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Research paper

Optimal sourcing strategy for enterprises to achieve 100% renewable energy

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A B S T R A C T

RE100 is a voluntary campaign for global companies to use 100% renewable energy in their business and production processes. Many global companies participating in RE100 have adopted various approaches for renewable energy sourcing. There is increasing awareness that global companies cannot indefinitely avoid participating in the RE100 campaign, however, there has been limited research on economically achieving RE100. This paper provides an optimal strategy for companies to source renewable energy to economically achieve RE100 in the future. The approaches for meeting energy demands with renewable electricity are analyzed, and a feasible sourcing strategy is presented. Additionally, using the linear programming optimization technique for quantitative analysis, an annual strategy is derived for cost minimization while achieving RE100 during the analysis period. The analysis shows that as the renewable energy generation cost decreases over time, the cost-effective strategy is to deviate from the utility environment at a specific time and select corporate power purchase agreements for implementing RE100, and it further demonstrates the need for policymakers to create an environment in which companies can freely choose from a combination of power purchase options and various certification methods to maximize their enterprise competitive power.

1. Introduction

The 100% renewable energy campaign (RE100) is a voluntary global response to climate change and is representative of the practical efforts made by companies to address climate change. RE100 was first launched in 2014 by the Climate Group and Carbon Disclosure Project, a US non-profit organization. It is an initiative aimed at converting the electricity power used by companies into 100% renewable energy by 2050. RE100, which began with the participation of 13 companies at the time of its launch, included 342 global companies as of November 2021 (RE100, 2021). As of 2020, companies that participated in RE100 sourced 113 TWh of total renewable energy per year, which was almost double that in 2015 (The Climate Group and CDP, 2020a). There is a concern whether RE100 campaign really brings an additionality and just be used for a marketing reason of the participating companies. However, in some countries which has an insufficient national support scheme for renewable energy to meet their ambitious climate targets, the corporate sourcing is also meaningful approach to help the efficient achievement of the national target. Specifically, in Republic of Korea (Korea), the government subsidy scheme does not cover the whole penetration target of renewable energy due to its structural limitation in the law where the target cannot beyond 25% of the generation volume of conventional energy. In order to reduce the gap, the additional demand of corporates for renewable energy is needed to complement the government procurement scheme.

There are various approaches for companies participating in RE100 to source renewable electricity. "Direct line to an off-site generator with no grid transfers", "purchase from on-site installations owned by a supplier", "self-generation", "direct procurement from offsite grid-connected generators through power purchase agreements (PPAs)", "contract with suppliers", and "unbundled energy attribute certificate (unbundled EAC) purchase" are some representative approaches. In 2019, RE100 companies had a share of 42% in unbundled EAC, 30% in contract with suppliers, 26% in PPAs, 2.5% in self-generation, and less than 1% in other approaches. Among these approaches, PPAs have more than tripled from 3.3% in 2015 to 26% in 2019, emerging as a major scheme to secure renewable energy (RE100, 2021).

Unfortunately, some countries have difficulty in sourcing renewable energy owing to structural difficulties in the electricity

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Nomenclature

Indices

h	Index for hour
d	Index for day
y	Index for year

Parameters

p_{capex}^{y}	Unit price for capital expenditures of generator for self-generation in year y (USD \$/kW)
p_{opex}^{y}	Unit price for operating expenditures of generator for self-generation in year y (USD \$/kW)
$p_{tariff}^{y,d,h}$	Unit price of energy charge for industrial customer in utility rate system at hour h on day d in year y (USD \$/kWh)
$p_{ppa}^{y,d,h}$	Contract unit price including ancillary service payment and network tariff in corporate PPAs with owner of renewable energy generator at hour h on day d in year y (USD \$/kWh)
p_{cert}^{y}	Unit price of certificate in year y (USD \$/kWh)
p_{fems}^{y}	FEMS installation price in year y (USD \$)
$N_{ls,fems}$	Life span of FEMS (year)
$N_{ls,sg}$	Life span of generator for self-generation (year)
N_{yr}	Analysis period (year)
$Area$	Area of the corporate site (m^2)
Cap_{area}	Capacity installable by area (kW/m^2)
r_{fems}	Demand reduction rate by FEMS (%)
r_{x}^{y}	Renewable energy achievement rate against power demand in year y (%)
$r_{discount}$	Annual discount rate (%)
Cap_{re}	Max feasible capacity with renewable energy generator in corporate PPAs (kW)
$A_{re}^{d,h}$	Capacity factor of renewable energy generator at hour h on day d (%)
$E_{load}^{y,d,h}$	Power demand of the corporate buyer at hour h on day d in year y (kWh)

Dependent variables

C_{elec}^{y}	Cost of electricity procurement in year y
C_{cert}^{y}	Cost of certificate purchase in year y
C_{self}^{y}	Cost of self-generation in year y
$C_{utility}^{y}$	Cost of utility rate system in year y
C_{ppa}^{y}	Cost of corporate PPAs in year y
C_{fems}^{y}	Cost of FEMS construction in year y
R_{res}^{y}	Revenue due to residual value in year y
$E_{self}^{y,d,h}$	Power produced by self-generation at hour h on day d in year y (kWh)

Decision variables

Cap_{self}^{y}	Installation capacity for self-generation in year y (kW)
$E_{utility}^{y,d,h}$	Power purchased from utility rate system at hour h on day d in year y (kWh)
$E_{ppa}^{y,d,h}$	Power purchased from corporate PPAs at hour h on day d in year y (kWh)
$E_{cert}^{y,d,h}$	Power changed from non-renewable energy to renewable energy by certificate in year y (kWh)
u^{y}	Binary variable, which is equal to 1 if the corporate buyer opts for FEMS construction in year y

market or difficulties in securing renewable energy. Mainland China and the Korea face challenges in implementing RE100 owing to the absence of feasible approaches due to their regulatory complexity. Indonesia and New Zealand have limited approaches to purchase renewable energy. For example, New Zealand has the problem that a renewable energy tracking system is absent despite the existence of abundant renewables in the grid. In the case of Russia, it is difficult for companies to secure renewable energy because of the non-availability of unbundled EAC (The Climate Group and CDP, 2020b).

