# *MIT Joint Program on the Science and Policy of Global Change*

# Analysis of Strategies of Companies under Carbon Constraint: *Relationship Between Profit Structure of Companies and Carbon/Fuel Price Uncertainty*

*Susumu Hashimoto*

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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# Analysis of Strategies of Companies under Carbon Constraint:
## *Relationship Between Profit Structure of Companies and Carbon/Fuel Price Uncertainty*

Susumu Hashimoto*

### Abstract

*This paper examines the relationship between future carbon prices and the expected profit of companies by case studies with model companies. As the future carbon price will vary significantly in accordance with the political and economic situation, a specified probability density profile for the carbon price in the future has been assumed in this paper and the expected profits of the model company have been calculated on the basis of this profile. A power company has been selected as the model company representing a typical instance of a large-scale emitter of* $CO_2$*. In the case of a single-fuel using company, it has been established that the influence on corporate profits can be assessed quantitatively by determining the profit break-even line with the carbon price as the parameter using the company's carbon emission intensity and its operating profit per unit of production output. For multi-fueled companies, it is shown that the future optimum fuel mix is determined not only by the carbon price but also by the operating profit ratio for the fuels concerned. These studies have thus confirmed that corporate profits are governed by the ratio of the operating profit levels achieved per unit of production output for the different fuels and the carbon price.*

### Contents

## 1. INTRODUCTION

There seems to be no doubt that we will face carbon constraints in the near future though it is not clear whether the Kyoto Protocol will be in effect or not at this moment. The problem is that we are not certain when and how these carbon constraints will come into effect and what impact they will have. Those companies that emit tons of $CO_2$ at present, such as companies in the energy intensive industries, would be affected very badly.

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[*] Hashimoto is employed by the Electric Power Development Co., Ltd. (J-Power) and he was a visiting researcher at the Joint Program on the Science and Policy of Global Change when this paper was written.

In this paper, we have singled out a power company as a typical large-scale emitter of $CO_2$ and taken it as a model case for examining the impact of future carbon constraints in a quantitative manner in terms of the corporate profit structure and the future carbon price. Moreover, one of the options available to companies under such carbon constraints would be to switch fuels (for example, from coal to gas), and we have examined this possibility to establish the pluses and minuses of fuel switch with regard to price and operating profit of both fuels (Section 2).

In Section 3, the profit structure of the model company is generalized, and examined again to see how the profit structure in the carbon constraint world would affect corporate profit. First, we have examined the expected profit for a uni-fueled firm in relation to the carbon price. The profit break-even line for the predicted carbon price is shown for such companies. Second, we have examined the profit structure of multi-fueled companies to determine the optimum coal and gas fuel mix by considering the carbon price and the relative price difference between these fuels.

In the conclusive part, we have noted that there is a possibility that the benefits of switching fuels might be lost when the operating profit for gas as a fuel with lower carbon emissions is less than a certain critical level applicable to the use of coal as a fuel with higher carbon emissions. It is therefore necessary to accept a trade-off between the carbon price and the fuel price when resorting to fuel switching as a means of reducing emissions.

## 2. MODEL COMPANY ANALYSIS

### 2.1 Outline of the Model Company

The model company used for this study is a power-generating company that owns coal-fired power plants. As coal-fired power plants emit more $CO_2$ than other plants, the effects can be seen more clearly.

The model company owns plants with a total of eight 1,000 MW capacity coal-fired power generation units operated at over 60% of their capacity. The plant units are assumed to be a mixture ranging from old to state-of-the-art systems with different levels of combustion efficiency. We have taken the average emission rate of the 8 units as being 0.22 t-C/MWh.

**Table 1** is a summary of features of the model company for the reference year, which will be the base data for our later calculations.

**Table 1**. Features of the Model Company

| Operational/Financial Features | Figures |
|---|---|
| Power generation | 44,500,000 MWh/yr |
| $CO_2$ emissions | 9.8 Mt-C/yr |
| Operating revenue | 2,800 M$/yr |
| Operating profit ratio | 20 % |

In the following subsection, we will calculate the profit the model company can reasonably expect in the future (in this paper, after 5 years) using above data.

## 2.2 Assumption of the Future Carbon Price

At present, we have no way of knowing what regulations might be implemented after 5 years. Even when we assume the model company is in a country that has ratified the Kyoto Protocol, we cannot be certain that the Protocol will actually have come into effect within the next 5 years.

Moreover, even if we assume that the Kyoto Protocol will have come into effect over the next 5 years, we would have no way of knowing what regulatory measures the government of that country might institute. The model company might have a cap imposed on its $CO_2$ emissions and/or be subject to a severe carbon tax. Alternatively it is also conceivable that noregulations might be passed for certain political or economic reasons.

In view of this uncertainty as to the future political and/or economic situation, we have supposed in this paper that the carbon price is distributed according to a certain probability density profile that takes into account all possible political and economic factors.

**Figure 1** shows an example of a Γ profile for the probability density function with a peak price at $25 which is expressed by following equation with $q = 2$ and $\sigma = 25$.

$$f(x) = \frac{1}{\Gamma(q)\sigma^q} x^{q-1} e^{-\frac{1}{\sigma}x}$$

Although we can assume various profiles for the probability density function, this Γ profile is used in this paper as an expedient example. It is, evidently, not necessary to limit ourselves to this Γ profile.

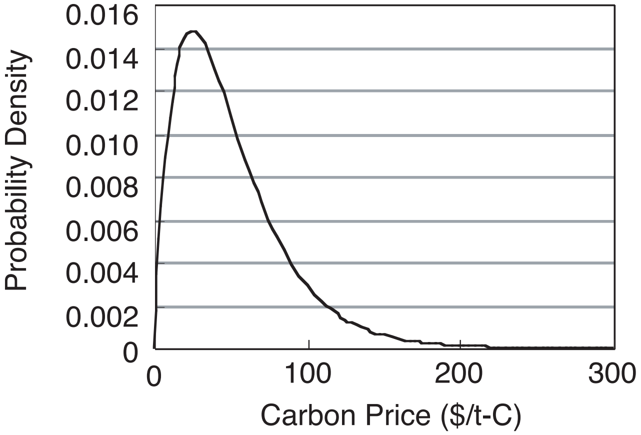

**Figure 1**. Probability Density of Carbon Price (Γ profile peak price at $25)

## 2.3 Expected Profit for the Model Company

We have made the following assumptions in order to simplify our analysis in this section:

- -The model company has relatively long-term contracts with its customers (buyers) and can reasonably expect that its electricity price will remain fixed over a period of 5 years.
- -The model company can reasonably expect that the level of its power sales will remain the same by virtue of its long-term supply contracts. (This means that this company can reasonably expect that without carbon constraints its profits will remain the same as the reference year.)

