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Stochastic Modeling of the Levelized Cost of Electricity for Solar PV

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Received: 25 April 2020; Accepted: 10 June 2020; Published: 11 June 2020

Abstract: With the development of renewable energy, a key measure for reducing greenhouse gas emissions, interest in the levelized cost of electricity (LCOE) is increasing. Although the input variables used in the LCOE calculation, such as capacity factor, capital expenditure, annual power plant operations and maintenance cost, discount and interest rate, and economic life, vary according to region and project, most existing studies estimate the LCOE by using a deterministic methodology. In this study, the stochastic approach was used to estimate the LCOE for solar photovoltaic (PV) in South Korea. In addition, this study contributed to deriving realistic analysis results by securing the actual data generated in the solar PV project compared to the existing studies. The results indicate that the LCOE for commercial solar power ranged from KRW 115 (10 cents)/kWh to KRW 197.4 (18 cents)/kWh at a confidence level of 95%. The median was estimated at KRW 160.03 (15 cents)/kWh. The LCOE for residential solar power ranged from KRW 109.7 (10 cents)/kWh to KRW 194.1 (18 cents)/kWh at a 95% confidence level and a median value of KRW 160.03 (15 cents)/kWh. A sensitivity analysis shows that capital expenditure has the most significant impact on the LCOE for solar power, followed by the discount rate and corporate tax. This study proposes that policymakers implement energy policies to reduce solar PV hardware and soft costs.

Keywords: LCOE; stochastic; solar PV; South Korea; renewable energy

1. Introduction

Since the Paris Agreement came into effect in November 2016, the issue of reducing greenhouse gas (GHG) emissions gained traction globally. As a result, most countries are required to submit and implement Nationally Determined Contributions in an effort to address this issue. For example, South Korea is expected to reduce GHG emissions by 37% from business-as-usual levels by 2030. However, the reduction targets submitted per country are currently lower than the global target of maintaining a temperature rise below 2 °C above pre-industrial levels for this century [1]. Further GHG reduction targets for each country are to be discussed in order to meet the universal target, which is therefore likely to become a major constraint on the global economy.

A transition to renewable energy is one of the key measures for reducing GHG emissions. Solar photovoltaic (PV) is the fastest-growing source of numerous renewable energy sources, leading to a sharp reduction in cost and an increase in demand. Therefore, it is essential to accurately estimate the cost of solar PV and to compare it with other energy sources. To do so, it is necessary to compare the costs incurred for producing equivalent amounts of power. For this reason, many studies have introduced the levelized cost of electricity (LCOE) [2–6].

This study has marginal contributions to the previous study from three perspectives. First, this study considers more sophisticated input variables than previous studies. Most existing studies consider capacity factors, capital expenditure (CAPEX), annual power plant operations and maintenance (O&M), discount rate, and economic life as input variables [2–5]. In this study, a more realistic analysis is attempted in additional consideration of the project's corporate tax, debt cost, inflation rate, and loan interest rate. Second, existing LCOE-related studies were analyzed from a deterministic point of view. Since the input variables used in the LCOE calculation vary according to region and project, simulation techniques are useful to account for these changes. This study aims to stochastically estimate the LCOE based on a Monte Carlo simulation to consider the variation of input variables. Third, while existing stochastic approach studies subjectively assume input variables, this study derives the optimal distribution using actual data in the case of capacity factor. The distribution is analyzed by using the actual generation data of the solar PV project and the Kolmogorov–Smirnov statistics test.

The target of the analysis is solar PV in South Korea, which is growing rapidly. As a result of stochastic approach using Monte Carlo simulation, significant statistical values such as a reference value, an average, a median value, a standard deviation, a minimum value, and a maximum value are derived. The methodology proposed in this study can be applied to various energy sources in multiple countries globally. In addition, these results are expected to prove valuable in countries' energy policy development and economic analysis.

The structure of this paper is as follows. Section 2 demonstrates the current status of the global solar LCOE. Section 3 introduces the methodology used in this study. Section 4 examines the stochastic LCOE results, and Section 5 discusses the results and presents policy implications.

2. Literature Review

Bhandari and Stadler [7] compared the average LCOE of residential and commercial solar PV in Cologne, Germany, with the electricity rate to determine grid parity. By comparing the LCOE to the high electricity bills of consumers, it was estimated that grid parity would be achieved in 2013 or 2014. However, by considering low wholesale electricity prices, it was found that grid parity would be achieved in 2023. Branker et al. [8] estimated the LCOE by focusing on cases in North America and conducted a sensitivity analysis on the major variables. The LCOE variables of initial investment (installation) costs, investment methods, economic life, and debt redemption period responded sensitively. With developments in financing techniques and industry and technology improvements, it was revealed that solar PV could be more cost effective than traditional energy sources, thereby reaching grid parity more efficiently. Mendicino et al. [4] suggested an appropriate contract price for the Corporate Power Purchase Agreement (CPPA) using the LCOE. CPPA is a contract between electricity consumer and a power generator with renewable energy. The results show that the appropriate price range is between EUR 75/MWh and EUR 100/MWh.

Rhodes et al. [9] calculated the LCOE for 12 plant technologies by county in the United States. For some technologies, the average cost has increased when internalizing the cost of carbon and air pollutants. Including the cost of USD 62/tCO_2 for CO_2 emissions, combined cycle gas turbine, wind and nuclear power showed the lowest LCOE. Clauser and Ewert [10] analyzed the LCOE of geothermal energy and other primary energy. The LCOE was calculated by varying the conditions of geothermal energy, and as a result of these cost comparisons, it was concluded that geothermal energy could be converted into electrical energy at an attractive cost, particularly for steam use in natural or engineered geological reservoirs.

Chadee and Clarke [11] conducted a technical and economic assessment to determine the level of LCOE of wind power in the Caribbean islands. The assessment was conducted on two sites with eight wind turbines ranging from 20 to 3050 kW. Mundada et al. [12] calculated the LCOE for a hybrid system of solar PV, batteries and combined heat power (CHP). Sensitivity analysis of these hybrid systems for LCOE was performed on the capital costs of the three energy subsystems, capacity factor of PV and CHP, efficiency of CHP, natural gas rates and fuel consumption of CHP. The results of sensitivity have provided decision makers with a clear guide to distributed generation LCOE with off-grid PV + battery + CHP systems. Nissen and Harfst [13] proposed an 'Energy price adjusted LCOE' that allows for more accurate LCOE calculations in consideration of rising energy prices.

As such, the LCOE methodology is useful for a variety of countries and for various energy sources. However, the existing studies analyzed LCOE from a deterministic point of view, and thus did not reflect much uncertainty about the input variable. Therefore, this study has a marginal contribution compared to previous studies in that it analyzes the LCOE using a stochastic approach. In addition, in assuming the distribution of the input variable, in the case of capacity factor, the distribution was derived using actual data. Lastly, this study is contributing to deriving a more realistic LCOE in that it considers more specific input variables, such as corporate tax, debt cost, inflation rate, and loan interest rate than previous studies.

