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A portfolio theory based optimization model for steam coal purchasing strategy: A case study of Taiwan Power Company

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ABSTRACT

The price of coal has fluctuated dramatically in recent years, resulting in the uncertainty of the coal purchasing decision. As a result, reducing costs and managing risk are issues of tremendous importance to power companies. This study developed a model for the purchase of steam coal, taking into account the risks associated with fluctuations in the price of coal. The proposed model combines portfolio theory with conventional mathematical programming. The model also considers limitations in the demand for coal, the upper limit of imports from specific sources, power plant operational requirements, and environmental constraints. Scenario analysis was conducted to simulate changing patterns in the factors influencing the purchase of coal. Simulation results reveal that incorporating the dimension of price risk within a conventional coal purchasing model shifts purchasing decisions toward contracts with long-term suppliers, thereby reducing susceptibility to fluctuations in coal prices. However, the case study in this paper is a state-owned company; therefore, its coal purchasing portfolio lacks flexibility due to complex prequalification requirements. Related restrictions (e.g. strict qualification requirements) must be relaxed to increase the number of available sources and take advantage of the benefits provided by the proposed model.

1. Introduction

In recent years, coal-fired power plants have been facing many challenges related to fluctuations in fuel prices and environmental protection. For example, the monthly price of Australian thermal coal (steam coal) skyrocketed to USD 192.86 per metric ton in July 2008, representing a USD132.86 increase (221%), compared to the USD60 per metric ton in May 2007 (Index Mundi website, 2012). Generally speaking, coal has been regarded as a cheaper and stable-pricing energy among other forms like crude oil or natural gas. However, according to Bacon and Kojima (2008), the volatility of spot Australian coal prices[1] was much lower than that of spot crude oil prices until 2004. Since then, the volatility of both fuels has been almost the same. It means the volatility of coal price has been catching up to with other energy forms since the beginning of 2004 and shows that coal prices have been fluctuating dramatically in recent years. Hence, determining how best to distribute the price risk and reduce costs are issues of great importance to power companies. The issue of environmental protection is also under the spotlight. The introduction of environmental restrictions to reduce output levels of sulfur dioxide, nitrous oxide and greenhouse gas emissions, have added additional constraints that further complicate the purchase of coal.

Coal is one of the most important energy resources in Taiwan. Due to continued economic growth and development, the demand for electricity has been rapidly increasing with an average annual growth rate of 4.89% in the past two decades (BOE, 2012). A large and growing percentage of electricity, which is mostly provided by the state-owned Taiwan Power Company (TPC), is generated by imported coal. Hence, an electric utility company (e.g. TPC) faces the coal procurement decisions of source, method, and order set selection in an environment where multiple sources, periods, multi-mode procurement methods, multiple power plants, emission constraints and plant operational constraints exist. Thus, a robust coal procurement strategy can not only reduce the risk of a power shortage but also reduce costs and assure the quality control of imported coal.

The conventional approach to the purchase of coal is the least-cost method, in which quantities of coal purchased are determined without assessing risks associated with the price of coal (Kondragunta and Walker, 1984; Lyu et al., 1995; Lai and Chen, 1996;

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[1] Standard deviations of fuel price volatility are calculated on returns on logarithms of monthly prices expressed in nominal USD per unit of energy. Coal is Australian coal. Oil is the average of Dubai, Brent, and WTI crudes.

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Shih, 1997; Liu and Sherali, 2000; Liu, 2008; Yucekaya, 2013). Furthermore, the quality of coal can vary widely with regard to heating value, sulfur content, and ash content. The heat content ranges from low to high which affects the energy amount gained when the coal is burned. On the other hand, the ash content of each coal type is also different and less ash is desired from the burned coal. Another issue is the gaseous emissions from coal-fired power plants which have been an important problem since the 1990s. Sulfur dioxide emissions that are produced from the burning of coal in the power plants cause the acid rain problem in nature. Hence, blending various grades of coal fuel is necessary to maintain reliable boiler operations, while satisfying environmental restrictions.

This study applied portfolio theory to the conventional purchasing approach and employed TPC as a case study. The proposed model was designed to minimize the purchasing cost of steam coal after adjusting price risk by considering both the present value of purchasing cost as well as variance in the purchasing cost. The model also considers limitations in the demand for coal, the upper limit of imports from specific sources, power plant operational requirements, and environmental constraints. Scenario analysis was performed using the proposed model, while taking into account a variety of factors. Finally, suggestions are provided according to the simulation results.

The paper is structured into seven sections. The following section provides a review of relevant literature. Section 3 introduces the current status and future trends related to coal in Taiwan. Section 4 provides a description of the model. Section 5 describes data sources. Section 6 presents the simulation results and the final section provides our conclusions.

2. Literature review

Early research efforts related to the purchase of coal concentrated on the optimal acquisition and blending of coal using linear programming, goal programming, and mixed integer programming techniques. Kondragunta and Walker (1984) demonstrated the use of linear programming to determine the coal acquisition requirements from multiple sources in order to generate the power required to serve load requirements. The objective was to serve the load at minimum cost, while satisfying SO_2 emissions and inventory constraints. SO_2 emission constraints were met by blending high and low sulfur coal. The linear programming approach can be used to determine the coal requirements in a cost effective manner. Lyu et al. (1995) presented a coal blending management system, which calculates the quantities of coal required from different stockpiles to maintain a consistent feed of blended coal, while meeting environmental and boiler performance requirements. Lai and Chen (1996) proposed a cost minimization model for the import of steam coal to Taiwan. The objective was to satisfy coal usage requirements at a minimum cost, subject to the company's internal policy, boiler requirements, and environmental standards, while reflecting actual operational constraints. That study demonstrated the use of mixed 0–1 integer programming to determine the coal acquisition requirement from multiple sources. Shih (1997) proposed a mixed integer programming model that plans and schedules coal imports from multiple suppliers. The objective was to minimize total inventory costs by minimizing costs for procurement, transportation, and holding. Constraints included company procurement policy, power plant demand, harbor unloading capacity, inventory balance equations, blending requirements, and safety stock.

