지속가능경영

Evaluation on Large-scale Biowaste Process: Spent Coffee Ground Along with Real Option Approach

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Abstract

This study aims to introduce a biowaste processing system that uses spent coffee grounds and implement a real options method to evaluate the proposed process. Energy systems based on eco-friendly fuels lack sufficient data, and thus along with conventional approaches, they lack the techno-economic assessment required for great input qualities. On the other hand, real options analysis can estimate the different costs of options, such as continuing or abandoning a project, by considering uncertainties, which can lead to better decision-making. This study investigated the feasibility of a biowaste processing method using spent coffee grounds to produce biofuel and considered three different valuation models, which were the net present value using discounted cash flow, the Black-Scholes and binomial models. The suggested biowaste processing system consumes 200 kg/h of spent coffee grounds. The system utilizes a tilted-slide pyrolysis reactor integrated with a heat exchanger to warm the air, a combustor to generate a primary heat source, and a series of condensers to harness the biofuel. The result of the net present value is South Korean Won (KRW) -225 million, the result of the binomial model is KRW 172 million, and the result of the Black-Scholes model is KRW 1,301 million. These results reveal that a spent coffee ground-related biowaste processing system is worthy of investment from a real options valuation perspective.

Keywords : Biowaste process, Spent coffee ground, Net present value, Real option, Economic assessment

1. Introduction

Energy production systems based on fossil fuels generate greenhouse gases such as carbon dioxide [1]. Further, energy transition to new and renewable energy sources is becoming more critical [2]. Biomass has strong advantages over other renewable sources as it includes organic materials from plants to organic wastes. Biofuels obtained from biomass consist of three different generations: first-generation biofuels are obtained from biomass that is generally edible; second-generation biofuels are obtained from a wide range of feedstock, and third-generation biofuels are obtained from algal-related biomass [3].

Spent coffee ground (SCG) as a raw material can play an imperative role in producing second-generation biofuels [4]. According to the statement of Korean Ministry of Environment, approximately 149,000 tons of SCG were wasted in 2019, which was 1.6 times the amount in 2012; this indicates that large amounts of SCG are available for use in bioenergy systems [5]. Moreover, one study has demonstrated that the biodiesel derived from SCG outperforms other biowaste-based biodiesels [6].

Various SCG-based biodiesel production systems, such as esterification technology, exist; however, the tilted-slide pyrolysis reactor has been recently highlighted for its great feasibility after economic assessment [7]-[9]. Steps in the development of large-scale processes rely on imagining, incubating, demonstrating, promoting, and sustaining, and the major activity in-between steps is to provide specific strategies for decision-makers to keep continuing the process development [10], [11].

As such, valuation methods from an economic perspective (e.g., benefic-cost ratio, net present value [NPV], internal rate of return, payback period method, real options) must be implemented to determine the feasibility of proposed technologies or processes [12], [13]. The benefit-cost ratio is used to determine economic feasibility

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if the ratio is >1 [14]. NPV indicates the difference between the present value of cash inflows and the present value of cash outflows over a certain period. NPV scores directly relate to investment valuation, indicating whether the projected worth of a company is positive or negative. However, it does not consider the size of the investment, which means that it is not useful for comparing projects of different sizes [15]. The internal rate of return, also knowns as a discount rate, aims to estimate the profitability of potential investments to make sure that the NPV of all possible cash flows equals zero in a discounted cash flow (DCF) [16]. In the payback period method, the payback period refers to the necessary time to earn back the invested amount to assess investment opportunities and risk [17].

While conventional valuation methods are based on a few scenarios, real options valuation integrates diverse uncertain situations, which would result in flexible valuations for decision-makers [18]. Therefore, projects incorporating uncertainties related to a technology investment should be reviewed in terms of a real options approach [19]. Regarding a business valuation throughout the investment lifecycle, the real options method can be extended for investment management services, scenario analysis, and key performance indicators. The real options approach suggesting several options may be more comprehensive than traditional valuation methodologies from the perspective of economic assessment [18].

It is crucial to evaluate the economic feasibility of large-scale projects. Therefore, this study aimed to 1) investigate a large-scale biowaste-to-biofuel processing system using SCG and 2) employ the real options method to implement economic assessment. In the case of renewable processes, various available scenarios are required (e.g., timing options, scale change options, switching options, abandon options, and design options) because of the inevitable uncertainties of starting a new business related to renewable sources of energy.

The study was organized as follows. Section 2 provides information on the SCG-based biofuel production process and theories on economic assessment. Section 3 describes the case study of a large-scale biowaste-to-biofuel plant including relevant parameters and assumptions. Section 4 shows the results of real options and situational assessments (i.e., strengths, weaknesses, opportunities, and threats analysis).

2. Material and methods

Figure 1 displays a general framework of this study, indicating that the main steps are to 1) analyze the target material and process and 2) conduct and compare different economic assessments to evaluate the proposed system.

2.1. Spent coffee ground

The main components of SCG and its range are displayed in Table 1 [20], [21].

