Investigating strategies to reduce CO₂ emissions from the power sector of Taiwan

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Abstract

This paper investigates strategies to reduce CO₂ emissions from the power sector of Taiwan. A multi-objective mix integer model for power generation strategy in Taiwan is proposed. A power supply problem with integer constraints on lowest power generation to meet the practical operation of power unit is also presented. This model can be used to plan future power units’ expansion strategy, as well as to study the effect of CO₂ emission constraints. Further, this model is used to investigate optimal strategies for stabilizing CO₂ emissions to the desired level from the power sector in Taiwan; these accounted for about 40% of CO₂ emissions in the country in 2000. Real operational data from the Taiwan Power Company are used for testing the model effectiveness. In addition, recommendations are made for implementation.

Keywords: CO₂ emissions; Multi-objective programming; Power sector

1. Introduction

Global climate change is recognized as one of the most important problems in international environmental protection issues. Greenhouse effect, one of the factors of resulting global climate change, leads to increase global temperatures and to raise sea level, constitutes a threat to human life. Recently, international society has expressed its concern about the problem of the major greenhouse gas-CO₂ emissions more than ever. The effectiveness of CO₂ control methods as well as their economic impacts can also be estimated only within a large range of uncertainty. The relationship between CO₂ emissions and fuel energy consumption has been recognized as highly interrelated. CO₂ emissions from fuel energy consumed account for over 90% of all emissions in which power sector is responsible for more than one-third of the part of CO₂ emissions in Taiwan. Generally, CO₂ control strategies for the power generating sector may include one or more of the following options: a carbon tax, CO₂ emission standard, fuel alternatives, electric energy conservation, reduced peak load, improved electric efficiency and CO₂ capture technologies. Therefore, to understand how to protocol suitable strategies for power sector in future is very important to reduce CO₂ emissions in Taiwan.

In recent years, many types of energy models have been extensively applied to discuss the issue of CO₂ mitigation. These include top-down (or macroeconomic) models [1–3], bottom-up (or energy-systems) models [4], computable general equilibrium (CGE) models [5,6], decomposition analysis models [7,8] and mathematical programming models [9–12]. The purpose of this study is to construct a model of multiple objectives programming and mixed integer programming to evaluate the effect of possible CO₂ emission decrease plans in the power generating sector in Taiwan. Empirical data are collected for the model formulated and various scenarios for mitigating power generating sector CO₂ emissions are simulated. Results of this study from all simulated cases would be compared in order to provide some suggestions for the power authorities to take some strategies to reduce future CO₂ emissions in Taiwan.

2. Taiwan power market and the power sector CO₂ emissions

Taiwan Power Company (Taipower), a government entity, is the sole utility up to now in Taiwan. In 2000,
Taipower served over 21 million customers and operated 30 thermal power plants, 3 nuclear plants and 39 hydropower stations for a total production capacity of 29,634 MW (IIPs included). Peak load occurs during summer (July or August). Record of peak load reached 25,854 MW on July 26, 2000, about 1.76 times that of 1990. The energy production in 2000 reached 156,511 million kW h, of which 36,996 million kW h (23.6%) was nuclear, 8,843 million kW h (5.7%) was hydro and 110,672 million kW h (70.7%) was thermal. In addition, nearly 11.7% of the whole production, 18,355 million kW h, was purchased from IPPs. Total energy sales in 2000 were 142,413 million kW h, of which industrial sales shared 66.5%, domestic lighting 24.4% and commercial lighting 9.1%. The major power consuming sectors were electronic, steel making, textile and chemical industries, and service trade. The detail data of Taiwan power market are shown in Table 1.

As we know, the relation between economic growth and electricity consumption is very close. The fuel energy use can lead to a great deal of CO₂ emissions. The trend of electricity product, CO₂ emissions and GDP of Taiwan are shown in Fig. 1. The total CO₂ and power sector CO₂ emissions of Taiwan from 1989 to 2000 are shown in Table 2. From Table 2 we can find that the power sector CO₂ emissions ratio has increased from 33.28% (1989) to 40.52% (2000). Thus, to plan future power sector development strategies is very important to reduce CO₂ emissions in Taiwan.