Liu and Sherali (2000) presented a mixed 0–1 integer programming model for determining optimal shipping and blending combinations using coal from overseas suppliers. That study developed a procedure using heuristic rules in conjunction with branch-and-bound methods. The practicality of this approach was illustrated using real-world data collected from an electric power company. Liu (2008) proposed a coal blending and inter-modal transportation model to find optimal blending and distribution decisions for coal fuel from overseas contracts to domestic power plants. The objective was to minimize total logistics costs, including procurement cost, shipping cost, and inland delivery cost. The developed model was mixed 0–1 integer programming problem. A real-world case problem was presented using the coal logistics system of a local electric utility company to demonstrate the benefit of the proposed model. Results from this study suggested that the obtained solution was better than the rule-of-thumb solution and the developed model provided a tool for management to conduct capacity expansion planning and power generation options. Yucekaya (2013) developed a multi-objective model that considers multimode transportation alternatives, multiple coal products with different price and quality, and multiple suppliers for efficient coal supply of an electric power company with more than one plant at different locations. Constraints included the capacity limitations on transportation routes, supplier capacity for a particular product, product emission specifications, emission costs, and plant burn capability. Multi-objective linear programming and analytic hierarchy process were employed to solve the problem. The solution methodology was applied to a case study in the Midwestern United States. That study demonstrated that the proposed model can be used by the power companies to find a desired solution for their coal supply and hence generate power with coal of lower cost, lower emission, and ash.

These references used a variety of programming techniques to optimize the acquisition and blending of coal from multiple sources based on the least-cost approach. Recent price volatility in fossil fuels underlines the importance of price risk; however, none of these studies take into account the enormous price fluctuations to which the purchase of coal is subject.

One way to quantitatively determine the price risk is by means of portfolio theory. Portfolio theory has been used for decades in the financial sector to identify portfolios of bonds or assets capable of minimizing risk for a given level of profit (Roques et al., 2010). The foundation of portfolio theory was laid by Markowitz (1952). The basis of the theory states that by diversifying a portfolio of assets, the overall risk can be lowered compared to the risk of the individual assets (Delarue et al., 2011). A number of researchers have applied the theory of risk analysis to the energy market. One early application to the electricity sector was presented by Bar-Lev and Katz (1976). Awerbuch and Berger (2003) utilized this portfolio approach to consider an optimal generation mix for the European Union. They used an expected rate of return [MW h/€] (as an inverse of cost) and a given standard deviation (i.e. risk) on that return [MW h/€]. The authors further assumed a total amount of installed capacity and test different scenarios. Other examples that followed this approach have been presented in different countries, including the EU (Awerbuch and Berger, 2003; Awerbuch and Yang, 2007), Switzerland, the United States (Krey and Zweifel, 2006), Japan (Bhattacharya and Kojima, 2012), Italy(Arnesano et al., 2012), Spain (Muñoz et al., 2009), Turkey (Gökgöz and Atmaca, 2012) and China (Zhu and Fan, 2010).

The utilization of portfolio theory in a liberalized electricity market environment was described by Roques et al. (2008). Another example of making use of portfolio theory in the purchase of electricity was presented by Huisman et al. (2009). Other applications in the energy market have included marine technologies (Allan et al., 2011), cogeneration technologies (Westner and Madlener, 2010), and wind power (Roques et al., 2010; Rombauts et al., 2011). Despite the growing number of studies using portfolio

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theory in electricity planning problems or individual energy technologies, very little attention has been paid to strategies associated with the purchase of coal. No in-depth study has focused exclusively on coal purchasing strategies incorporating price risk. This study fills this gap in the literature by combining portfolio theory with the conventional model used in the purchase of coal.

In short, this paper complements the conventional coal purchasing model to minimize the purchasing cost of steam coal by adjusting price risk. The model also accommodates components of the conventional coal purchasing model including the demand for coal, the upper limit of imports from specific sources, power plant operational requirements, and environmental constraints. This allows us to analyze coal purchasing decisions in accordance with the actual operation of individual coal-fired power plants. Finally, the model was implemented in a case study of an electric utility company to illustrate the application of portfolio theory to the development of an appropriate purchasing strategy.

3. Overview of current status and future trend of coal in Taiwan

Coal is the cheapest and most abundant fossil fuel, and it is the primary fuel to generate electricity in many countries. Coal is the second largest energy contributor in Taiwan. Coal production in Taiwan summed up over five million metric tons annually from 1964 to 1968, afterward the production is to taper off due to increasing competition from imported coal and spiraling local production costs. Since Taiwan joined the World Trade Organization (WTO) in 2001, all of Taiwan's coal requirements have been met by foreign imports. Coal consumption in 2010 totaled 62.93 million metric tons. Steam coal makes up the largest proportion of these imports (84.26%) followed by coking coal (8.77%) for iron and steel production. Most of the steam coal[2] is used for power generation, followed by cement production and various other industrial uses. The expansion of nuclear capacity is unlikely, due to intense public pressure; therefore, for the foreseeable future, power demands will be met mainly from coal-fired, LNG-fired power plants, and to a limited extent, renewable energies.

Currently, the production of power in Taiwan is controlled by one state-owned utility (i.e. TPC), nine independent power producers, and a number of self-use power generation utilities including cogeneration and renewable energies. TPC provides 67.7% of the electricity in Taiwan, approximately 39% of which comes from coal. Between 70% and 90% of the coal imported by Taiwan is secured by long-term contracts, while the remainder is obtained from spot markets. The major sources are Indonesia, Australia, and China.