Although global enterprises are required to take part in RE100 campaign, unfortunately, academic research regarding achieving cost-effectively RE100 for enterprises is limited.

Ходоченко (2018) shows RE100 campaign participation status of global enterprises and presents various barriers in RE100 achievement, even if global enterprises want to take part in RE100 campaign. Concretely, policy barriers from regulated electricity market, technical barriers from shortage of traceability system, and financial barriers from high cost of renewable energy are proposed as the main reasons. Kaenzig et al. (2013) concluded that product price and energy mix of production are most important attributes of customer preferences. In addition, the authors in Kaenzig et al. (2013) revealed that the German customers were willing to pay 16% premium for electricity produced from renewable sources. The study clearly shows that renewable energy use in enterprises affects their long-term strategies and simultaneously contributes toward attainment of the national energy policy. Chang and Lo (2022) concluded that the enterprises that set science-based target initiative are willing to use renewable energy and particularly try to invest in renewable energy through PPAs and unbundled EAC. Furthermore, they emphasized energy transition toward renewable energy in the industry rather than target setting at the government level but the need for support through policy and subsidy.

Jung and Hue (2020) emphasized the need for voluntary participation of enterprises in RE100 and conceptually explained how companies can implement various approaches for electricity purchase. The research focused on third-party PPAs mediated by utility among other approaches. Mun and Kim (2020) explained the need for Korean enterprises to participate in RE100 and cited the obstacles in the implementation of RE100. They expected the method to reduce social costs owing to linking the Emission Trading System (ETS) and RE100 certification system. Korea electric power corporation Economy & Management Research Institute (KEMRI, 2019) estimated and compared the cost of sourcing the entire power requirement of an enterprise through self-generation and that of purchasing the electricity from PPAs based on the levelized cost of energy (LCOE) and the network tariff, respectively. The results of the research showed that the costs of both the aforementioned methods were higher than the costs borne by companies in countries with widespread adoption of RE100. Therefore, the study proposed the preparation of a support policy such as ensuring profitability of renewable energy generation and providing tax privileges so that RE100 companies can operate competitively. Lee et al. (2019) presented the current state and implications of RE100 in Korea, and analyzed the sourcing methods for renewable energy. The research also proposed the introduction of RE100 certification systems. Han (2018) identified the industrial sectors participating in RE100 and the RE100 implementation targets. In addition, they analyzed the response of these companies to approaches for achieving RE100.

This study proposes a generalized and universally applicable method that does not focus on specific electricity market and a quantitative approach for enterprises to cost-effectively achieve RE100. Quantitative analysis was performed to identify the optimal and feasible sourcing strategy. Under the complex consideration that utility tariff will rise with falling renewable energy prices worldwide, this paper presents a cost-effective sourcing strategy that reflects the stochastic characteristics of variable price through Monte Carlo simulation.

The major contributions of this study are summarized as follows:

(1) Providing optimal power sourcing strategies for companies to source renewable energy economically with the objective of facilitating the adoption and achievement of RE100.
(2) Performing quantitative analysis using linear programming optimization technique to derive a strategy considering cost minimization.
(3) Performing comparative analysis regarding RE100 achievement cost of each enterprise in Korea and United States in terms of cost differences in renewable energy.

The rest of this paper is organized as follows. Section 2 describes the representative approaches for corporates to achieve RE100. Section 3 discusses the sourcing strategies that corporates can adopt for achieving RE100. Section 4 provides an approach based on linear programming (LP). Section 5 provides the optimal result and analysis using Monte Carlo simulation. Section 6 presents the conclusions and provides insights for policy makers.

2. Instruments for sourcing renewable energy for RE100

2.1. Self-generation

Self-generation is a method in which a corporate buyer produces and utilizes renewable energy by installing a generator within the premises, with the expectation of reducing electricity purchase from the market. To be certified as using renewable energy, the generator must generate electricity without carbon emission.

Self-generation avoids the influence of volatility in energy prices and ensures stable power demand. It can contribute to carbon regulation by reducing Scope 2 carbon emissions. Because the generator is installed within the premises for the purpose of self-sufficiency, the approach does not involve costs such as land and grid connection costs, thus reducing the capital expenditure (CAPEX) and operating expenditure (OPEX). However, because the installable capacity is limited to the available area, the approach alone may be insufficient to handle the total demand of the company. Moreover, owing to the intermittent nature of renewable energy, additional devices such as energy storage systems are required to supply the desired amount of electricity at the desired time. Therefore, complementary supply will be additionally required to meet surplus renewable energy demand through other methods.

The approach based on self-generation can avoid variable energy costs, but requires high initial installation costs and continuous maintenance costs. The initial cost for self-generation is decreasing due to the learning effect and expansion of the scale of solar photovoltaic (PV) market. Although the global installation cost of PV has shown a declining trend, the initial cost for self-generation remains high in some countries owing to the economic situation, labor costs, and low learning effects.

2.2. Unbundled EAC purchase

An unbundled EAC is a contractual instrument containing information about the origin of the energy generated. It allows markets to track renewable energy production and permits consumers to make credible claims of renewable energy use (IRENA, 2018). Unbundled EAC is used for trading information such as the type and location of the power plant and the actual power production. One unit of unbundled EAC can be issued when 1 MWh of renewable energy flows into the grid. In addition, if a certificate is issued once, it is premised that it should be discarded to prevent the use of duplicate certificates.

The unbundled EAC purchase is also a simple and flexible method for a corporate buyer to prove the use of renewable energy. Small and large companies and residential customers can avoid installing a generator for self-generation and prove the use of renewable energy and their contribution to carbon emission reduction simply by purchasing certificates. However, it is considered that the purchase of unbundled EAC does not provide revenue certainty to the owner of the generation unit (Serrurier, 2020).