When the components of different types of coffee beans were analyzed, the main components were mannose, galactose, glucose, and arabinose. Among them, mannose and galactose accounted for the majority [20], [21]. These differences in the chemical

Table 1. Primary components of SCG and approximate ranges thereof

	Mannose	Galactose	Glucose	Arabinose
Range [%]	46.8–57	26–30.4	11–19	3.8–6

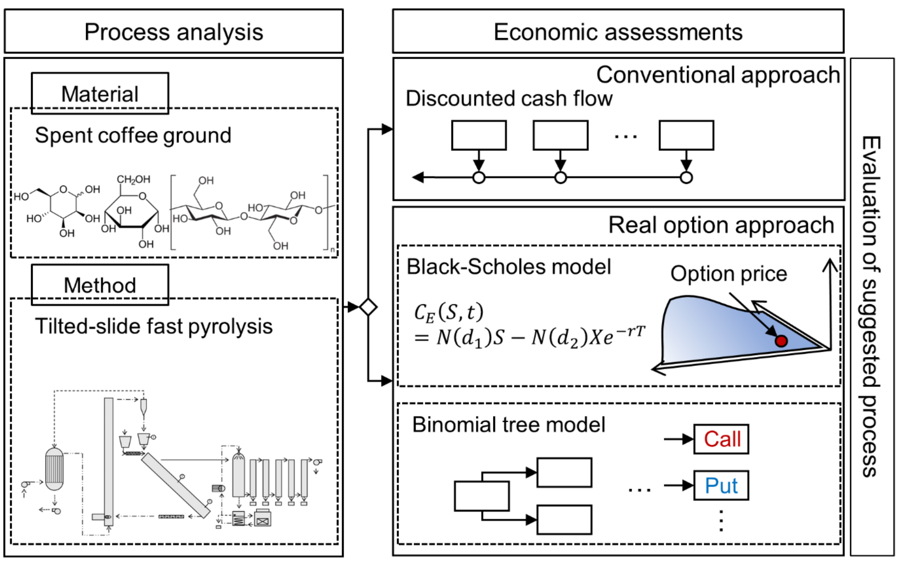

Figure 1. A general framework of this study.

composition of SCG appear to be due to the different types of coffee beans and processes used for roasting [22].

Table 1 shows that although the SCG ratio varies slightly based on the type of SCG, the degree of the ratio remains consistent across all types. Therefore, regardless of the type of coffee beans, almost all of types of SCG can produce biocrude.

In this study, a tilted-slide fast pyrolysis reactor was selected among biodiesel production methods using SCG. The reactor was designed in an inclined descending structure, so that when the coffee grounds fall, they can more efficiently contact the hot sand, which is the heating medium. When biomass and hot sand are introduced into the process, the biomass is rapidly pyrolyzed and descends to the bottom of the reactor. SCG starts rubbing with sand that has been heated to around 500 ℃, which transforms into steam in the absence of air. When this steam is collected and cooled, it becomes biocrude oil. The fast pyrolysis gas is condensed while passing through a multistage condenser in which direct and indirect condensers are combined. First, the cooled biocrude oil is directly sprayed into the pyrolysis steam. The steam phase in this situation transforms into liquid biocrude oil. In order to optimize the yield of biocrude oil, an indirect cooling procedure is used to capture most steam as biocrude oil. To reduce waste, the charcoal powder produced as a byproduct of the reaction process was further burnt and used to heat the sand [9]. Strong benefits of this method include the fact that no additional materials are required and that biodiesel may be constantly extracted owing to the recyclable sand. In this process, SCG with a relatively high hydrogen content was used. Therefore, triglyceride and tannin, which are extract components, were added to the research findings to approximate the component results and provide more accurate component data. The SCG elemental analysis findings informed the usage of additional parameters, and the following results were attained as a consequence of depicting the representative components in a carbon-hydrogen graph (Table 2) [23].

Table 2. Main components in the spent coffee ground [23]

Component	Composition [wt%]
Cellulose	36.65
Hemicellulose	16.08
Lignin-H	8.36
Lignin-O	10.80
Lignin-C	2.89
Triglyceride	19.82
Tannin	-
Ash	3.40
Moisture	2.00
Total	100

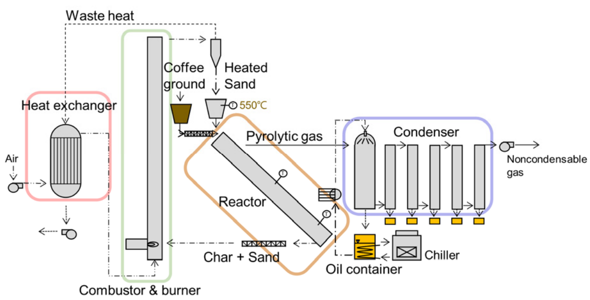

Figure 2. Simplified diagram of tilted-slide fast pyrolysis systems for biomass processing based on SCG [8].

2.2. Discounted cash flow to calculate the net present value

The DCF method is the most commonly used analysis method for investment decision-making for a specific project. One of the most popular DCF methods is the NPV method [24].