According to the long-term load forecasting and long-term power development programming issued by TPC (2012), coal requirements will rise from 26 million metric tons in 2010 to 42 million metric tons in 2020. Thus, the problem of securing a stable coal supply at a reasonable price is crucial. Currently, coal purchasing decisions are made mainly by experts based on experience, with little in the way of theoretical grounding.

This study provides a theory-supported framework, a portfolio theory based optimization model, which takes into account many characteristics of power plant operations, environmental constraints, and the price risk associated with the purchase of coal. We then apply the model to a case study of an electric utility company to formulate a coal purchasing strategy.

4. Methodology

4.1. Portfolio theory

Portfolio theory, based on Markowitz (1952) seminal work, was initially developed for financial securities and has found wide applications in the energy industry. Markowitz's portfolio theory is based on a mean-variance optimization which searches for an efficient portfolio that provides minimum risk for a given level of return or maximum return for a given level of risk. The main assumptions of the mean-variance analysis are based on the following issues (Gökgöz and Atmaca, 2012):

- All investors are risk averse so that they prefer less risk for the same level of the expected return.
- Investors have the information regarding the expected return, variance and covariance of all assets.
- Investors need only to know the expected return, variance and the covariance of returns to determine optimal portfolios.
- And there exist no transaction costs or taxes limitations.

Under these assumptions, the objective function and constraints of the mean-variance optimization model can be set as follows.

$$\text{Min}\sigma_{\text{p}}^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} X_i X_j \sigma_{ij}$$

Subject to

$$\sum_{i=1}^{N} X_i r_i = r_e$$

$$\sum_{i=1}^{N} X_i = 1$$

$$X_i \geq 0, \forall X_i \in \left[i = 1, 2, \ldots, N\right]$$

where N denotes number of assets in the portfolio; X_i denotes the proportion (weight percentage) of ith asset in portfolio; r_i denotes the expected return of ith asset; and σ_{ij} is the covariance between the returns on the ith asset and the jth asset. The required inputs necessary for this model are the expected return for each asset, the variance of each asset, and the covariance between assets.

With the solution of the mean-variance optimization model, the efficient frontier can easily be drawn but these results only produced possible solution sets. To reach the optimal solution, it is needed determination of utility function which represents investors' risk aversion level. Investors assign a utility score that reflect investors' risk aversion level to investment portfolios based on the expected return and risk of those portfolios. Combining two, a quadratic utility function can be determined in terms of the expected return, risk aversion level and variances of returns as follows.

$$U = E(r_p) - \frac{1}{2} A \sigma_p^2$$

Subject to

$$\sum_{i=1}^{N} X_i = 1$$

$$X_i \geq 0, \forall X_i \in \left[i = 1, 2, \ldots, N\right]$$

where

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[2] The paper focuses on the steam coal purchasing strategy (excluding coking coal). Henceforth steam coal is referred to coal in short.

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$$E(r_p) = \sum_{i=1}^{N} X_i r_i$$

$$\sigma_p^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} X_i X_j \sigma_{ij}$$

Here, U is the utility function value and A is representing the index of investor's risk aversion. The factor of 1/2 is a scaling convention. This quadratic programming problem is also applied in our proposed model, which combines the present value of purchasing cost and variance in the purchasing cost as the objective function.

In summary, portfolio theory has the advantage of explicitly capturing the benefits from diversification in the framework of risk-averse decision-making. For example, the conventional planning model suggests that optimal investments should focus on those technologies projected to have the least cost in the future. However, this ignores the potential of currently high-cost alternatives providing a more favorable risk profile. Hence, the portfolio theory has been employed with increasing frequency to account for risk reduction due to the portfolio diversification. However, some limitations associated with use of the portfolio theory should be acknowledged (Ambachtsheer, 2005; Bronshtein and Zav'yalova, 2006; Rockafellar et al., 2007; Vaclavik and Jablonsky, 2012; Xidonas et al., 2010). The theory assumes that asset returns are normally distributed random variables. Another major flaw in the theory relates to the static assumption that investors should allocate their assets if they only care about the mean and the variance of return over a single time period. However, this static setup prevents the construction of dynamic portfolios that properly address the progressive uncertainty. Despite some defects from the theory's assumptions, the portfolio theory is still a useful tool in modeling risk reductions in energy supply systems. Consequently, our study demonstrates the applicability of portfolio theory to solve conventional coal purchasing problems.

4.2. Model description

The portfolio theory based optimization model for coal purchasing portfolio represented a quadratic programming problem. The aim was to determine optimal coal acquisition from different methods and multiple sources, subject to quality and environmental restrictions, so as to satisfy demand at a minimum purchasing cost[3] after adjusting price risk. In other words, the objective was to minimize both the present value of purchasing cost and the risk in purchasing cost. In the model, risk was introduced for volatile coal prices. The constraints can be partitioned into five types: 1. demand for coal; 2. upper limit for imports from specific sources; 3. heating value restriction; 4. sulfur content restriction; 5. ash content restriction. The full model comprised the objective function that must be minimized, subject to constraints 1–5. The formulation of each part is described as followings. The details of input parameters, decision variables, and indices are summarized as the nomenclature listed in Appendix A.

4.2.1. Objective function

4.2.1.1. Present value of purchasing cost. $C_{i,j,t}$ represents the unit price of coal by procurement method i from source j during period t. Suppose that $C_{i,j,t}$ takes place at a given expected proportional rate ($\delta_{i,j}$) and with given expected variance of that rate (Huang and Wu, 2008; Wu and Huang, 2014; Zon and van Fuss, 2005, 2006).