3. Methodology

3.1. Levelized Cost of Electricity

The LCOE is the average cost per unit of electricity generated by a particular plant. It is calculated by dividing the present value of the total generation cost of the facility by the present value of total power generation. The LCOE allows the evaluation of the costs in relation to the generated amount of power during the economic lifetime of a plant and across the entire energy generation process, including initial construction capital, operations, and maintenance [14,15].

The total cost incurred in the generation of energy comprises of the initial CAPEX and annual O&M costs. More specifically, the initial CAPEX can be separated into hardware and soft costs. Hardware costs refer to equipment and materials, civil engineering, power generation equipment, and annex buildings, while soft costs include design, permits and authorizations, and construction supervision services. O&M costs cover annual operations and maintenance costs of the power plant and financial services fees, such as insurance premiums [16,17].

The LCOE is affected by construction costs, operations and maintenance costs, the lifespan of the power plant, power generation technology, energy efficiency, system degradation rates, inflation and interest rates, and corporate taxes. The formula for calculating the LCOE may be defined as follows [10]:

$$LCOE_t = \frac{CAPEX_t + \sum_{n=1}^{T} \frac{OM_n + FC_n}{(1+r)^n}}{\sum_{n=1}^{T} \frac{(1-d)^n \times CF \times 365(days) \times 24(hours) \times Capacity}{(1+r)^n}} \quad (1)$$

In the above formula, $CAPEX_t$ refers to initial investment (facilities), which include equipment and materials, the construction of structures, grid connection, permits, design, supervision, and inspection at time t. Indirect costs, OM_n, are the O&M costs at time n; FC_n, the finance costs at time n; r, the discount rate; d, the degradation rate; CF, the capacity factor; capacity, the energy generating capacity of the power plant; and T, the operation period of the power plant. that is interest cost due to debt. In this study, interest cost due to debt is considered as finance cost. The capacity factor is the rate at which the power generator operates for one year. For example, the capacity factor of Korea's solar PV is about 14.78%, which means that it produces only 14.78% of power capacity per year. The discount rate is affected by the inflation rate and the interest rate of safe assets in a country. It could also be interpreted that the LCOE represents the recovery of costs disbursed during the lifetime of a generation facility at a discounted rate r in the form of an equal amount paid annually.

3.2. Stochastic Approach

Economic analysis methodologies can be categorized as deterministic and stochastic models depending on the relationship between the input and output variables. The characteristics of the deterministic model are the relations between the input and output variables that are certain, and that the model allows an analytical solution. Contrarily, the model contains three weaknesses. First, it excludes potential future alternatives as it sets long-term variables at fixed values. Second, if all the scenarios with possible variables are combined, the number of cases increases exponentially, hindering the application of the sensitivity analysis. Third, the model does not allow for the reflection of correlation between variables.

The stochastic model does not enable the development of a solution, meaning that a confidence interval must be identified in the results by incorporating the probabilistic characteristics of the input variables using a simulation technique that generates random numbers [18]. The advantages of the stochastic simulation technique are as follows. First, it enables the estimation of a solution for a comparatively difficult mathematical question. Second, for uncertain variables, it allows for the establishment of a correlation between the probability distributions of the variables. However, a disadvantage is that the estimate produced through the stochastic simulation is an approximate value calculated by repeated sampling, thus requiring a statistical interpretation [19]. Among the stochastic simulation techniques, the Monte Carlo simulation is a method that is used universally. Assuming that the input variable is a probabilistic variable, an adequate probability distribution is selected, and a random number that follows the relevant distribution is produced [20–23].

To explain the value of the Monte Carlo simulation, the probability variable X has a probability density function $f_x(x)$ and assumes an arbitrary function $g(x)$. The expected value of $g(x)$ is as follows:

$$E(g(X)) = \int_{x \in X} g(x) f_x(x) dx \tag{2}$$

To estimate the expected value of g(x) as per the above, n number of samples ($x_1, \ldots, x_n$) are extracted from a distribution of the probability function X, and the average of g(x) is calculated as below:

$$\widetilde{g}_n(X) = \frac{1}{n} \sum_{i=1}^{n} g(x_i) \tag{3}$$

$\widetilde{g}_n(X)$ is the Monte Carlo estimator of $E(g(X))$, which is based on the law of large numbers. In the case where the weak law of large numbers is expressed as the formula below, it could be concluded that when the number (n) of samples is infinite, the average of g(x) based on the sampling can be found at $E(g(X))$ [24].

$$\lim_{n \to 0} P(\left|\widetilde{g}_n(X) - E(g(X))\right| \geq \varepsilon) = 0 \tag{4}$$

As a result, $\widetilde{g}_n(X)$ satisfies the identity below and becomes the unbiased estimator of $E(g(X))$.

$$E(\widetilde{g}_n(X)) = E(\frac{1}{n} \sum_{i=1}^{n} g(x_i)) = \frac{1}{n} \sum_{i=1}^{n} E(g(x_i)) = E(g(X)) \tag{5}$$

If $g(x)$ is given as a complex function, the integral calculation becomes problematic, and so does finding a solution. However, if the Monte Carlo simulation is used, the expected value of the function can be estimated without having to conduct a complex calculation process [25,26].

In the Monte Carlo simulation, the value and size of the extracted sample has an absolute effect on the results. Therefore, the method used to generate the random number that follows the given probability distribution is highly important. Figure 1 shows the analysis procedure of the Monte Carlo simulation [27]. An appropriate distribution can be selected based on available data, on the judgment of a knowledgeable expert, or on a combination of data and judgment. Factors for judgment are discrete or continuous, having bound or not, number of modes, and symmetric or skewed. The size of the extracted sample depends on the estimated standard deviation, the desired margin of error, and the critical value of the normal distribution for significant level [28]. As a general rule of thumb, 10,000 iterations are used [29].

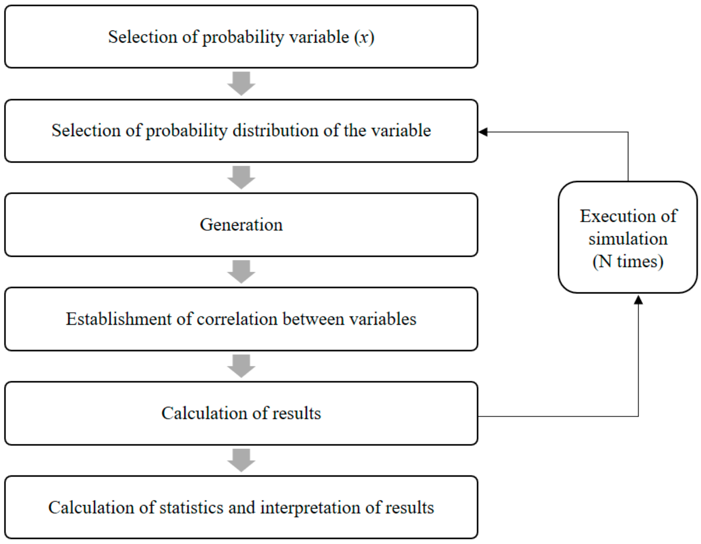

Figure 1. Procedure for the Monte Carlo simulation analysis.