What amount of profit can this model company expect when the predicted carbon price probability shown in Figure 1 comes into play? (To simplify matters, we will assume in our calculations below that the inflation rate and the discount rate will not change during this 5-year period.)

### *2.3.1 Auction case*

In this subsection, we will examine the expected profits of the model company on the assumption that cap & trade approach will be applied as the regulatory measure by the government. As a result, companies that emit $CO_2$ will be required to obtain $CO_2$ emission permits through auction procedures to acquire emission rights covering the full amount of their $CO_2$ emissions.

Although it is likely that the model company may negotiate with its customer (buyers) on a possible increase in power tariff in order to pass some portion of their excess cost of purchasing the permits on to the power price, we will assume in this paper that the model company will bear 100% of its costs for obtaining the emission permits. In this way we can study the worst scenario case. Also, the effect on corporate profits of the different means of distributing allowances is more clearly shown.

The expected profit of the company can be expressed by the following equation.

$$EP = a \times p - ER \times p \times \int_0^\infty CP(x) * f(x)dx \tag{1}$$

$EP$: expected profit of the company ($)
$a$: profit per unit power generation output ($/MWh)
$p$: power generation output (MWh)
$ER$: $CO_2$ emissions per unit power generation output (t-C/MWh)
$CP(x)$: carbon price in relation to the probability density variable $x$ ($/t-C)
$f(x)$: probability density function.

Let us substitute the values $a$ = 12.6 (\$/MWh), $p$ = 44,500,000 (MWh), $ER$ = 0.22 (t-C/MWh) for the model company in the above equation and take the carbon price as being zero. It can be seen that the model company can reasonably expect a profit of $EP$ = 560M\$, which is as same as in the reference year.

Let us now examine the level of profit the model company can expect after 5 years, if we predict the carbon price probability profile shown in Figure 1, that is, the Γ profile with a peak price of \$25. The profit probability density function of this case is shown in **Figure 2**.

As Figure 2 shows the profit PDF(probability density function) of the model company, for example, we can see the probability of \$560 million of profit for this company is zero. It is because the probability of a zero carbon price is zero in Figure 1. The modal, most-likely, or peak profit is \$316 million that is corresponding to the peak price of \$25. The expected value for future profit of this company is approximately 70M\$ according to the calculation.

The 70M\$ expected profit level is much lower than the 560M\$ profit of the reference year with carbon price = 0. This means, 5 years later, the model company would face the difficult situation of nearly a 90% fall in expected profit and of a significant probability of a loss.

### *2.3.2 Grandfathering case*

In the former case, we have assumed that companies are required to purchase carbon emissions permits covering their entire emissions and bear the full costs involved in the acquisition of these permits. In view of the critical effect of this policy on company profitability, however, a grandfathering approach might possibly be adopted in certain instances as the substantial decline in the profit levels of carbon-intensive companies could be seen as a social problem.

In view of the above, let us assume that the government decides to grant these carbon-intensive companies $CO_2$ emission permits as a result of political bargaining. Let us therefore assume that an amount corresponding to 95% of the 1990 emissions is allocated to the companies after due political bargaining among the stakeholders.

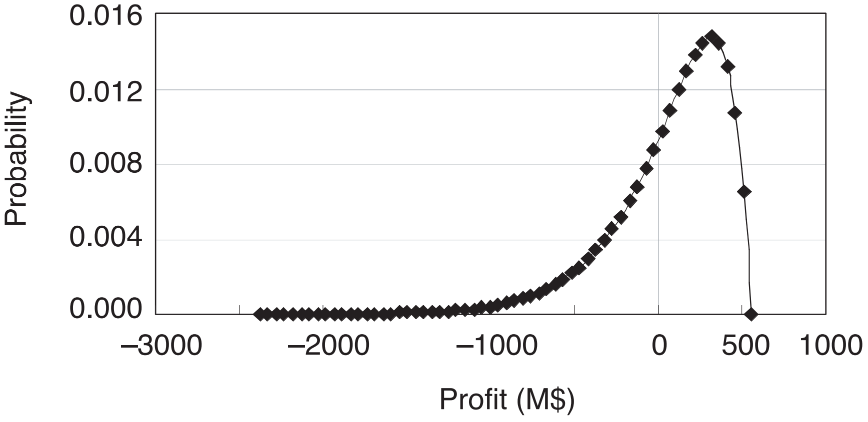

**Figure 2**. Profit PDF (peak price \$25) $EP$ = 70M\$

If, for example, the model company emitted 6.8 Mt-C of $CO_2$ in 1990, it will thus qualify for emission permits worth approximately 6.5 Mt-C ( = 6.8 Mt-C * 95%). In this case, the question is how much profit the model company can reasonably expect 5 years later with the carbon price predicted to be as shown in Figure 1. (This is the Γ profile with a peak price of $25.)

For this grandfathering case, a slight modification is needed in equation (1) as shown below.

$$EP = a \times p - (ER \times p - GF) \times \int_0^\infty CP(x) * f(x)dx \qquad (2)$$

where $GF$ = grandfathered permits (t-C).

Calculation according to the above equation gives us an expected value of 400M$ for the model company's profit after 5 years in the grandfathering case (Profit PDF is shown as square symbols in **Figure 3**). Moreover, the probability of a loss has been reduced to a negligible 1%. The company can expect greater profits in the grandfathering rather than the auction case. Yet, even in the grandfathering case, the company must still be prepared to accommodate a roughly 30% fall in its profit.

Let's take a look at the following calculation based on a higher carbon price. Here we assume that the carbon price is raised significantly due to certain political and economic factors. When using the Γ profile with the peak price of $75 as the probability profile of the carbon price, the expected value for the model company's profit is approximately 70M$ (Profit PDF is shown as triangle symbols in Figure 3). This entails a 80% drop from the $25 peak case and a 90% drop from the reference year profit.