2.3. Green pricing

The special tariff system adds green premium at the same level as the unbundled EAC and demonstrates the use of renewable energy. Enterprises and individuals can sign up for this rate system. Moreover, it is expected that the profit obtained from green premium is reinvested in the renewable energy field to contribute to the promotion of renewable energy. A corporate buyer, who has joined green pricing, does not physically receive the electricity produced from renewable energy sources. However, the buyer can receive a certificate to certify the use of renewable energy equivalent to the amount of power purchased. The certificates are generally issued based on the amount of electricity generated from the renewable energy generation sources and other projects managed by the utility (Johnson, 2020). The certificate must be discarded once it is paid to a businessperson or individual to prevent the use of duplicates. Green pricing has the advantage of allowing businesspersons and individuals to easily participate in the program. Moreover, flexible participation is possible owing to the short contract period.

2.4. Corporate PPAs

Corporate PPAs allow renewable energy generators and corporate buyers to directly enter into long-term contracts with fixed prices outside the electricity market. PPAs may be divided into physical PPAs and virtual PPAs. In physical PPAs, energy is physically sourced directly through the grid from the electricity generator. Virtual PPAs, regardless of the physical procurement of energy, can certify the use of renewable energy through financial contracts for the total annual production of renewable energy of the electricity generation unit. The contract period is generally approximately 5 to 20 years. Because trading occurs at a fixed price, the problem of variability in the energy price can be avoided. Moreover, it is possible to have various non-standardized forms of contracts. For example, the contract might include stipulations for stakes in investment or might reflect other non-price factors. It is also possible to cooperate with the owner of an electricity generation unit from the beginning of the project. Direct contracts with large projects can enable the procurement and use of renewable energy at cheaper prices. However, it may be necessary to pay off-site traders the network tariffs or balancing cost for supply and demand. Furthermore, a corporate buyer can directly contribute to renewable energy by providing a renewable generator owner with stable financing.

3. Strategic planning to achieve RE100

The RE100 certification can be obtained using renewable energy entirely or by submitting a certificate to prove that the company used electricity generated from a renewable source. As discussed in Section 2, there are various approaches for sourcing renewable electricity. However, there are difficulties in implementing RE100 through only a single method. For example, a large enterprise would need enormous initial and maintenance costs to procure 100% of electricity through self-generation. Areas for installation of a generator for self-generation might be limited. Furthermore, to purchase only unbundled EAC, most of the energy requirement for RE100 certification must be met from the spot market. This is risky owing to difficulties in securing the certificate or market price fluctuations. Likewise, it will be difficult in the case of corporate PPAs to procure 100% renewable electricity owing to its intermittent nature. In other words, a complementary supply will be needed to procure additional electricity, which cannot be met through the renewable energy supply, requiring an additional RE100 certification method.

Apple Inc. is a representative company that has achieved RE100, with an annual electricity consumption of 1.45 TWh (IRENA, 2018). Apple Inc. devised the RE100 implementation ratio of 3% green pricing, 41% PPAs, 32% unbundled EAC purchase, and 24% self-generation. Microsoft Corporation met 4.79 TWh of its 4.85 TWh electricity demand through renewable energy and devised the RE100 implementation ratio of 17% PPAs and 83% unbundled EAC purchase. Volkswagen AG met 4.03 TWh of its 12.36 TWh electricity demand through renewable energy and devised the RE100 implementation ratio of 92% PPAs and 8% self-generation. As discussed earlier, many global enterprises have used a combination of various approaches rather than using one approach to achieve RE100.

This study followed the assumption that a corporate buyer can select various approaches for renewable electricity sourcing. A corporate buyer can purchase renewable electricity from an off-site grid-connected sources through corporate PPAs. Further, the corporate buyer procures the deficient electricity through complementary supply. At this time, a certificate regarding the electricity procured through complementary supply is necessary.

4. Formulation of optimal sourcing strategy

4.1. Objective function

The optimal sourcing strategy problem for achieving RE100 can be formulated as Eq. (1).

$$Minimize \left[\sum_{y \in Y} \frac{C^y_{elec} + C^y_{cert} + C^y_{fems} - R^y_{res}}{(1 + r_{discount})^y} \right]. \tag{1}$$

The four terms of the objective function in Eq. (1) are as follows: The first term is the cost used in electricity procurement, including the installation and operation cost of self-generation, electricity tariff from the utility rate system, and direct electricity procurement cost through corporate PPAs and complementary supply. The second term is the cost used in the certificate purchase due to buying non-renewable energy, including buying the certificate from green pricing provided by the utility and from the unbundled EAC market. The last two terms are the factory energy management system (FEMS) installation cost and the residual value from fixed assets, respectively.

4.1.1. Electricity procurement

The cost used in electricity procurement can be formulated as

$$C^y_{elec} = C^y_{self} + C^y_{utility} + C^y_{ppa} \quad for\ \forall y \in Y. \tag{2}$$

The terms of the electricity procurement cost are explained in detail as below:

(1) CAPEX and OPEX for self-generation: The cost used in CAPEX and OPEX can be formulated as

$$C^y_{self} = Cap^y_{self}(p^y_{capex} + p^y_{opex})\ for\ y = 0, \tag{3}$$

$$C^y_{self} = p^y_{capex}(Cap^y_{self} - Cap^{y-1}_{self}) + p^y_{opex}Cap^y_{self} \quad for\ y \geq 1. \tag{4}$$

We considered the year index for the unit price of CAPEX and OPEX for PV installation in the workplace. Moreover, it reflects that the CAPEX is considered for the additional installation capacity at a certain year index and OPEX is considered for the cumulative installation capacity. The unit prices of the CAPEX and OPEX depend on the year index.