We then have:

$$C_{i,j,t} = C_{i,j,0} \times e^{\delta_{i,j} \times t}$$

The positive (negative) value for the expected proportional rate ($\delta_{i,j}$) means that coal prices will increase (decrease) over time. Hence, the purchasing cost can be calculated by multiplying the unit price of coal ($C_{i,j,t}$), with the quantity of coal purchased ($X_{i,j,t}$). Through the discounted process, the present value (PV) of purchasing cost can be expressed as a following equation,

$$\mathrm{PV} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \frac{1}{(1+r)^t} \times C_{i,j,t} \times X_{i,j,t}$$

4.2.1.2. The risk in purchasing cost (the variance in purchasing cost). For a depletable resource such as coal, in addition to the level of the log price trajectory, its slope fluctuates over time in response to fluctuations in demand, extraction costs, and reserves (Pindyck, 1999). Hence, the unit price of coal takes place at a given expected proportional rate and with a residual (i.e. price volatility) as following equations.

$$C_{i,j,1} = C_{i,j,0} \times e^{\delta_{i,j} + \varepsilon_1^{C_{i,j}}}$$

$$C_{i,j,2} = C_{i,j,1} \times e^{\delta_{i,j} + \varepsilon_2^{C_{i,j}}}$$

....

$$C_{i,j,t-1} = C_{i,j,t-2} \times e^{\delta_{i,j} + \varepsilon_{t-1}^{C_{i,j}}}$$

$$C_{i,j,t} = C_{i,j,t-1} \times e^{\delta_{i,j} + \varepsilon_t^{C_{i,j}}}$$

Such that continuous iteration obtains

$$C_{i,j,t} = C_{i,j,0} \times e^{\delta_{i,j} \times t + \sum_{t=1}^{t} \varepsilon_t^{C_{i,j}}}$$

The residual ($\varepsilon_t^{C_{i,j}}$) is assumed to have zero expectation,[4] constant variance,[5] and is serially uncorrelated[6] (Huang and Wu, 2008; Wu and Huang, 2014; Zon and van Fuss, 2005, 2006). According to the assumptions, we have $E(\varepsilon^{C_{i,j}})=0$[7]; $E((\varepsilon^{C_{i,j}})^2)=\sigma_c^2$; $E(\varepsilon_t^{C_{i,j}} \cdot \varepsilon_{t-1}^{C_{i,j}})=0$.

By adding the above equation into our model, PV can be rewritten as

$$\mathrm{PV} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \frac{1}{(1+r)^t} \times C_{i,j,0} \times e^{\delta_{i,j} \times t + \sum_{t=1}^{t} \varepsilon_t^{C_{i,j}}} \times X_{i,j,t}$$

$\because e^{\mu} = 1 + \mu + \frac{\mu^2}{2!} + \frac{\mu^3}{3!} + \cdots$, when μ is small, $e^{\mu} \approx 1 + \mu$

Hence, a first-order approximation of PV is given as a following equation,

$$\mathrm{PV} \approx \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \frac{1}{(1+r)^t} \times C_{i,j,0} \times e^{\delta_{i,j} \times t} \times \left(1 + \sum_{t=1}^{t} \varepsilon_t^{C_{i,j}}\right) \times X_{i,j,t}$$

By reason of $\mathrm{Var(PV)=E[PV\text{-}E(PV)]^2}$

Based on the above assumption $E(\varepsilon^{C_{i,j}}) = 0$, and we can calculate E(PV) as a following equation,

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[3] Henceforth the purchasing cost of steam coal is referred to purchasing cost in short.

[4] In statistics, the expected value means the sum (for discrete variables) or integral (for continuous variables) of the product of a random variable with its probability density function, over its range of values. Zero expectation represents the expected value of the error term (or residual) is zero.

[5] In statistics, variance measures how far a set of numbers are spread out. Constant variance, also known as homoscedasticity, means that the error term has the same variance at different points in time.

[6] Serial correlation, also known as autocorrelation or cross-autocorrelation, is the cross-correlation of a signal with itself at different points in time. Serially uncorrelated means the residual does not have a serial correlation.

[7] Generally, the expected value of X is denoted by E(X).

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$$E(PV) \approx \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\frac{1}{(1+r)^{t}} \times C_{i,j,0} \times e^{\delta_{i,j}\times t} \times X_{i,j,t}$$

Using PV and E(PV). Then

$$PV - E(PV) \approx \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\frac{1}{(1+r)^{t}} \times C_{i,j,0} \times e^{\delta_{i,j}\times t} \times X_{i,j,t} \times \sum_{t=1}^{t}\epsilon_t^{C_{i,j}}$$

Suppose $\frac{1}{(1+r)^t} \times C_{i,j,0} \times e^{\delta_{i,j}\times t} \times X_{i,j,t} = B_t^{i,j}$; $Q_t^{i,j} = \sum_{t=1}^{t}\epsilon_t^{C_{i,j}}$, then

$$Var(PV) = E(PV - E(PV))^2$$

$$= E\Big[\sum_{i_1=1}^{I}\sum_{j_1=1}^{J}\sum_{t_1=1}^{T}\left(B_{t_1}^{i_1,j_1} \times Q_{t_1}^{i_1,j_1}\right)$$

$$\times \sum_{i_2=1}^{I}\sum_{j_2=1}^{J}\sum_{t_2=1}^{T}\left(B_{t_2}^{i_2,j_2} \times Q_{t_2}^{i_2,j_2}\right)\Big]$$

$$= \sum_{i_1=1}^{I}\sum_{j_1=1}^{J}\sum_{t_1=1}^{T}\sum_{i_2=1}^{I}\sum_{j_2=1}^{J}\sum_{t_2=1}^{T}\left(B_{t_1}^{i_1,j_1} \times B_{t_2}^{i_2,j_2} \times E\left(Q_{t_1}^{i_1,j_1}.Q_{t_2}^{i_2,j_2}\right)\right)$$

$$= \sum_{i_1=1}^{I}\sum_{j_1=1}^{J}\sum_{t_1=1}^{T}\sum_{i_2=1}^{I}\sum_{j_2=1}^{J}\sum_{t_2=1}^{T} \min\left(t_1, t_2\right) \times B_{t_1}^{i_1,j_1} \times B_{t_2}^{i_2,j_2} \times \sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$$

If $i_1=i_2$and $j_1=j_2$ then $\sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$is the variance; otherwise $\sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$is the covariance. In addition, min(t_1,t_2) represents the minimum of t_1 and t_2. The minimum function arises here since there can only be non-zero correlation between two sums of residuals over different periods of time to the degree that these periods of time are overlapping. In other words, the non-contemporaneous correlation between residuals is zero. Hence, the time-length of common period between both residuals would be the minimum of t_1 and t_2.