For the purpose of this study, the LCOE analysis of solar PV, the major variables that determine the economics of power generation are the generation amount of power and cost. However, these two variables fluctuate significantly and contain uncertain factors related to the solar radiation amount, technological advancement, and market conditions. When applying the deterministic technique to the economic analysis of photovoltaics, with both volatile and uncertain variables, it becomes difficult to reveal the characteristics of the variables since uncertain future factors are simplified. However, the stochastic simulation method can produce results by considering input variables that are uncertain or volatile through an adequate probability distribution and could therefore be a more appropriate method.

3.3. Sensitivity Analysis

The sensitivity of the contribution of the solar LCOE distribution enables a comparative analysis of the direction and extent of the impact of probability variables on the LCOE. The distribution contribution can be calculated according to the following.

In the first phase, the sample and results of input variables extracted through the simulation are organized in order, and the correlation between the input variable samples and results are identified.

In the second phase and as per Equation (6), the distribution contribution (v_i) of input variable i represents the proportion of the ordinal correlation coefficient squared (R_i^2) over the summation from i to N of the ordinal correlation coefficient squared (R_i^2).

$$v_i = \frac{R_i^2}{\sum_{i}^{N} (R_i^2)} \tag{6}$$

The numerator (ordinal correlation coefficient [R_i]) acquires the original negative (−) or positive (+) sign. The reason being, that when the ordinal correlation coefficient is negative (−), the resulting value decreases as the input variable increases. In contrast, when it is positive (+), the resulting value increases.

4. Empirical Results

4.1. Data

In this section, we apply the above-mentioned stochastic simulation technique to establish the probability distribution for variables with uncertainties. Thereafter, a random sample will be extracted from the relevant distribution, and the resulting value of the probability distribution will be estimated by repeatedly conducting the LCOE calculation.

Table 1 shows the input variables required for the LCOE analysis. The subjects of the analysis are 100 kW commercial facilities installed on the ground and 3 kW residential facilities installed inside buildings. The random variables can be classified as internal and external factors. The internal factors consist of costs and facility characteristics, with the costs comprising CAPEX and O&M costs. In terms of facility characteristics, the capacity factor (which determines the generation amount of power) and system degradation rate are considered random variables. The external factors include the discount rate and corporate tax. Other variables, such as the debt ratio, loan interest rate, inflation, and lifespan, have been granted fixed values, considering their significance and the fact that they fluctuate.

Table 1. Input variables for the solar levelized cost of electricity (LCOE).

	Solar (Commercial)	**Solar (Residential)**
Standard size	100 kW	3 kW
CAPEX (100 million won/MW)	Normal distribution (average = 16.1, deviation = 10% of average)	Normal distribution (average = 18.3, deviation = 10% of average)
O&M costs (10,000 won/MW·year)	Normal distribution (average = 1167, deviation = 5% of average)	Normal distribution (average = 3737; deviation = 5% of average)
Capacity factor (%)	Logistic distribution (average = 14.78, scale = 0.22)	
Discount rate (%)	Triangular distribution (minimum = 4.5, mode = 5.5, maximum = 7.5)	
Corporate tax (%)	Triangular distribution (minimum = 0, mode and maximum = 24.2)	0
System degradation rate (%)	Triangular distribution (minimum = 0, mode = 0.7, maximum = 0.8)	
Loan interest rate (%/year)	3.46	
Inflation (%)	0.97	
Lifespan (year)	20	
Debt ratio (%)	70	

In the probability distribution, the most appropriate distribution was determined through verification when there were sufficient data samples. Contrarily, the probability distribution cases presented in preceding studies were referred to when the data was lacking or insufficient. A representative study on probability distribution estimation is Spooner [30], which estimated the cost distribution of a construction project and proposed the application methods for normal distribution, log-normal distribution, triangular distribution, beta distribution, and uniform distribution. Uniform distribution is used when there is an insufficient amount of data and the fluctuation range is relatively small. Triangular distribution is used when the maximum likelihood estimation (MLE) is certain, and the information about the maximum and minimum values is considered concrete. However, when the possibility for the reduction of variables is very low, the minimum value does not have to be designated. This study therefore proposed that it is reasonable to estimate the probability distribution for relevant variables using the triangular distributions, which are skewed distributions. This study used the probability simulation analysis software Crystal Ball (version 11).

4.1.1. Capacity Factor

The capacity factor of solar PV is based on data on photovoltaic energy generation provided by the Korea Energy Agency. The goodness-of-fit test was conducted to establish the probability distribution for the capacity factor. The number of capacity factor samples totaled 106,654, and the Kolmogorov–Smirnov (K–S) statistics test is the test method used. As per Equation (7), this test method extracts the maximum value statistics (D_n) by subtracting the cumulative distribution function for the fitting distribution $F(x)$ from the cumulative percentile of the actual measurement data $F_n(x)$. The smaller the statistic, the higher the goodness-of-fit.

$$D_n = \max\left|F_n(x) - F(x)\right| \tag{7}$$

The goodness-of-fit test was conducted with a total of 14 probability distributions, from the logistic distribution to the exponential distribution. Table 2 lists the test results according to each probability distribution. The test results show little difference of the K–S statistics between the logistic distribution and the student t distribution. In this study, the logistic distribution (an average of 14.78%, scale of 0.22%) with the smallest value of the K–S statistics was selected as the probability distribution for capacity factors.

Table 2. Probability distribution test results.

Distribution	K-S Statistics (Dn)	Statistics
Logistic	0.0147	Average = 14.78%, Scale = 0.22%
Student t	0.0149	Intermediate point = 14.78%, Scale = 0.35%, Freedom = 7.28199
Normal	0.0369	Average = 14.78%, Standard deviation = 0.41%
Log-normal	0.0369	Location = −4714.30%, Average = 14.78%, Standard deviation = 0.41%
Beta	0.0376	Minimum = 9.01%, Maximum = 20.54%, Alpha = 100, Beta = 100
Gamma	0.0378	Location = 8.85%, Scale = 0.03%, Form = 207.5021
Weibull	0.0447	Location = 13.02%, Scale = 1.91%, Form = 4.92757
Minimum extreme value	0.0868	Highest probability = 14.98%, Scale = 0.42%
Maximum extreme value	0.1214	Highest possibility = 14.57%, Scale = 0.48%
BetaPERT	0.1801	Minimum = 12.65%, Highest possibility = 14.85%, Maximum = 16.47%
Triangular	0.2268	Minimum = 12.65%, Highest possibility = 14.85%, Maximum = 16.47%
Uniform	0.3409	Minimum = 12.66%, Minimum = 16.46%
Pareto	0.4606	Location = 12.66%, Form = 6.47827
Exponential	0.5933	Ratio = 676.83%

The probability density function (PDF) of a logistic distribution is presented as follows [31]:

$$f(x) = \frac{e^{-\frac{x-\mu}{s}}}{s\left(1+e^{-\frac{x-\mu}{s}}\right)^2} = \frac{1}{4s}\operatorname{sech}^2\left(\frac{x-\mu}{2s}\right) \tag{8}$$

The distribution average is calculated as the average of μ and variance $\frac{s^2\pi^2}{3}$. A unique feature of the logistic distribution is its bell-shaped curve similar to a normal distribution, but with the possibility of a kurtosis through scale variables (s). Figure 2 illustrates the logistic distribution with an average of 14.78% and scale of 0.22% selected in the distribution based on the actual measurement data for the capacity factor.