(2) Electricity tariff from the utility rate system: The cost used in the utility rate system can be formulated as

$$C^y_{utility} = \sum_{d \in D} \sum_{h \in H} E^{y,d,h}_{utility}\, p^{y,d,h}_{tariff} \quad for\ y \in Y. \tag{5}$$

(3) Electricity procurement cost from corporate PPAs: The cost applied for the settlement using corporate PPAs can be formulated as

$$C^y_{ppa} = \sum_{d \in D} \sum_{h \in H} E^{y,d,h}_{ppa} p^{y,d,h}_{ppa} \quad for\ y = 0, \tag{6}$$

$$C^y_{ppa} = \sum_{d \in D} \sum_{h \in H} (E^{y,d,h}_{ppa} - E^{y-1,d,h}_{ppa}) p^{y,d,h}_{ppa} + C^{y-1}_{ppa}\ for\ y \geq 1. \tag{7}$$

Corporate PPAs facilitate off-site trading in the electricity market between the corporate buyer and owner of a renewable generation unit. The corporate buyer receives the electricity at a predetermined price during the contract period. However, corporate PPA trading may incur an imbalance between the contracted and delivered electricity because of unexpected interruption of work in the workplace or prediction errors in both generation and demand. In turn, the corporate buyer should pay the ancillary service payment. Moreover, it is considered that the corporate buyer should pay the network operator the network tariff, if the existing network is used through corporate PPAs.

As corporate PPAs require long-term contracts of approximately 10–15 years, it is required that the corporate buyer should purchase electricity at a constant price throughout the period. However, it should be considered that the electricity additionally procured is priced according to the unit price of the time, which should be constant for the remaining analysis period.

(4) Procurement cost of electricity from complementary supply: The cost function used for complementary supply can variously be formulated such as the direct purchase from the wholesale electricity market, or supplement from the utility. Therefore, the detailed formulation is omitted regarding complementary supply.

4.1.2. Certificate purchase

The cost used for the certificate purchase can be formulated as

$$C_{cert}^{y}=E_{cert}^{y}p_{cert}^{y}\quad for\ \forall y\in Y. \tag{8}$$

Certificate to verify renewable energy use can be obtained from unbundled EAC spot market and utility green pricing program. p_{cert}^{y} of Eq. (8) denotes the unit price from unbundled EAC or green premium from green pricing program. Moreover, E_{cert}^{y} is non-renewable electric energy to be additionally verified with the renewable certificate.

4.1.3. Additional elements

Additional cost and revenue should be considered for the corporate buyer, except the cost owing to electricity procurement and certificate purchase. The terms for the additional cost factor are explained in detail below.

(1) FEMS installation cost: The cost for FEMS installation can be formulated as

$$C_{fems}^{y}=p_{fems}^{y}u^{y}\quad for\ y=0, \tag{9}$$

$$C_{fems}^{y}=p_{fems}^{y}(u^{y}-u^{y-1})\quad for\ y\geq 1. \tag{10}$$

The corporate buyer has the option of using FEMS, which assesses the energy used by the enterprise, and monitors and controls the facilities at the workplace in real time for reducing the energy consumption. We additionally considered this system because it is a helpful option for RE100 by reducing the electricity consumption through energy efficiency.

The cost for FEMS installation comprises an installation cost and a binary integer indicating whether to install FEMS. It is sufficient to consider the cost only in the year when the FEMS was installed. Subsequently, it is assumed that the additional cost need not be considered.

(2) Residual value of fixed assets: If the fixed assets are constructed during the analysis period, it will be possible to normally operate these facilities even after the analysis period. Therefore, the residual value function can be formulated as

$$R_{res}^{y}=\frac{p_{fems}^{y}[N_{ls,fems}-(N_{yr}-y)]}{N_{ls,fems}}u^{y}+\frac{p_{capex}^{y}[N_{ls,sg}-(N_{yr}-y)]}{N_{ls,sg}}Cap_{self}^{y}\quad for\ y=0, \tag{11}$$

$$R_{res}^{y}=\frac{p_{fems}^{y}[N_{ls,fems}-(N_{yr}-y)]}{N_{ls,fems}}(u^{y}-u^{y-1})+\frac{p_{capex}^{y}[N_{ls,sg}-(N_{yr}-y)]}{N_{ls,sg}}(Cap_{self}^{y}-Cap_{self}^{y-1})\quad for\ y\geq 1. \tag{12}$$

The fixed assets are assumed to depreciate constantly every year during the installed life. Hence, the residual value function should be formulated according to the installation year and installed life of the fixed assets.

4.2. Constraints

The constraints in the achievement of RE100 by a corporate buyer are grouped into three parts, namely, binary decision constraints, electricity procurement constraints, and RE100 certification and demand constraints. These are explained in detail the following.

4.2.1. Binary decision constraints

The binary decision constraint can be formulated as

$$u^{y}-u^{y-1}\geq 0\quad for\ y\geq 1. \tag{13}$$

The notation u is the binary decision variable indicating whether FEMS should be installed. The constraint in Eq. (13) implies that once the FEMS is installed, it should be maintained during the analysis period.

4.2.2. Electricity procurement constraints

The electricity procurement constraints can be formulated as

$$Cap_{self}^{y}-Cap_{self}^{y-1}\geq 0\quad for\ y\geq 1, \tag{14}$$

$$0\leq Cap_{self}^{y}\leq Area\cdot Cap_{area}\quad for\ \forall y\in Y, \tag{15}$$

$$E_{self}^{y,d,h}=A_{self}^{y,d,h}Cap_{self}^{y}\quad for \forall y\in Y,\forall d\in D,\forall h\in H. \tag{16}$$

In the constraint expressed in Eq. (14), it is determined not to downsize the generator during the analysis period because the generator for self-generation is a fixed asset. However, it is possible to enhance the capacity of the generator. Moreover, the generator is supposed to be installed in the workplace by Eq. (15). Therefore, it is considered that the capacity of the generator depends on the installable capacity by area and area of the workplace.

$$0\leq E_{utility}^{y,d,h}\leq E_{load}^{y,d,h}(1-r_{fems}u^{y})\quad for\ \forall y\in Y,\forall d\in D,\forall h\in H. \tag{17}$$

The constraint in Eq. (17) is related to electricity procurement from the utility. The hourly quantity of electricity purchased from these sources is the decision variable, unlike the hourly electricity generation through self-generation. The quantity of electricity purchase should be lower than the amount of electricity consumption. In addition, if FEMS has been installed that year, the demand reduction rate due to FEMS should be considered.