After combining the present value of purchasing cost and variance in the purchasing cost, we can obtain the objective function called “the purchasing cost of steam coal after adjusting price risk”. That is,

Minimize: $Z = PV + \lambda \times Var(PV)$

λ is the risk-averse parameter. It also represents the relative contribution of the variance in purchasing cost in the objective function. If λ is zero, the price risk will be excluded from the sources of portfolio. The higher value means the more risk-averse the investor has.

4.2.2. Constraints

This model is subject to five types of constraints, which are explicated by mathematical models shown as followings

Constraint 1: Demand for coal

$$\sum_{i=1}^{I}\sum_{j=1}^{J} X_{i,i,t} = D_t\ (t = 1\ldots T)$$

This constraint of total quantity of coal purchased must meet the demand for coal during the planning stage.

Constraint 2: An upper limit for imports from specific sources

$$\sum_{i=1}^{I} X_{i,i,t} \le \left(\sum_{i=1}^{I}\sum_{j=1}^{J} X_{i,i,t}\right) \times U_{j,t}\ (j = 1\ldots J,\ t = 1\ldots T)$$

The term $\sum_{i=1}^{I}\sum_{j=1}^{J} X_{i,i,t}$multiplied by $U_{j,t}$ refers to the upper limit of coal purchased from source j in period t. Hence, the constraint represents the fact that the amount of coal imported from a certain source should not exceed the upper limits. For coal supply, Taiwan relies entirely on imports; the constraint prevents to import massive coal from a certain source and reduces the risk of interruption.

In order to increase the efficiency of boilers and meet increasingly stringent environmental emission standards, the quality of coal is also considered in the model (Constraint 3–Constraint 5).

Constraint 3: Heating value restriction

$$\sum_{i=1}^{I}\sum_{j=1}^{J} H_j \times X_{i,j,t} \ge \sum_{k=1}^{K} LH_k \times X_{t,k}\ \ (t = 1\ldots T)$$

Heating value influences the energy output, such that the higher heating value means the more energy output the coal had. The heating value of each power plant is constrained by the lower bound of the heating values required to maintain boiler performance.

Constraint 4: Sulfur content restriction

$$\sum_{i=1}^{I}\sum_{j=1}^{J} S_j \times X_{i,j,t} \le \sum_{k=1}^{K} US_k \times X_{t,k}\ \ (t = 1\ldots T)$$

Sulfur dioxide emissions are a primary environmental concern for coal-fired power plants. This constraint ensures that the sulfur content of coal remains below the upper limit of sulfur content allowed by the *k**th* power plant.

Constraint 5: Ash content restriction

$$\sum_{i=1}^{I}\sum_{j=1}^{J} A_j \times X_{i,j,t} \le \sum_{k=1}^{K} UA_k \times X_{t,k}\ \ (t = 1\ldots T)$$

The lower ash content means the higher energy efficiency will be accompanied. The ash content of each power plant is constrained by the upper bound of ash content required to maintain the boiler efficiency.

5. Data sources

The proposed optimization model focuses on strategies for purchasing coal under various price risks. The model deals primarily with supply-side data, such as the correlation coefficient matrix of coal prices between long-term contracts and spot market prices, pertaining to multiple sources and levels of quality. Details related to data sources are presented in the following sections.

5.1. Price and quantity data

TPC can purchase coal via long-term contracts and short-term

Table 1
Initial price and price growth rate of coal from various sources and various purchasing channels.

Import sources/Procurement methods	Initial date	Period	Initial price (USD per metric ton)	Growth rate of price[a] (%)
Indonesia/contract	2002/01/01	2002–2010	24.29	1.86
Indonesia/spot market	2002/01/01	2002–2010	25.69	1.22
Australia/contract	2002/01/01	2002–2010	35.40	1.32
China/contract	2002/01/01	2002–2010	29.94	8.83
China/spot market	2002/01/01	2002–2010	26.12	7.57

[a] The growth rate of price is in an annual basis.

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Table 2
Correlation matrix of coal prices.

Import sources/ Procurement methods	Indonesia/ contract	Indonesia/ spot market	Australia/ contract	China/ contract	China/ spot market
Indonesia/ contract	1	0.6298	0.8596	0.4554	0.5714
Indonesia/spot market	0.6298	1	0.5991	0.5641	0.1712
Australia/ contract	0.8596	0.5991	1	−0.0635	−0.3976
China/contract	0.4554	0.5641	−0.0635	1	0.8372
China/spot market	0.5714	0.1712	−0.3976	0.8372	1

spot market transactions. Due to the complexity of the pre-qualification process, the imported sources only includes Indonesia, Australia and China. Thus, there are six combinations in Table 1. In addition, price data for various contracts and spot markets were provided by TPC (2010) to estimate price growth rates, as shown in Table 1. Historical data of coal prices were estimated growth rates.

5.2. *Correlation matrix of coal prices*

A correlation matrix[8] derived from the historical data of coal prices is presented in Table 2. This matrix was calculated according to contracts signed by TPC as well as spot market prices between year 2002 and 2010 (a total of 247 data).

5.3. *Demand for coal in individual power plants*

There are five coal-fired power plants using coal to generate electricity in TPC. Coal demand at Shenao power plant from 2008 to 2010 was zero due to service suspension from 2008. Coal usage in all other power plants is shown in Table 3.