NPV is the present value of net cash flows, which is the value obtained by subtracting the present value of cash outflows, such as investments, from the present value of net cash inflows. If certainty is taken into account, NPV can be regarded as legitimate [25]. The basic NPV formula is as follows: [26]

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r_d)^t} - C_i \approx PV \times e^{-r_d t} - C_i \times e^{-r_d t} \tag{1}$$

$$PV = \sum_{t=1}^{T} \frac{C_t}{(1+r_d)^t} \tag{2}$$

Here, C_t is the cash flow, C_i is the initial investment cost, and r_d is the discount rate. When it comes to the discount rate, it alternates with the weighted average cost of capital (WACC) [27]. WACC is a concept calculated by the weighted average of the cost of other people's capital and own capital among the methods of raising capital [28]. The WACC formula is as follows: [29].

$$WACC = R_e \frac{E}{V} + R_d (1 - T_c) \frac{D}{V} \tag{3}$$

$$V = E + D \tag{4}$$

$$R_e = R_f + \beta (R_m - R_f) \tag{5}$$

In equations (3) ~ (5), E is the market value of the firm's equity, D is the market value of the firm's debt, R_e is the cost of equity or expected return of investment, and R_d is the cost of debt, T_c is the corporate tax rate, R_f is the risk-free rate, and β is the beta of the investment. Traditional economic analysis methods can be used effectively in some projects, but are not suitable for projects with large volatility of investment variables and market uncertainty [30]. NPV-based DCF assumes that the future probability distribution of the cash flow and related variables of the project to be invested is the same as at the initial decision-making point. This is equivalent to assuming that, regardless of changes in the internal or external environment, a manager's investment choice or company strategy would remain the same throughout the planning period [19].

In other words, before investing, the fixed interest rate and rate of return forecast future outcomes. Assuming that the subject of analysis is exposed to many changes in government policy and is vulnerable to the impact of international financial markets and climate change, since it is difficult to modify cash flows that have already estimated, management or managerial flexibility that can adapt or change subsequent decision-making in response to unexpected changes in market conditions cannot be properly reflected in the valuation [24]. For example, it is becoming increasingly difficult to evaluate the economics of investments in bioenergy initiatives. This is because there is a significant amount of profit uncertainty as a result of shifting governmental policies, fluctuating equipment costs brought on by the rapid advancement of bioenergy technology, and specific issues with the supply of raw materials [26].

Therefore, since most future situations proceed differently from the forecast, it is necessary to continuously alter the plan to adapt to these variations. To reflect this, many recent studies apply real options analysis to the economic analysis of bioenergy projects. Based on the assumption that project and market risks would impact future cash flows and cause project profitability to fluctuate, real options analysis examines the economic viability of a project [31].

2.3. Real options valuation

2.3.1. The concept of real options methodology

An option is a right to select the benefits of a promised transaction based on the market's current situation and the investor's unique situation. At this time, the buyer pays the option premium in exchange for the seller's obligations as the buyer/seller he exercises their rights. As such, options give the buyer a right and the seller an obligation. Therefore, in the market, a certain option price, called option premium, is formed by reflecting factors such as the price of the underlying asset, strike price, remaining period, price volatility, risk-free interest rate, and income such as dividends or interest. In a transaction, a call option is an optional right to buy or not to buy a specific asset at a pre-agreed price (also known as the strike price) to the option buyer within a certain period. Examples include extension, postponement, step, and exclusive options. Conversely, the option to sell or not sell is called a put option, and examples include reduction and liquidation options [32].

Table 3. Comparison of conventional valuation methods and real options approach

	Cash flow reflection	Consideration of risk	Multi-period analysis	Flexibility in decision-making
Real options	O	O	O	O
NPV	O	O	O	X
Decision analysis	O	X	O	O
Economic benefit	O	O	X	X

The real options theory begins with the understanding that uncertainty presents investment possibilities and applies options theory to the assessment of actual physical assets rather than financial assets. In other words, while existing theories regard uncertainty as an object to be avoided or minimized, the real options theory evaluates it as an opportunity factor that can be actively utilized as an object that creates new opportunities. In this respect, the approach through real options is emerging as a more persuasive method than the existing theory in measuring and specifying the value of a company under uncertainty (Table 3). Therefore, real options is widely applied as an approach to new contracts and market creation in various industries, including the energy industry [32].

As a result, the real options approach evaluates the flexibility of investment decision-making according to changes in the future business environment faced by corporate decision-makers as very valuable. By enabling them to react quickly, it provides investment possibilities rather than eliminating these risks [32].

Forecasting volatility and choosing the right options type are essential for effective options analysis. When examining option prices, it is crucial to identify the project's uncertainty and anticipate return volatility. Economic analysis based on real options begins with the evaluation of the degree of impact because the uncertainty of a project can have either a positive or negative influence on profitability. The method of obtaining volatility is the log cash flow return method, which predicts the cash flow of a business or calculates the standard deviation of the relative profit for each unit of time based on past data. However, if it is difficult to estimate the actual cash flow of the project, there are methods to obtain standard deviation by simulation using the Monte-Carlo simulation method and volatility by proxy method borrowing the volatility of similar projects or market substitutes [33].

Option pricing models reflect these factors and show how option prices are determined. The first is the binomial option pricing model developed by Cox and Rubinstein based on the dynamic program, and the second is the Black-Scholes option pricing model developed by Black and Scholes in 1973 based on the partial differential equation approach [25].

2.3.2. Binomial tree model

This model obtains an analytical approximation of the movement of a random variable and assumes that the value of an asset is discretely distributed. To compute the underlying asset S_0, the free cash flow (FCF) is first converted to the present value using WACC, which functions as a discount rate. Based on this, the binomial expansion is performed as long as the analysis period uses the increase rate u and the decrease rate d [34].

$$u = e^{\sigma\sqrt{T/n}} \tag{6}$$

$$d = e^{-\sigma\sqrt{T/n}} \tag{7}$$

In equations (6) and (7), σ is the volatility, T is the total number of binomial expansions, and n is the number of expansions to each node. It is also known as a replication portfolio at this stage, and the worth of the project is determined by converting it to a present value while taking into account the flexibility of company operations [34].