3. Multi-objective mixed integer-programming formulation

The optimal power generation strategy with the objective of CO₂ emissions decrease is modeled by a multi-objective mixed integer programming technique. The aim is to determine suitable schedules for the power units, subject to quality requirement restrictions, so as to satisfy the power demand at a minimum total generation cost or minimal CO₂ emissions. The objectives are to minimize (1) the total cost that includes fixed unit installation cost and variable fuel cost, and (2) CO₂ emissions. The constraints can be partitioned into four types: (1) load balance and limitation of units’ generation; (2) unit operation limits; (3) lowest generation constraint of units; and (4) non-negative constraints. The formulation is presented as follows.

3.1. The objective functions are to minimize

\[
\text{Min} \sum_{i=1}^{15} (C_{iy}E_{iy} + Y_{iy}S_{iy}f_{iy})
\]
Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Total sectors CO$_2$ emissions (10$^3$ T)</th>
<th>Electricity sector CO$_2$ emissions (10$^3$ T)</th>
<th>Electricity sector CO$_2$ emissions ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1989</td>
<td>111,502</td>
<td>37,104</td>
<td>33.28</td>
</tr>
<tr>
<td>1990</td>
<td>113,540</td>
<td>35,930</td>
<td>31.65</td>
</tr>
<tr>
<td>1991</td>
<td>125,803</td>
<td>41,740</td>
<td>33.18</td>
</tr>
<tr>
<td>1992</td>
<td>134,171</td>
<td>44,325</td>
<td>33.04</td>
</tr>
<tr>
<td>1993</td>
<td>145,073</td>
<td>49,742</td>
<td>34.29</td>
</tr>
<tr>
<td>1994</td>
<td>151,300</td>
<td>53,722</td>
<td>35.51</td>
</tr>
<tr>
<td>1995</td>
<td>161,961</td>
<td>58,116</td>
<td>35.88</td>
</tr>
<tr>
<td>1996</td>
<td>170,843</td>
<td>61,866</td>
<td>36.21</td>
</tr>
<tr>
<td>1997</td>
<td>184,629</td>
<td>69,046</td>
<td>37.40</td>
</tr>
<tr>
<td>1998</td>
<td>196,624</td>
<td>77,503</td>
<td>39.42</td>
</tr>
<tr>
<td>1999</td>
<td>204,771</td>
<td>81,715</td>
<td>39.91</td>
</tr>
<tr>
<td>2000</td>
<td>218,279</td>
<td>88,440</td>
<td>40.52</td>
</tr>
</tbody>
</table>

(3) = (2)/(1).

\[
\text{BE}_{iy} = \text{BPG}_{iy} \times 8760
\]
\[
\sum_{i=1}^{15} \text{MPG}_{iy} \geq (m_l - b_l)(1 + \text{loss}_y)
\]
\[
\text{ME}_{iy} = \text{MPG}_{iy} \times 8760\alpha
\]
\[
\sum_{i=1}^{15} \text{PPG}_{iy} \geq (p_l - a_l)(1 + \text{loss}_y)
\]
\[
\text{PE}_{iy} = \text{PPG}_{iy} \times 8760\beta
\]
\[
\sum_{i=1}^{15} \text{RPG}_{iy} \geq \text{pl}_y \text{r}_y
\]
\[
\text{PG}_{iy} = \text{BPG}_{iy} + \text{MPG}_{iy} + \text{PPG}_{iy} + \text{RPG}_{iy}
\]
\[
\text{PG}_{iy} \leq s_y(1 - w_{iy}) + \text{BE}_{iy}(1 + w_{iy})
\]
\[
\text{E}_{iy} \leq 8760 \times s_y \text{re}_{iy}
\]

