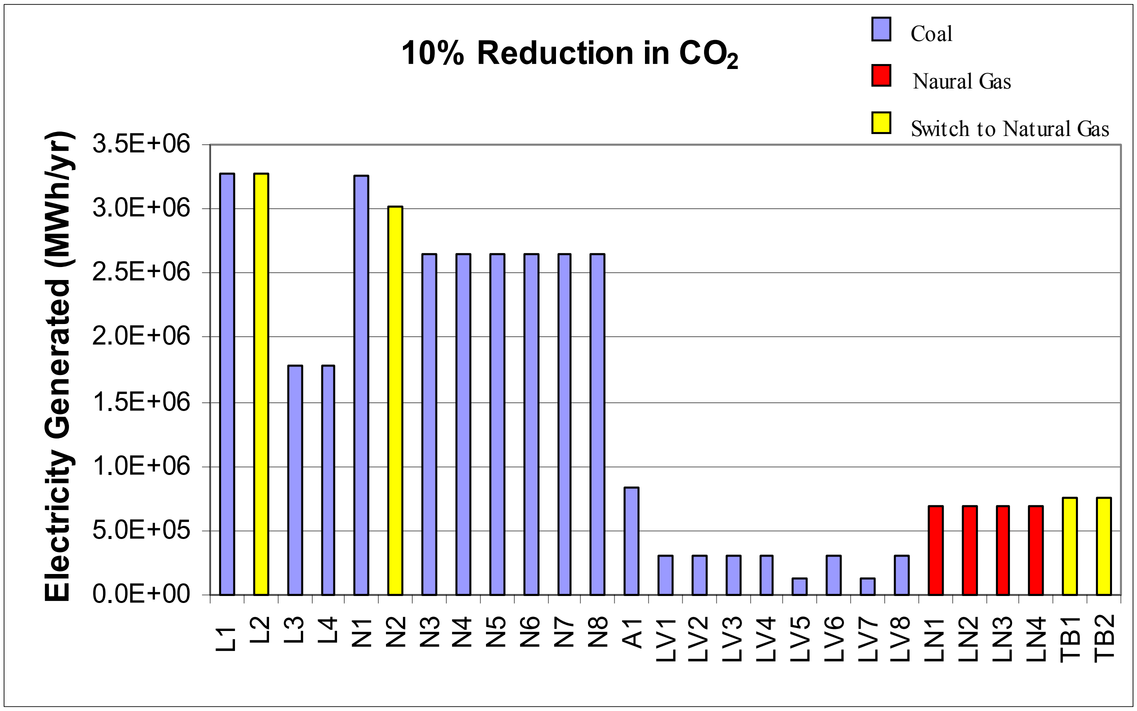

Figure 8. Electricity generation strategy for 10% CO_2 reduction.