To explain Copeland's four stages as a whole, first, a standard NPV is obtained using a traditional method such as DCF (predicting the FCF of the company and discounting it to the present value). The next step is the creation of an event tree based on uncertainty. The event tree is a binomial form that takes the assumption that the project is rigid and simulates the stochastic behavior of the underlying asset. At this time, the volatility of the project is defined as the standard deviation of the rate of return. The present value determined by the event tree is equal to the value determined by DCF in step 1 since there is no flexibility until step 2. The event tree then transforms into a decision tree by determining how much latitude may be provided at each decision branch. Priorities must be determined when there are several options available because of flexibility at one decision-making branch. In the final step, the value of the option is calculated using the new cash flow replicating the portfolio or risk-neutral probability. The value of options can be enhanced by reflecting flexibility at this stage [35].

2.3.3. The Black-Scholes model

The Black-Scholes model is a pricing model used to determine a fair price or theoretical value for a call or put option based on six variables: volatility, option type, price of the underlying asset, time, strike price, and risk-free rate of return [36].

The Black-Scholes model formula is as follows: [37]

$$C = SN(d_1) - Ke^{-r_r T_e} N(d_2) \tag{8}$$

$$d_1 = \frac{ln\left(\frac{S}{K}\right) + \left(r_r - \frac{\sigma^2}{2}\right)T_e}{\sigma\sqrt{T_e}} \tag{9}$$

$$d_2 = d_1 - \sigma\sqrt{T_e} \tag{10}$$

In equations (8) ~ (10), C is the call option price, S is the underlying asset price (i.e., the present value of company cash flows), K is the strike price (i.e., amount of business investment expenditure), r_r is the risk-free interest rate, σ is the underlying asset volatility (i.e., expected cash flow volatility), T_e is the expiry time to maturity (i.e., investment period), and $N(d)$ is the cumulative probability density function of standard normal distribution. This model is primarily used by options traders who buy an option priced below the calculated price and sell the option at a price higher than the Black-Scholes calculated value [36].

There are several assumptions in the use of the Black-Scholes model. First, returns are not correlated with the passage of time and follow a normal distribution. Second, the direction of stock prices is not uniformly predictable and completely random. Third, volatility is constant and can be known in advance. Fourth, the risk-free rate is constant and given in advance. Next, there are no transaction costs and the market is completely liquid, so you can buy or sell in any quantity at any time. The final assumption is that there are no dividends. However, these assumptions of the Black-Scholes model do not always hold true in reality, and many stocks pay dividends, so this formula cannot be used for those stocks. It is also available only for European options and assumes that returns on the underlying asset follow a normal distribution, but this is not always the case [38].

Nevertheless, the Black-Scholes model can calculate the various prices of European put and call options in a short period. Additionally, investors who invest in European options benefit from the ability to base their judgments on more precise information [39].

3. A case study of spent coffee ground process

3.1. Assumptions on economic assessment

To start, the following assumptions were made in the economic

Table 4. Main assumptions for economic assessment on the suggested large-scale biowaste process

Factor	Value
Initial investment [40]	KRW 3,500 million
Corporate tax rate [41]	20%
Operations and maintenance [42]	10%
WACC [43]	13%
Biocrude oil yield [44]	50%
Price per unit of biocrude (5 years average) [45]	1,500 USD/ton
Exchange rate (5 years average) [46]	KRW 1,165 per USD 1
Rate of increase in the unit price of biocrude oil [47] (10 years inflation rate)	1.68%

Table 5. A set of net incomes considering taxation and capital expenditure

[Unit: KRW 100 million]

	Year					
	2025	2026	2027	2028	2029	2030
Before tax	6.30	9.77	13.28	14.61	16.37	19.64
After tax	4.54	7.03	9.56	10.52	11.78	14.14
Accumulate		11.57	21.13	31.65	43.43	
CapEx	7.91	7.91	7.91	7.91	7.91	

CapEx: Capital expenditure

analysis of this project (Table 4).

Energy payback times are approximately 3.5 years in the initial investment cost setting, as previously shown [40]. According to Table 5, an initial investment cost of KRW 3,500 million is used as the cumulative net income between 2028 and 2029. It is assumed that all investments are made in the first year. In addition, WACC used as the discount rate was estimated at 3% and calculated as 13% by adding a correction factor of 10%.

$$\begin{aligned} &\mathit{Unit\ price\ of\ biocrude\ oil\ of\ R.O.K}\ [KRW/ton] \\ &= \mathit{Unit\ price\ of\ biocrude\ oil\ of\ U.S.A.}[USD/ton] \\ &\times \mathit{exchange\ rate}[KRW/USD] \\ &\times (1 + \mathit{rate\ of\ increase\ in\ unit\ price\ of\ biocrude\ oil}) \end{aligned} \tag{11}$$

Using Equation (11), KRW 1.82 million per ton is the result of the unit cost of biocrude oil in Korea. During biocrude production, 200 kg of SCG each hour is processed to produce 100 kg of biocrude, based on the fundamental assumption that biocrude yields at 50%. Also, assuming an annual utilization rate of 80%, the biocrude that can be produced in one year is 691.2 tons. According to the Korean biocrude unit price and production volume previously determined, the year sales profit was KRW 1,260 million.