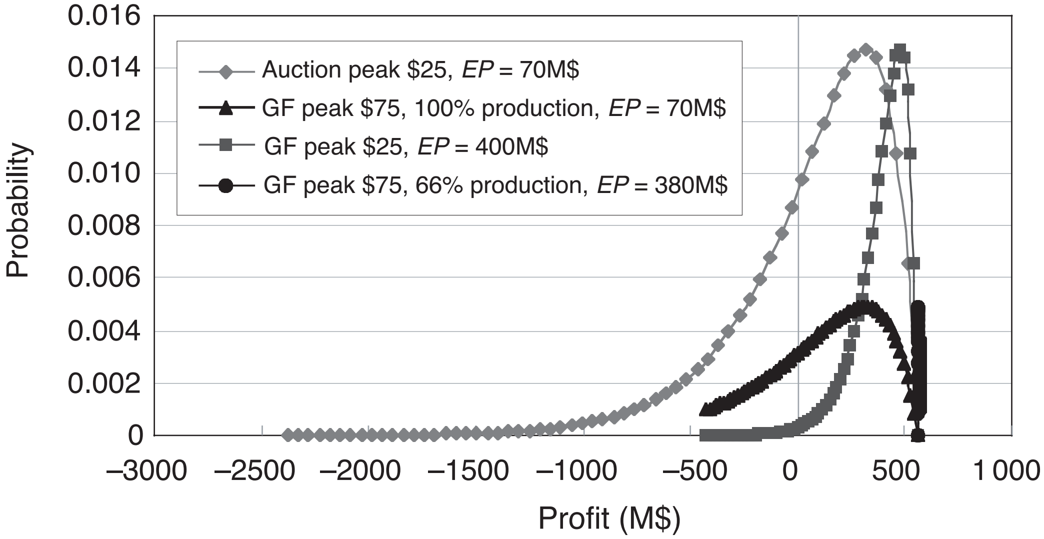

**Figure 3**. Profit PDF (Auction vs. GF, peak $25 vs. $75)

On the other hand, if the model company reduces its output to 66%, a level of output equivalent to the 6.5 Mt-C of $CO_2$ emissions corresponding to the grandfathered permits, the expected value of the company's profit will rise to approximately 380M$ (Profit PDF is shown as circle symbols in Figure 3). This suggests that, when the carbon price is expected to be high, it would be wise to operate plant at an output level not requiring any extra $CO_2$ emission permits rather than to run the plants at full capacity in order to maximize profits.

We can also note a similar trend in the auction case. **Figure 4** shows that when the carbon price is high the extent of profit decline can be limited by reducing the output level in the auction case. Although profits are down in both the full-capacity operation case and the reduced capacity (66% availability) operation, plant operation at reduced capacity is more favorable.

Figure 4 also indicates that, if we expect grandfathering measures to be effective 5 years later, the model company would be better off operating its plants at 100% availability until the predicted peak carbon price is about $30. Yet it would be wise for this company to throttle output if a higher carbon price peak profile of $30 or above seems likely. In the auction case, the same strategy might be adopted although expected profits would turn negative after the predicted peak carbon price has risen beyond the $30 level.

## 2.4 Asset Adjustment

### *2.4.1 Conversion from coal to gas*

When the profit mechanism described in the previous section can be anticipated, companies may respond by adopting some other strategy to cope with the situation. For example, companies might resort to asset adjustment, such as the conversion of its plants from coal to gas fuel.

To make the story simple, we will assume that the model company is able to convert all of its coal-fired power plants to natural gas while retaining the same output level of 44,500,000 MWh/yr

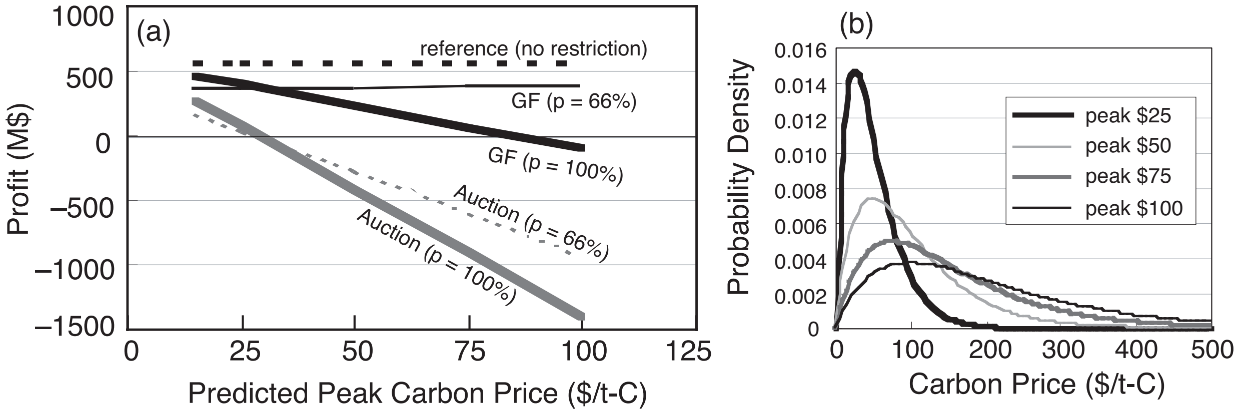

**Figure 4**. (a) Expected Profit for Model Company by Predicted Peak Carbon Price, (b) Carbon Price Probability Profile

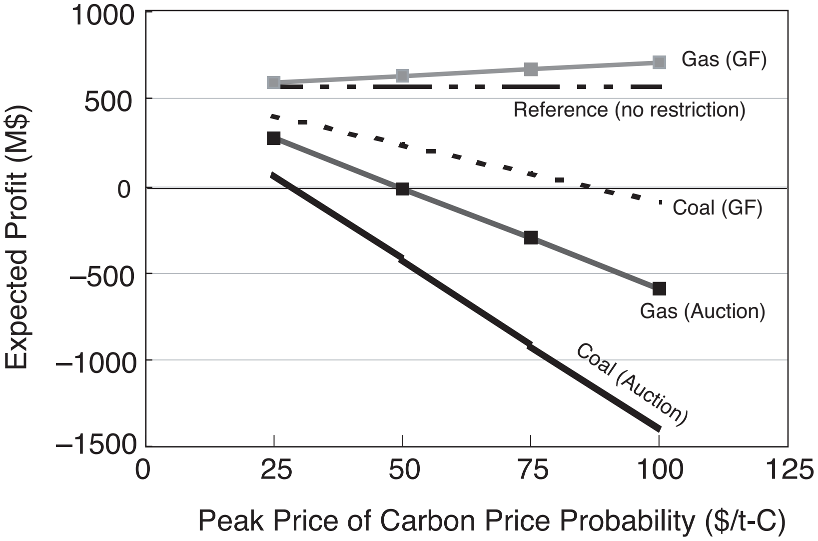

**Figure 5**. Expected Profit for Model Company (Gas vs. Coal)

through the 5 year period. We will assume, furthermore, that profit per unit power output remains the same as before (12.6 $/MWh) and the only factor that changes is the $CO_2$ emission level which will be down to only 60% ( = 0.13 t-C/MWh) as compared with the coal-fired model power plants ( = 0.22 t-C/MWh).