5.4. *Properties of coal used in individual power plants*

Each power plant is subjected to unique limitations as to the properties of the coal consumed; therefore, we have also incorporated the quality requirements for coal used in each power plant. These limitations were obtained from the Steam Coal Allocation Plan provided by TPC (2010). The limitations of coal properties in each power plant are summarized in Table 4.

5.5. *Coal properties of different sources*

This study also took into account the properties of coal imported from various sources, according to the Steam Coal Allocation Plan provided by TPC (Table 5). As shown in Table 5, this covers wide properties. This study adopted a conservative approach, including the lowest heating value, the highest sulfur and ash contents. For instance of Australian case, the study utilized heating value of 6100 kcal/kg, sulfur content of 0.7% and ash content of 16%.

5.6. *Other parameters*

The discount rate (r) remains constant at 5%,[9] and the modeling period is 9 years, from 2002 to 2010.

6. Results

6.1. *Scenario design*

The study purpose was to evaluate the strategy employed by TPC for purchasing coal under various price risks. We sought to determine whether the portfolio of imported coal corresponds to the portfolio of coal imported by TPC between 2002 and 2010. Furthermore, parameters related to risk-aversion were applied to reveal the price risk inherent in the purchasing cost. Historical coal purchasing data gathered from TPC to simulated TPC's risk-aversion parameter.[10] Fig. 1 presents the simulation results, in which TPC's risk-aversion parameters fell between 0.75 and 3.

In the following, we present the simulation scenarios employed in this paper.

Case 0 (C0) is the baseline scenario used to examine annual coal purchasing portfolios under the least-cost principle (i.e. the risk-aversion parameter setting at 0) and objective function without considering the impact of price risk. Cases 1–4 (C1-C4) explore differences in the coal purchase according to different level of risk aversion with risk-averse parameters set at 0.75, 1, 2, and 3. The settings complied with the simulation results of TPC's risk-aversion parameters, gradually increase and reflect the influence of risk-aversion parameters on the coal purchasing portfolio.

Heating value influences energy output and can cover a wide range. Case 5 (C5) outlines the influence of altering operational requirements on the portfolio of imported coal. Case 5 set the heating value requirement of each power plant to increase 3% from its original value, while the risk-averse parameter was at 0.75 to exploit the impact of increasing the power plant's operation requirements on the coal purchasing portfolio. The parameters adopted for the simulations are summarized in Table 6.

6.2. *Simulation results*

The proposed model was programmed in GAMS (General Algebraic Modeling System) (Brooke et al., 2005) and results were obtained using the non-linear problem (NLP) solver MINOS. The model involves 165 variables and 228 equations.[11] It is solved with an exact algorithm which is provided by MINOS solver within several minutes. Fig. 2 illustrates the proportion of coal imports during the planning stage. Minimizing purchasing costs was the objective in this scenario (C0). The purchase of coal from Indonesian contracts gains precedence over coal from other import sources due to low cost, accounting for between 60% and 68% of the total. In contrast, a proportion of coal purchased from Chinese spot markets for blending would help to meet power plant operational requirements and environmental emission standards. Coal from Australian and Chinese contracts is uncompetitive due to high purchasing cost, such that the quantities purchased remained at zero throughout the planning period. At the end of the

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[8] As mentioned in “the risk in purchasing cost” section, we need a variance-covariance matrix to calculate the variance in purchasing cost. However, we can easily convert a correlation matrix to a variance-covariance matrix using commercial software (such as MATLAB, R).

[9] The discount rate (5%) was determined by employing actuarial methods to

(*footnote continued*)
calculate the most recent 10-year treasury rate (1.3%), which represents the risk-free interest rate and risk premium (3.7%).

[10] Actually, according to economic theory, the real risk-adverse parameter of TPC should be derived from its utility function through first-order and second-order differential equations. However, due to the lack of relevant data for deriving the unity function, alternatively, the simulation method is utilized to obtain TPC's risk-aversion parameter.

[11] Due to one decision variable ($X_{i,j,t}$) and scarce importers, the number of decision variables and equations is somewhat limited. However, the proposed model programmed in GAMS can easily be expanded from smaller to larger data sets.

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Table 3
Demand for Coal in each power plant.[a]

Power Plants/Year	Linkou (2 units)	Shenao (3 units)	Taichung (10 units)	Dalin (2 units)	Hsinta (4 units)	Total demand
2002	1,392,680	1,277,663	13,101,034	1,539,871	5,704,303	23,015,550
2003	1,443,283	1,324,087	13,577,066	1,595,823	5,911,571	23,851,831
2004	1,479,419	1,357,239	13,916,997	1,635,778	6,059,580	24,449,012
2005	1,594,217	1,462,555	14,996,907	1,762,708	6,529,782	26,346,169
2006	1,674,342	1,536,064	15,750,655	1,851,302	6,857,970	27,670,334
2007	1,709,048	1,567,904	16,077,138	1,889,677	7,000,124	28,243,890
2008	1,801,106	0	17,514,071	2,067,495	5,567,327	26,950,000
2009	1,795,092	0	17,455,582	2,060,591	5,548,735	26,860,000
2010	1,812,000	0	17,620,000	2,080,000	5,601,000	27,113,000

[a] Unit: metric tons.

Table 4
Limitations regarding the properties of the coal used in each power plant.

Properties/Power plants	Heating value (kcal/kg)	Sulfur content (%)	Ash content (%)
Linkou	5800	0.4–1.5	18
Shenao	5800	0.8–1	18
Taichung	5900	0.4–1.5	12
Dalin	5800	0.4–1.5	18
Hsinta	5800	0.4–1.5	18

Table 5
Properties ofcoal obtained from various sources.