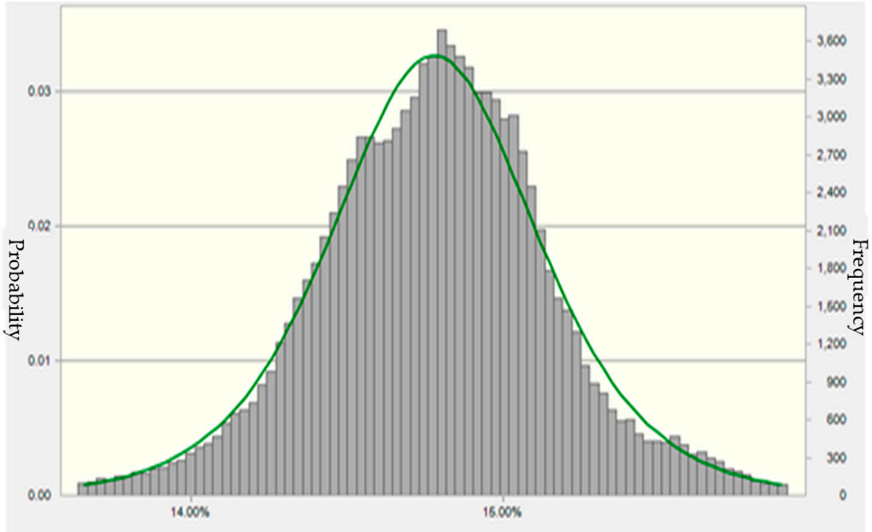

Figure 2. Probability distribution for capacity factor (logistic distribution).

4.1.2. Discount Rate

The triangular distribution was used in considering the uncertainty surrounding the characteristics of the discount rates. This distribution can be used when the MLE is accurate, and information on the maximum and minimum is certain. The PDF of the triangular distribution is provided as follows [32]:

$$f(x) = \frac{2(x-a)}{(m-a)(b-a)} \quad (9)$$

In the above formula, a refers to the minimum value; m, to the mode; and b, to the maximum value. The average (μ) and variance (σ^2) of this distribution are as follows:

$$\mu = \frac{a+m+b}{3} \quad (10)$$

$$\sigma^2 = \frac{(a^2+b^2+m^2-ab-am-bm)}{18} \quad (11)$$

According to the study conducted by Choi and Park [33], the discount rate reached a maximum of 7.5% in 2001 and currently equates to 5.5%, but requires a reduction of 1% in the future. Therefore, this study applied the triangular distribution of a minimum of 4.5%, a mode of 5.5%, and a maximum of 7.5%. Figure 3 shows the triangular distribution generated based on the above assumptions.

4.1.3. O&M Costs

The preceding study by the International Energy Agency (IEA) [34] was referenced in establishing the probability distribution for O&M costs, with the establishment of the normal distribution for this purpose. This distribution is applicable when the probability of MLE is high. The PDF of the normal distribution is presented as the following:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (12)$$

In the above formula, μ refers to the average, while σ represents the standard deviation. In this study, the surveyed average for commercial facilities was KRW 37,365 (USD 33.97 (In this study, USD 1 = KRW 1100 is applied))/kW, and KRW 11,667 (USD 10.61)/kW for residential facilities. The standard deviation was assumed at an average of 5%, identical to the study by the IEA [34], with the standard deviations for commercial and residential facilities as KRW 1 868 (USD 1.70)/kW and KRW 583 (USD 0.53)/kW, respectively. Figures 4 and 5 are normal distributions based on the above-mentioned assumptions.

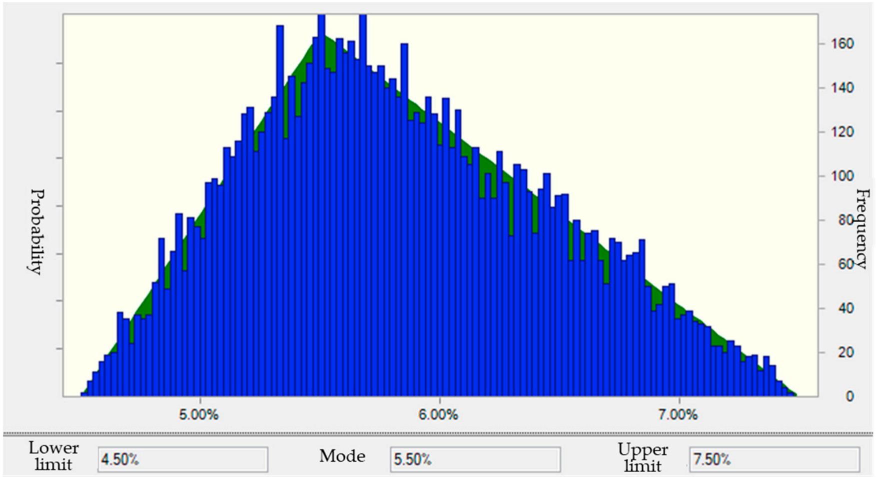

Figure 3. Probability distribution for discount rate (triangular distribution).

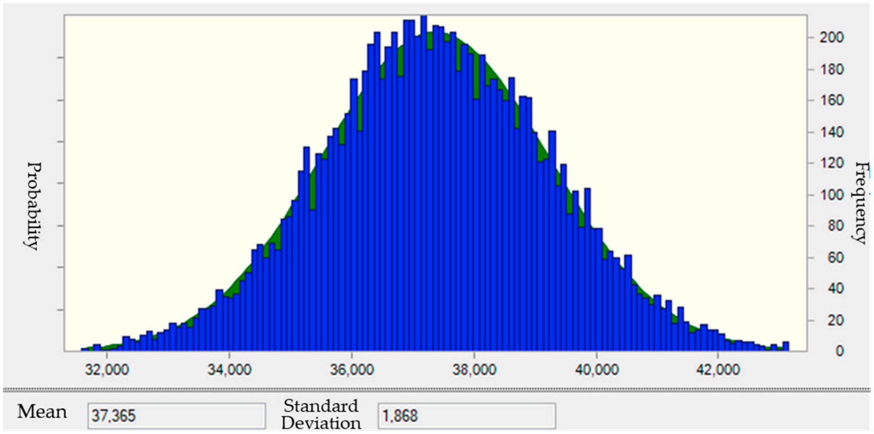

Figure 4. Probability distribution for commercial operations and maintenance (O&M) costs (normal distribution).