We can calculate the expected profit for these natural gas plants by using the various predicted carbon price levels anticipated for the future (see **Figure 5**).

The square symbols in Figure 5 refer to the model company's natural gas plants. If grandfathering measures are provided, the model company can expect a profit in excess of 560M$, which is the profit level applicable in the event that no restrictions on carbon emissions are imposed. Given an equal level of profit for coal and gas-fired generation, profit will increase as the higher carbon price imparts more value to the "surplus" grandfathered allowances for a gas plant.

Even in the auction case, the model company can expect positive profits for gas conversion until the expected carbon price reaches $100 ( = peak price $50). Still, the company must be prepared for a considerable fall in profits from the reference case of 560M$.

### *2.4.2 Influence of natural gas price*

We must note that the conclusion reached in Section 2.4.1 holds true only on the assumption that the price of natural gas will be the same after 5 years. However, it is reasonable to expect some price increase for natural gas as the carbon constraint intensifies. The carbon constraint pushes up the demand for, and with it also the price of, clean energy. The influence caused by a price increase for natural gas will be examined in a little more detail in this section.

More detailed structure of generation cost can be expressed by the next equation,

$$I = \frac{C\gamma}{8760L} + \frac{860f}{\eta}$$

where $I$: Generation Cost (\$/MWh)

$C$: Construction Cost (\$/MW)

$\gamma$: Annual capital charge rate (interest depreciation and O&M) (%)

$L$: Capacity factor (%)

$f$: Fuel price per unit of heat (\$/$10^3$kcal)

$\eta$: heat efficiency (%)

860: inverse factor for converting kilocalories into megawatt-hours assuming no heat loss ($10^3$ kcal = $4.184*10^6$ J = $1.162*10^{-3}$ MWh)

For the present, for example, the coal price is assumed as being 0.75 yen/$10^3$ kcal and the LNG (liquefied natural gas) price as being 2.25 yen/$10^3$ kcal (see **Figure 6**). Now, let us consider what the operating profit of the model company would be if the price of LNG were to increase to 150% and the price of coal would remain unchanged. The parameters $C$, $\gamma$, $\eta$ shall have the values given in **Table 2** and $L$ (plant availability) is taken as 70%.

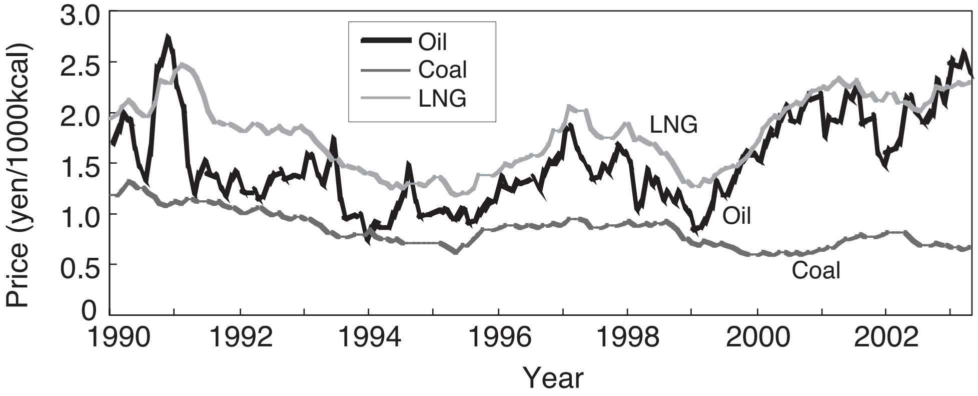

**Figure 6**. Energy Price (CF Price at Japan)

**Table 2**. Generation Cost Input Data (by Ellerman & Tsukada [1])

| Code | Unit | Oil | Coal | LNG |
|---|---|---|---|---|
| $C$ | yen/kW | 206,000 | 304,000 | 214,000 |
| | \$/MW | 1,717,000 | 2,533,000 | 1,783,000 |
| $\gamma$ | % | 13.27 | 13.30 | 14.23 |
| $f$ | yen/$10^3$kcal | 1.607307 | 0.899545 | 1.795355 |
| | \$/$10^3$kcal | 0.01339 | 0.007496 | 0.01496 |
| | \$/mmBtu | 3.38 | 1.89 | 3.77 |
| $\eta$ | % | 39.98 | 39.10 | 40.00 |

Note: yen converted to dollars with exchange rate 120 yen/\$

**Table 3**. Operating Profit with LNG 50% Price Increase

| Cost $ Margin | unit | Coal | LNG | LNG (f = 150%) |
|---|---|---|---|---|
| fuel price (*f*) | yen/$10^3$kcal<br>$/$10^3$kcal<br>$/mmBtu | 0.75<br>0.00625<br>1.58 | 2.25<br>0.01875<br>4.73 | 3.375<br>0.028125<br>7.09 |
| Capital + O&M cost | $/MWh | 55 | 41 | 41 |
| Fuel cost | $/MWh | 14 | 40 | 61 |
| Operating profit[a] | $/MWh | **17**[a] | **17**[b] | -4[c] |
| Selling price | $/MWh | 86 | **98** | **98** |

Notes: a) set as 20% of selling price; b) set same margin as coal plant; c) balance of keeping the selling price as 98 $/MWh

The calculation results are shown in **Table 3**. The model company would lose its entire operating profit if it maintained its selling price for power at the same as before the natural gas 50% price rise, namely at 98 $/MWh. Note that as of June 2003, the price of natural gas in North America has risen to 6 $/mmBtu, so our assumed price of 3.375 yen/$10^3$ kcal ( = 7.1 $/mmBtu) does not seem unrealistic in the light of this trend.