In this case study, net income was calculated considering the increase in production to 75% in 2026 and 100% in 2026 after producing 50% of the biocrude due to the initial business demand in the first year of plant operation. Furthermore, it is assumed that the revenue will rise by 5%, 7%, 10%, and 12% over the prior year using a compound annual growth rate (5.7%) and inflation rate from the second to the fifth years. When this analysis is performed, the net income is calculated as shown in the table below.

CapEx is usually the cost of investing in a year plus a depreciation expense. Depreciation expense can be interpreted as a value that is paid back by dividing the initial installation cost every year. In this case study, it is assumed that the cost incurred in relation to the investment during the year is approximately equal to the depreciation expense. Additionally, it is anticipated that the depreciation expense will be paid back by simply dividing the total cost by the discount rate from the initial investment cost over 5 years.

Net income after tax was obtained by subtracting the corporate tax rate and operating expenses from net income before tax. Through this, the NPV of DCF, which is an existing evaluation method, can be obtained as follows using equations (1) and (2). First, the PV required to calculate the NPV is KRW 3,167 million. Therefore, in this case study, the NPV of this project is KRW -225 million. This valuation method's limitation, however, is that it does not consider the value of the project's intrinsic non-deterministic investment decisions.

3.2. Call/put options and Monte-Carlo simulation

Each call and put option that has been considered is as follows.

- Time to build option (call option): Cash flow can be improved by 5% according to stricter regulations on sulfur content in diesel, which can temporarily generate an investment effect of KRW 400 million.
- Option to contract (put option): Cash flow should be decreased by 20% and investment must be suspended deliberately. A temporary savings of KRW 700 million can be expected.

To calculate the rate of increase and decrease in asset value, sources of uncertainty are identified, and their average rate of increase and standard deviation are calculated. The rate of rise u and the rate of drop d are calculated using this value. The Monte-Carlo approach was used to calculate the project's average rate of return and standard deviation of that rate of return; in this case study, the average rate of return was 11% and the standard deviation was 115%.

3.3. Parameters of the Black-Scholes model

The following values were entered into the Black-Scholes model equation that was stated in Section 2.

The following formula is used to calculate the underlying asset value (S), which is the present value of the company's cash flow.

$$S = (\text{initial investment})\ \text{PV}\ \times e^{-r_d t} \tag{12}$$

In equation (12), r_d is the discount rate (here, WACC), and t is the remaining period until expiry. The initial investment PV is KRW 3,167 million, r_d is 0.13, and t is 3 years, so S is KRW 2,144 million by equation (12).

The strike price (K) is the initial investment cost of KRW 3,500 million, expiry time to maturity (T_e) is the investment period of 3 years from 2022 to 2025, and risk-free interest rate (r_r) is set

Table 6. Assumptions needed for the design of the Black-Scholes model

Factor	Value
Underlying asset (price present value of company cash flows) (***S***)	KRW 2,144 million
Strike price (amount of business investment expenditure) (***K***)	KRW 3,500 million
Expiry time to maturity (investment period) (T_e)	3 years
Risk-free interest rate (r_r) [48]	1.6%
Underlying asset volatility & Expected cash flow volatility (σ)	115%

at 1.6%, resulting from that the 5-year geometric average (from 2017 to 2021) of the 3-year Korean treasury rates. The underlying asset volatility (σ) is used as 115%, which is the standard deviation of the rate of return obtained by the Monte-Carlo simulation method.

4. Results and discussion

4.1. Binomial tree model - 4-step analysis

The cash flow statement for the net income reported in Section 3 is displayed in Table 6.

FCF is the cash remaining after investments in operating assets after generating cash through the company's primary operating activities. It is the result of subtracting CapEx from net income after tax in Table 6. In the statement of cash flow, FCF/NPV represents the dividend rate. For the years 2023 and 2024, this value is negative. In this case, it should be treated as 0% because it means that dividends are not possible.

According to equations (6) and (7), the rates of rise u and drop d are about 3.16 and 0.32, respectively, when standard deviation values from the Monte-Carlo simulation approach in Section 3 above are used. Based on these calculation results, the event tree is expanded as follows.

In Figure 3, each node's upper value represents the outcome of reflecting the rate of rise and drop, and the value that remains

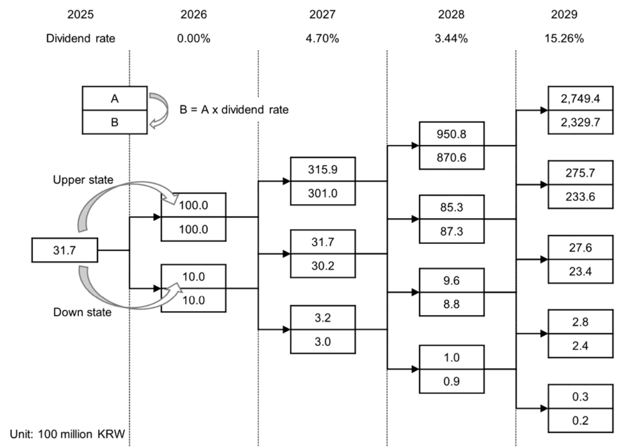

Figure 3. The second step of the event tree in the binomial model using upper/down states and dividend rates.

after the dividend rate is subtracted is displayed below it. A case study in this project assumed that there are two options. Accordingly, the option with the maximum value is chosen by comparing the intrinsic value, the value at the time of the call option, and the value at the time of the put option at each node to develop a decision tree. If this process is extended to all nodes, it is shown in Figure 4.