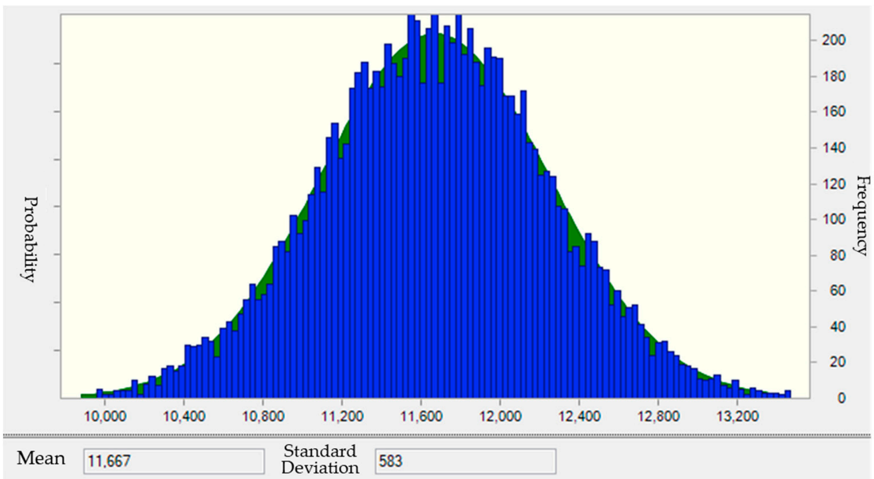

Figure 5. Probability distribution for residential O&M costs (normal distribution).

4.1.4. CAPEX

A normal distribution is assumed for the probability distribution for CAPEX, similar to the O&M costs as per above. One difference is the application of the standard deviation. The surveyed numbers are identical in that they were applied according to an average, but the standard deviation was assumed as 10% of the average. The reason for this is the greater uncertainty of CAPEX compared to O&M costs, caused by a reduction in costs resulting from technological advances or factors causing unexpected cost increases.

The CAPEX for commercial facilities recorded an average of KRW 1.6 million (USD 1 454.55)/kW, while the standard deviation totaled KRW 160,000 (USD 145.45)/kW. As for residential facilities, the average reached KRW 1.8 million (USD 1 636.36)/kW, while the standard deviation amounted to KRW 180,000 (USD 163.64)/kW. Figures 6 and 7 display the normal distributions for commercial and residential facilities.

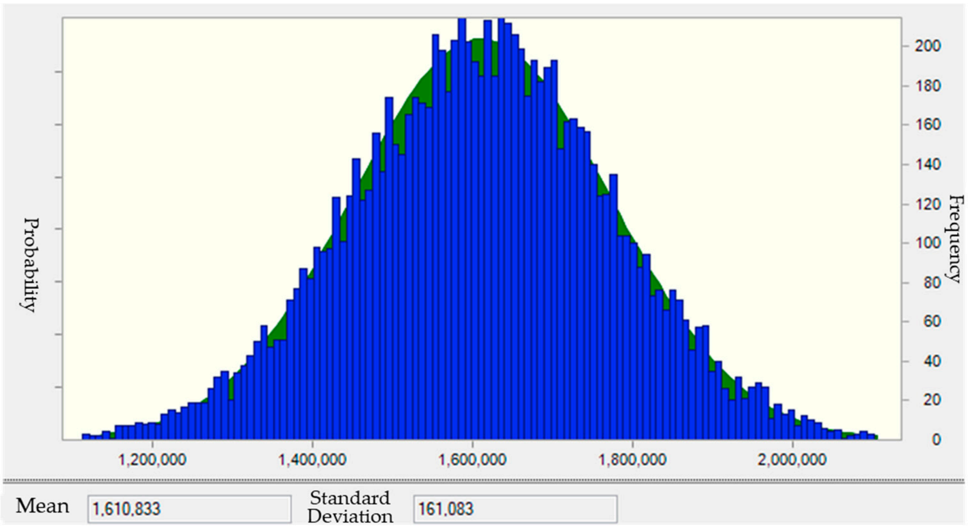

Figure 6. Probability distribution for commercial facility capital expenditure (CAPEX) (normal distribution).

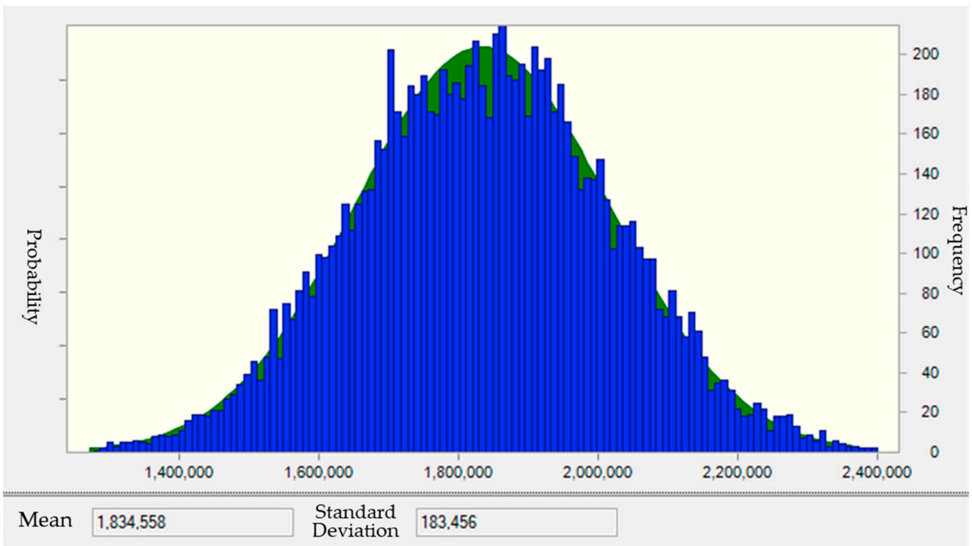

Figure 7. Probability distribution for residential facility CAPEX (normal distribution).

4.1.5. System Degradation Rate

The triangular distribution is assumed for the system degradation rate after referring to the preceding study by the IEA [34]. The technological threshold for photovoltaic energy generation is clear, meaning that the use of a triangular distribution seems reasonable. In IEA [34], a mode of 0.5% was applied, whereas this study applied 0.7%, as surveyed. The minimum and maximum values were applied at 0% and 0.8%, respectively, identical to the study by the IEA [34]. Figure 8 shows the triangular distribution generated based on the above assumptions.

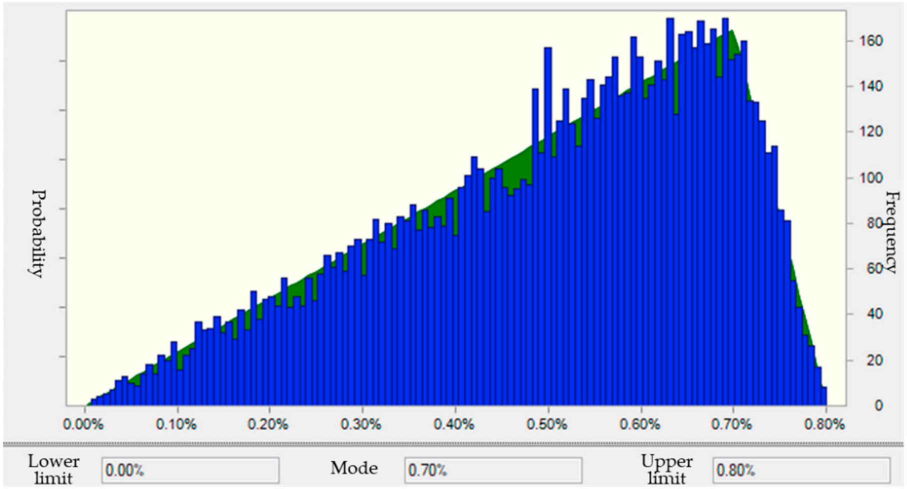

Figure 8. System degradation rate probability distribution (triangular distribution).