where

\[
\text{BPG}_{iy} \quad \text{base load power supply of unit } i \text{ in year } y \text{ (MW)}
\]
\[
\text{MPG}_{iy} \quad \text{mid-load power supply of unit } i \text{ in year } y \text{ (MW)}
\]
\[
\text{PPG}_{iy} \quad \text{peak load power supply of unit } i \text{ in year } y \text{ (MW)}
\]
\[
\text{RPG}_{iy} \quad \text{reserved power supply of unit } i \text{ in year } y \text{ (MW)}
\]
\[
\text{BE}_{iy} \quad \text{energy output of unit } i \text{ in base load (MW h)}
\]
\[
\text{ME}_{iy} \quad \text{energy output of unit } i \text{ in mid-load (MW h)}
\]
\[
\text{PE}_{iy} \quad \text{energy output of unit } i \text{ in peak load (MW h)}
\]
\[
b_l, m_l, \text{ and } p_l \quad \text{base load, mid-load and peak load of year } y, \text{ respectively (MW)}.
\]
\[
\text{loss}_y \quad \text{percentage of power loss in year } y \text{ (%)}.
\]
\[
\alpha, \beta \quad \text{the time ratio of mid-load and peak load, respectively, in the whole year}.
\]
\[
w_{iy} \quad \text{power consumption rate of the unit } i \text{ in year } y.
\]
\[
\text{re}_{iy} \quad \text{available rate of unit } i \text{ in year } y.
\]

(2) Unit operation limits

If unit $i$ is base load units, then

\[
\text{PPG}_{iy} = 0
\]
\[
\text{RPG}_{iy} = 0
\]

(3) Lowest power supply constraint of units

\[
\text{PG}_{iy} - M I_{iy} \leq \text{pg}_{iy}^{\text{min}}
\]
\[
\text{PG}_{iy} \leq M I_{iy}
\]

where

\[
M \quad \text{a very large positive number}
\]
\[
\text{pg}_{iy}^{\text{min}} \quad \text{the lowest power supply of unit } i \text{ in year } y.
\]
\[
I_{iy} \quad 0 \text{ if unit } i \text{ is suspended for the year } y, \text{ otherwise, } I_{iy} = 1.
\]
4. Empirical results

An ex post power generation simulation for 2000 is made for model verification. Fig. 2 shows the results of all initial compromise solutions of our multi-objective model \((P_1, P_2, \ldots, P_6)\) in 2000. To verify the effectiveness of our model, a detail comparison has been made and the result is shown in Fig. 3. Fig. 3 shows the comparisons of proposed power generation strategy from our model and real operation record in 2000. Power generations of all units from the results are so close to the real case. This could reveal that our model could mimic the real power generation effectively.

After verifying our power supply model, with the objective to investigate optimal satisfaction limit on CO\textsubscript{2} emissions, the analysis was carried on six alternative scenarios to simulate the power generation for the target year 2010. Each scenario assumption is described as follows:

*Case A: minimal total cost.* Under this case, the business is as usual. The model has only minimized the total cost objective faction and to simulate the power generation of the year 2010.

*Case B: minimal CO\textsubscript{2} emissions.* Same as Case A, but minimized the CO\textsubscript{2} emissions objective faction.

*Case C: decreased LNG price.* Nowadays, Taiwan’s LNG supply is almost imported from Southeast Asia. The high taxation on import goods, made the LNG lose its price competition ability in electricity generation market. In this case, we simulate how much decrease range in LNG price would make it possible to substitute gas for oil in power generation. The model has only minimized the total cost objective faction and to simulate the power generation of the year 2010.

*Case D: improved thermal generating efficiency.* The main purpose of this case is to simulate the effect of feasible thermal generating efficiency improvement. We assume the coal-fired generator and oil-fired generator net generating efficiency can rise from the current average level of 35–40% and combined cycle gas turbine generator rise from 40 to 50%. The model has only minimized the total cost objective faction and to simulate the power generation of the year 2010.

*Case E: active plan with minimal total cost.* In this case, we combine the assumptions mentioned in Cases C and D to minimize the total cost objective faction to simulate the power generation of the year 2010.