For example, looking at the first node in 2026, the intrinsic value is KRW 10,020 million, the value of the call option is KRW 10,102 million, and the value of the put option is KRW 8,702 million. At this time, the value of the call option is the highest, so the call option is selected. To generate a replicating portfolio, update the cash flows and option prices based on Figure 4. The optimal execution of additional options is analyzed in the reverse direction from the last node of the event tree. It is determined by the maximum value among the "Intrinsic value" shown in Figure 4, the value when the "Time to build option" is executed, and the value when the "Option to contract" is executed.

Starting from the last nodes in the event tree, valuation updates.

$$Value\ of\ each\ node = MAX\begin{bmatrix} Intrinsic\ value\ of\ event\ tree, \\ Value\ of\ time\ to\ build\ option, \\ Value\ of\ option\ to\ contract \end{bmatrix} \tag{13}$$
$$+\ Diminished\ value\ (Value\ deducted\ from\ dividend\ rate)$$

Table 7. Statement of cash flow for a case study of large-scale SCG process

[Unit: KRW 100 million]

	Investment point	2025	2026	2027	2028	2029
FCF	(2025.1.1)	-3.37	-0.88	1.65	2.61	3.87
WACC	13%					
PV	31.67	35.79	35.90	33.54	28.34	21.50
NPV (FCF + PV)		32.41	35.03	35.20	30.95	25.37
FCF/NPV (%)		0.00	0.00	4.70	8.44	15.26

FCF: Free cash flow
WACC: Weighted average cost of capital
PV: Present value
NPV: Net present value

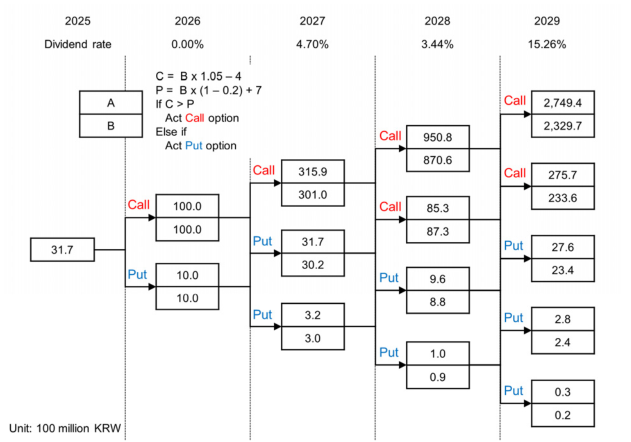

Figure 4. The third step of the event tree in the binomial model to determine call/put options.

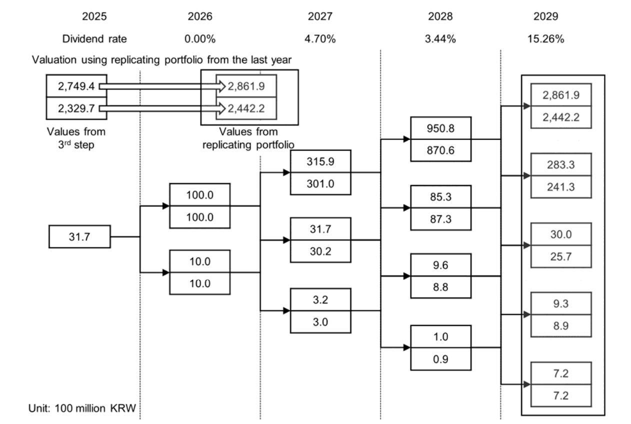

Figure 5. The first stage in the last step of the event tree in the binomial model; estimating values of final nodes based on replicating portfolio.

Calculating this for all nodes results in the following.

In Figure 4, in the case of 2029, the intrinsic value at the first node is KRW 232,973 million, the value of the time to build option is KRW 244,221 million, and the value of the option to contract is KRW 187,078 million. The largest value among them is KRW 244,221 million, which is the value of the time to build option. Because the diminished value must be added, the node's upper value in this case is KRW 286,188 million after adding the existing diminished value of KRW 41,966 million.

In the second node, the time to build option has the maximum value (KRW 24,125 million), and when the diminished value (KRW 4,207 million) is added, the node's upper value rises to KRW 28,333 million. In the third node, the option to contract has the maximum value (KRW 2,573 million), and when the diminished value (KRW 422 million) is added, the node's upper value rises to KRW 2,995 million. Also in the fourth node, the option to contract has the maximum value (KRW 888 million), and when the diminished value (KRW 420 million) is added, the node's upper value rises to KRW 930 million. The upper value is calculated similarly to the last node by adding the maximum value of the option to contract and the diminished value.