$$0\leq E_{ppa}^{y,d,h}\leq E_{load}^{y,d,h}(1-r_{fems}u^{y})\quad for\ \forall y\in Y,\forall d\in D,\forall h\in H, \tag{18}$$

$$0\leq E_{ppa}^{y,d,h}\leq A_{re}^{d,h}Cap_{re}\quad for \forall y\in Y,\forall d\in D,\forall h\in H. \tag{19}$$

The constraint in Eq. (18) conveys that the electricity energy through corporate PPAs should be lower than the amount of electricity consumption. In addition, the constraint in Eq. (19) shows that the hourly amount of purchase is limited through the feasible maximal capacity multiplied by the capacity factor from renewable energy generators. In other words, if the amount of electricity used is more than the available electricity at a certain time, it will be taken as the upper limit through the feasible maximal capacity. In the inverse case, it will be taken as the upper limit through the amount of electricity consumption.

$$\sum_{d\in D}\sum_{h\in H}E_{ppa}^{y-1,d,h}\leq\sum_{d\in D}\sum_{h\in H}E_{ppa}^{y,d,h}\quad for\ y\geq 1. \tag{20}$$

It is limited not to be diminished than the amount of electricity purchased already in previous year through constraint (20). This reflects that corporate PPAs represent long-term fixed contracts.

4.2.3. RE100 certification and electricity demand constraints

The constraint related to RE100 certification and electricity demand can be formulated as

$$\sum_{d\in D}\sum_{h\in H}(E_{self}^{y,d,h}+E_{ppa}^{y,d,h})+E_{cert}^{y}\geq\sum_{d\in D}\sum_{h\in H}E_{load}^{y,d,h}r_{x}^{y}(1-r_{fems}u^{y})\quad for\ \forall y\in Y. \tag{21}$$

The corporate buyer should purchase the certificate for the quantity of electricity above the yearly demand to prove the use

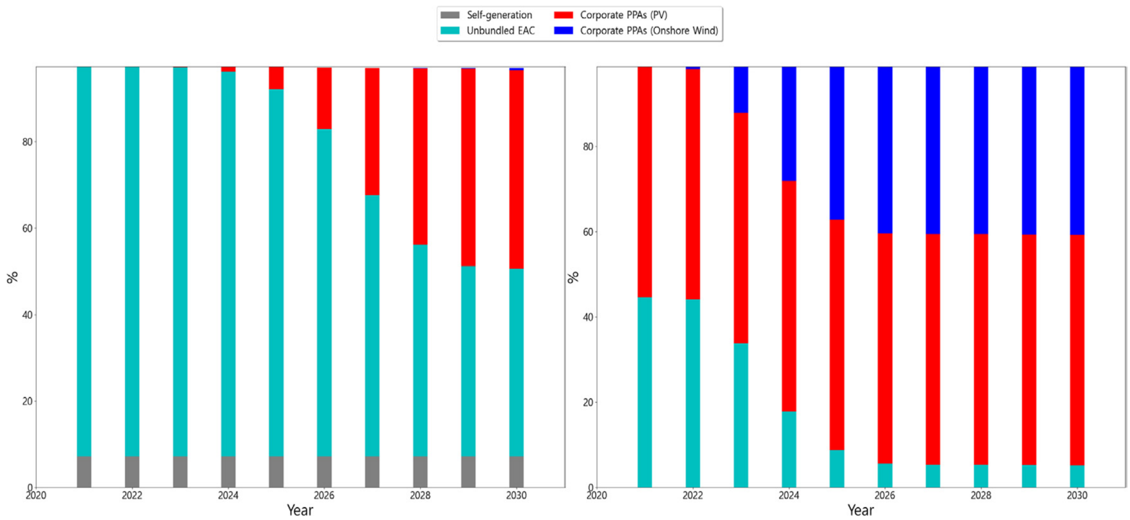

Fig. 1. Optimal portfolios for renewable electricity sourcing by year in Korea (left) and United States (right), respectively.

of renewable energy. Because the objective function is a cost minimization problem, it is expected that the quantity of energy for which the certificate is purchased should meet the lower limit. Further, we consider the demand reduction rate due to the installation of the FEMS.

$$E_{self}^{y,d,h} + E_{utility}^{y,d,h} + E_{ppa}^{y,d,h} \geq E_{load}^{y,d,h}(1 - r_{fems}u^{y})$$
$$for\ \forall y \in Y, \forall d \in D, \forall h \in H. \tag{22}$$

The constraint in Eq. (22) implies that the yearly total electricity from various procurement methods should be more than the yearly electricity demand. Because the hourly generation from self-generation can be higher than the hourly electricity demand, the equations utilize the inequality, not the equality.

5. Case study

This work used Monte Carlo simulation, which is a computer-based technique employing statistical sampling and probability distribution function (Johansen and Evers, 2007). The cost parameters, time horizon, and discount rate were incorporated into the Monte Carlo simulation to determine the net present value (NPV) of the optimal sourcing strategy for RE100. With this method, a case study was conducted considering the effects of uncertain parameters. This research conducted a thousand multi-dimensional simulations and extracted the uncertain parameters using a uniform distribution. Generally, electricity procurement costs and certificate purchase costs are considerably dependent depending on the unit price of the utility rate system and trading price of the certificate. Therefore, we identified and estimated various realistic and feasible parameters. Appendix provide complete details of identification and estimation of the parameters for the electricity procurement, certificate purchase, and additional elements. In addition, Tables A.2 and A.3 provide the parameters with uncertainty range and the initial parameters in tabulated form, respectively.

5.1. Optimal portfolios for renewable energy sourcing by year in Korea and United States

In Fig. 1, the x-axis is the year (2021–2030) and the y-axis is the share of the optimal sourcing strategy in the Monte Carlo simulation. This figure shows the share of the optimal instruments in renewable electricity sourcing for consumption by year.