4.1.6. Corporate Tax

Corporate tax is a policy variable, and the following scenario was proposed as a hypothesis. The corporate tax will decline from its current state until it reaches a range where all corporate tax is exempt. The probability distribution suited to this hypothesis is the triangular distribution, which can arbitrarily establish a threshold.

This study assumes the triangular distribution, while the mode and maximum value were set at the current level of corporate tax at 24.2% (including residence tax), with the minimum value set at 0% (exemption of corporate tax scenario). Finally, as per Figure 9, a right triangle distribution was generated where the probability reaches its highest point at 24.2% and then declines gradually.

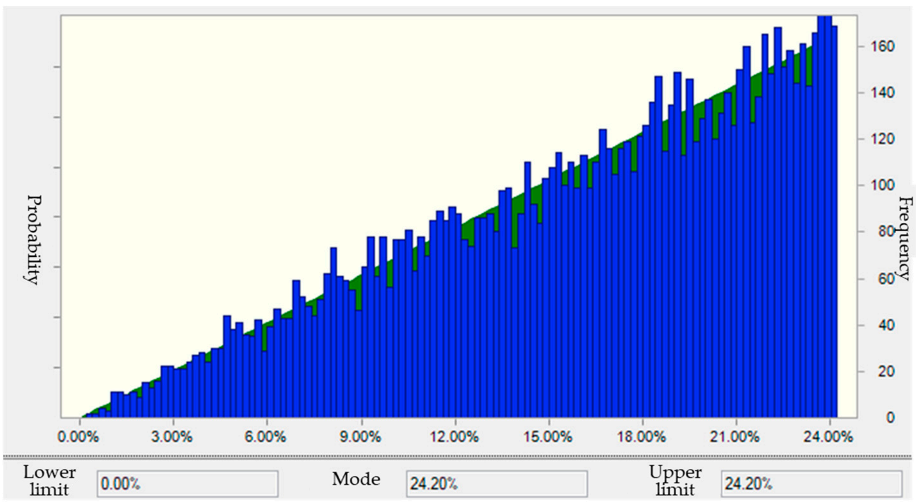

Figure 9. Corporate tax probability distribution (triangular distribution).

4.2. Results of Stochastic Simulation

This study uses the Monte Carlo simulation technique and encompasses the characteristics of variables that reflect the uncertainty and variability of solar PV generation in order to select a probability distribution. Arbitrary random numbers were generated within the distribution, and by repeating this process 10,000 times, this study estimates the range of meaningful solar LCOE with a confidence interval of 95%.

In the case of commercial solar energy, the LCOE records an average of KRW 159.49 (14 cents)/kWh with a standard deviation of KRW 13.31 (1 cent)/kWh. The 95% confidence interval was between KRW 133.60 (12 cents)/kWh and KRW 186.52 (17 cents)/kWh. Figure 10 shows the probability distribution for commercial solar energy generation, while Table 3 provides the relevant statistics.

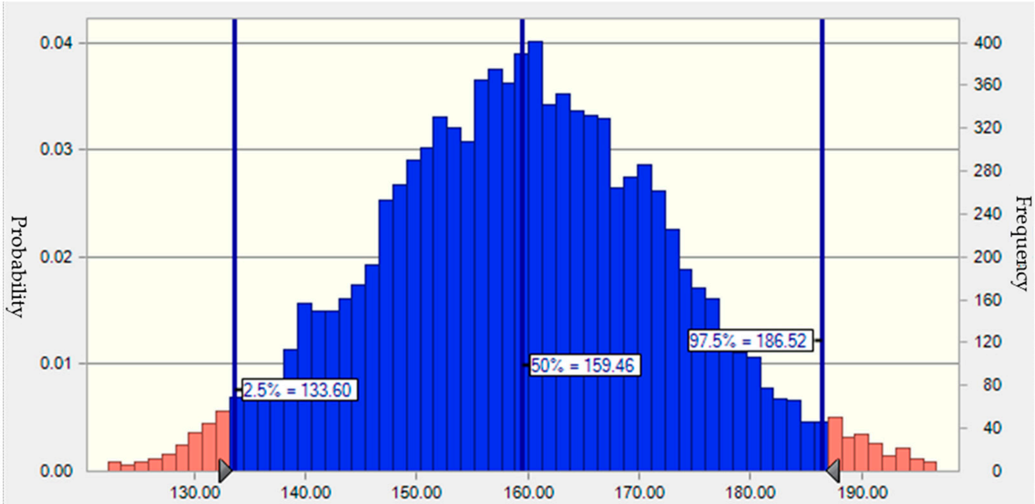

Figure 10. Probability distribution for commercial solar LCOE.

Table 3. LCOE statistics for commercial solar energy generation.

Statistics	Value	Statistics	Value
Reference value	165.97	Kurtosis	3.04
Average	159.49	Variation coefficient	0.0835
Median value	159.46	Minimum	114.84
Standard deviation	13.31	Maximum	216.08
Variance	177.29	Range width	101.24
Skewness	0.0647	Standard error	0.13

In the case of residential solar LCOE, an average of KRW 137.15 (12 cents)/kWh was recorded with a standard deviation of KRW 14.80 (1 cent)/kWh. The confidence interval at 5% significance level showed a minimum value of KRW 109.67 (10 cents)/kWh and a maximum of KRW 167.35 (15 cents)/kWh. Figure 11 and Table 4 illustrate the probability distribution and statistics for residential solar LCOE, respectively.

Table 4. Residential solar LCOE statistics.

Statistics	Value	Statistics	Value
Reference value	135.65	Kurtosis	2.97
Average	137.15	Variation coefficient	0.1079
Median value	136.75	Minimum	75.77
Standard deviation	14.80	Maximum	197.15
Variance	219.06	Range width	100.56
Skewness	0.1977	Standard error	0.15

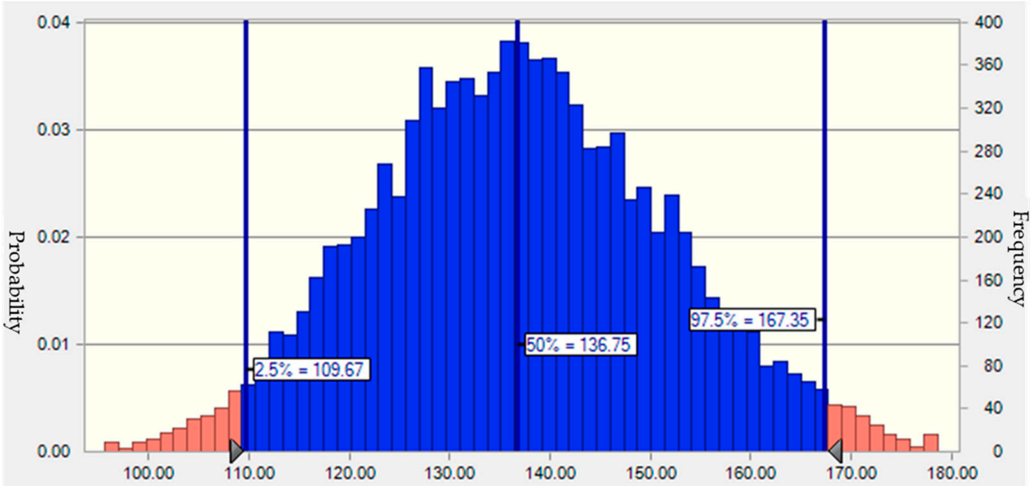

Figure 11. Probability distribution for the residential solar LCOE.