Intrinsic value in different years should be calculated using a replicating portfolio. It is calculated by the following:

$$C_0 = m V_0 + B \tag{14}$$

$$m = \frac{C_u - C_d}{V_u - V_d} \tag{15}$$

$$B = \frac{V_u C_d - V_d C_u}{(V_u - V_d)(1 + r_r)} \tag{16}$$

In equations (15)-(17), V_u is the upper value of the node in Figure 4, V_d is the upper value of the lower node in Figure 4, is the intrinsic value of the previous year in Figure 4, C_u is the

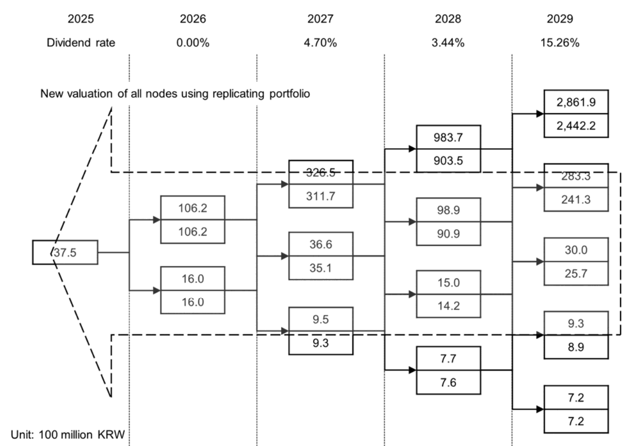

Figure 6. The second stage in the last step of the event tree in the binomial model; calculating values of all relevant nodes in reverse based on replicating portfolio.

upper value of the node in Figure 5, C_d is the upper value of the lower node in Figure 5, and C_o is the intrinsic value of the previous year in Figure 5. The result calculated using this formula is shown in Figure 6.

For the first node in 2028, m is 1.04 and B is KRW -394 million, so C_0 is KRW 90,350 million. Therefore, the value includes the diminished value, totaling KRW 98,370 million. For the second node, m is 1.02 and B is KRW 169 million, so C_0 is KRW 9,086 million. Therefore, the value includes the diminished value, totaling KRW 9,890 million. For the third node, m is 0.83 and B is KRW 689 million, so C_0 is KRW 1,416 million. Therefore, the value includes the diminished value, totaling KRW 1,497 million. Using the same calculation for the last node, C_0 is KRW 762 million, and the total amount including the diminished value is KRW 770 million. Using the calculated value of nodes in 2028, the value of nodes in 2027 could also be calculated. The first and second nodes in 2028 are used to obtain the value of the first node in 2027, and the second and third nodes are used to obtain the second

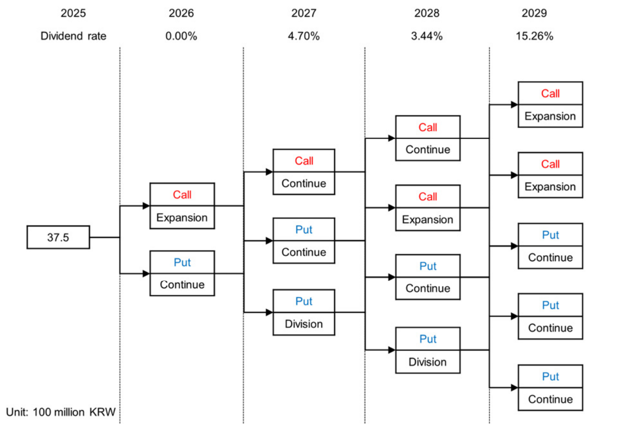

Figure 7. The final decision tree of the case study resulting from the binomial model-based real option.

node in 2027. In this method, a new value is calculated in the reverse direction from the last node. According to Figure 6, the project's PV by 2026, when the replicating portfolio is considered, is KRW 3,753 million. Therefore, the NPV is KRW 172 million. This is an increase of KRW 397 million compared with the NPV (KRW -225 million) obtained by DCF after selecting the option according to the node value and completing the decision tree creation as shown in Figure 7.

If the event tree's value is less than the maximum value when using the "Call option," "Continue"; if it is more, "Expansion." If the event tree's value is less than the maximum value when using the "Put option," "Division"; if it is more, "Continue."

4.2. The Black-Scholes model and results comparison

The source and results of calculating the Black Scholes' NPV using MATLAB software based on the values set in Section 3.3 are shown in Figure 8.

As a result, using the Black-Scholes model, KRW 1,301

Use sym to create symbolic numbers that represent the values of the Black–Scholes parameters.

```
syms t d
S = sym(21.44);        % current stock price (spot price)
K = sym(35);         % exercise price (strike price)
sigma = sym(1.15);   % volatility of stock
T = sym(3);        % expiry time in years
r = sym(0.016);        % annualized risk-free interest rate
```

Calculate the option price without approximation. Create a symbolic function N(d) that represents the standard normal cumulative distribution function.

```
PV_K = K*exp(-r*T);
d1 = (log(S/K) + (r + sigma^2/2)*T)/(sigma*sqrt(T));
d2 = d1 - sigma*sqrt(T);
N(d) = int(exp(-((t)^2)/2),t,-Inf,d)*1/sqrt(2*sym(pi))
```

N(d)=

$$\frac{\operatorname{erf}(\frac{\sqrt{2}d}{2})}{2}+\frac{1}{2}$$

```
Csym = N(d1)*S - N(d2)*PV_K
```

Csym =

$$\frac{268\operatorname{erf}(\frac{10\sqrt{2}\sqrt{3}\left(\log(\frac{536}{875})+\frac{8127}{4000}\right)}{69})}{25}+35e^{-\frac{6}{125}}\left(\frac{\operatorname{erf}\left(\frac{\sqrt{2}\left(\frac{23\sqrt{3}}{20}-\frac{20\sqrt{3}(\log\left(\frac{536}{875}\right)+\frac{8127}{4000})}{69}\right)}{2}\right)}{2}-\frac{1}{2}\right)+\frac{268}{25}$$

To obtain the numeric result with variable precision, use vpa. By default, vpa returns a number with 32 significant digits.

```
Cvpa = vpa(Csym)
```

Cvpa = 13.010424054279894843621159320818

To change the precision, use digits. The price of the option to 6 significant digits is $12.5279.

```
digits(6)
Cvpa = vpa(Csym)
```

Cvpa = 13.0104

Figure 8. Source code to calculate the NPV of the Black-Scholes model.