For the near future, it is most realistic to anticipate higher natural gas prices as the impact of carbon constraint comes into its own. This calls for a great measure of caution in any attempt to convert power plants from coal to gas fuel in an attempt to trade off the rising carbon price against the benefits of gas due to lower emissions.

### *2.4.3 Operating profit in case of natural gas power plant*

For fuel conversion from coal to natural gas, it is necessary to realize that, in general, natural gas power plants are less favorable than their coal-fired counterparts in terms of profitability per unit output. Although in the previous discussion, it has been assumed for simplicity's sake that the operating profit per unit power output from natural gas remains the same as that from coal, the operating profit with natural gas is significantly lower as shown in **Table 4** in the event that the selling price of power generated with natural gas has to be kept the same as the coal-generated power price. This may apply, for example, in the case of a liberalized power market.

**Table 4**. Operating Profit of Coal and LNG

| Cost & Profit | unit | Coal | LNG |
|---|---|---|---|
| fuel price (*f*) | yen/$10^3$kcal<br>$/$10^3$kcal<br>$/mmBtu | 0.75<br>0.00625<br>1.58 | 2.25<br>0.01875<br>4.76 |
| Capital + O&M cost | $/MWh | 55 | 41 |
| Fuel cost | $/MWh | 14 | 40 |
| Operating profit[a] | $/MWh | 17[a] | 5[b] |
| Selling price | $/MWh | **86** | **86** |

Notes: a) set as 20% of selling price; b) balance of keeping the selling price same as coal

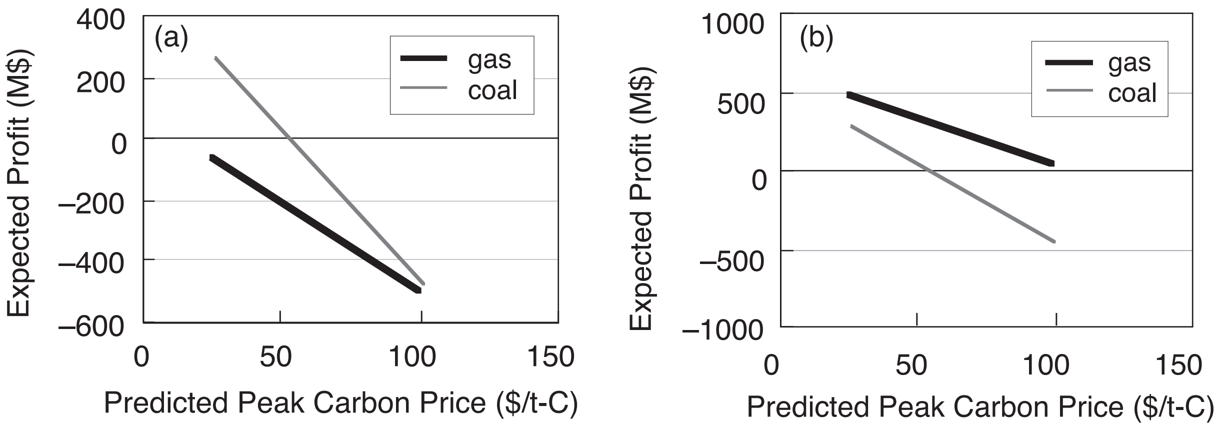

**Figure 7**. Expected Profit for (a) Gas Margin = 30% of Coal, (b) Gas Margin = 100% of Coal

Using the operating profits in Table 4, the relationship between the future carbon price and the expected profit of the company can be expressed as shown in **Figure 7**. The advantage of gas is totally lost if the gas/coal operating profit ratio is approximately 30%. This suggests that the operating profit for a gas-fired power plant is as important a factor for any decision to convert the power plant from coal to gas as the possibility of future price increases for natural gas.

## 3. GENERAL APPROACH

### 3.1 Case of a Uni-fueled Company

A more generalized approach can be applied to the profit structure of companies. The expected profit EP for companies that use only one fuel (uni-fueled company) for production can be expressed using the equation below. This is equation (2) already introduced in Section 2.3.2.

$$EP = a \times p - (ER \times p - GF) \times \int_0^\infty CP(x) * f(x)dx$$

$EP$: expected profit of the company ($)
$a$: profit per unit output ($/unit)
$p$: output (unit)
$ER$: $CO_2$ emissions per unit output (t-C/unit)
$GF$: grandfathered permits (t-C)
$CP(x)$: carbon price in relation to the probability density variable $x$ ($/t-C)
$f(x)$: probability density function

Expressing $GF$ as $GF = b*ER*p$ ($b$: ratio of grandfathered permits and emissions at 100% production) gives:

$$EP = a * p - (1 - b) * p * ER * ACP \qquad (3)$$

*ACP*: average or expected price of carbon

$ACP = q*\sigma$ when probability density function $\Gamma$ profile can be expressed by:

$$f(x) = \frac{1}{\Gamma(q)\sigma^q} x^{q-1} e^{-\frac{1}{\sigma}x}$$

From equation (3), the expected profit, *EP*, of the model company will fall as the expected carbon price increases according to the line with the slope $-(1-b)*p*ER$ and intercept $a*p$. **Figure 8** shows this relationship for the grandfathering, auction, and reduced production cases. **Table 5** presents the unit price of power generation for LNG-, oil- and coal-fired plants calculated by METI (Ministry of Economy, Trade and Industry in Japan) using model plants [2] and the $CO_2$ emissions per unit power generation output for LNG-, oil- and coal-fired plants calculated by CRIEPI (Central Research Institute of Electric Power Industry) [3]. These power generation outputs (LNG, Oil, Coal) are plotted on the *ER*-*a* plane in **Figure 9** on the assumption that each plant has a 20%[1] operating profit and that permits are auctioned.