In case of Korea (left), the results of selecting self-generation in the first year in all simulations are shown. This shows that the current level of construction cost of self-generation is lower than the sum of the cost of electricity procurement and renewable energy certificates. However, its share is constant at 7.16% during the analysis period due to limitations related to the availability of usable area. From 2021 to 2022, the sourcing strategy was to purchase all unbundled EAC except for self-generation. In turn, this also implies that choosing corporate PPAs between 2021 and 2022 is not a cost-effective approach. The choice of selecting a sourcing strategy through corporate PPAs appears from 2023, when the share is 0.13%. Subsequently, the proportion of corporate PPAs gradually increases and almost equals the purchase of unbundled EAC at 2029, when the share is 46.49%.

In case of United States (right), the results of selecting self-generation in all year are not shown. This shows that the sum of the cost of electricity procurement and renewable energy certificates is always lower than the construction cost of self-generation. Meanwhile, in United States, corporate PPAs through PV generator is already cost-effective than to be delivered electricity from utility. Although, in 2021 and 2022, the cost of corporate PPAs through onshore wind generator is relatively higher than the sum of the cost of the tariff from utility and unbundled EAC, the proportion of corporate PPAs gradually increases and takes up the bulk of portfolio. The major difference of the share of corporate PPAs in two countries come from that United States already reached to grid parity (Breyer and Gerlach, 2013), whereas did not in Korea (Chung, 2020).

Moreover, we analyzed the frequency of the FEMS installation decision from the Monte Carlo. FEMS installation decision largely occurred in 2021. Once FEMS for facility efficiency is installed, the electricity consumption of the factory undergoes constant annual reduction during the analysis period. Moreover, it shows that reducing the electricity consumption through FEMS installation can be a cost-effective strategy at the initial stage, as the price of renewable energy is comparatively high.

5.2. NPV result analysis by RE100 implementation time

Fig. 2 shows NPV of optimal sourcing strategy for immediate (left) and progressive (right) RE100 between 2021 and 2030 in Korea based on Monte Carlo simulation. In Fig. 2, the x-axis is the NPV result for RE100. The immediate RE100 (left) means that the corporate buyer achieves RE100 from the starting time

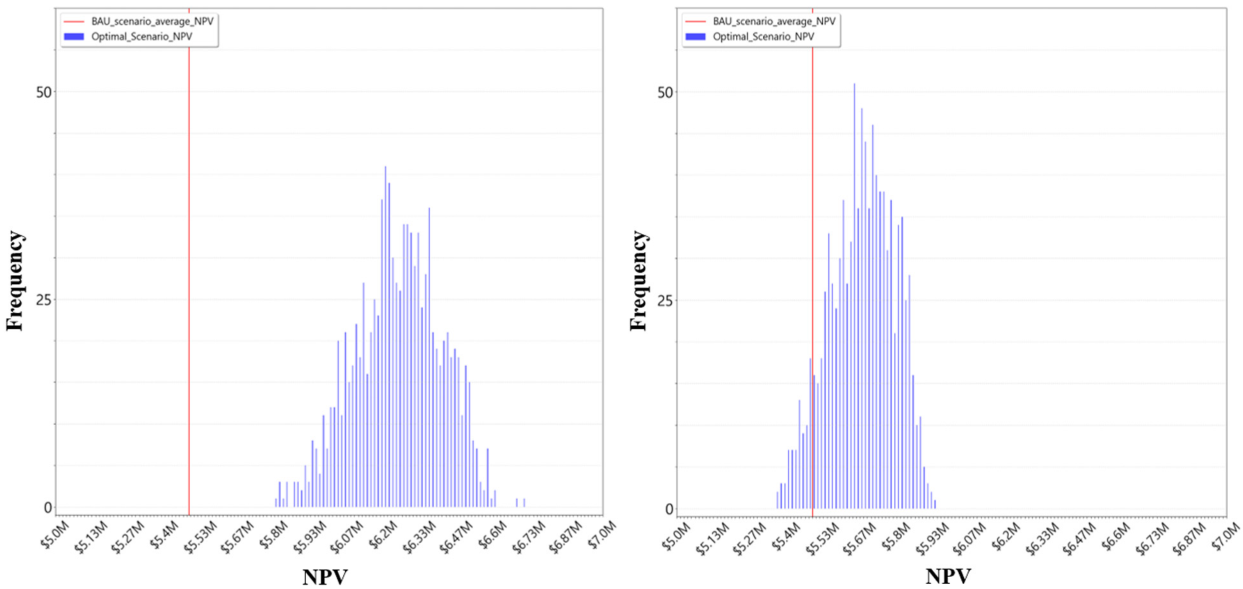

Fig. 2. NPV of optimal sourcing strategy for immediate (left) and progressive (right) RE100 in Korea.