*Case F: active plan with minimal CO\textsubscript{2} emissions.* Same as Case E but minimized the CO\textsubscript{2} emissions objective faction.

Although Taiwan now is not a member of UN, she should still obey the rules set by the international community. Under negotiation, Taiwan government wants that the CO\textsubscript{2} emissions standard is leveledized on the emissions of the year 2000. In this point of view, the emissions of 88 million tons would be the goal for the power sector to take some steps to strive toward the future.

Table 3, Figs. 4 and 5 show the simulation results from our power supply model. The simulation results for scenarios A and B indicate that under the business as usual assumption, the power generation cost and CO\textsubscript{2} emissions in 2010 will be 285 and 309 billion NT$, 129 and 120 million tons, respectively. In Table 3 we also find that in scenario A and B the CO\textsubscript{2} emissions are both higher than the goal of CO\textsubscript{2} emissions standard. It means if we do not take any action, even under the objective of minimal CO\textsubscript{2} emissions, the power sector of Taiwan could not be able to reduce CO\textsubscript{2} emissions as was the level in the year 2000.

Under scenario C, if the LNG generating cost could decrease to 35%, the gas-fired units will substitute for all oil-fired units and some coal-fired units. The power generating cost and CO\textsubscript{2} emissions will be 265 billion NT$ and 127 million tons, respectively. A straight comparison of the results obtained under scenarios A and C shows the impact of fuel switch. As Table 3 and Fig. 5 show, the total cost will reduce to about 19,822 million NT$ and CO\textsubscript{2} emissions will also decrease to 2,271 thousand tons.

Under scenario D, the gas-fired units will substitute for some oil-fired units. The power generating cost and CO\textsubscript{2}
emissions will be 268 billion NT$ and 112 million tons, respectively. By comparing the results obtained from scenarios A and D, it indicated that the improvement effect of power generating efficiency will reduce total cost about 16,940 million NT$ and CO2 emissions 16,708 thousand tons. Besides, from the results of scenarios C and D, we can find that the power generating efficiency improvement has more CO2 emissions reduced than the fuel switch.

Under scenario E, the power generating cost and CO2 emissions will be 233 billion NT$ and 110 million tons, respectively. After comparing the results of scenarios E and A, we can see the impact of fuel switch combine generating efficiency improvement. The total cost will reduce about 51,431 million NT$ and CO2 emissions will decrease 18,858 thousand tons. We also find that the combination effect of scenario E is larger than single option (scenarios C and D) not only in reducing total cost but also in decreasing CO2 emissions.

Under scenario F, the total cost is close to the scenario E and the CO2 emissions is the lowest one among all scenarios. The power generating cost and CO2 emissions will be 249 billion NT$ and 96 million tons, respectively. In all simulation results, only scenario F could have the power sector CO2 emissions close to the level of the year 2000.

Our simulation results show that we cannot achieve the goals if we use only the control strategies of fuel alternatives or generating efficiency improvement. For achieving the CO2 emissions standard, control strategies must include both fuel alternatives and generating efficiency improvement.

5. Conclusion

This paper has demonstrated the use of mixed 0–1 integer programming to evaluate the effect of possible CO2 emission decrease plans in the power generating sector in Taiwan. The objectives are to serve the power needs at minimum cost and minimum CO2 emissions, subject to load balance and limitation of units’ generation, unit operation limits, lowest generation constraint of units, non-negative constraints that could reflect real operational constraints effectively.

Our empirical results show that, if power sector use only the fuel switch or generating efficiency improvements, it is hard to achieve the goal of power sector CO2 emissions standard levelized on the emissions of the year 2000. Although lower-carbon or non-carbon power units can be very helpful in achieving the goal of CO2 emissions decrease, it is still needed to improve the power generating efficiency in order to stabilize the CO2 emissions under the goal for 2010. It is worth conducting a further study to establish several policy options such as demand-side management, T and D improvements, cogeneration and self-generation to simulate the above finding in the near future.
References