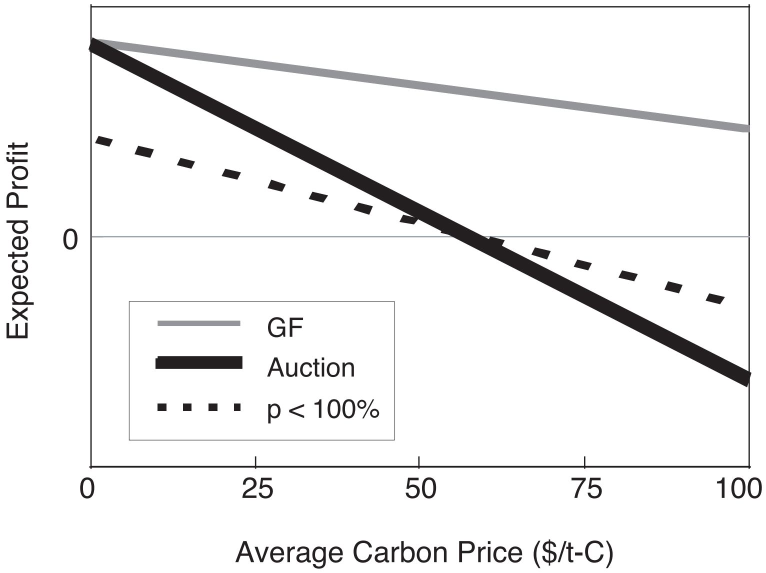

**Figure 8**. Average Carbon Price (*ACP*) vs. Expected Profit (*EP*)

**Table 5**. Unit Price and Emissions per Generation by Fuels

| **Fuel** | **Unit price per generation** calculated based on asset life | **$CO_2$ emissions per generation** (generation only) | ***ER*: $CO_2$ emissions per power generation** (t-C/MWh) | ***a*: profit per power generation** ($/MWh) operating profit = 20% |
|---|---|---|---|---|
| LNG | around 10 yen/kWh | 478 g-$CO_2$/kWh | 0.13 | 16.7 |
| Oil | around 9 yen/kWh | 704 g-$CO_2$/kWh | 0.19 | 15.0 |
| Coal | around 10 yen/kWh | 887 g-$CO_2$/kWh | 0.24 | 16.7 |

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[1] 20% is not the real operating profit for each fuel. This figure is used only for simplifying the discussion here. It is known that operating profit for coal is greater than that for LNG in Japan.

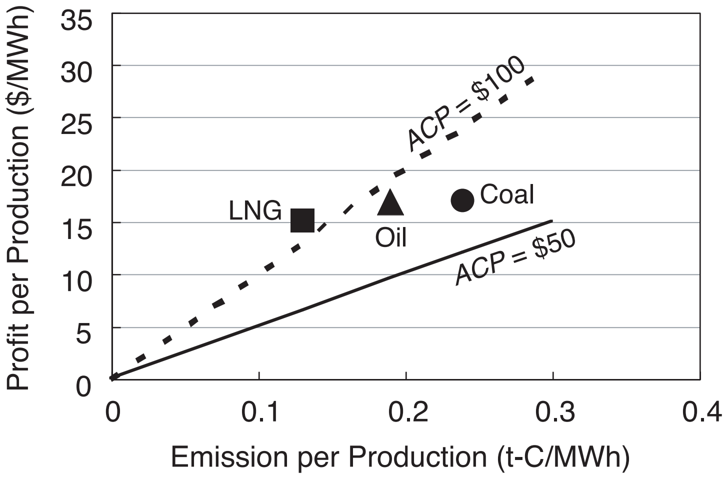

**Figure 9**. Profit Break-Even Line

If the average carbon price is predicted at $50 (peak price = $25), for example, a profit for each of these plants can be expected since each plot is above the line indicating the emission rate and pre-carbon-tax profit level that separate positive from negative profits when *ACP* = $50. However, if the average carbon price increases to $100, coal and oil fired plants will be below the break-even line of *ACP* = $100 so that these two plants cannot be operated profitably on the assumption that they started out with a 20% operating profit.

We must note that, however, even if the plot is above the break-even line, this only signifies that the profit is not zero and that the companies concerned must be prepared for significant losses as compared with the no carbon constraint case. We have seen this in the case of our model company.

### 3.2 Case of Multi-fueled Company

Although companies might be able to reduce the carbon emissions per unit output associated with coal-fired power plants by fuel conversion from coal to gas, as seen in Sections 2.4.2 and 2.4.3, the profit achieved by fueling the power plants with gas can be easily diminished as a result of an increase in gas price and/or a squeeze of the operating profit of the plants. While the coal-fired and gas-fired plants have each their particular advantages, such as a relatively stable coal price for the former, and low carbon emissions for the latter, companies may have to consider the best mix of both fuels.

In this section, the profit structure of multi-fueled companies will be examined in a general manner. Let us assume that a given multi-fueled company is planning to have both coal-fired power plants and gas-fired power plants in the future and that it is studying the best coal/gas plant mix in order to achieve the expected maximum profit.

Thus, for example, when the company expects a future carbon price probability distribution equivalent to the Γ profile of Figure 1 (peak carbon price $25), the question will be what coal/gas plant mix would provide the maximum profit?

The expected profit for this multi-fueled company can be expressed by the next equation.

$$EP = a_{coal} * p_{coal} + a_{gas} * p_{gas} - (ER_{coal} * p_{coal} + ER_{gas} * p_{gas} - GF) \times ACP$$

$EP$: expected profit of the company ($)
$a_{coal}$: profit per unit power output from the coal-fired plant ($/MWh)
$a_{gas}$: profit per unit power output from the gas-fired plant ($/MWh)
$p_{coal}$: Power output from coal-fired plant (MWh)
$p_{gas}$: Power output from gas-fired plants (MWh)
$ER_{coal}$: $CO_2$ emissions per unit power output from coal-fired plant (t-C/MWh)
$ER_{gas}$: $CO_2$ emissions per unit power output from gas-fired plant (t-C/MWh)
$GF$: grandfathered permits (t-C)
$ACP$: average carbon price ($/t-C)

If we substitute $GF$ with $b*ER_{gas}*p$ (where $p$ is total power output and $b$ is the ratio between grandfathered permits and total $CO_2$ emissions in the case of 100% gas-fired power production) and if we substitute, furthermore, $p_{gas}$ with ($p - p_{coal}$), the above equation will be:

$$EP = a_{coal} * p_{coal} + a_{gas} * (p - p_{coal}) - (ER_{coal} * p_{coal} + ER_{gas} * (p - p_{coal}) - b * ER_{gas} * p) \times ACP$$

If we substitute $p_{coal}/p$ with $p^*$ and $a_{gas}$ with $k \cdot a_{coal}$ after dividing the above equation by the total power output, $p$, the company's expected profit per unit power output, $ep$ ( = $EP/p$) can be expressed by the following equation.

$$ep = a_{coal} * p^* + k * a_{coal} * (1 - p^*) - \left[ (ER_{coal} - ER_{gas}) * p^* + (1 - b) * ER_{gas} \right] \times ACP$$

This equation suggests that the company's expected profit per unit power output $ep$ will be a function of the percentage share of coal-fired power generation $p^*$, of the gas/coal operating profit ratio $k$ and the average carbon price $ACP$, in other words, $ep = f(p^*, k, ACP)$.