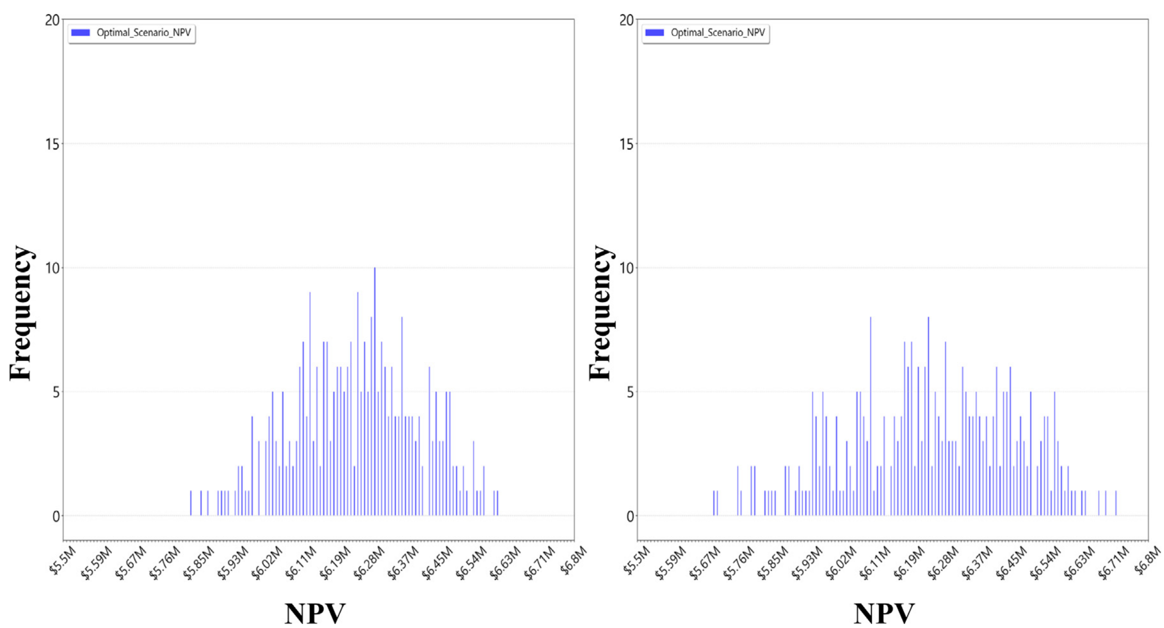

Fig. 3. NPV of optimal sourcing strategy for size of uncertainty range [100% (left), 200% (right)] in Korea.

to termination time of analysis. The progressive RE100 means that the corporate buyer achieves linearly from RE10 to RE100 (2021–2030). In Fig. 2, the bar graph is the frequency of the NPV result of 1000 trials from optimal sourcing strategy, and thin line indicates the average NPV result from Business as Usual (BAU) scenario, where the corporate buyer does not seek to RE100. In this analysis, it was assumed that the sample space of the input cost parameter would be in the form of a uniform distribution, and the NPV was estimated through random sampling. On the one hand, in the case of immediate RE100, the analysis shows that NPV resulted from RE100 is always higher than the average NPV resulted from BAU scenario. On the other hand, in the case of progressive RE100, the analysis shows that the probability that NPV resulted from RE100 is lower than the average NPV resulted from BAU scenario is 8.6%, which it implies that achieving RE100 progressively, not immediately, may be cost-effective than doing nothing as in the BAU scenario.

5.3. Sensitivity analysis based on size of uncertainty range

Fig. 3 shows the sensitivity analysis based on size of uncertainty range for the retail tariff of industrial customers between 2021 and 2030 in Korea based on Monte Carlo simulation. In Fig. 3, the bar graph is the frequency of the NPV result of 300 trials from optimal sourcing strategy. 100% (left) of existing uncertainty range is as with Table A.2. 200% (right) of existing uncertainty range means the twice of existing size. This figure shows that the variance of distribution becomes larger, as the size of uncertainty range becomes larger. This can be interpreted that the tariff level of utility rate system is sensitive to the path of RE100. We additionally conducted the sensitivity analysis regarding the size of uncertainty range for LCOE of PV and onshore wind, respectively. The result of analysis did not make significant difference between 100% and 200% of existing range. This can be interpreted that the existing uncertainty range that we set up in Table A.2 reflects sufficiently the uncertainty of price change.

6. Conclusion and policy implications

The optimal sourcing strategy analysis for RE100 of an enterprise supports the identification of a feasible electricity procurement approach and certification method for renewable energy use, which a corporate can utilize to take optimal decisions to achieve RE100. This study is recommended for corporates wishing to achieve RE100 cost effectively and for policy-makers wishing to develop helpful policies to assist corporates in implementing steps toward RE100.

This study presented reasonable and feasible combinations of strategies for corporates to achieve RE100 based on the electricity market of Korea and United States, respectively. Moreover, the range of uncertainty parameters was set based on the study on influential institutions. It was also concluded that the Monte Carlo simulation should be paired with optimal cost analysis when incorporating the risk and uncertainty of future cost parameters. By performing sensitivity analysis based on size of uncertainty range, it has been found that the retail tariff of industrial customers is sensitive to the path of RE100, whereas the LCOE is not.

This study showed that setting a plan for progressively achieving RE100 may be rational for corporates even compared with the case of doing nothing. In addition, when ambitious corporate tries to achieve RE100 immediately, purchasing the unbundled EAC after sourcing electricity from an existing utility ecosystem is the best option in Korea currently owing to the high unit price of renewable energy generation during the next few years. However, as renewable energy generation costs are falling, corporate PPAs will become the cost-effective option after a certain year, and corporations will increasingly disengage from utility ecosystem.

In the case of United States, the costs of corporate PPAs with PV generators was already lower than the sum of the cost of the tariff from utility and unbundled EAC from first time. However, owing to high contract price of corporate PPAs with onshore wind generator, optimal result from 2021 to 2022 was to procure electricity by selecting corporate PPAs with PV generators and utility rate system. The proportion of corporate PPAs gradually increases and takes up the bulk of portfolio. Moreover, additional supply except corporate PPAs is covered by utility rate system.

Most cost parameters used in the study were estimated based on reference or historical data. However, in the case of green pricing, owing to the short implementation term in Korea, it was not considered in our case study.

Although there are several approaches for renewable electricity sourcing, such as purchase from on-site installations owned by a supplier and a direct line to an off-site generator with no grid transfers, only critical approaches popularly used by global corporations were considered in this study because the use of the abovementioned approaches is less than 1% (The Climate Group and CDP, 2018).

Lastly, this study did not consider many practical things in real operation of electricity market and power system. The risk preference will affect the sourcing strategy and may be varying for companies. In addition, managing the imbalance caused by the trading outside spot market is important in practical power system operation. In the Korean electricity market, the imbalance from the renewable generation and corporate demand occurred in real time is managed by the system operator first, and then its cost is charged to the uplift payment of demand side. Even if we consider the payment in our formulation, it does not guarantee that the payment reflects real costs of imbalance from the renewable sourcing in a cost-causal way. Furthermore, consideration on the location of demand and supply for corporate sourcing is necessary in efficient system operation. There are the policy options to induce reasonable contract with consideration of location of demand and supply through locational wholesale price or locationally differentiated network tariff. For our future work, an advanced analysis reflecting various risks such as financing, policy change, risk preference of each corporate, location, and uncertainty in energy prices and electricity tariffs in formulation can be conducted.

Table A.1
Trend of the retail tariff of industrial customers for past 6 years (2015–2020).