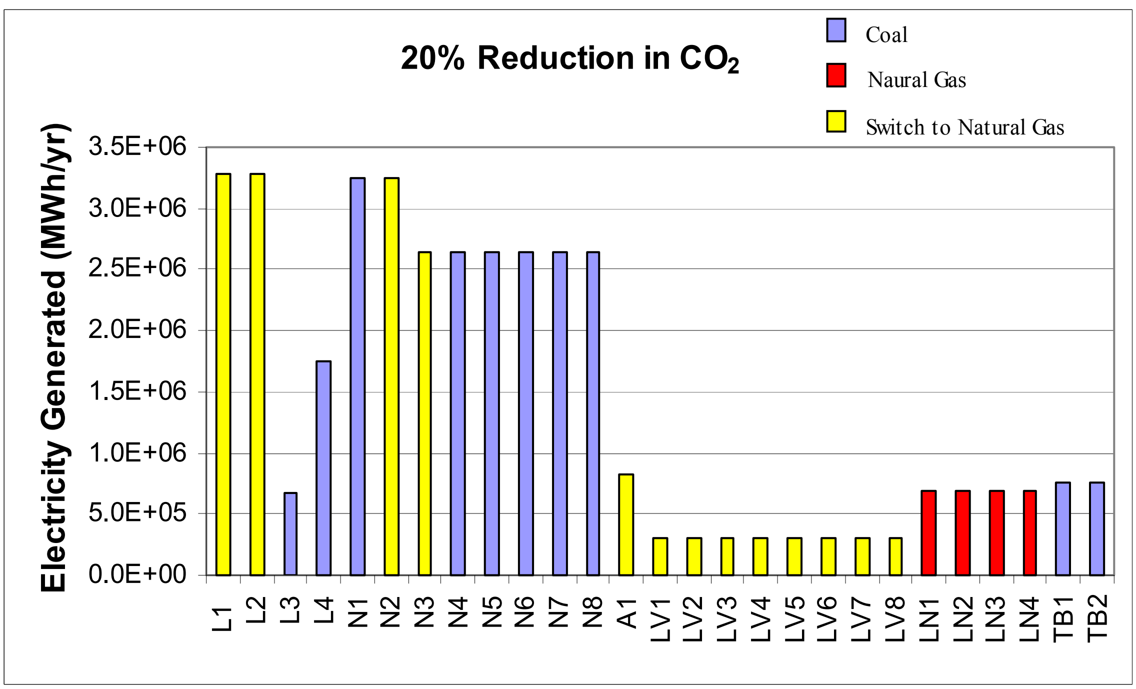

Figure 9. Electricity generation strategy for 20% CO_2 reduction.

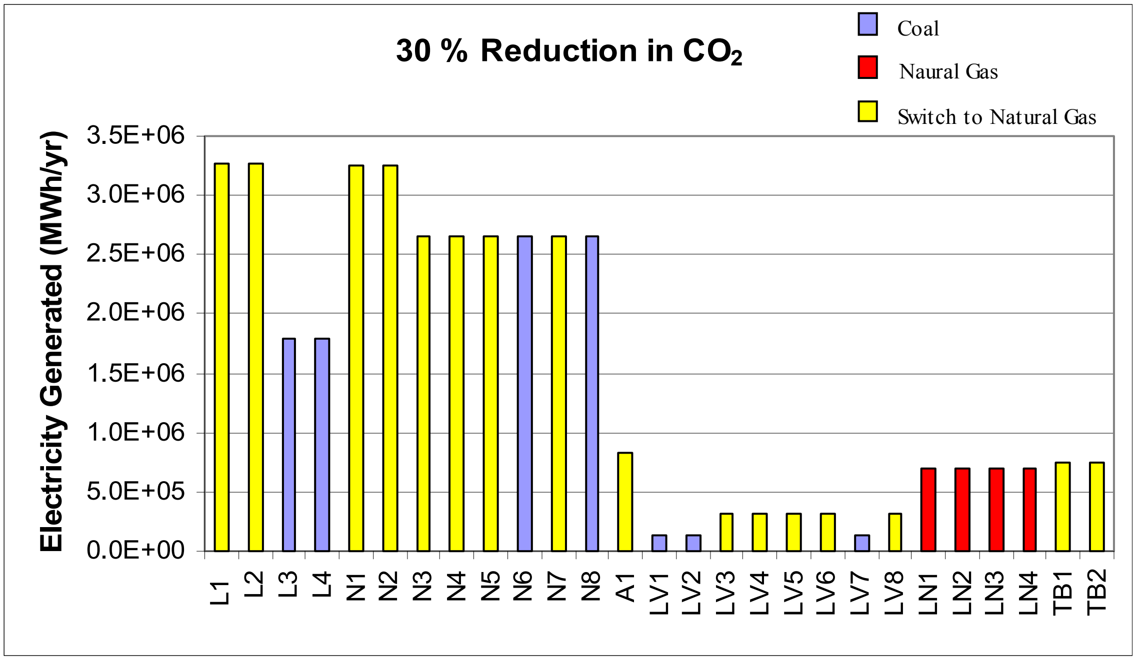

Figure 10. Electricity generation strategy for 30% CO_2 reduction.