Import sources	Types of steam coal	Heating value (kcal/kg)	Sulfur content (%)	Ash content (%)
Indonesia	Bituminous coal	5500–6100	0.3–0.6	4–6
	Sub bituminous coal	5000–5500	0.5–0.9	4–6
	Envirocoal	5000–5300	0.1–0.2	1–3
Australia	Bituminous coal	6100–6400	0.4–0.7	14–16
China National Coal	Bituminous coal	6200	0.3–0.5	7–10
China Ganghua	Bituminous coal	6050–6200	0.3–0.5	7–10

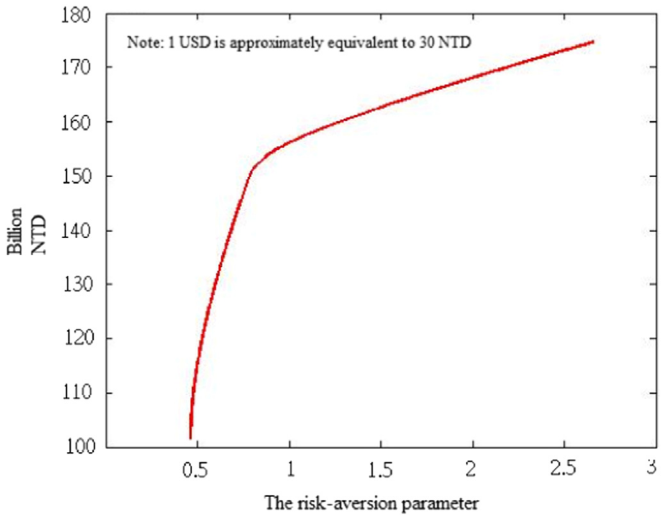

Fig. 1. Risk-aversion parameters related to the Taiwan Power Company.

Table 6
Parameters adopted for the simulations.

	Considering price risk impact				
Scenarios	Case0 (C0)	Case1 (C1)	Case2 (C2)	Case3 (C3)	Case4 (C4)
Risk-aversion parameters	0	0.75	1	2	3
	Alteration to operational requirements of power plants				
Scenarios	Case5 (C5)				
Risk-aversion parameters	0.75				
External factors change	Heating value requirement of each power plant following an increase of 3% from its original value				

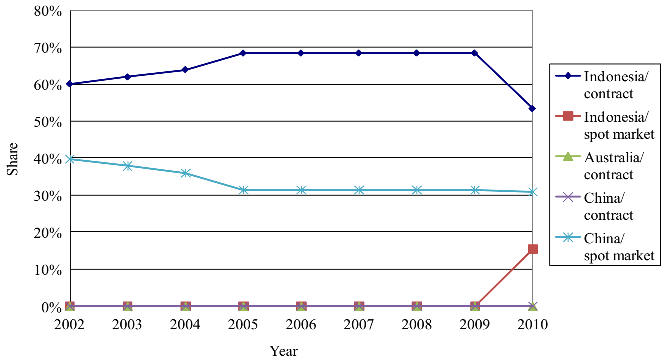

Fig. 2. Share of coal purchasing in the least-cost scenario (C0).

planning period, the proportion of coal from Indonesian spot markets increased due to prices below those of coal from the Indonesian contract. In short, the decision to purchase coal strong depends on purchasing costs and the quality of coal required to meet the operational requirements and environmental emission standards of power plants. Without accounting for price risk, coal from Indonesian contracts and China spot markets accounts for the lion's share of total coal imports.

Taking price risk into consideration, the percentage change of each scenario (C1-C4) is inconsequential, regardless of changes in the risk-aversion parameters. This is because coal purchases are restricted by heating value, sulfur content and ash content limitations to meet the practical operation of each power plant. In addition, as a state-owned power company, the coal procurement executed by TPC is governed by the Taiwanese Government Procurement Act, such that the long-term contracts for imported coal must meet prequalification. The prequalification evaluation deals with coal reserves, the minimum acceptable quality specifications and delivery performance as well as spot checks of the mining area. The complexity of these regulations severely limits the number of potential suppliers.

To sum up, the coal purchase according to the risk level (C1-C4) is constrained by numerous limits like heating value, sulfur and ash content as well as qualifications. Changes remain insignificant regardless of risk-averse parameters; therefore, a risk aversion parameter of 0.75 (Fig. 3) is provided only as a reference.

Next, we provide comparative analysis of coal purchasing with

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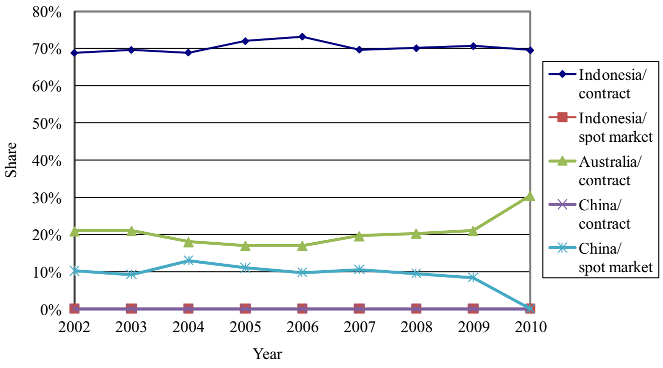

Fig. 3. Share of coal purchases considering impact of price risk (C1).

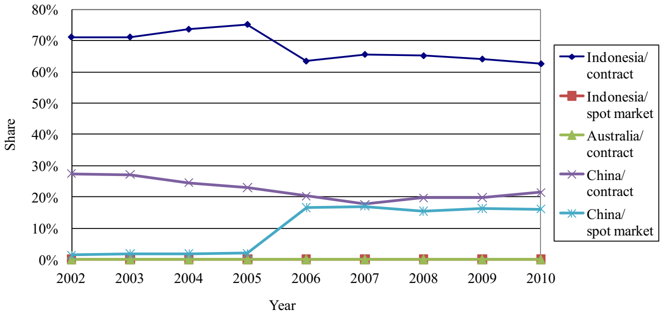

Fig. 4. Coal purchasing behavior following a 3% increase in required heating values (C5).

and without consideration of price risk (i.e. a comparative analysis between Figs. 2 and 3). When price risk is taken into account, the proportion of coal from China spot markets (high price risk) is replaced with coal from Australian contracts (more stable price). Reducing the proportion of coal from spot markets and increasing coal from long-term contracts reduces cost volatility. When price risk is not taken into account, approximately 30% of coal is obtained from spot markets; when price risk is taken into account this share is reduced to 10% (90% from long-term contracts).