The expected profit per production of the multi-fueled model company can be calculated using the above equation on the assumption that the future carbon price probability profile will correspond to the Γ profile with a peak of $25 ($ACP$ = $50).

The energy price is taken as 0.75 yen/$10^3$ kcal for coal and 2.25 yen/$10^3$ kcal for gas (LNG) in the same manner as in Section 2.4.2. This implies $a_{coal}$ = 17 $/MWh and $a_{gas}$ = 5 $/MWh using the calculation procedures of Table 4. The assumed emission rates are $ER_{coal}$ = 0.22 t-C/MWh and $ER_{gas}$ = 0.13t-C/MWh. Finally, allowances are assumed auctioned, that is, $b$ = 0.

The expected profit per unit power output for this set of assumptions is shown in **Figure 10** with the coal production percentage, $p^*$, varying from 0% to 100% and the gas/coal operating profit ratio, $k$, from 0% to 100%.

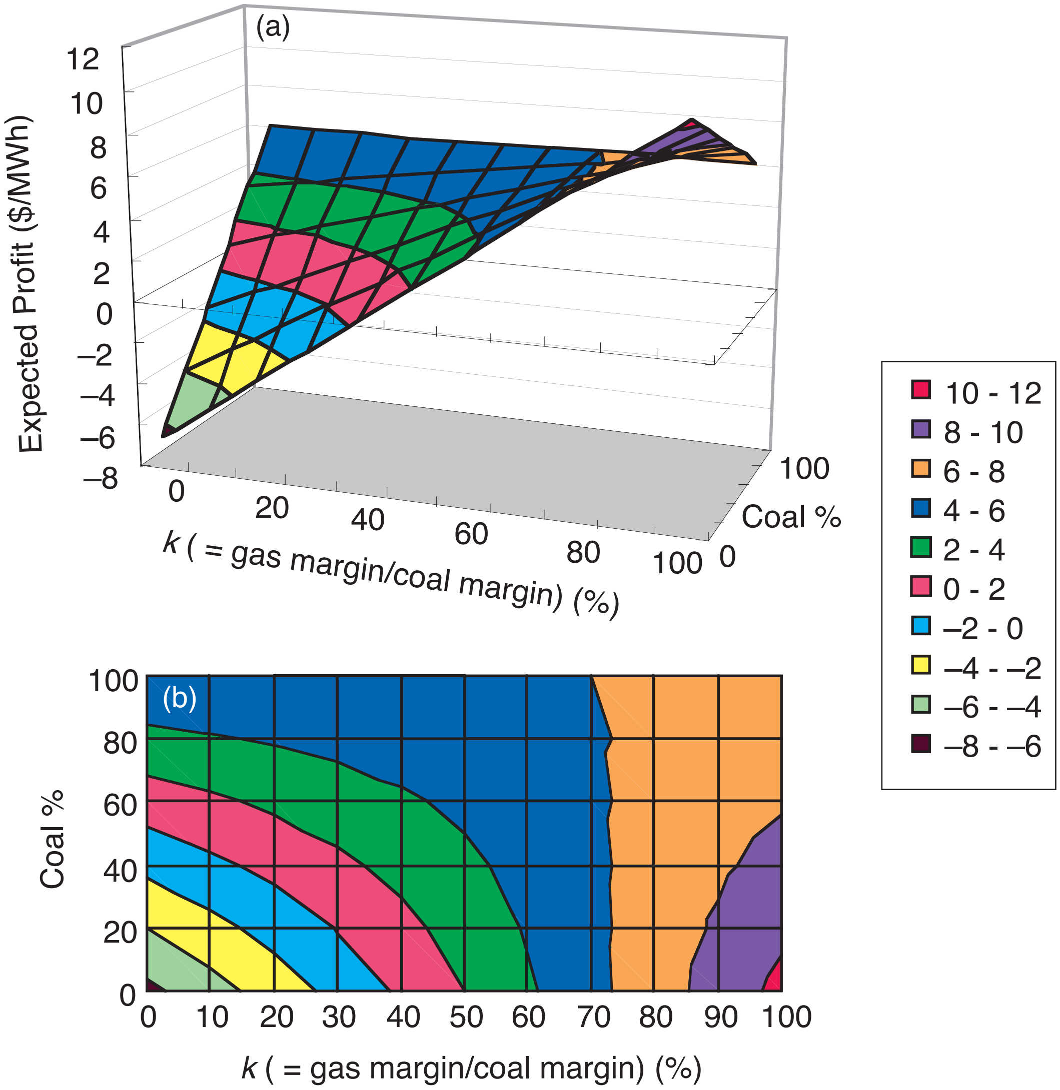

**Figure 10**. (a) Expected Profit per Production, (b) Expected Profit per Production Contour (*ACP* = $50)

Figure 10 demonstrates that for $p^*<1.0$ the expected profit of the company will decline with a decrease in the operating profit ratio $k$ ( = $a_{gas}/a_{coal}$). When we have large proportion of gas-fueled power production, the profit downturn is relatively large compared with the case of a large proportion of coal-fueled production. In the latter case, we can reasonably expect a relatively more stable profit level the greater the share of the coal-fired power generation is. Conversely, when we have only gas-fired power plants, the expected profit will vary substantially as the operating profit ratio $k$ changes.

If we were able to predict the range of variation of *k* in the future, we would be in a position to determine the optimal fuel mixture in this predicted range of *k* using Figure 10. However, since *k* is governed by the future fuel price variations, as shown in the equation below, it would be difficult for us to predict the range of *k* variation in the real world.

$$k = \frac{a_{gas}'}{a_{coal}'} = \frac{a_{gas} - \dfrac{860\Delta f_{gas}}{\eta_{gas}}}{a_{coal} - \dfrac{860\Delta f_{coal}}{\eta_{coal}}} \qquad (4)$$

where $a_{gas}'$ and $a_{coal}'$: future operating profit of gas and coal

$\Delta f_{gas}$ and $\Delta f_{coal}$: future variation of price of gas and coal

$\eta_{gas}$ and $\eta_{coal}$: energy efficiency of gas and coal

Although, for example, our calculation uses $a_{coal}$ = 17 \$/MWh and $a_{gas}$ = 5 \$/MWh by way of reference (this means that $k = a_{gas}/a_{coal}$ = 5/17 = 29%), it cannot be taken for granted that this ratio will remain in this range for the scheduled lifetime of the plant. Yet we will need some clue as to the possible changes of this ratio to enable us to estimate the optimized gas/coal plant mix when we need to develop the company's future asset plan.