Table 8. Comparison of results from different valuation methods applied for the case study

[Unit: 100 million KRW]

	DCF	Binomial tree model	Black-Scholes
PV in early 2025	31.67	37.53	-
NPV in early 2022	-2.25	1.72	13.01

million was determined to be the NPV value. A comparison of all the results from valuation methods considered in this study is displayed in Table 7.

4.3. Future perspectives based on strengths (S), weaknesses (W), opportunities (O), and threats (T) analysis

S	Due to the implementation of renewable fuel standard (RFS), the biodiesel mixing ratio will increase. The SCG plays an important role in a recycled resource.
W	Parameter values can vary in uncertain ranges. Detailed cost analysis for process operation should be carried out.
O	Further clean technology can be implemented using industrial waste heat. The supply of raw materials can be stable by cooperating with regional coffee manufacturers. Local energy systems can be constructed in terms of smart grid networks.
T	Regional variations in the supply and demand for raw materials can occur. Instability in business due to irregular raw material supply should be overcome.

It has been announced that the objective of 8% for the biodiesel mixing ratio in 2030 would be implemented as part of the RFS, which has been in effect since August 2021 [49]. This implies that there will be a future increase in the supply of biodiesel. After March 15, 2022, SCG was also acknowledged as a recycled resource. This suggests the opportunity to exploit various SCG uses in collaboration with local coffee businesses. Therefore, it is acknowledged that SCG is a biomass alternative to finite fossil fuels now and in the future.

Based on the credible literature values and modifiers, the average value was derived and calculated based on similar literature values, and then the economic evaluation was conducted. The parameter value is unclear, though, which may be a disadvantage. The paper adopted the "gradient-descent rapid pyrolysis reaction process." This implies that the process technology development lacks innovation. In other words, specific process operating costs, such as utility prices, were not carefully taken into account. In the event of commercialization in the future, it is necessary to proceed thoroughly because currently this procedure is being used only for research purposes.

Nonetheless, this is not to say that we have not considered the troublesome aspects of the process. In the section on the overall process, we identified the drawback of having to quickly increase the temperature to 550 ℃ and investigated possible solutions. As a result, it was proposed that clean technology from using waste heat from nearby factories should be realized. Refineries already have several locations where the temperature is raised between 1,200 and 1,300 ℃. If this waste heat is utilized, the process can be run in an environmentally beneficial manner. However, it might happen that the supply and demand of SCG raw materials would be uncertain. Therefore, the process may be run steadily with there being no problems in supply and demand as long as the stability of raw material supply and demand is maintained. To compensate for this, a plan to collaborate with local coffee brands was devised. The smart grid format is suitable for this project. As a result, cooperation with local coffee brands and the development of a regional energy infrastructure suggest the course that new and renewable energy should take in the future.

However, even if the smart grid project is carried out, there will be differences in SCG raw material supply and demand by region domestically. When commercialized, this can be done by localization of the region. However, it seems that there are enough points to overcome by detailing the economic evaluation such as local site price and transportation cost. As previously noted, there is a substantial risk that the firm will be unstable as a result of inconsistent SCG raw material supply. On the other hand, if there is adequate connectivity across SCG partners in the area, this might be considered a manageable risk factor.

5. Conclusions

This research has demonstrated the feasibility of the biowaste-to-biofuel production process based on SCG in terms of the real options approach. Tilted-slide pyrolysis systems consisting of a heat exchanger, a combustor, and several condensers, enabling the generation of 100 kg/h of biofuel, have been considered, and option pricing methods depending on the binomial and Black-Scholes models have been employed for investment decision-making in the proposed system. The results from NPV using DCF, binomial model, and Black-Scholes model show KRW -225 million, KRW 172 million, and KRW 1,301 million, respectively. With regard to different options explicitly dependent on uncertainty, the SCG material is fit-for-purpose of a bioenergy process from an economic perspective. Furthermore, SWOT analysis was used to make sense of strategic planning toward a sustainable and eco-friendly world.

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APPENDIX

1. Nomenclature

Abbreviation	Definition
C_t	Cash flow
C_i	Initial investment cost
r_d	Discount rate
E	Market value of the firm's equity
D	Market value of the firm's debt
R_e	Cost of equity or expected return on investment
R_d	Cost of debt
T_c	Corporate tax rate
R_f	Risk-free rate
β	Beta of the investment
R_m	Expected return on a market portfolio
R_m-R_f	Market risk premium
C	Call option price
S	Underlying asset price (present value of company cash flows)
K	Strike price (amount of business investment expenditure)
r_r	Risk-free interest rate
σ	Underlying asset volatility & expected cash flow volatility
T_e	Expiry time to maturity (investment period)
$N(d)$	Cumulative probability density function of standard normal distribution
T	Total number of times a binominal tree occurs
n	Expansion count for each node
t	Remaining period until expiry
V_u	Upper value of node in step 2
V_d	Lower value of node in step 2
V_0	Step 2 internal value of the previous year
C_u	Upper value of node in step 4
C_d	Lower value of node in step 4
C_0	Step 4 internal value of the previous year