We also look at the influence of changes in the operational requirements of the power plants. Fig. 4 shows that the proportion of coal purchased from various sources changes when the heating value requirement is increased. As a result, coal obtained from Indonesian contracts drops (lower heating value), while the proportion of coal from Chinese contracts (higher heating value) replaces the coal from Australia under the conservative constraints adopted in the study (see Table 5). To require an increase of heating value, coal is first supplemented by Chinese contracts, and then by the Chinese spot market.

In conclusion, incorporating price risk within the conventional coal purchasing model creates a preference for coal from long-term contracts (less risk). Our simulation results correspond to the current purchasing strategies of TPC. For example, in 2009, 86.37% of all imported coal was secured by long-term contracts.

Our results also illustrate that despite differences in risk level, changes in purchasing behavior are limited by inflexible coal purchasing strategies associated with the selection of import sources. In the future, strict qualification requirements should be relaxed in order to increase the number of supply sources, thereby taking advantage of the benefits provided by the incorporation of portfolio theory in the proposed model.

7. Conclusions

Traditional coal purchasing models apply the least-cost method to minimize purchasing, transportation and holding costs. This approach disregards the enormous price fluctuations to which coal is susceptible. Recent price volatility in fossil fuels highlights the critical issue, price risk. For Taiwan, high as 99.3% and 100% of energy and coal, respectively, are imported in 2010. Under such circumstance, integrating price risk into a coal purchasing framework is a critical issue.

No previous in-depth study has focused exclusively on coal purchasing strategies that incorporate with price risk. This study fills this gap in the literature by combining portfolio theory with the conventional coal purchasing model. This study provides a theory-supported framework, a portfolio theory based optimization model, which takes into account many characteristics of power plant operations, environmental constraints, and upper limit of imports from specific sources. This enabled us to analyze the coal purchasing decisions required for the operation of individual coal-fired power plants.

Simulation results show that changes in purchasing decisions are constrained by regulations related to heating value and sulfur and ash content as well as a strictly selected tendering process, demonstrating the inflexibility associated with the coal purchasing strategies of TPC. Portfolio theory requires a high degree of substitutability; however, the coal purchasing portfolio of TPC is inflexible. Related restrictions (e.g. strict qualification requirements) must be relaxed to increase the number of available sources and take advantage of the benefits provided by the proposed model.

We also presented a comparative analysis of purchasing decisions with and without the consideration of price risk. Under least-cost principle, approximately 30% of coal is obtained from spot markets; with price risk consideration, this figure drops to 10% (90% from long-term contracts). Clearly, incorporating with price risk in the conventional coal purchasing model enhances the appeal of long-term contracts, which reduce exposure to fluctuations in coal prices. Incorporating with price risk within the conventional coal purchasing model creates a preference for coal from long-term contracts (less risk). These results correspond to the current purchasing strategies of TPC, in which most of the imported coal was secured by long-term contracts.

The significance of our research is to introduce the dimension of price risk in a conventional coal purchasing model. Under the circumstance, the objective function is no longer based on the least-cost principal but considers the risks associated with fluctuations of coal price. There are no country-specific constraints included in the model formulation. The general model can be universally applied to any electric company, provided essential data for operating model. Therefore, coal purchasing portfolio can be clear identified based on a theory-supported framework as demonstrated herein.

The model developed in this paper is a preliminary tool to formulate an optimization model based on portfolio theory. Further research can be focused in potential improvements of the model in several directions. Promising issues include in particular:

(1) Relaxing some of the assumptions associated with conventional portfolio theory (e.g. the normal distribution assumption of coal prices) could make the outcomes more realistic.
(2) Additional disaggregated data for the parameters could enhance the applicability of the model.
(3) The price growth rates used in the model is in an annual basis. However, this setup prevents the construction of dynamic portfolios that properly address the progressive uncertainty of coal prices in recent years. Therefore, Dynamic Asset Allocation Theory could be integrated to the proposed model in future work so that the results can reflect dynamic portfolio strategies for purchasing coal.

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Appendix A

Nomenclature

Sets, subsets and indices

$i \in I$ procurement methods (i.e. purchasing through long-term contracts or spot market)
$j \in J$ procurement sources
$t \in T$ time period ($t=0$ means the initial period)
$k \in K$ power plants

Parameters

$C_{i,j,t}$ the unit price of coal by procurement method i from source j during period t
$C_{i,j,0}$ the initial price of coal by procurement method i from source j
$\delta_{i,j}$ the expected proportional rate of change of the unit price of coal
$\varepsilon_t^{Ci,j}$a residual (price volatility) of the unit price of coal procurement method i from source j during period t
$\sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$If $i_1=i2$and $j1=j2$ then $\sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$is the variance in purchasing cost; otherwise $\sigma_{t_1,t_2}^{i_1,i_2,j_1,j_2}$is the covariance between purchasing cost
D_t demand for coal in period t
$U_{j,t}$ the upper percentage limits on the total purchase amount from source j during period t
H_j the average heating value of coal from source j
LH_k the lower limit of heating value in the k*th* power plant
S_j the sulfur content of coal from source j
US_k the upper limit of sulfur content allowed by the k*th* power plant.
A_j the ash content in coal from source j
UA_k the upper limit of ash content produced by the k*th* power plant
$\lambda$the risk-averse parameter

Constants

r discount rate

Variables

$X_{i,j,t}$ quantity of coal purchased by procurement method i from source j during period t.

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