**Figure 11** shows the variation of *k* simulated by using the historical data for the variations of gas and coal prices during 1993-2003 and introducing the variations of the values for this period into equation (4) on a monthly basis with keeping $a_{coal}$ = 17, $a_{gas}$ = 5 and $\eta_{coal}$ = 0.3910, $\eta_{gas}$ = 0.4000.

The simulation results make clear that the average *k* in this period is 23% and that the standard deviation is 35%. If it were reasonable to expect that the future variations of *k* would follow the same pattern as these historical variations, we would arrive at an asset mix favoring

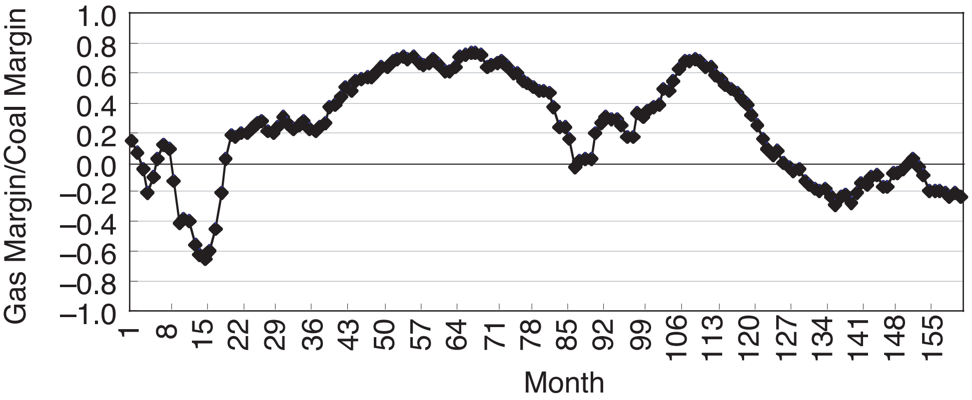

**Figure 11**. Simulation for Profit Margin Ratio of Gas/Coal using Historical Data

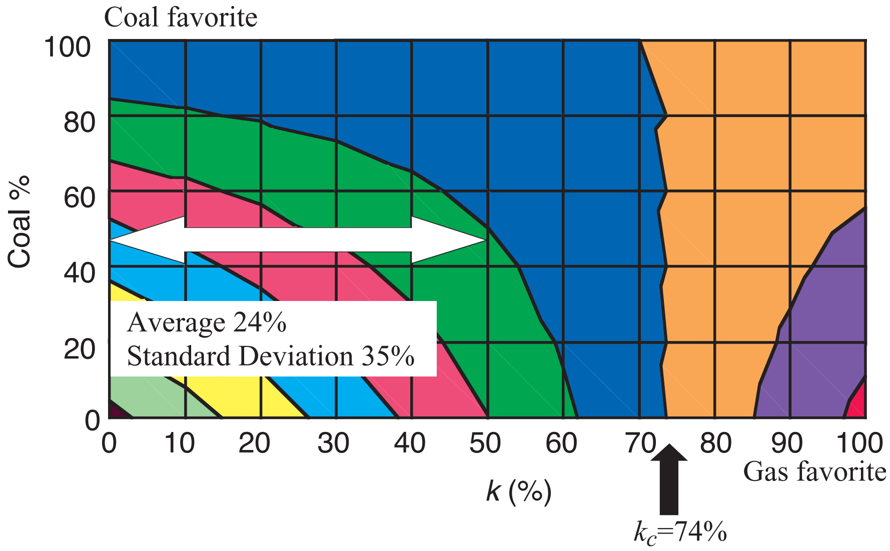

**Figure 12**. Expected Profit vs. *k* and Coal%

coal-fired power plants, given the critical margin ratio $k_c$ in **Figure 12**. $k_c$ shows the critical *k* with 0 slope for the expected profit per unit output *ep* consistent with a coal-fired share of coal% $p*$ (see equations below). In this case, we have $k_c$ = 74%. This means that when *k* is smaller than 74%, 100% coal-fired power generation would provide the maximum profit and when *k* is larger than 74%, 100% gas-fired power generation would lead to the maximum profit.

$$\frac{\partial(ep)}{\partial(p^*)} = a_{coal} - k * a_{coal} - (ER_{coal} - ER_{gas}) * ACP = 0$$

$$k_c = 1 - \frac{(ER_{coal} - ER_{gas}) * ACP}{a_{coal}} = 1 - \frac{(0.22 - 0.13) \times 50}{17} = 0.74$$

## 4. CONCLUSIONS

The results of this study related to a model company show that the expected profit of companies emitting $CO_2$ on a large scale as is the case in the energy intensive industry are significantly affected by an increase in the carbon price. It can be seen that if the company responds by fuel conversion from coal to gas, for example, to mitigate the profit decline, the evolution of the gas price in the future will have a significant impact on the company's profit and so will the change in the future carbon price. This means that the relationship between fuel margins determined by relative fuel prices and the expected carbon price in the future is a key factor for the company in maintaining its profit level.

In order to examine the above relationship quantitatively, we have generalized the profit structure of a company using two fuels for power generation. The results show evidence that the benefits of fuel conversion might be compromised or lost when the operating profit for fuels with a lower carbon emissions fuel is below a certain critical level of the operating profit for a fuel with a higher carbon emission level. This is because, a reduction in the operating profit can cancel out, in certain cases, the benefit of the reduction in the payable carbon emissions brought about by the change of fuel.

Applying the above relationship to multi-fueled companies that have coal and gas plants, it can be seen that the company's expected profit per unit power output will vary with percentage share of coal-fueled generation and the gas/coal operating profit ratio as well as the average carbon price. Using the predicted range of the future gas/coal operating profit ratio, we can determine the optimized asset plan for such multi-fueled companies.

However, further study on future gas and coal price variation is needed, since it is difficult but very important to predict the range of the gas/coal operating profit ratio in the future in order to develop appropriate asset plans for the companies concerned.

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