4.3. Sensitivity Analysis Results

Figures 12 and 13 show the results of the analysis on the variance contribution of the LCOE for solar PV. The factor with the greatest impact on the LCOE of commercial and residential solar PV is established as CAPEX. The contribution of this variable was recorded at 57.3% and 74.8% for commercial and residential facilities, respectively, while the proportion accounts for an absolute majority. This implies that CAPEX is the most common and significant factor to consider when seeking to improve the economics of solar power generation activities of both commercial and residential facilities. Therefore, it is essential to determine the factor that will reduce the relevant costs.

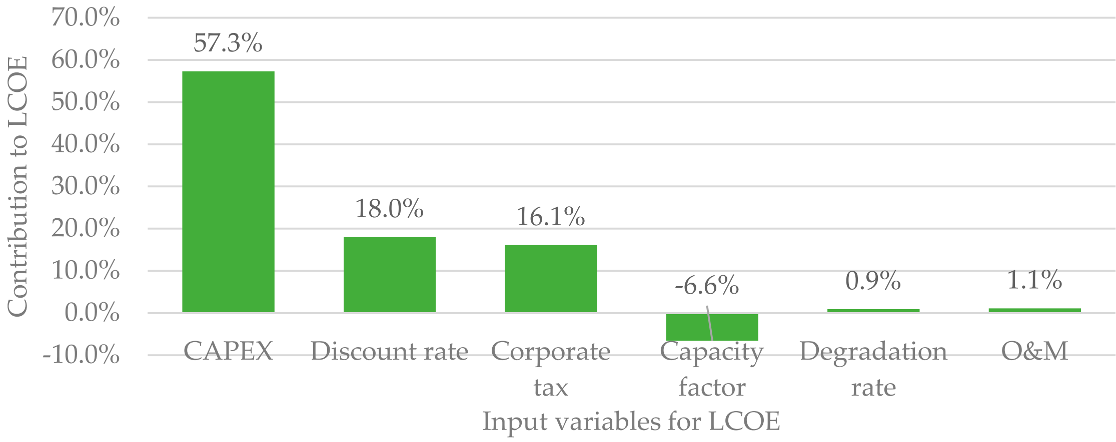

Figure 12. Sensitivity of the commercial solar LCOE.

The second most crucial factor to consider in improving the economy is the discount rate for commercial solar energy generation, which accounted for 18% of the variance contribution. Similarly, it was also the second-most important factor for residential generation facilities, accounting for 17.7% of the variance contribution. This implies that the development of a policy aimed at reducing the burden of financial costs may be effective.

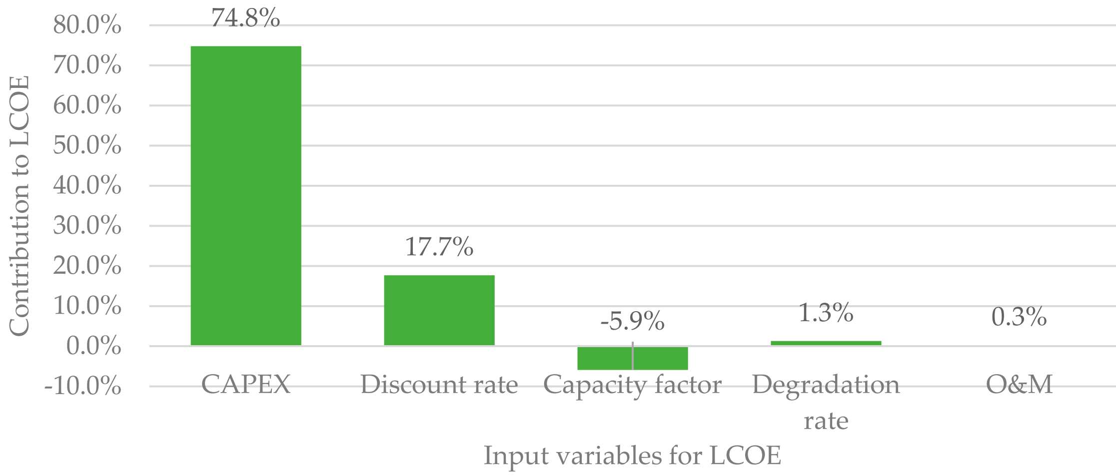

Figure 13. Sensitivity of the residential solar LCOE.

5. Discussion

The stochastic LCOE analysis methodology proposed in this study was applied to solar PV for residential and commercial use in South Korea. The deterministic LCOE performed in most existing studies does not indicate the uncertainty of the input variable. Although the sensitivity analysis of the deterministic methodology shows the uncertainty of input variables, the number of scenarios is limited. This study is meaningful in that the confidence interval of the results is derived by reflecting the stochastic characteristics of the input variable instead of finding the deterministic LCOE. This study also contributed to producing realistic analysis results by collecting the actual data generated in the solar PV project.

Among the input variables, the capacity factor was set to the optimal distribution function using the actual power generation data of solar PV. As a result of statistical analysis, significant statistical values, such as a reference value, an average, a median value, a standard deviation, a minimum value, and a maximum value, were derived. Commercial solar LCOE was estimated to range between KRW 115 (10 cents)/kWh and KRW 197.4 (18 cents)/kWh at a 95% confidence level. The median was valued at KRW 160.03 (15 cents)/kWh. The LCOE of residential solar was estimated to range between KRW 109.7 (10 cents)/kWh and KRW 194.1 (18 cents)/kWh at a 95% confidence level and a median value of KRW 160.03 (15 cents)/kWh. The sensitivity analysis showed that CAPEX had the most significant impact on solar LCOE, followed by the discount rate and corporate tax.

Therefore, to reduce the LCOE of solar PV, it is necessary to strive to reduce CAPEX. The increasing dissemination of solar PV could also lower CAPEX in PV. The reasons behind the high hardware and soft costs of solar PV facilities in Korea are twofold: the unique economic environment and lack of experience. For example, Germany is continuously lowering costs by steadily distributing solar PV systems across the country. If Korea followed suit and gained valuable learning experiences as a result, it is important to consider how much solar LCOE could be reduced. To answer this question, we assumed that Korea holds the equivalent level of knowledge and experience to Germany. Specifically, we assumed that Korea's hardware costs, including the costs of modules, inverters, connection bands, electric wiring, structures, and installation and construction, are reduced to the same level as they are in Germany. In addition, we assumed the same for soft costs, including supervisory costs, design costs, and general management costs, as well as the O&M costs (costs of replacing parts, safety management costs, etc.), excluding land leasing rates. Table 5 shows cost breakdown of a 100 kW solar system in Korea.