Year	Price (USD $/kWh) in Korea	Price (USD $/kWh) in United States
2020	0.088925	0.07155
2019	0.089838	0.06454
2018	0.090954	0.06270
2017	0.092491	0.06456
2016	0.085738	0.06060
2015	0.077848	0.05464

CRediT authorship contribution statement

Ji Woo Lee: Software, Data curation, Writing – original draft. **Eo Jin Choi:** Investigation. **Min Ji Jeong:** Investigation. **Rodrigo Casamayor Moragriega:** Writing – review & editing. **Pilar Gascón Zaragoza:** Writing – review & editing. **Seung Wan Kim:** Conceptualization, Methodology, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix

(1) Self-generation

It is assumed that the annual CAPEX decreases in proportion to the LCOE reduction rate of PV. In case study, the land area that the corporate can install the PV generator is assumed 10 000 m^2. According to IRENA (2021), an area of 19 400 m^2 is required on a flat basis to install a 1 MW PV system. Based on the above reference, we set maximal PV installation capacity for self-generation to 515 kW. Moreover, we set CAPEX of PV to USD $940.4/kW and USD $1085/kW as initial price in Korea, United States, respectively (IRENA, 2021). In the case of OPEX of PV, we assumed 3% of CAPEX.

(2) Utility rate system

We set the retail tariff of industrial customers to USD $0.09348/kWh (GlobalPetrolPrices, 2021) and USD $0.0726/kWh (EIA, 2022) as initial price in Korea, United States, respectively. Moreover, the rates of increase during the analysis period were determined based on the historical rate trends. Table A.1 shows the trend of the retail tariff of industrial customers of Korea

Table A.2
Parameter values with uncertainty range.

Parameter category	Rate of change projected from 2021 to 2030	
	Korea	United States
LCOE change rate of PV	0.6921–0.7967	0.4653–0.8803
LCOE change rate of onshore wind	0.9011–0.9324	0.5473–0.8299
The change rate of the retail tariff of industrial customers	1.00–1.19	1.00–1.33
The change rate of yearly certificate price	0.6500–0.9885	0.5097–1.6839
FEMS investment cost	USD $229,775–USD $1,449,234–	
Energy reduction rate	0.032–0.064	

Table A.3
Initial parameter values.

Table network tariff	USD $0.002918/kWh	USD $0.013607/kWh
Ancillary service payment	USD $0.01109/kWh	USD $0.01279/kWh
The certificate price	USD $0.0332/kWh	USD $0.0066/kWh
Analysis periods	10 years (2021–2030)	
Load profile	Real demand data of Korea	
Discount rate	0.045	
Life span for PV	20 years	

and United States in the last 6 years. By applying linear regression to these trends, it was found that the industrial electricity bill will increase by 20% and 33% after 10 years on Korea and United States, respectively. In addition, the uncertainty in the rate of increase was considered by sampling from the uniform distribution.

(2) Corporate PPAs

Corporate PPAs should consider the contract price for the purchased electricity, including ancillary service payment and network tariff. The contract price can be determined by the corporate buyer and generator owner by considering various factors. Based on the historical data, we set the contract price with the PV owner to USD $0.036/kWh and onshore wind owner to USD $0.052/kWh in United States. However, in Korea, owing to absent data, we set the contract price with the PV owner to USD $0.1022/kWh and onshore wind owner to USD $0.1150/kWh based on each LCOE in 2020.

When purchasing directly outside the electricity market, additional costs must be considered. The ancillary service payment and network tariff were applied in the case of Korea (KEPCO, 2021) and United States (Zhou et al., 2016; California ISO, 2021) from reliable references.

Furthermore, it can also be assumed that the contract price for corporate PPAs will decrease as the LCOE of PV and onshore wind sources decreases over time. Accordingly, the annual contract price was determined by applying the rate of LCOE reduction to the contract price for the first year.

(3) Certificate purchase

The certificate purchase cost for RE100 certification depends on the unit price of unbundled EAC and the green premium price. We considered only the unit price of unbundled EAC except for green pricing owing to the short implementation term of green pricing in Korea.

To understand the trend of unbundled EAC, this study identified the REC price trend from March 2016 to July 2021 of Korea (Korea Power Exchange, 2021) and the voluntary national REC prices from January 2012 to August 2018 of United States (NREL, 2018). In this study, the REC yearly change rate was calculated after estimating the annual average REC price for each historical data. After that, the yearly change rate was extracted probabilistically using the minimum and maximum values of the change rate during the analysis period through uniform distribution. Then, the yearly average REC price was estimated from the yearly change rate. In the case of the first year of the REC, the average unit price of the last year was applied to the unit price.

(4) Additional elements

The FEMS investment cost and energy reduction rate should be determined. In the case of the FEMS, the investment cost may vary depending on the energy reduction rate targeted by the company, and different investment costs will be required depending on how the demand is reduced. In this study, the FEMS investment cost and energy reduction rate for each industry and business site, proposed by Huh (2018), were collected. Then, the parameters were determined through sampling from the uniform distribution using the minimum and maximum value.

Lee and Kim (2020) predicted the LCOE change rate for PV and onshore wind power from 2020 to 2030 in the case of Korea. Similarly, Vimmerstedt et al. (2022) predicted LCOE change rate for utility-scale PV and land-based wind in the case of United States. In this study, it was estimated that the LCOE of utility-scale PV will decrease by 20.3–30.8% in Korea and by 11.97–53.47% in United States. In addition, the LCOE of onshore wind was expected to decrease by 6.76–9.89% in Korea and by 17.01–45.27% in United States. Additionally, the range of the reduction rate was sampled from the uniform distribution. Then, assuming that the LCOE decreased linearly during the analysis period, the LCOE decrease rate by year was estimated.

The analysis period was assumed to be 10 years, and an annual discount rate of 4.5% was used. In addition, the demand pattern of the corporate buyer was extracted from Korea's automatic meter reading data based on hourly electricity consumption in the manufacturing industry. The maximum demand for electricity during the year was assumed as the installed capacity. After estimating the capacity factor, it was preprocessed and used as the demand pattern of the company with the installed capacity of 1 MW.

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