Table 5. Cost breakdown of a 100 kW solar system.

Items of Hhardware Costs	KRW	Items of Soft Costs	KRW	Items of O&M Costs		KRW
Modules	62,124,000	License and permits	9,000,000	Land lease costs		1,500,000
Inverters	14,375,000	Standard facility charges	8,390,000	Parts replacement costs	Inverters	718,750
Connection bands	2,200,000	Insurance premiums	1,141,623		Fuses, etc.	240,000
Electric wiring	601,678	Supervisory costs	1,500,000	Safety management costs		1,277,760
Structures	5,895,677	Other expenses	5,136,649	Total		3,736,510
Installation construction costs	23,933,435	Design costs	1,500,000			
Total	109,129,790	General management costs	6,924,483			
		Profits	5,570,428			
		Total	39,163,183			

Figure 14 indicates how Korea's solar LCOE could be reduced through the reduction of domestic installation costs for solar energy generation facilities to the same level as Germany. If done effectively, Korea's solar LCOE would drop KRW 26.6 (2 cents)/kWh. Similarly, if the soft costs and O&M costs are also reduced to Germany's level, the solar LCOE would be reduced by KRW 17 (1.5 cents)/kWh and KRW 6.3 (0.6 cents)/kWh, respectively. Therefore, if Korea's overall installation costs are reduced as per Germany's levels, the solar LCOE would decrease to KRW 97.2 (9 cents)/kWh. This is even less than Germany's current solar LCOE of KRW 122 (11 cents)/kWh, due to Korea's advantage in terms of capacity factor and corporate tax. However, decreasing installation costs cannot be achieved within a limited period of time. Germany managed to reduce costs based on experience gained through years of installing solar energy generation facilities. Therefore, if Korea continues to deploy solar energy systems, reduced solar LCOE below KRW 100 (9 cents)/kWh can be achieved.

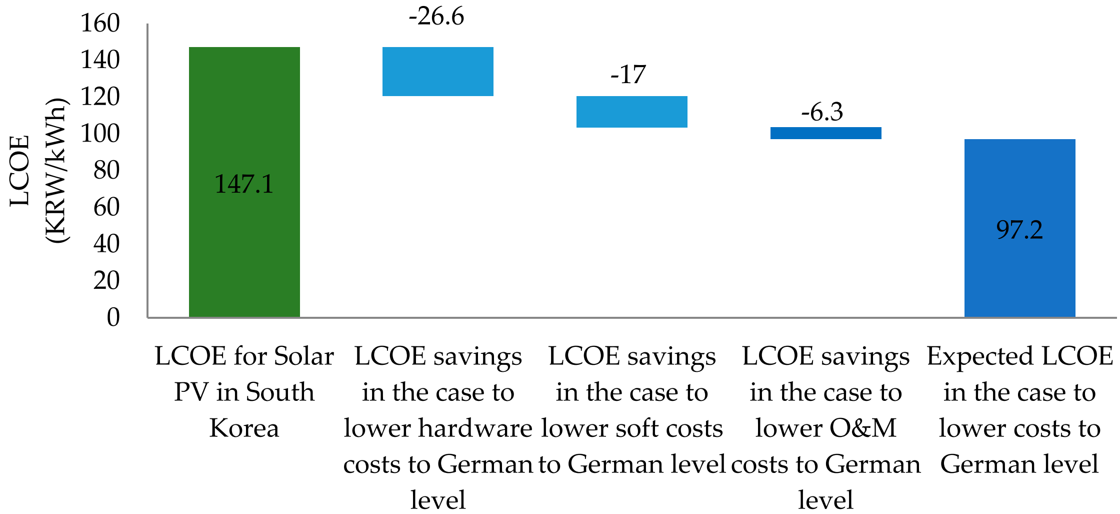

Figure 14. Commercial solar LCOE adjustment in South Korea after lowering costs to the level of Germany.

The higher cost of domestic modules and inverters in Korea also indicated that increased efforts are required to lower costs in the manufacturing sector. In addition, the high installation and construction costs are attributable to the country's high labor costs and extended construction periods. With limited scope to lower labor costs, efforts should be focused on reducing construction periods. Due to civil complaints often prolonging construction projects, a policy to increase public acceptance of solar energy generation facilities is also required.

Subsequently, we examine license and permit costs. License and permit costs paid to local autonomies in Korea are 10 times higher than in Germany and 50 times higher than in China. The greatest challenge for solar energy generators in Korea is securing licenses and permits for development activities from local autonomies. This urgently calls for the development of a policy to lower license and permit costs and to streamline related procedures. In addition, domestic grid connection costs in Korea are more than four times higher than in China, highlighting the need for lowering these costs. Domestic general management costs are also higher, exceeding those of other countries by more than 10 times. Cost reductions must be achieved by systemizing domestic projects.

This study also recommends the reduction of value-added tax on the installation of solar energy generation facilities. Recently, the National Energy Administration of China announced a policy to reduce taxes for solar generators, introducing a refund of 50% on value-added taxes for supplies associated with solar energy and the lowering of taxes on the use of farmlands. This policy will be adopted by 2020 to promote solar PV in the country. The reduction of corporate tax on the profits of solar energy generators should also be considered. The United States is accelerating the deployment of renewable energy sources through an investment tax credit and production tax credit, serving as adequate reference points.

Policy efforts to lower discount rates are also required. Discount rates comprise the cost of debt and the cost of equity, which can be lowered strategically. For instance, the cost of debt can be lowered by offering preferential interest rates for loans to generators of renewable energy. The promotion and support of renewable energy project financing (PF) should be additionally considered. The cost of debt can also be lowered through the government's active promotion of PF and support for the development of new investment products, with the objective to establish an industry ecosystem for renewable energy.

The promotion of renewable energy is an absolute necessity, considering the need to reduce GHG emissions and improve air quality. However, if the promotion of renewable energy becomes a burden to consumers in the form of excessive electricity bills, the deployment of renewable energy could be restricted. Should the cost of solar PV be reduced based on the results of this study, it would lead to a decrease in the unit cost of solar energy generation. Consequently, a reduction in power generation-related payments and, ultimately, relief in terms of electricity bills for consumers will follow.

The methodology proposed in this study is expected to be applicable to solar and other energy sources in other countries. A stochastic approach could be generalized if the methodology of this study is widely used in future studies. In addition, meaningful implications can be drawn from comparing countries and energy sources.

Author Contributions: C.-Y.L. designed the study, reviewed the related literature, and interpreted the results. J.A. outlined the methodology, and developed the model. All authors provided substantial writing contributions and significant comments on numerous drafts. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Energy Economics Institute (KEEI) grant funded by the South Korean Prime Minister's Office.

Conflicts of Interest: The authors declare no conflict of interest.

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